Mechanisms to improve fuzz testing for message brokers

Luis Gustavo Araujo Rodriguez

Thesis presented to the
Institute of Mathematics and Statistics
of the University of São Paulo
in partial fulfillment
of the requirements
for the degree of
Doctor of Science

Program:	Computer Science
Advisor:	Prof. Dr. Daniel Macêdo Batista

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, and by CNPq (grant 381249/2022-0).

São Paulo
September, 2023

Mechanisms to improve fuzz testing for message brokers

Luis Gustavo Araujo Rodriguez

This PhD thesis is dedicated to my dear and beloved mother, Dilma Nereyda Rodriguez Saravia. I love you mom.

Acknowledgments

La grandeza de una persona no esta en su superficie, sino en las Honduras de su alma y mente.

First and foremost, I thank God for giving me the opportunity to pursue and complete the doctoral program. I can not thank you enough for so many blessings I have received throughout my life. Thank you for making my dream come true, and for giving me the experience of a lifetime at the University of São Paulo. I also want to thank God for my wonderful family and friends.

I would like to thank my family, whose support was one of the driving forces behind my hard work and dedication. Thank you to my dear and beloved mother, Dilma Nereyda Rodriguez Saravia, for her hard work and huge sacrifice in order to give me a good education. Thank you for loving me despite my imperfections, and for always putting my happiness, future, dreams, ambitions, and well-being first rather than your own. I can not thank you enough for everything you have done for me, and I promise that no matter what happens I will continue making you proud. This thesis is dedicated to you because I know that I would not have been able to even apply to a doctoral program without your unconditional and everlasting love. I am so incredibly blessed to have you as my mother, and I hope that my accomplishments brought joy and happiness into your life. Thank you to my sister, Nereyda Maria Araujo Rodriguez, for the support during the graduate studies. Thank you to Katie Thompson, a family member, true friend, and incredible mentor who has supported me since my childhood. Thank you Katie for believing in me and caring about my future. I am incredibly honored and grateful to have you always by my side. Thank you to my aunts and uncles for looking out for me. Thank you to my aunt Miriam Rodriguez for her generosity. Thank you to my aunt Josefa Rodriguez for her compassion. Thank you to my aunt Alba Rodriguez for always lending a helping hand. Thank you to my uncle Carlos Rodriguez for teaching me the importance of education for both personal and professional growth. Thank you to my aunt Norma Saravia for taking care of me when I was young. Thank you to my uncles Luis Rodriguez and Rafael Soto for the conversations.

Thank you to my cousins Yami Soto, Paulina Rivera, Samuelito Rivera, Samuel Rivera, Larissa Soto, Nelson Rodriguez, and Fanny Rodriguez for being by my side through tough times. Thank you to Martha Andino for being such a kind-hearted person to my family. Thank you to Vilma Bonano for being so supportive of my decision to pursue a doctoral degree. Thank you to Ricardo Cervantes for teaching me the importance of aspirations and goals in life. Thank you to Jenny Giron, Mariela Giron, and Mirna Cano for being extremely generous whenever I needed assistance. Thank you to Norma Rivera for always having my back.

In addition to my family, there are so many people that played a *key* role in my journey towards finishing the doctoral degree. I want to thank my wonderful friends that I had the pleasure of meeting at the University of São Paulo. Thank you to Thamillys Marques, the first friend I made at the university, for providing the necessary strength to overcome all the challenges faced during the first years of the doctoral program. Thank you to Carlos Enrique Paucar Farfan for the comforting words to handle stressful situations. Thank you to Erik Miguel de Elias for always taking the time off to have stress-reducing conversations over a cup a coffee. Thank you to Fatemeh Mosaiyebzadeh for always reassuring me that I was going to earn the doctoral degree. Thank you to Felipe Caetano Silva and Julio Kenji Ueda for reducing my anxiety with humor, laughter, video games, and subway sandwiches. Thank you to Antônio Kaique Barroso Fernandes for always showing friendliness and generosity towards me. Thank you to Guilherme Vieira dos Santos for being so kind and supportive during the writing process of this thesis. Thank you to Igor Moreira Félix and his family for their trust and company during the COVID-19 pandemic. Thank you to Bernardo Martins, Gabriel Morete, Lucas Stankus, Marcelo Schmitt, Matheus Tavares, Pedro Siqueira, Pedro Arraes, Renato Cordeiro Ferreira, Thiago Lima Oliveira, and Ygor Requenha Romano for their friendliness towards me. Thank you to Priscila Lima for helping me to overcome self-doubt.

I especially wanted to thank the following friends who have made such a profound and positive impact on my life. I will forever cherish the moments we shared at the University of São Paulo. In particular, I will always remember how we persevered and supported one another in order to earn our graduate degrees. Thank you to Danilo Pereira Escudero for giving me hope and strength in moments of despair. Thank you to Douglas Chagas da Silva for always helping me whenever I was struggling in life. Thank you to Luiz Felipe Fronchetti Dias for always supporting me, despite the distance. Thank you to Luiz Henrique Neves Rodrigues for being a friend I could rely on anytime and anywhere. Thank you to Mairieli Santos Wessel for always wanting the best for me. Thank you to Samuel Plaça de Paula for always being by my side on this long and arduous journey; and for being an encouraging, a dependable, a humorous, and most importantly, a true friend. I am truly happy for your constant presence in my life. Thank you to Thatiane de Oliveira Rosa, my loyal companion on this journey since the first day of the doctoral program. Thank you for lifting me up everytime I felt life was dragging me down. We have endured many hardships together, and I am incredibly lucky and blessed to have you by my side helping me to overcome every obstacle in my life. Thank you for the real and wonderful friendship you have given me.

Thank you to my friends at the Regional Center of Environmental Documentation and Interpretation (CREDIA), which is an institute that taught me so much about the importance of discipline and hard work. Thank you to Gaby Montoya for always making me laugh and feel calm despite all the hardships and challenges faced over the last few years. Thank you to Miriam Elisa Lopez Rosales for being a major support system throughout the doctoral studies; for always believing in my capabilities, and encouraging me to face my fears and to never give up on my dreams. I would not have gotten to where I am today without your guidance and friendship.

I also would like to thank my dear friends from Colombia that have supported me ever since we met in Maringá. Thank you to David Fernando Posso Suarez for always providing me with words of encouragement whenever I needed them the most. Thank you to Yessica Acosta Urian for the everlasting support, continuous presence, and real friendship provided during stressful times.

I'd also like to thank my friends from the Catholic University of Honduras for being so supportive and understanding since pursuing my graduate studies. A special thanks to Cindy Montoya, Diana Calix, Debby Martinez, Hector Pallares, Jeny Aguilera, Karen Rodriguez, Karen Pinto, Kenia Gutierrez, Mariela Raudales, Rony Fiallos, Sory Streber, and Tiffany Coca.

I'd also like to express gratitude to my friends from La Ceiba Bilingual School. Thus, thank you to Andrea Galindo, Carlos Fermin Arellano Oliva, Cinthia Klarissa Corea Santos, Jonathan Villafranca, and Rodrigo Sabillon for their continuous presence and support in my life.

This thesis would not have been possible without the unconditional support and valuable guidance from Prof. Dr. Daniel Macêdo Batista, my advisor, who I have had the pleasure of collaborating with for five years. Thank you for the lessons learned, patience, and most importantly for the belief that I could undertake this research project. It was a great honor conducting research with you, and I hope we can continue working together in the future.

I'd also like to thank my professors at the Institute of Mathematics and Statistics who have imparted so much knowledge and wisdom in order to better hone my skills as a researcher. Thank you to Prof. Dr. Fabio Kon for supporting me financially, and caring about my future. Thank you to Prof. Dr. Jose Coelho de Pina Junior for the engaging and insightful conversations during our lunch breaks. Thank you to Profa. Dra. Kelly Rosa Braghetto for being so kind and supportive to me. Thank you to Prof. Dr. Leônidas de Oliveira Brandão for the positive messages during the COVID-19 pandemic.

Thank you to my examining committee, Profa. Dra. Michelle Wangham, Prof. Dr. Alfredo Goldman, Prof. Dr. Fabio Costa, and Prof. Dr. Lucas Cordeiro for their valuable and insightful suggestions to improve the doctoral thesis.

I also would like to thank employees at IME-USP for their support and kindness. Thank you to the security personnel who always kept me company, especially during the difficult times of the COVID-19 pandemic. In that regard, thank you to Alice Ferreira, Daniel Jeferson, Denilson Ribeiro, Fatima Silverio, Gabriel Flores, Gabriela Borges, Guilherme Almeida, José Geraldo, Jozined Ferreira, Kaique Gustavo, Ketreson Silva, Rosineide Dias, Leandro Maia, Luan Carlos de Jesus, Lucimar Ribeiro, Manuel Izau, Marcone da Silva, Milton Rafael, Thiago Wesley, Valuquira Fernandes, and Wendell Augusto.

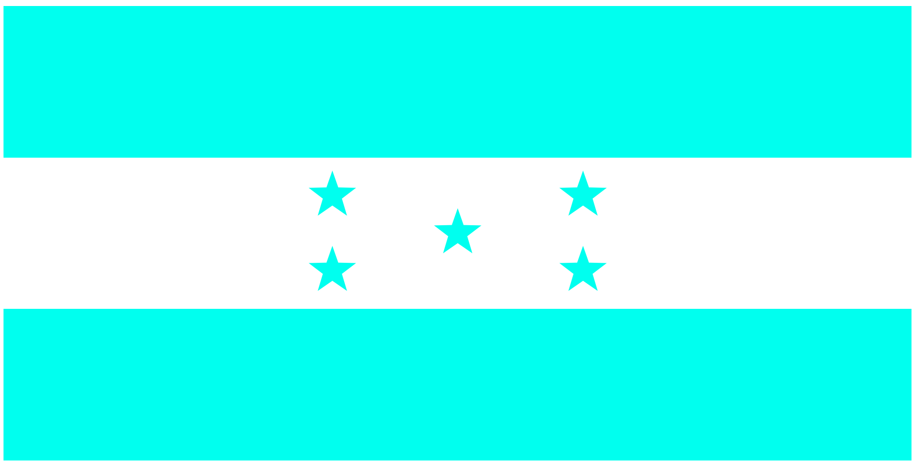
I also want to deeply thank the library staff of the Institute of Mathematics and Statistics for their constant support, kindness, and friendship during my last few months as a PhD candidate. Thank you to Maria das Graças Silva de Lima for always taking the time to listen to my worries, and providing the necessary words to ease my fears. Thank you to Ricardo Vila Real Tanaka for being so kind and willing to help me focus on the doctoral studies. Thank you to Daniel Feltrin Amaral for always providing assistance whenever I needed it.

I would like to thank the staff of the graduate program in computer science for their crucial assistance throughout the doctoral studies, especially in the months leading up to the defense. Thank you to Katia Kiesshau for the patience, advice, and kindness whenever I had inquiries about the PhD program. Thank you to Luiza Ribeiro Camilo da Silva for also always willing to help me in times of need. Thank you to Ana Carla de Souza, Cristiane de Fátima Braulino, and Edina Arouca for always caring about my well-being during the doctoral studies.

I could not leave out the professors and employees from the State University of Maringá who encouraged me to send my application to the University of São Paulo. Thank you to Prof. Dr. Anderson Faustino da Silva, my Master's advisor, for inspiring me with words of wisdom and teaching me the importance of self-improvement, perseverance, and critical thinking. The lessons learned from you played a big role in preparing me for the doctoral studies. Thank you to Prof. Dr. Elvio João Leonardo and Prof Dr. Nardênio Almeida Martins for their unconditional support and trust in me. Thank you to Inês Laccort for the friendship, encouragement, and support during the difficult times of my graduate studies. Thank you to Elenir Voi Xavier, my portuguese teacher and friend, for always believing in me. Thank you to Denise Dalcol for the friendship we have maintained after earning our Master's degrees.

Thank you to CAPES and CNPq (grant 381249/2022-0) for the financial support, which was crucial for the completion of this thesis.

Finally, thank you to everyone who has supported me on this incredible journey. I am truly honored and blessed to have known every single one of you, and to have represented my home country Honduras for the last couple of years.



Resumo

Luis Gustavo Araujo Rodriguez. **Mecanismos para melhorar testes fuzzing em brokers de mensagens**. Tese (Doutorado). Instituto de Matemática e Estatística, Universidade de São Paulo, São Paulo, 2023.

Os protocolos de publicação-assinatura têm desempenhado um papel fundamental no sucesso da Internet das Coisas. À medida que a Internet das Coisas se expande para novos usuários e ambientes, a necessidade de testar melhor os protocolos de publicação-assinatura torna-se ainda maior. No entanto, a área de testes para protocolos publicação-assinatura é pouco explorada, com poucos estudos que examinam estratégias eficazes para aumentar a confiabilidade e a robustez de *brokers* de mensagens contra pacotes malformados. Considerando que diversas falhas descobertas nos *brokers* são por causa de pacotes malformados, testes baseados em *fuzzing* surgiram como uma das técnicas mais importantes para mitigar esse problema. No entanto, o *fuzzing* enfrenta muitos desafios quando aplicado aos protocolos de publicação-assinatura, que se distinguem de outros protocolos por sua funcionalidade de publicação de mensagens e arquitetura orientada a eventos. Isso levanta a questão sobre se os desenvolvedores e as ferramentas baseadas em *fuzzing* (ou *fuzzers*) estão considerando os atributos exclusivos do padrão publicação-assinatura na hora de realizar os testes. O objetivo desta tese de doutorado é apresentar estratégias eficazes de *fuzzing* para os protocolos de publicação-assinatura, com o objetivo de contribuir para o desenvolvimento de aplicações mais robustas na Internet das Coisas e Cidades Inteligentes. De acordo com as pesquisas preliminares, há uma falta de abordagens sistemáticas baseadas em *fuzzing* na literatura para testar os protocolos de publicação-assinatura. Além disso, MQTT se destaca como o protocolo de publicação-assinatura mais popular para o qual os desenvolvedores propuseram técnicas de *fuzzing* na literatura. Por tanto, MQTT oferece uma oportunidade de entender os requisitos e estratégias para testar efetivamente um protocolo de publicação-assinatura. Esta pesquisa de doutorado foi dividida em três fases. Na primeira fase, foi analisado se uma abordagem de *fuzzing* baseada em gramática pode ser aplicada a um protocolo de publicação-assinatura, entendendo assim os desafios e requisitos necessários. Assim, foi proposta uma metodologia e arquitetura para desenvolver um fuzzer baseado em gramática para testar um protocolo de publicação-assinatura. O resultado final é um fuzzer chamado `MQTTGRAM`, que foi então comparado com duas outras abordagens de *fuzzing*, e superou ambas, apesar de realizar menos testes. Na segunda fase, foi desenvolvida uma taxonomia que classifica todas as técnicas de *fuzzing* existentes para MQTT, das quais seis foram avaliadas em condições equivalentes para determinar se os desenvolvedores estão considerando os atributos exclusivos do padrão publicação-assinatura na hora de realizar os testes. Além disso, os fuzzers para MQTT foram avaliados em termos de testes de estresse. Na terceira fase, `MQTTGRAM` foi aprimorado, incorporando três elementos essencias para testar os protocolos de publicação-assinatura: comunicação bidirecional; conhecimento de tópicos; e suporte a múltiplas versões. Esta pesquisa de doutorado fornece três contribuições principais: (1) o desenvolvimento e aprimoramento de uma abordagem de *fuzzing* baseada em gramática para um protocolo de publicação-assinatura; (2) taxonomia e avaliação de desempenho de *fuzzers* para MQTT em condições equivalentes; e (3) identificação de deficiências dos *fuzzers* para trabalhos futuros.

Palavras-chave: Publicação-assinatura. Fuzzing. Testes. Protocolos de Rede. Broker de Mensagens. MQTT. IoT.

Abstract

Luis Gustavo Araujo Rodriguez. **Mechanisms to improve fuzz testing for message brokers**. Thesis (Doctorate). Institute of Mathematics and Statistics, University of São Paulo, São Paulo, 2023.

Publish/subscribe (or pub/sub) protocols have played a *key* role in the success of the Internet of Things. As the Internet of Things expands to new users and environments, the need to better test pub/sub protocols becomes even more pressing. However, pub/sub protocol testing is an under-explored field, with few research studies examining effective strategies to increase the reliability and robustness of message brokers against malformed packets. Considering that several bugs discovered in message brokers are related to malformed packets, fuzz testing (or fuzzing) has emerged as one of the most promising, necessary, and ideal techniques to mitigate this issue. However, fuzzing faces many challenges when applied to pub/sub protocols, which distinguish themselves from other network-based systems by their message-publishing features and event-driven architecture. This poses the question as to whether developers and existing fuzz testing tools (or fuzzers) consider the unique attributes of the pub/sub messaging pattern. The objective of this PhD thesis is to study and develop effective fuzzing strategies for pub/sub protocols, aiming at contributing to the development of more robust applications in IoT and Smart Cities. According to the research findings, there is a lack of *systematic* approaches in the literature to fuzz-test pub/sub protocols. Furthermore, MQTT stands out as the most popular pub/sub protocol for which developers have proposed fuzzing techniques in the literature. However, as MQTT is the most widely-used pub/sub protocol, it provides an opportunity to understand the requirements and strategies to effectively fuzz a pub/sub protocol. This PhD research was divided into three phases. In the first phase, it was analyzed whether a systematic testing approach such as grammar-based fuzzing can be applied to a pub/sub protocol such as MQTT, thereby understanding the challenges and necessary requirements. A grammar-based methodology and architecture was therefore conceived and proposed for a pub/sub protocol. The end result is a fuzzer called `MQTTGRAM`, which was then compared with two other fuzzing approaches and outperformed both of them, despite exchanging up to 9x fewer packets. In the second phase, a taxonomy was developed that classifies *all* existing fuzzing techniques for MQTT, six of which were evaluated under equivalent conditions in order to determine whether developers are considering the unique attributes of the pub/sub design pattern. Furthermore, the fuzzers were evaluated in terms of their resource usage or stress-testing capabilities. In the third phase, `MQTTGRAM` was improved by incorporating three essential elements for pub/sub protocol fuzzing, which are lacking across all fuzzing techniques proposed for MQTT: two-way communication; topic awareness; and version support. Overall, this PhD research provides three main contributions: (1) the development and refinement of a grammar-based fuzzing approach for a pub/sub protocol; (2) taxonomy and performance evaluation of MQTT fuzzers under equivalent conditions; and (3) identification of shortcomings for future work.

Keywords: Publish-subscribe. Fuzzing. Testing. Network Protocols. Message Broker. MQTT. IoT.

List of Abbreviations

ACL	Access Control Lists
AMQP	Advanced Message Queuing Protocol
CoAP	Constrained Application Protocol
DDS	Data Distribution Service
DoS	Denial of Service
DTLS	Datagram Transport Layer Security
HTTP	Hypertext Transfer Protocol
IETF	Internet Engineering Task Force
IME	Institute of Mathematics and Statistics
IoT	Internet of Things
ITS	Intelligent Transportation Systems
M2M	Machine-to-Machine
MQTT	Message Queuing Telemetry Transport
NVD	National Vulnerability Database
OASIS	Organization for the Advancement of Structured Information Standards
OMG	Object Management Group
Pub/Sub	Publish/Subscribe
QoS	Quality of Service
SDK	Software Development Kit
TCP	Transmission Control Protocol
TLS	Transport Layer Security
UDP	User Datagram Protocol
USP	University of São Paulo
XMPP	Extensible Messaging and Presence Protocol

List of Figures

List of Tables

Contents

Appendixes

Chapter 1

Introduction

For decades, Smart Cities have been envisioned as technologically advanced urban areas that offer automated, efficient, and immersive services to their citizens (Zanella *et al.*, 2014). Smart Cities began merely as a proof of concept, but have recently taken off after the rise of the Internet of Things (IoT). The objective of a Smart City is to improve the lives of its citizens through the use of information and communication technologies. However, the heterogeneous and ubiquitous environments of a Smart City demand a *flexible* messaging model capable of withstanding the multitude of requests from its citizens. In that regard, the traditional client-server model is unsuitable for Smart Cities because the server provides information *only* upon receiving client requests. This could result in the server receiving far too many simultaneous requests than it can handle, possibly leading to a city-wide denial of service.

The publish/subscribe (pub/sub) messaging model mitigates this issue to a certain degree by allowing the server to provide information *automatically* without the need for a client request. In order to accomplish this task, clients subscribe to a topic of their choice, receiving new and updated messages from the server automatically at any given moment. The pub/sub messaging model is therefore integral to the realization of Smart Cities, whose success relies heavily on automated services. In contrast to their traditional client-server counterparts, pub/sub networks usually have *three* main components: (1) subscriber, (2) publisher, and (3) broker. The latter component is *the* most important to the success of the network, and it is responsible for receiving messages from publishers and sending them to interested subscribers.

For example, Figure 1.1 presents an IoT scenario in which temperature sensors and light sensors act as publishers. Both types of sensors inform their status (ON) to a ventilation and illumination system, which act as interested subscribers. For clarity purposes, publishers and their respective subscribers are highlighted in the same colors. The broker acts as an intermediary between the publishers and subscribers, receiving messages from the former component and sending them to the latter.

Although successful, the pub/sub messaging model introduces several challenges that have yet to be studied or addressed. Most notably, adapting client-server applications, frameworks, and testing techniques to the pub/sub model requires further research efforts. In fact, *pub/sub protocol testing* is a field that is extremely important, yet somehow unex-

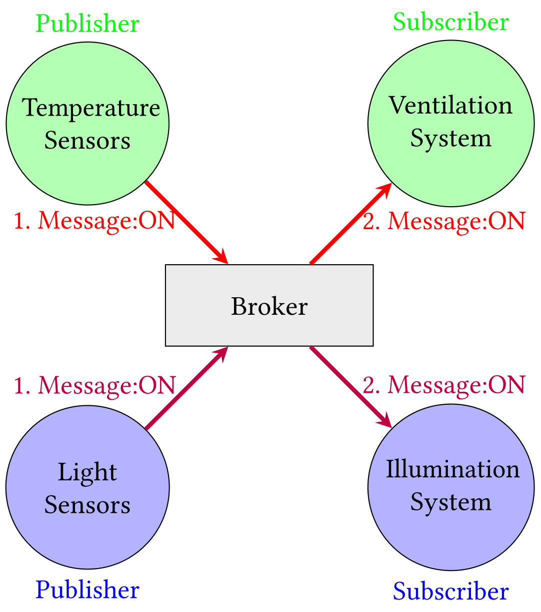


Figure 1.1: *Components of a Pub/Sub Network*

plored and neglected to a certain extent in the literature. This research gap is especially worrisome when considering that the majority of bugs found in message or pub/sub brokers are related to malformed packets (Araujo Rodriguez and Macêdo Batista, 2020), most of which are officially disclosed several days after their discovery (Araujo Rodriguez, Selvatici Trazzi, *et al.*, 2018). In addition to vulnerability disclosure delays, deploying and applying patches to pub/sub brokers in real-world environments is usually complex due to either their location or lack of auto-update functionality (Husnain *et al.*, 2022).

The root cause of these problems stems from the heavy emphasis placed on functionality rather than security in IoT (Săndescu *et al.*, 2018), meaning that pub/sub protocols tend to be *insecure by design* and unreliable in large-scale areas such as Smart Cities. In fact, *insecure design* and *injection* are two of the most common causes of vulnerabilities globally (OWASP, 2021). Insecure design refers to weak protocol implementations with design flaws, whereas injection refers to untrusted inputs. Specifically, weak protocol implementations are considered to be the most serious security threat in IoT (Munea, Lim, *et al.*, 2016; Munea, Luk Kim, *et al.*, 2017; Makhshari and Mesbah, 2021; Husnain *et al.*, 2022), potentially exposing smart applications to catastrophic cyberattacks.

All of the aforementioned issues can be mitigated or avoided altogether with effective testing mechanisms for pub/sub brokers. In that regard, one of the most ideal and necessary testing techniques for pub/sub protocols is *fuzzing* (Luo *et al.*, 2018; Praveen *et al.*, 2023), which consists in generating and sending random inputs to a message broker. The output of the broker is then analyzed for potential weaknesses. Fuzzing emerged in the early 1990s as an effective testing strategy for `UNIX` utilities (Miller *et al.*, 1990). The success of fuzzing led to its application across several target systems, including network protocols. Fast forward to the present, and pub/sub protocol fuzzing is an under-explored field, with few research studies examining effective strategies to increase the reliability and robustness of message brokers against random or malformed packets.

1.1 Objectives of Doctoral Studies

Considering the important role of message brokers and their susceptibility to malformed packets, the objective of this PhD research is to study and develop effective fuzzing strategies for pub/sub protocols, aiming to contribute to the development of more robust applications in IoT and Smart Cities. This PhD research focuses specifically on fuzzers for *broker-side* implementations of pub/sub protocols because of their *primary* and *critical* role in the network. In order to satisfy the objective of this doctoral research, a preliminary study was first conducted to examine the advancements and trends of pub/sub protocol fuzzing since its inception. The research findings of the preliminary study revealed two important findings. First, at the time of writing, the Message Queuing Telemetry Transport (or *MQTT*) stands out as the *only* pub/sub protocol for which developers have proposed *several different* fuzzing techniques in the literature. Second, there is a lack of *systematic* approaches in the literature to fuzz-test pub/sub protocols (Araujo Rodriguez and Macêdo Batista, 2020). Considering the preliminary studies, the research questions formulated for the doctoral studies are as follows:

> *RQ1: How can a grammar-based fuzzer for a pub/sub protocol such as MQTT be developed?*

Research Gap: As their name suggests, *grammar-based fuzzers* generate test cases by using a grammar, which describes the syntax and structure of an input (or packet in the case of network protocols). Despite being renowned as one of the most effective testing strategies for network protocols (Godefroid *et al.*, 2017), grammar-based fuzzing has been avoided in favor of other alternatives throughout the years due to its complicated nature (Hernández Ramos *et al.*, 2018; Sochor *et al.*, 2020b). The situation is further aggravated by the fact that there are no sources explaining how to adapt grammar-based fuzzing to pub/sub protocols. Thus, the goal of *RQ1* is to propose and explain a grammar-based methodology and architecture for a pub/sub protocol, which can be used as a reference by developers and researchers in future studies.

> *RQ2: What fuzzing techniques have been proposed for MQTT over the last few years?*

Research Gap: Research on MQTT fuzzing has grown considerably, with several different techniques found across the literature, more so than for any other IoT or pub/sub protocol. Thus, the goal of *RQ2* is to develop a taxonomy based on fuzzing techniques proposed for MQTT across *all* research studies. The taxonomy can be used by researchers to either gain a better understanding of advancements in the field for future studies, or benchmark each technique for the most optimal decision-making.

> *RQ3: How effective are fuzzing frameworks for MQTT in terms of their testing and pub/sub capabilities?*

Research Gap: The current state of the art lacks a comprehensive performance comparison between MQTT fuzzers. The problem stems from the fact that few research papers on MQTT fuzzing consider traditional testing metrics (Zeng *et al.*, 2020; Sochor *et al.*, 2020b; Araujo Rodriguez and Macêdo Batista, 2021). Moreover, fuzzing performance is measured differently across research studies, either by calculating the number of paths (path coverage) or statements (statement coverage) executed in the source code, thereby hindering a comparison. The situation is further aggravated when considering that there are no standardized methods or metrics in the literature to evaluate fuzzers for pub/sub protocols such as MQTT. This research gap also raises the question of whether developers are considering the *unique* characteristics of the pub/sub design pattern when building their own fuzzers. The goal of *RQ3* is to examine open-source MQTT fuzzers in terms of their testing and pub/sub capabilities, identifying shortcomings and missteps by developers for the aforementioned design pattern.

> *RQ4: How effective is an MQTT fuzzer when considering three essential elements for pub/sub fuzzing: two-way communication capabilities; topic awareness; and multiversion support?*

Research Gap: Regardless of their technique, MQTT fuzzers are essentially pub/sub test suites, whose overall goal *should* be to cover functionalities pertaining to the unique attributes of the design pattern. In that regard, developing an effective and high-coverage fuzzer for MQTT or any other pub/sub protocol requires a keen focus on *message publication*, which is not only the most defining, distinguishing, and important feature of the broker, but also the most computationally intensive. However, the research findings indicate that *all* fuzzers have shortcomings in regards to pub/sub protocol testing. The goal of *RQ4* is to improve an existing MQTT fuzzer by incorporating three essential elements for successful pub/sub fuzzing: (1) two-way communication capabilities; (2) topic awareness; and (3) multiversion support.

> *RQ5: How effective are existing fuzzing strategies at impacting the CPU and memory usage of the broker during testing?*

Research Gap: At the time of writing, *none* of the open-source MQTT fuzzers are capable of receiving resource-related feedback about the broker during testing. Developers have no choice but to select and extend one of the open-source fuzzers available for testing purposes. It is therefore important for developers to understand the capabilities of each option available. The goal of *RQ5* is to survey, benchmark, and evaluate existing state-of-the-art fuzz testing tools for MQTT brokers to determine their capabilities in detecting CPU- and memory-consumption bugs. In order to move the state of the art forward, shortcomings and guidelines will be provided for developers to build better resource-heavy fuzzers for MQTT brokers in Smart Cities.

It is worth noting that all of the aforementioned research questions arose sequentially throughout the doctoral studies, rather than all at once. In other words, the findings of an experiment led to another research question, and so forth.

1.2 Phases and Contributions of Doctoral Studies

Based on the five research questions, the doctoral studies consisted of three phrases. Figure 1.2 presents an overview of the research activities performed for each phase throughout the doctoral studies.

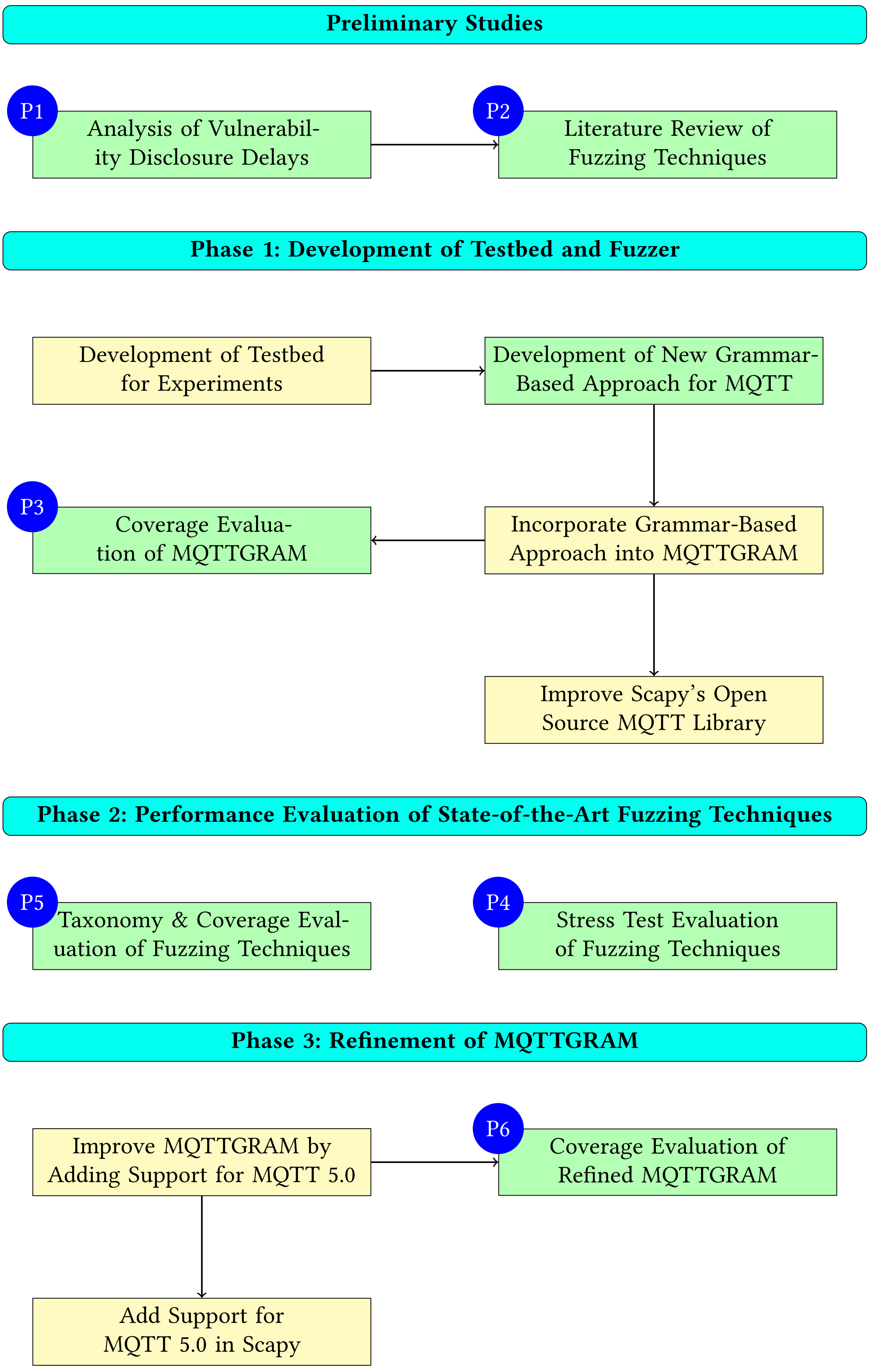

Preliminary Studies
P1
Analysis of Vulnerability Disclosure Delays
P2
Literature Review of Fuzzing Techniques
Phase 1: Development of Testbed and Fuzzer
Development of Testbed for Experiments
Development of New Grammar-Based Approach for MQTT
P3
Coverage Evaluation of MQTTGRAM
Incorporate Grammar-Based Approach into MQTTGRAM
Improve Scapy's Open Source MQTT Library
Phase 2: Performance Evaluation of State-of-the-Art Fuzzing Techniques
P5
Taxonomy & Coverage Evaluation of Fuzzing Techniques
P4
Stress Test Evaluation of Fuzzing Techniques
Phase 3: Refinement of MQTTGRAM
Improve MQTTGRAM by Adding Support for MQTT 5.0
P6
Coverage Evaluation of Refined MQTTGRAM
Add Support for MQTT 5.0 in Scapy

Figure 1.2: *Overview of Doctoral Studies*

The technical contributions of this research are highlighted in yellow, whereas the scientific contributions are highlighted in green. A total of six papers (indicated by blue circles) were written to disseminate the research findings, four of which have been published in peer-reviewed conferences and journals at the time of writing. The remaining two papers are currently under review for publication.

1.2.1 Dissemination of Research Findings

P1 Luis Gustavo Araujo Rodriguez, Julia Selvatici Trazzi, Victor Fossaluza, Rodrigo Campiolo, and Daniel Macêdo Batista. **Analysis of Vulnerability Disclosure Delays from the National Vulnerability Database**. In: *Proceedings of the Workshop on CyberSecurity in Connected Devices at the Brazilian Symposium on Computer Networks and Distributed Systems.*, 2018. URL: https://sol.sbc.org.br/index.php/wscdc/article/view/2394

The objective of this paper was to evaluate vulnerability disclosure delays from the National Vulnerability Database (NVD) in order to state its efficiency. Among several findings, it was observed that the majority of vulnerabilities are disclosed within 1-7 days after their discovery. Based on these results, the paper provided recommendations for those who currently rely on NVD, such as IoT manufacturers and developers. This paper won an honorable mention for the Best Paper Award.

P2 Luis Gustavo Araujo Rodriguez and Daniel Macêdo Batista. **Program-Aware Fuzzing for MQTT Applications**. In: *Proceedings of the ACM SIGSOFT International Symposium on Software Testing and Analysis.*, Doctoral Symposium, 2020. DOI: 10.1145/3395363.3402645

Due to vulnerability disclosure delays, **P1** confirmed the necessity for prevention and proactive approaches such as test-driven mechanisms in the field of IoT. In order to narrow down the scope of the PhD research, the objective of this paper was two-fold: (1) identify the test-driven approach that is most suited for IoT message brokers based on MQTT standards; and (2) analyze existing MQTT-based testing frameworks. This paper revealed that test-driven approaches for MQTT should be based on malformed or random packets, which are the most common causes of vulnerabilities in message brokers. At the time of publication, the paper also unveiled that testing frameworks were based on blackbox fuzzing, meaning that vulnerabilities are difficult and time-consuming to find. The paper therefore presented and proposed the overall design of a new greybox fuzzer for testing MQTT applications. Overall, one of, if not *the* most important finding of this paper was the lack of systematic and modern approaches in the literature to fuzz-test pub/sub protocols. The paper therefore presented a research proposal to study and develop effective fuzzing strategies for pub/sub protocols, aiming to contribute to the development of more robust applications in IoT and Smart Cities. The research proposal and findings of this paper were presented at a Doctoral Symposium, which offered PhD students the opportunity to receive feedback from field specialists. The main feedback received from field specialists was to develop a new grammar-based fuzzing technique for a pub/sub protocol.

P3 Luis Gustavo Araujo Rodriguez and Daniel Macêdo Batista. **Towards Improving Fuzzer Efficiency for the MQTT Protocol**. In: *Proceedings of the IEEE Symposium on Computers and Communications.*, 2021. DOI: 10.1109/ISCC53001.2021.9631520

A new grammar-based methodology and architecture was developed based on the feedback received from the Doctoral Symposium Program Committee. The end result is a fuzzer called `MQTTGRAM`, which was then compared with two other fuzzing approaches and outperformed both of them, despite exchanging up to 9x fewer packets with the broker. The research findings were presented in this paper, which at the time of its publication, was the *first* to evaluate the effectiveness of a grammar-based fuzzer for a pub/sub protocol (Araujo Rodriguez and Macêdo Batista, 2021).

P4 Luis Gustavo Araujo Rodriguez and Daniel Macêdo Batista. **Resource-Intensive Fuzzing for MQTT Brokers: State of the Art, Performance Evaluation, and Open Issues**. *IEEE Networking Letters.*, Volume 5, Issue 2 (2023). DOI: 10.1109/LNET.2023.3263556

This paper evaluates the resource consumption of state-of-the-art fuzzing frameworks, thereby understanding the degree to which brokers are tested before deployment. The research findings attest that only one framework shows the most promise for memory-intensive testing, outperforming its counterparts by more than 20%. This paper also highlights shortcomings that prevent existing frameworks from consuming considerable system resources. This paper was the *first* to investigate about the fuzzers' resource-exhaustion capabilities.

P5 Luis Gustavo Araujo Rodriguez and Daniel Macêdo Batista. **A Survey, Taxonomy, and Performance Evaluation of Fuzzing Techniques for the MQTT Protocol**. *ACM Computing Surveys.*, 2023. Under Review.

After developing a grammar-based approach for a pub/sub protocol, a question was raised as to whether developers were designing their fuzzers considering the unique attributes and features of pub/sub messaging. This uncertainty stems from the fact that there is currently a lack of research regarding the strengths and weaknesses of each fuzzing technique for MQTT. This situation also hinders a developer's understanding of the pros and cons of each technique in order to select the most appropriate for testing purposes. In order to mitigate these issues, this paper analyzes the existing fuzzing techniques in depth and under equivalent conditions, which will not only clarify and reveal their effectiveness to developers, but also identify future directions. Overall, this paper provides three main contributions. First, it presents a literature review and taxonomical classification of fuzzing techniques for MQTT, followed by an analysis and performance benchmarks of six popular frameworks. Finally, this paper presents open issues and proposes improvements for existing MQTT fuzzers. The research findings attest that most fuzzing frameworks for MQTT are incapable of testing all the pub/sub functionalities and features defined in the standard, thus providing research opportunities to mitigate their limitations and apply their techniques effectively on other pub/sub protocols.

P6 Luis Gustavo Araujo Rodriguez and Daniel Macêdo Batista. **Improving Pub/Sub**

Fuzzing for IoT Message Brokers: A Case Study of MQTT. *Elsevier Computer Networks*, 2023. Under Review.

After carefully reviewing the literature, the research findings presented in **P5** indicate that *all* fuzzers lack three essential elements for pub/sub fuzzing: (1) Two-way communication capabilities; (2) Topic awareness; and (3) Multiversion support. This paper therefore proposes a new fuzzer that incorporates all three elements within a single architecture. The proposed fuzzer manages to outperform *all* of its state-of-the-art competitors in terms of standardized testing metrics such as code coverage, executing up to 12x more statements in pub/sub-related files.

1.2.2 Development of Open Source Fuzzers and Testbed

Fuzzers

The source code of the original and refined version of `MQTTGRAM`, as well as the grammars, are freely available under the General Public License (Version 2)[1] [2], allowing developers to better test message brokers, and facilitating further research studies.

Testbed

The testbed built and used for the doctoral studies is also publicly available under the same license [3], providing developers the opportunity to evaluate their own fuzzers for testing purposes. Figure 1.3 presents the architecture of the testbed, whose main purpose is to monitor the broker while fuzzing.

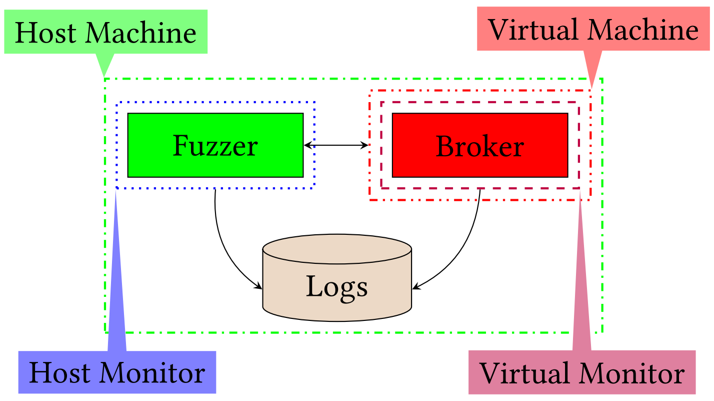


Figure 1.3: *Testbed Developed and Used for Doctoral Studies*

The repository for the testbed contains several automation scripts including a *Vagrantfile*, which is a configuration file that creates the exact same test environment used for the doctoral studies. More specifically, the Vagrantfile configures the broker according to the architecture presented in Figure 1.3. The Vagrantfile installs the necessary dependencies for the broker to communicate with the fuzzer over a private network. As a result,

[1] https://github.com/luisgar1990/MQTTGRAM. Accessed on May 17th, 2023

[2] https://github.com/luisgar1990/MQTTGRAM-R. Accessed on May 17th, 2023

[3] https://github.com/luisgar1990/mqtt-testbed. Accessed on May 17th, 2023

the automation scripts and Vagrantfile play a *key* role in improving and increasing the reproducibility of the research findings from the doctoral studies.

Experimental Setup for Doctoral Studies

The experiments for the doctoral studies were performed on an Intel(R) Core(TM) i7-2700K CPU @ 3.50GHz with 16GB of RAM running the Ubuntu 16.04.6 LTS operating system. The MQTT fuzzers ran natively on the system hardware, whereas the MQTT brokers were hosted on a virtual machine. The native and virtual machine have the same hardware specifications except for the RAM, which is 1 GB on the latter. The MQTT fuzzers and brokers were executed using default settings. The brokers interact with each MQTT fuzzer individually. The MQTT brokers selected as the target systems for the doctoral studies were *Mosquitto 1.6.8* and *Moquette 0.13*, both of which rank among the most popular in the literature (Hernández Ramos *et al.*, 2018; Palmieri *et al.*, 2019; Casteur *et al.*, 2020; Sochor *et al.*, 2020b; Zeng *et al.*, 2020; Aichernig *et al.*, 2021; Di Paolo *et al.*, 2021; Araujo Rodriguez and Macêdo Batista, 2021).

Test runs were repeated 100 times in order to calculate the average and standard deviation for each stopping criterion. The fuzzers test the brokers until a certain time has elapsed or a specific number of packets has been exchanged between both parties. After each test run, information regarding a fuzzer's performance is calculated and recorded in three different types of logs.

The *broker log* contains broker-related information such as the average CPU and memory usage, as well as the number of statements or lines executed in its source code during a test run. The latter metric is known as *statement coverage*, and it has proven to be more reliable than other metrics at predicting the quality of a test suite (Gopinath *et al.*, 2014). Statement coverage is calculated using `gcov` and `Cobertura`, which are coverage tools designed for programs written in C (Mosquitto) and Java (Moquette) respectively. A variant of statement coverage called *input coverage* was also used throughout the doctoral studies to measure a fuzzer's performance. Input coverage refers to the statement coverage achieved by a fuzzer *after exchanging a specific number of packets with the broker.*

In addition to statement and input coverage, fuzzers were evaluated based on their *feature coverage*, which refers to pub/sub functionalities or behaviors that were covered during testing. A tool called `tshark` was used to capture and record the network packets exchanged between the MQTT fuzzers and the broker in the *packet log* during the test run. The packet logs were then manually inspected to determine which pub/sub features were tested by the MQTT fuzzers.

The *fuzzer log* contains information regarding crashes. For each test run, the Mosquitto broker is compiled with `AddressSanitizer`, which is a debugging tool that detects potential memory corruption vulnerabilities even if a crash is untriggered. The fuzzing process is also monitored constantly during the test runs in case either Mosquitto or Moquette crashes.

Further details on the stopping criteria, metrics, MQTT brokers, and fuzzers chosen for each experiment are explained in later chapters of the thesis.

1.2.3 Contributions to Open Source Software

While developing the grammar-based fuzzer for MQTT, a popular Python library called Scapy was lacking functionality or features described in the MQTT 3.1.1 standard. Improvements were made to that library as an additional contribution of this research (Araujo Rodriguez, 2020). Scapy was further improved afterwards to support MQTT 5.0, which will play a major role in several research fields including Fuzzing. This contribution will allow developers to analyze, parse, craft, and modify MQTT 5.0 packets for their own research and needs. Although the pull request is still under review at the time of writing (Araujo Rodriguez, 2021), the changes requested by the maintainers are currently being addressed.

1.2.4 Contribution to Research Paper Unrelated to Doctoral Studies

During the doctoral studies, an opportunity emerged to collaborate on a research paper related to MQTT and intrusion detection systems:

Fatemeh Mosaiyebzadeh, Luis Gustavo Araujo Rodriguez, Daniel Macêdo Batista and Roberto Hirata, **A Network Intrusion Detection System using deep Learning against MQTT Attacks in IoT**. In: *Proceedings of the IEEE Latin-American Conference on Communications.*, 2021. DOI: 10.1109/LATINCOM53176.2021.9647850

Suggestions were provided throughout the writing process to further improve the research paper.

1.3 Thesis Outline

This PhD thesis is organized as follows. Chapter 2 first explains about architectural messaging patterns and fuzzing. These explanations are then followed by a literature review on pub/sub protocol fuzzing, as well as MQTT fuzzers that are available to developers for testing purposes. Chapter 3 presents the new grammar-based fuzzing technique for a pub-/sub protocol such as MQTT. Chapter 4 presents a taxonomy and performance evaluation of pub/sub fuzzers, which at the time of writing are mostly for MQTT. Chapter 5 presents a refined version of the grammar-based approach that incorporates three essential elements for pub/sub fuzzing. Chapter 6 presents and discusses the performance achieved by MQTT fuzzers in terms of the broker's CPU and memory. Chapter 7 marks the conclusions of this PhD thesis, and discusses future work.

Chapter 2

State of the Art in Pub/Sub Protocol Fuzzing

The aim of this chapter is to first explain the concepts of fuzzing and pub/sub protocol messaging. These explanations are then followed by an overview of the challenges and advancements regarding pub/sub protocol fuzzing. The final sections of this chapter focus on MQTT, which at the time of writing is the *only* pub/sub protocol for which developers have proposed *several different* fuzzing techniques in the literature.

2.1 Background

A vulnerability is a flaw or weakness that can be exploited because of design, implementation or configuration mistakes (Antunes *et al.*, 2010). Testing software applications with effective mechanisms is necessary to identify and mitigate design issues or flaws before deployment, thereby increasing their reliability (J. Chen *et al.*, 2018; Liljedahl, 2019). The tests can be performed either manually or automatically. However, finding bugs manually is complex in large-scale systems. Automated methods have therefore become the norm for bug finding. Automated program analysis is classified into two categories: *static analysis* and *dynamic analysis*.

Static analysis involves examining the source code of the program at *compile-time* to discover vulnerabilities (J. Chen *et al.*, 2018). In other words, static analysis searches for vulnerabilities without executing the program. Dynamic analysis, however, involves monitoring the program at *run-time* to detect potential vulnerabilities.

Automated test analysis may provide misleading claims regarding the existence or absence of bugs in a program. The former claim is known as a *false positive*, whereas the latter is referred to as a *false negative*. Static analysis may provide several false positives, requiring user intervention to identify genuine vulnerabilities. Furthermore, static analysis focuses only on limited properties of the program at compile-time, thereby hindering its detection capabilities. However, static analysis has higher statement coverage and detection speeds than its dynamic counterpart, which compensates for its low performance by having few false positives (Zaddach *et al.*, 2014).

One of the most common and popular types of dynamic analysis is Fuzz Testing (or fuzzing) (J. Li *et al.*, 2018), which is an automated technique that consists in generating and sending random or unexpected inputs to a target system. The system behavior is then constantly monitored for any errors (Manès *et al.*, 2019). The term *fuzzing* was introduced by Miller *et al.* (1990), which developed a tool called *fuzz* that generated and fed invalid inputs to eighty-eight UNIX utilities. Program behavior along with their corresponding inputs were stored in a *log* file for further analysis. The tool discovered several vulnerabilities, which were undetected by traditional testing practices.

Since then, fuzzing has become one of the most popular dynamic analysis techniques for several reasons. First, it has higher scalability and accuracy than other automated testing techniques (J. Li *et al.*, 2018). Second, it has proven to have considerable impact for detecting vulnerabilities in IoT (J. Chen *et al.*, 2018). Third, it can mitigate implementation issues and zero-day attacks. These benefits are reasons why fuzz testing is considered the primary bug-finding technique for most software applications (Munea, Lim, *et al.*, 2016; Munea, Luk Kim, *et al.*, 2017; Luo *et al.*, 2018; Boehme *et al.*, 2021; Vinzenz and Oka, 2021).

Figure 2.1 illustrates a simple interaction between a fuzzer and a software application, which will read and parse random inputs for the entire test run.

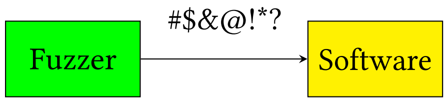


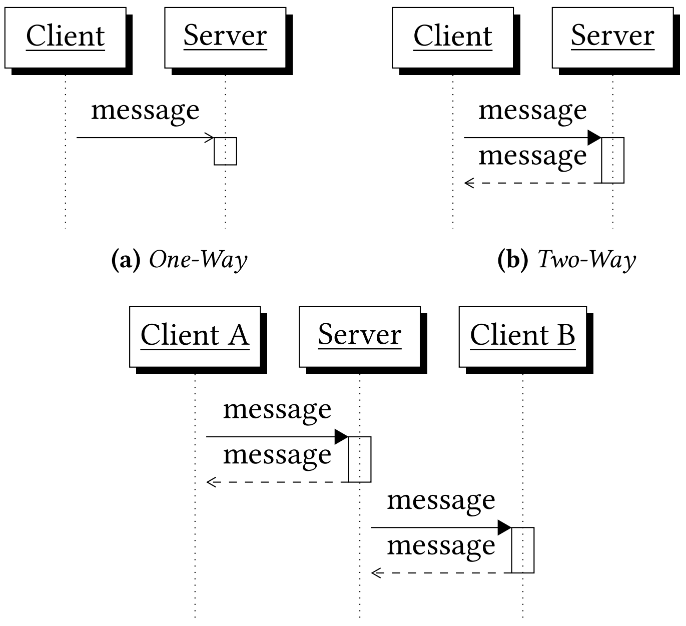
Figure 2.1: *Fuzz Testing/Fuzzing*

There are three potential outcomes of the software application while interacting with a fuzzer. The first, and probably the most devastating, outcome is a *crash* immediately after it reads a random input. The second outcome is an immediate *rejection* of a random input. The third and probably the most desired outcome by software testers is the *recognition and acceptance* of a random input. The latter outcome is the most promising as it will allow testers to monitor how random inputs affect the *functionality* of the software application. In order to produce promising outcomes, a fuzzer needs to interact *intelligently* with the target system in a *fully-automated* manner.

Target systems can range from simple file-processing programs to complex network protocols. Developers must tailor their fuzzers to the specific characteristics and architectures of a target system in order to ensure a successful test run. Network protocols, in particular, may vary considerably in terms of their architecture. For example, Figure 2.2 presents three different types of messaging patterns.

One-way communication (Figure 2.2a) refers to *unidirectional messaging*, meaning that packets flow in a single direction. In a two-way communication (Figure 2.2b), packets flow from a sender to a receiver, and vice versa. A two-way communication, or *bidirectional messaging*, is commonly used for distributed systems, in which its components are spread across multiple devices.

The *pub/sub messaging model* (Figure 2.2c) is another form of two-way communication that, despite also using the request-response pattern, has certain features that distinguishes



(a) *One-Way* **(b)** *Two-Way*

(c) *Pub/Sub*

Figure 2.2: *Architectural Messaging Patterns*

itself from its traditional client-server counterpart. Most notably, pub/sub communications are less isolated, meaning a client *A is* capable of sending messages to a client *B*, and vice versa. Clients interact with one another through the server (or *broker*), which redirects messages considering certain attributes such as topics of interest. The role of the broker in pub/sub communications is two-fold: (1) handle requests and (2) route messages to interested subscribers.

Pub/sub messaging has several advantages over traditional client-server approaches. First, subscribers receive messages regardless of their connectivity. For example, if a subscriber is offline, messages can be queued for delivery after regaining connectivity. Second, pub/sub messaging offers asynchronous communication, meaning data is transmitted at irregular intervals. This means that publishers and subscribers can send and receive messages quickly, without being synchronized by an external clock.

Due to pub/sub messaging being a promising design pattern, several pub/sub protocols have been developed for low-powered devices in the IoT. Examples of pub/sub protocols include, but are not limited to, the Advanced Message Queuing Protocol (AMQP), the Data Distribution Service (DDS), the Extensible Messaging and Presence Protocol (XMPP), and MQTT. Among the aforementioned pub/sub protocols, MQTT is the most popular in IoT environments (See Appendix B for a comparison between MQTT and other IoT protocols).

2.2 Challenges

Traditional network protocol fuzzing is difficult (Pham *et al.*, 2020), and follows the premise that the server interacts with *only one type of client (or requester).* Figure 2.3

presents the traditional approach for network protocol fuzzing, which involves the fuzzer exchanging messages with the server as if it were a normal client. The server perceives no difference whatsoever between a fuzzer and a legitimate client.

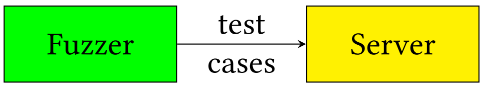


Figure 2.3: *Traditional Network Protocol Fuzzing (1 Client)*

For *most* one- and two-way communication protocols, the traditional approach will suffice to cover all of their functionalities during testing. For pub/sub messaging systems, however, the traditional approach is unsuitable because it is designed with single-client protocols in mind. In fact, several research studies have raised awareness about the shortcomings of traditional protocol fuzzers for pub/sub brokers (Sneha Suhitha Galiveeti and Pranitha Malae, 2020; Zeng *et al.*, 2020).

This concern is due in part to the literature lacking information about design considerations and challenges when developing a pub/sub protocol fuzzer. Most survey papers explain the common challenges of network protocol fuzzing, neglecting those associated with the unique attributes of the pub/sub design pattern. For example, Zhu *et al.* (2022) provide a roadmap for developers to grasp a better understanding of fuzz testing and its use across multiple domains such as network protocols. The authors mainly focus on file-transfer and cryptographic protocols, whereas pub/sub protocols were left out to limit the scope of their study. Their roadmap therefore provides insufficient information to developers interested in fuzzing pub/sub protocols.

Several other research papers focus specifically on two challenges regarding network protocol fuzzing (Munea, Lim, *et al.*, 2016; Manès *et al.*, 2019; Zhao, 2020; Liang *et al.*, 2018; J. Li *et al.*, 2018; Yurong Chen *et al.*, 2019; Boehme *et al.*, 2021): (1) highly-structured inputs and (2) state traversal. In terms of the former challenge, a network-based fuzzer *must* generate inputs that satisfy the syntax and structural requirements established by the protocol standard. Traditional fuzzers, such as American Fuzzy Lop (AFL) (Michael Zalewski, 2013), have difficulty meeting this criteria (Y. Li *et al.*, 2021), forcing developers to resort to more *specialized* approaches for pub/sub protocols. In terms of the latter challenge, the success of state traversal depends on a fuzzer's capability to generate highly-structured inputs, which *must* be sent in the correct order to guide the test run to a specific state. Although these are two of the most common challenges faced by developers when fuzzing network protocols, research studies fail to provide information regarding a third challenge: version support. Protocol implementations support *several* versions of a standard. For example, *Mosquitto* is a broker-side implementation that supports versions 3.1, 3.1.1, and 5.0 of the MQTT protocol. A fuzzer must therefore have an understanding of the input structure and state traversal for each version in order to increase its effectiveness. The effectiveness of protocol fuzzers therefore depends on their success to overcome all three of the aforementioned challenges (highly-structured inputs; state traversal; and version support).

Pub/sub protocols further complicate the testing process by locking its *core* features behind message subscriptions. This means that a pub/sub fuzzer *must* at the very least be capable of creating test scenarios based on message publishing features. This entails that fuzzers act as *both* a publisher and a subscriber for each test scenario in order to trigger the broker into publishing messages. A pub/sub fuzzer therefore distinguishes itself from its counterparts by its dual-role testing strategy and heavy emphasis on topic generation, both of which must be performed systematically because of two reasons. First, a pub/sub fuzzer can publish messages *only after* it creates a subscription topic. Second, a pub/sub fuzzer needs to be able to generate topics that match across publication and subscription requests, otherwise the broker will not route messages to interested subscribers. Figure 2.4 presents an example in which a fuzzer fails to create a test scenario that involves *both* a publisher and a subscriber.

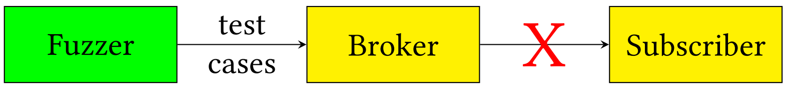


Figure 2.4: *Pub/Sub Protocol Fuzzing (2 Clients)*

In such a case, a fuzzer, in the role of a publisher, generates and sends random inputs to a broker, which *never* delivers messages to the subscribers. As a result, message publications are *completely* absent during testing, becoming a major hindrance towards effective pub/sub protocol testing. However, it is worth noting that the focus *should not* be strictly tied to publication and subscription requests during testing because specific pub/sub features may also depend on connection parameters established between the fuzzer and the broker.

2.3 Literature Review

Despite its importance for IoT brokers, pub/sub protocol fuzzing is *still* in its early stages of adoption. In fact, research on pub/sub protocol fuzzing has progressed slowly compared to other fields. For example, file fuzzing has advanced and improved drastically over the past decade, employing sophisticated algorithms based on the principles of natural selection and genetics to carefully select coverage-increasing test cases. This technique is commonly referred to as *greybox fuzzing*. `AFL`, in particular, is one of the most popular and successful greybox fuzzers for file-processing programs (Pham *et al.*, 2020). The success of `AFL` led to the emergence of several *extensions* that add support for different types of programs such as compilers and, more recently, network protocols.

The main issue of `AFL` and most of its extensions is their limited support for the pub/sub design pattern (Zeng *et al.*, 2020). This in turn has led to a lack of consideration for pub/sub target systems in popular benchmark suites such as `ProFuzzBench` (Natella and Pham, 2021), which at the time of writing supports only the client-server model. Over time, these issues have hindered the progression of pub/sub protocol fuzzing in two key aspects. From a technological point of view, the fuzzers, while advanced, are incapable of testing *core* features of the pub/sub design pattern such as message publication. From a developer's point of view, there is a lack of information in the literature regarding effective strategies to properly fuzz a pub/sub protocol. As a result, developers have applied ineffective testing strategies for pub/sub protocols across several research studies. For example, Sneha Suhitha Galiveeti and Pranitha Malae (2020) create two test scenarios in which the broker interacts with a publisher and a subscriber separately rather than collectively. Aljaafari *et al.* (2020) create test scenarios that involve only a publisher. Both of these research studies lack scenarios involving *both* a publisher and a subscriber, meaning message publishing features are most likely neglected during testing. In order to mitigate this issue, Zeng *et al.* (2020) propose `MultiFuzz`, which is an extension based on `AFL` that is designed to create test scenarios that involve publishing MQTT messages to interested subscribers. This makes MQTT the *first and only* pub/sub protocol supported by `AFL`.

Effort has been put into supporting MQTT because of its importance in the realization of Smart Cities. The popularity and adoption of MQTT for IoT applications has been unprecedented. In fact, MQTT has had a huge impact in real-world environments such as cloud computing (See Appendix A for further details). For example, `AWS IoT` [1], `Google Cloud IoT Core` [2], and `Azure IoT Hub` [3] connect IoT devices to cloud computing services via communication protocols such as MQTT.

Developers seem to prefer MQTT over other pub/sub protocols because of its simplicity and lightweight nature. For example, MQTT offers three levels of Quality of Service (QoS), whereas other pub/sub protocols such as the Data Distribution Service (DDS) offer twenty-three (see Appendix B, Table B.1 for further details). These and several other differences hinder the possibilities of developing a single *generic* fuzzer that is capable of testing *every* pub/sub protocol effectively. Developers are well aware of this difficulty, building fuzzers geared towards a specific pub/sub protocol. The most notable evidence of this trend has been the sheer number of fuzzers available specifically for MQTT. However, quantity does not equal quality, and in the case of MQTT, there is a lack of information regarding the testing capabilities of existing fuzzers for pub/sub functionalities. For developers, the main question is whether fuzzers are built and designed with the unique attributes of the pub/sub design pattern in mind (Zeng *et al.*, 2020).

2.4 MQTT Fuzzing

Despite these concerns, research on pub/sub or MQTT fuzzing lacked considerably until studies found faulty or weak protocol implementations in real-world environments (Anantharaman *et al.*, 2017; Alghamdi *et al.*, 2018; J. Chen *et al.*, 2018; Maggi *et al.*, 2018; Palmieri *et al.*, 2019). A manual study was later conducted to determine the root cause of vulnerabilities (Araujo Rodriguez and Macêdo Batista, 2020). The research study revealed that most MQTT-vulnerabilities are exploited because of malformed packets, which could allow information disclosure, remote code execution, and denial of service, thereby hindering confidentiality, integrity, and availability, respectively. In fact, a stack overflow vulnerability (CVE-2019-11779)[4] was discovered in 2019 by sending a crafted subscribe packet to the broker, as shown in Figure 2.5.

[1] https://docs.aws.amazon.com/iot/latest/developerguide/what-is-aws-iot.html. Accessed on April 3rd, 2023

[2] https://cloud.google.com/iot-core/. Accessed on April 3rd, 2023

[3] https://azure.microsoft.com/en-us/overview/iot/#overview. Accessed on April 3rd, 2023

[4] https://nvd.nist.gov/vuln/detail/CVE-2019-11779. Accessed on June 12th, 2023

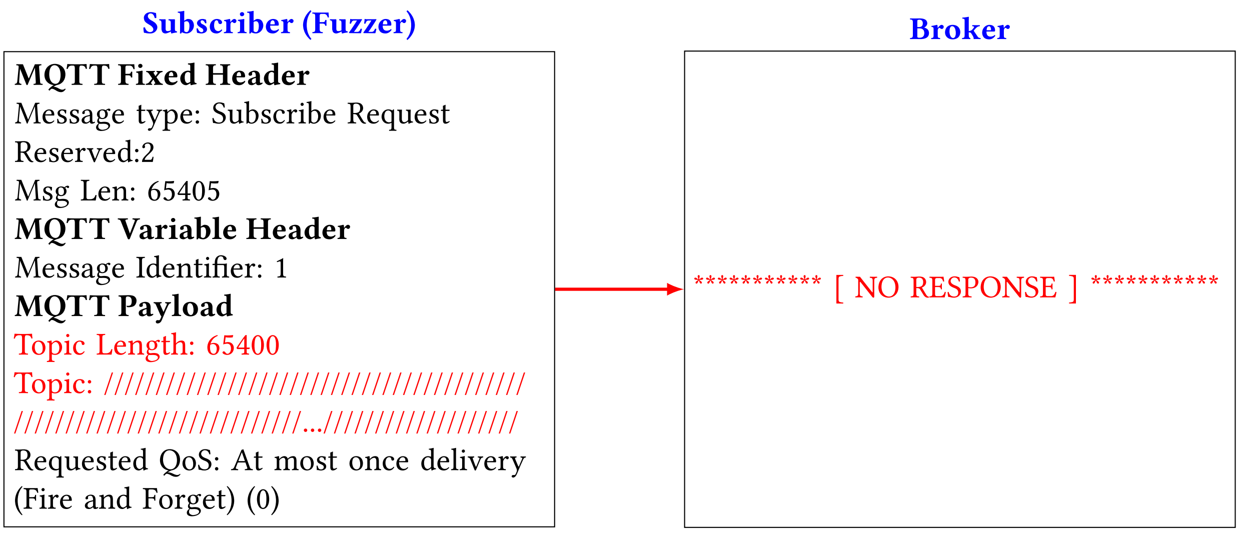

Subscriber (Fuzzer)
MQTT Fixed Header
Message type: Subscribe Request
Reserved:2
Msg Len: 65405
MQTT Variable Header
Message Identifier: 1
MQTT Payload
Topic Length: 65400
Topic: // ////////////////////////////...//////////////////
Requested QoS: At most once delivery (Fire and Forget) (0)
Broker
*********** [NO RESPONSE] ***********

Figure 2.5: *Network-Based Fuzzer Sending a Malicious Subscribe Packet to the Broker and Causing a Stack Overflow (CVE-2019-11779).*

Since then, the situation remains the same. As of April 19th 2023, searching for keywords related to MQTT brokers (*MQTT, mosquitto, mosca, Paho, ActiveMQ*) in the NVD database yields one-hundred and twenty vulnerabilities, ninety-four of which are triggered by malformed packets. Among the remaining vulnerabilities, seven are related to cryptographic issues, whereas nineteen are triggered by improper authentication or configuration. As of April 19th 2023, malformed packets account for 78.33% of all MQTT-related vulnerabilities, and have consistently been prominent for the last few years, as shown in Figure 2.6.

For seven consecutive years, malformed packets account for more than 60% of vulnerabilities discovered annually, representing a major threat to MQTT implementations in real-world environments. More specifically, malformed packets accounted for 75%, 82.4%, 61.0%, 76.9%, 100%, 90.9%, and 77.8% of vulnerabilities discovered in 2017, 2018, 2019, 2020, 2021, 2022, and 2023 respectively. It is expected that this trend will continue in the future (Anantharaman *et al.*, 2017), which is especially worrisome when considering that vulnerabilities are disclosed several days after their discovery (Araujo Rodriguez, Selvatici Trazzi, *et al.*, 2018). Figure 2.7 presents disclosure delays of vulnerabilities related and unrelated to malformed packets.

The horizontal line within each rectangle indicates the median, which is 8 and 7 days for the former and latter type of vulnerability respectively. The upper quartiles denote the median of the larger disclosure delays, which are more common for vulnerabilities related to malformed packets. It is worth noting that although all types of vulnerabilities had similar disclosure delays on average, vulnerabilities related to malformed packets had twelve disclosures delayed for over 100 days, whereas their counterparts had only one. Moreover, there were exactly nineteen vulnerabilities related to malformed packets that were disclosed after seventy days, whereas their counterparts had only four cases. Based on these results, vulnerabilities triggered by malformed packets had higher disclosure delays than their counterparts.

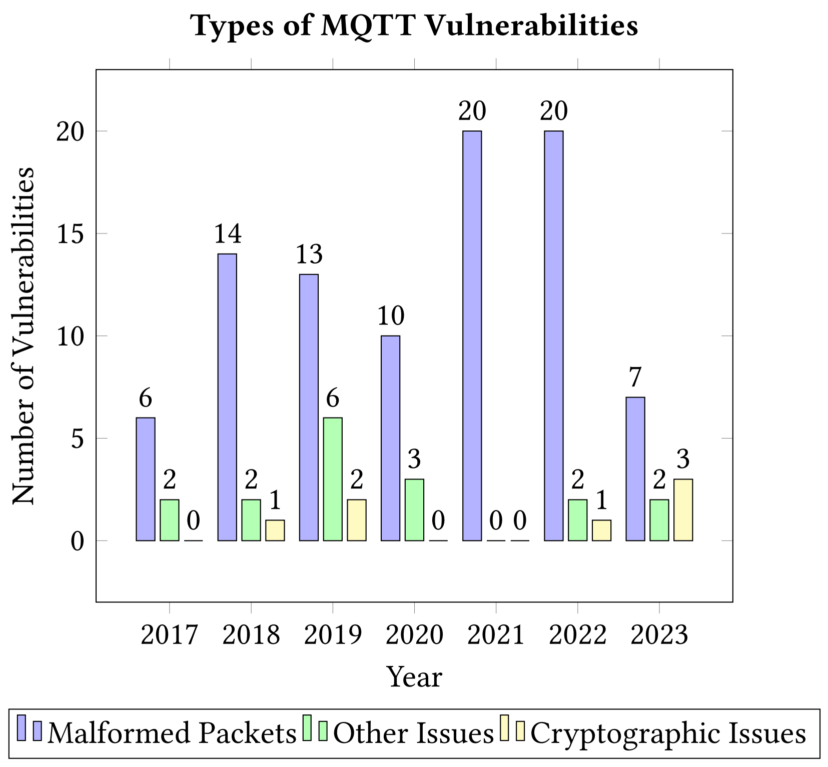


Figure 2.6: *Causes of Vulnerabilities in MQTT (As of April 19th, 2023)*

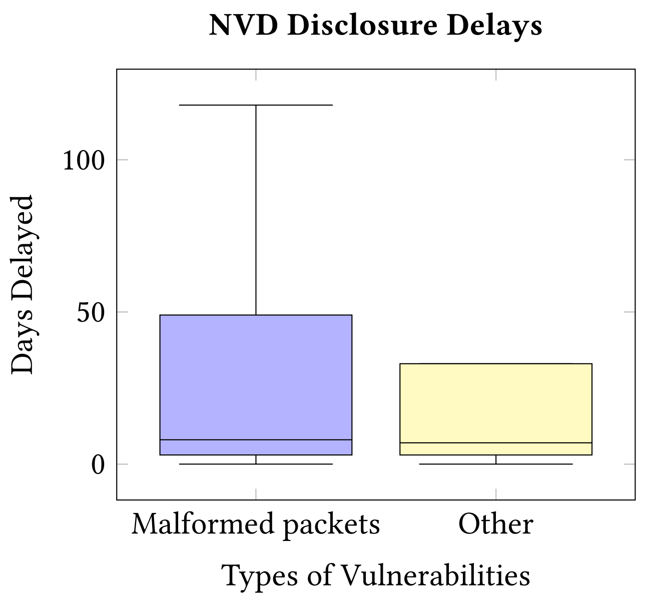


Figure 2.7: *Vulnerability Disclosure Delays (As of April 19th, 2023)*

However, regardless of disclosure delays, patching vulnerabilities found in brokers deployed to real-world environments is complex because of their limited hardware resources or location (Săndescu *et al.*, 2018; Thantharate *et al.*, 2019; Eceiza *et al.*, 2021; Newman and Al-Nemrat, 2021; Husnain *et al.*, 2022). As a result, it is common for brokers to use outdated versions of MQTT implementations (Araujo Rodriguez and Macêdo Batista, 2020). For example, searching for *mqtt* on the `Shodan` [5] search engine yields 52,411 MQTT brokers accessible from the Internet, with *Mosquitto* ranking as the most popular. Figure 2.8 presents the top eleven versions of Mosquitto accessible from the Internet as of April 19th, 2023.

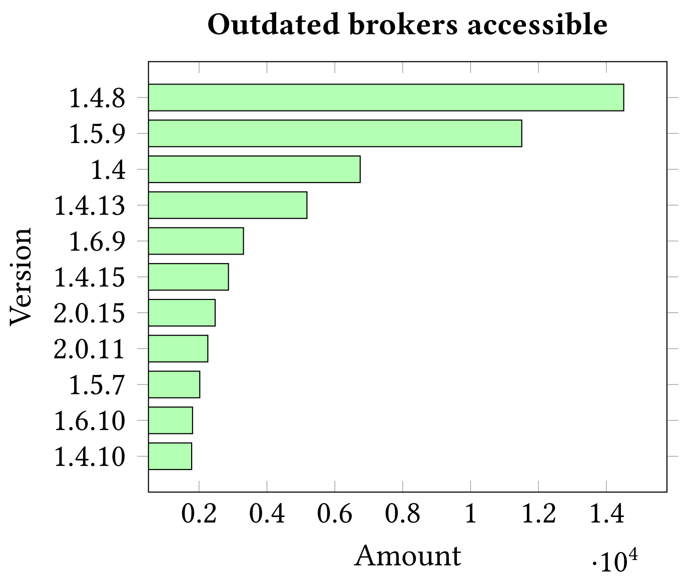


Figure 2.8: *Outdated Brokers Accessible (As of April 19th, 2023)*

Assuming that version numbers are incremented whenever a patch is applied, the results presented in Figure 2.8 confirm the lack of updates applied to MQTT brokers. This situation is especially worrisome when considering that it is common for multiple versions of Mosquitto to be released on the same day (Table 2.1), further reducing the likelihood of IoT devices being up to date.

2.4.1 Related Work

Over the last few years, several fuzzing frameworks have been proposed to mitigate these issues. In fact, MQTT is the *only* pub/sub protocol for which there have been a multitude of fuzzing techniques proposed in the literature. As of April 19th 2023, searching for *mqtt fuzzers* using `Google Scholar` yields several publications about fuzzing techniques for MQTT. These research papers have been published in a wide variety of sources, ranging from conference workshops to peer-reviewed journals. More specifically, publications about MQTT fuzzers were mainly found in 6 conferences and 2 journals. The 6 conferences are as follows: ACM International Conference on Availability, Reliability, and Security; IEEE Conference on Software Testing, Verification, and Validation; IEEE International Symposium on Computers and Communications; IEEE International Wireless Communications and Mobile Computing; IEEE World Congress on Services; and Italian Conference on Cybersecurity. The 2 journals are Sensors; and Wireless Communications and Mobile Computing.

[5] https://www.shodan.io/. Accessed on April 19th, 2023

Year	Month	Releases
Year 2020	Feb	**27** : *1.6.9*
	May	**25** : *1.6.10*
	Aug	**11** : *1.6.11* **19** : *1.5.10, 1.6.12*
	Dec	**03** : *2.0.0* **10** : *2.0.1, 2.0.2* **17** : *2.0.3* **22** : *2.0.4*
Year 2021	Jan	**11** : *2.0.5* **28** : *2.0.6*
	Feb	**04** : *2.0.7*
	Mar	**11** : *1.5.11, 1.6.13, 1.6.14, 2.0.8, 2.0.9*
	Apr	**03** : *2.0.10*
	Jun	**09** : *1.6.15, 2.0.11*
	Aug	**31** : *2.0.12*
	Oct	**27** : *2.0.13*
	Nov	**17** : *2.0.14*
Year 2022	Aug	**16** : *2.0.15*

Table 2.1: *Timeline of Mosquitto Version Releases (As of April 19th, 2023)*

There are also remote-hosting services such as GitHub that provide access to MQTT fuzzers based on different techniques than those proposed in the literature. As of April 19th 2023, searching for *mqtt fuzzers* on GitHub yields over 10 fuzzing frameworks specifically designed for MQTT. For this research, the search results were narrowed by considering high-ranking MQTT fuzzers on GitHub that were either developed by corporations or published in peer-reviewed sources. High-ranking repositories on GitHub are determined by the number of stars. Three MQTT fuzzers were found that meet this criteria: Scapy's `fuzz()` function (Philippe Biondi and the Scapy Community, 2023), `mqtt_fuzz` (F-Secure Corporation, 2015) and `IoT-Testware` (Eclipse Foundation, 2018). Table 2.2 presents URLs for every open source MQTT fuzzer found on `Google Scholar` and GitHub. The column *Published* highlights the fuzzers that were peer-reviewed and accepted for a journal or conference publication.

All of the fuzzers shown in Table 2.2 use different strategies for testing purposes. Thus, Table 2.3 further classifies each MQTT fuzzer into two categories: (1) understanding the target broker; and (2) test case generation technique.

Fuzzer	**GitHub Repository**	**Year**	**Last Updated**	**Published**
`fuzz()`	https://github.com/secdev/scapy/blob/master/scapy/packet.py	2008	April 8, 2023	
`mqtt_fuzz`	https://github.com/F-Secure/mqtt_fuzz	2015	March 21, 2022	
`Polymorph`	https://github.com/shramos/polymorph	2018	April 11, 2022	✓
`IoT-Testware`	https://github.com/eclipse/iottestware.fuzzing	2018	October 15, 2019	
`MQTTSA`	https://github.com/stfbk/mqttsa	2019	March 9, 2022	✓
`CyberExploit`	https://github.com/CyberExploitProject/CyberExploit	2020	August 9, 2020	✓
`MultiFuzz`	https://github.com/hdusoftsec/MultiFuzz	2020	September 3, 2021	✓
`AFLNet-MQTT`	https://github.com/SuhithaG/MQTT-fuzzing-using-AFLNET	2020	November 29, 2020	
Aichernig *et al.* (2021)	https://github.com/DES-Lab/Learning-Based-Fuzzing	2021	April 13, 2021	✓
Di Paolo *et al.* (2021)	https://github.com/aedoardo/mqtt	2021	September 22, 2021	✓
`FUME`	https://github.com/PBearson/FUME-Fuzzing-MQTT-Brokers	2022	March 6, 2023	✓

Table 2.2: *Open Source MQTT Fuzzers*

Existing Frameworks	**Understanding Target Broker**			**Test Case Generation Technique**				**Open Source**
	Blackbox	Greybox	Whitebox	Naive	Mutation-Based	Generation-Based	Hybrid	
`fuzz()`	✓			✓				✓
`mqtt_fuzz`	✓				✓			✓
`Polymorph`	✓				✓			✓
`IoT-Testware`	✓				✓			✓
`MQTTSA`	✓				✓			✓
`MultiFuzz`		✓			✓			✓
`AFLNet-MQTT`		✓			✓			✓
Ananthraman *et al.* (2017)	✓					✓		
`CyberExploit`	✓					✓		✓
Sochor *et al.* (2020a)	✓					✓		
Di Paolo *et al.* (2021)	✓					✓		✓
Aichernig *et al.* (2021)	✓					✓		✓
`Defensics`	✓						✓	
`FUME`	✓						✓	✓

Table 2.3: *Related Work*

The first category refers to a fuzzer's awareness of the internals of a broker. In that regard, a *blackbox fuzzer* is *completely unaware* of the internals of the broker. No program analysis is used to generate the test cases. A *greybox fuzzer* is *partially aware* of the internals of the broker. New test cases are generated based on feedback received during testing, such as the number of lines or statements executed in the source code (statement coverage). A *whitebox fuzzer* is *completely aware* of the internals of the broker. In terms of the second category, a *naive fuzzer* generates test cases without considering the formal specifications of the protocol. *Mutation-based fuzzers* introduce *small changes* to existing test cases, whereas *generation-based fuzzers* generate test cases *from scratch*. A *hybrid fuzzer* combines aspects of *both* mutation- and generation-based fuzzers to generate the test cases. For example, it generates test cases from scratch; mutates them; generates new test cases, and so forth. The following subsections are organized based on the second category, explaining each MQTT fuzzer in depth.

Naive

Recent works have used Scapy to generate malformed network packets (Melo and Geus, 2017; Eclipse Foundation, 2018; Hernández Ramos *et al.*, 2018). Network packets can be crafted from scratch and fuzzed using Scapy's `fuzz()` function [6], which can be

[6] https://github.com/secdev/scapy/blob/master/scapy/packet.py. Accessed on April 19th, 2023

classified as a *naive fuzzer* because it lacks knowledge of protocol specifications. Scapy's `fuzz()` function generates packets that are rejected by the broker almost immediately, and thus has difficulty reaching deep protocol states.

Mutation

F-Secure Corporation (2015) proposed `mqtt-fuzz`, a mutation-based fuzzer whose goal is to be user friendly for testing purposes. `mqtt-fuzz` is currently one of the most popular MQTT fuzzers (Hernández Ramos *et al.*, 2018; Palmieri *et al.*, 2019), renowned recently for finding a flaw in a message broker (Kwon *et al.*, 2021). However, in its current form, `mqtt_fuzz` is unaware of certain features and syntax rules defined in the standard, meaning it may (1) occasionally craft syntactically invalid inputs; (2) require considerable amount of test cases to reach deep protocol states; and (3) cover limited functionality of MQTT.

Hernández Ramos *et al.* (2018) proposed `Polymorph`, a template-based fuzzer that aims to reduce user effort. The architecture of `Polymorph` consists of three modules. The *sniffer module* captures network packets exchanged between the client and the broker. The *template module* generates templates based on network packets captured by the sniffer module. The templates enable the *fuzzer module* to perform three tasks: (1) mutate user-selected fields; (2) recalculate field attributes to maintain packet consistency; and (3) send mutated packets to the broker. Despite having low CPU consumption, `Polymorph` lacks syntactic knowledge about MQTT messages. Moreover, the test effectiveness of `Polymorph` depends on packets captured by the sniffer module, which may not understand all of MQTT's functionality.

Similar to Hernández Ramos *et al.* (2018), Eclipse Foundation (2018) proposed `IoT-Testware`, a fuzzer that is incapable of generating MQTT messages on its own, requiring valid templates to gain program knowledge. Moreover, the fuzzer's mutation strategy is based on rules predefined by the user, which requires a deep understanding of MQTT to configure the tests effectively.

Palmieri *et al.* (2019) proposed `MQTTSA`, a tool that detects security misconfigurations in MQTT brokers, and then suggests mitigation strategies to users. `MQTTSA` consists of several penetration-testing mechanisms, including a data tampering module that mutates and sends packets to MQTT brokers. However, a recent study by Araujo Rodriguez and Macêdo Batista (2020) showed that `MQTTSA` has low statement coverage during testing.

Zeng *et al.* (2020) proposed `MultiFuzz`, a coverage-based fuzzer specifically designed for multi-party protocols. The main feature of `MultiFuzz` is its ability to support multiple connections during the fuzzing campaign, enabling it to act as multiple clients. In contrast to other coverage-guided approaches such as `AFL` and `AFLNet` (Pham *et al.*, 2020), `MultiFuzz` can act as both a publisher and subscriber, thus being capable of generating test cases that cover the main functionalities of the pub/sub design pattern. `MultiFuzz` has higher *path coverage* than generic fuzzers such as `AFL`, `MOPT`, and `AFLNet`. For this thesis, *path coverage* is defined as the number of paths executed in the source code. However, at the time of writing, its coverage performance against fuzzers designed *specifically* for MQTT is unknown.

Sneha Suhitha Galiveeti and Pranitha Malae (2020) proposed `AFLNet-MQTT`, a coverage-guided approach based on `AFLNet` for MQTT. The architecture of `AFLNet-MQTT` is mostly the same as `AFLNet`, with the only two differences being the request and response sequence parser, which are slightly modified to support MQTT. `AFLNet-MQTT` offers both a stateless and stateful mode of execution. Sneha Suhitha Galiveeti and Pranitha Malae (2020) evaluate `AFLNet-MQTT` using three metrics: number of hangs, number of crashes, and path coverage. Despite testing Mosquitto for approximately 20 hours, `AFLNet-MQTT` was incapable of triggering hangs or crashes in stateless mode (Sneha Suhitha Galiveeti and Pranitha Malae, 2020). However, `AFLNet-MQTT` manages to produce better results in stateful mode, triggering 29 unique hangs within 18 hours. Regardless of the execution mode, `AFLNet-MQTT` underperforms considerably in terms of path coverage, achieving at most 3.75%.

Generation

Anantharaman *et al.* (2017) developed MQTT parsers that recognize valid and invalid messages, thereby avoiding potential security vulnerabilities. A parser and input language were developed for specific MQTT messages. The message is processed only if it is recognized by the parser, otherwise it is discarded. The authors developed a generation-based fuzzer to test their parsers. The main limitations of this research are as follows. First, their fuzzer only sends MQTT messages to the broker in correct order, meaning incorrect functionality is neglected during testing. Second, more focus is given to the parsers than their fuzzer's input generation capabilities.

Casteur *et al.* (2020) demonstrated the effectiveness of Docker containers[7] to fuzz MQTT. For their fuzzer, the authors opted to define packet fields manually or randomly, rather than systematically using a grammar. As a result, their fuzzer does not cover all of MQTT's functionality during testing. For example, analyzing their fuzzer's packet generator[8] reveals that if the User Name Flag of a *CONNECT* packet is set to 1, then the Password Flag is also set to 1. However, according to the MQTT 3.1.1 standard, passwords are optional if the User Name Flag is set to 1.

Sochor *et al.* (2020a) proposed a fuzz testing architecture for MQTT. The architecture mainly consists of a test case generator and a test adapter. The test cases are generated using `Randoop`, which is an online random test case generator. The test adapter is responsible for the following tasks. First, it handles messages exchanged between the client and the broker. Second, it sends packets based on existing vulnerabilities to the MQTT broker. Although the architecture proved to be effective, the test case generator is not designed with MQTT's complex packet syntax or structure in mind, increasing the likelihood of it crafting invalid messages more frequently.

Di Paolo *et al.* (2021) performed fuzz testing on five broker implementations and three client implementations of MQTT. The authors developed a fuzzing framework to detect undefined behaviors in MQTT implementations. The fuzzing framework receives a `JSON`

[7] https://www.docker.com/. Accessed on March 23rd, 2023

[8] https://github.com/CyberExploitProject/CyberExploit/blob/master/PacketsGenerator/v1/mqtt_gen.py. Accessed on March 23rd, 2023

file as input, which specifies the message sequence for each test scenario. The behavior of the target system was monitored when handling long message topics, incorrect packet sequences/fields, and delayed transmissions. Despite detecting potential weaknesses in MQTT implementations, the authors failed to provide information regarding their fuzzer's statement or path coverage.

Aichernig *et al.* (2021) introduced a tool that uses a technique based on automata learning to automatically infer the message syntax and sequence of a network protocol. The learned model is then used to generate test cases for the fuzzing campaign. The authors performed a case study on five MQTT implementations to validate their learning-based technique. According to the authors, the learning-based fuzzing approach found inconsistencies in five MQTT implementations, proving to be effective. The fuzzing framework supports only version 5.0 of the MQTT protocol, which is considerably less popular than version 3.1.1 (Di Paolo *et al.*, 2021).

Hybrid

Synopsis (2021) developed `Defensics`, which is a hybrid fuzzer for multiple domains, including interfaces, files, and network protocols. `Defensics` allows users to: (1) customize pre-built test cases, or (2) write custom-made test cases using a Software Development Kit (SDK). `Defensics` is updated regularly to support new protocol specifications. However, at the time of writing, `Defensics` lacks support for the latest version (5.0) of MQTT. Further details of `Defensics`' test generation capabilities are unknown due to its proprietary nature.

Pearson *et al.* (2022) proposed `FUME`, a hybrid fuzzer that uses Markov modeling and finite state machines to make several choices throughout the fuzzing campaign, such as selecting between mutation- and generation-based approaches.

Chapter 3

A Grammar-Based Fuzzing Technique for a Pub/Sub Protocol

It is important for fuzzers to: (1) possess knowledge of MQTT's specifications; (2) cover all functionalities; and (3) guarantee acceptance by the broker. However, current fuzzing frameworks have limitations in all three categories.

Existing naive fuzzers, such as Scapy's `fuzz()` function (Philippe Biondi and the Scapy Community, 2023), lack program knowledge, meaning that fuzzed packets may be immediately rejected by the broker, and thus deep protocol states are difficult to reach during testing. Although injecting abnormal packets is effective, it is important to adhere to protocol specifications.

Existing mutation-based fuzzers (F-Secure Corporation, 2015; Hernández Ramos *et al.*, 2018; Eclipse Foundation, 2018), gain program knowledge through samples or templates. Although mutation-based fuzzing speeds up test generation, it also lacks knowledge of protocol specifications, meaning it may occasionally: (1) craft syntactically invalid inputs; (2) require considerable amount of test cases to reach deep protocol states; (3) cover limited functionality of MQTT; and (4) require a deep understanding of MQTT's specifications to configure the fuzzer effectively.

Existing generation-based fuzzers (Casteur *et al.*, 2020; Sochor *et al.*, 2020b), have limited knowledge of MQTT's specifications, and thus have difficulties to cover all of its features.

All of the aforementioned problems stem from the lack of a systematic and effective input generation scheme, which is a current research challenge for several target systems (C. Chen *et al.*, 2018) including pub/sub protocols. Among several schemes, *grammar-based fuzzing* is considered to be *the* most effective for applications with complex input structures (Godefroid *et al.*, 2017). Grammar-based fuzzers, as their name suggests, gain knowledge from grammars, which are among the most reliable sources for knowledge acquisition.

Thus far, research on grammar-based fuzzing for MQTT or any other pub/sub protocol is currently non-existent and unexplored. Developers have opted for alternatives to grammar-based approaches throughout the years due to their complicated and time-consuming nature (Hernández Ramos *et al.*, 2018). For example, Aichernig *et al.* (2021) propose an automata-learning technique to infer the message syntax of MQTT without the need for a grammar. Hernández Ramos *et al.* (2018), Zeng *et al.* (2020), Casteur *et al.* (2020), Di Paolo *et al.* (2021), and Pearson *et al.* (2022) provide their MQTT fuzzers with templates for them to gain an understanding of the message syntax, thereby avoiding grammars altogether.

Despite their complexity, grammars offer several advantages over other knowledge acquisition sources: (1) higher level of automation for generating packets; (2) higher flexibility for integrating into fuzzing frameworks; (3) better understanding of the protocol and its control packet structure; (4) higher flexibility for developers to modify for their own needs, (5) guaranteed acceptance by the broker; (6) higher feature coverage of the protocol; and (7) systematic and efficient test generation.

Grammar-based approaches for MQTT are not only necessary, but also demanded across several research studies (Hernández Ramos *et al.*, 2018; Sochor *et al.*, 2020b). Although developers and researchers have expressed interest, the literature lacks information about how to apply grammar-based fuzzing to pub/sub protocols. Thus, the main question worth answering is:

> *RQ1: How can a grammar-based fuzzer for a pub/sub protocol such as MQTT be developed?*

The following sections propose a new methodology and an architecture in order to develop a grammar-based fuzzer for a pub/sub protocol such as MQTT.

3.1 Architecture

The grammar-based approach is incorporated into a new network-based fuzzer called `MQTTGRAM`. The architecture of `MQTTGRAM` consists of two major components, which are the Response Engine and the Packet Generator, as shown in Figure 3.1.

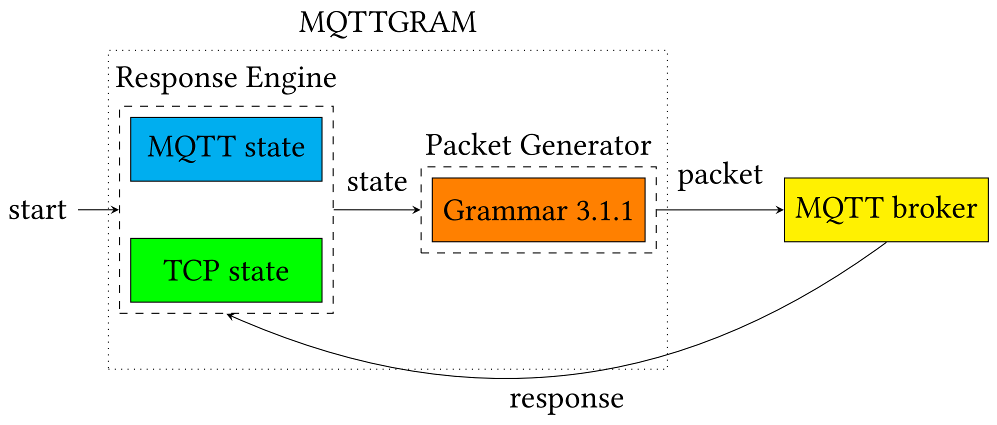


Figure 3.1: *Architecture of* `MQTTGRAM`

The response engine and packet generator work collectively to fuzz a pub/sub broker. The response engine is mainly responsible for supporting a *two-way communication* between the fuzzer and the broker. The response engine consists of two subcomponents. The first subcomponent, `TCP State`, handles the TCP sequence and acknowledgment numbers for each packet sent to the broker. The second subcomponent, `MQTT State`, handles and analyzes messages received from the broker in order to identify which *state* of the protocol has been reached at a particular moment during testing. This information is then provided to the packet generator, which generates a response message to guide the fuzzing process to the next state considering the sequence defined by the standard (See Appendix C, Section C.2 for further details). The messages are in hexadecimal notation, which is often used in networking to represent packet formats. The packet generator of `MQTTGRAM` generates hexadecimal strings from a grammar considering the format defined by the MQTT 3.1.1 standard (Andrew Banks and Rahul Gupta, 2014). The hexadecimal string is then sent to the broker as an MQTT packet. A simple example of the MQTT 3.1.1 grammar and its expansion rules is shown below:

```
⟨start⟩           ::= ⟨packets⟩
⟨packets⟩         ::= ⟨publish⟩
⟨publish⟩         ::= ⟨fixed-header⟩⟨variable-header⟩
                    | ⟨fixed-header⟩⟨variable-header⟩⟨payload⟩
⟨fixed-header⟩    ::= 'Hexadecimal string of fixed header'
⟨variable-header⟩ ::= 'Hexadecimal string of variable header'
⟨payload⟩         ::= 'Hexadecimal string of payload'
```

Figure 3.2: *Simple Example of the MQTT 3.1.1 Grammar in Backus-Naur Form*

Nonterminal symbols are on the left and enclosed between angle brackets (<>). Substitution options or expansion rules for the nonterminal symbol are on the right. Expansion rules describe how to replace nonterminals with terminal symbols, which can not be substituted or expanded any further. The end result is a string that consists entirely of terminal symbols, which in this case are hexadecimal digits representing an MQTT packet. The proposed grammar has a nonterminal symbol `<packets>` that describes expansion rules for each MQTT packet. The selection of the expansion rule depends on the packet required by the response engine to reach the next protocol state. For example, if the response engine requires a publish packet, then the nonterminal symbol chosen to be expanded is `<publish>`. The algorithm then randomly selects a production rule to generate a publish packet either with or without a payload. It is worth noting that network packets are usually divided into three fields: (1) the fixed header; (2) the variable header; and (3) the payload (See Appendix C, Section C.1 for further details). Following this premise, the grammar developed for `MQTTGRAM` has production rules to generate each field accordingly. The end result of the proposed grammar is the concatenation of hexadecimal strings for the fixed header, variable header, and payload, which together make up an MQTT 3.1.1 message.

3.2 Algorithms

Algorithm 1 presents the pseudocode of a generation-based fuzzing approach that uses a grammar to generate network packets from scratch. The algorithm is explained in the following subsections.

Algorithm 1: Grammar-Based Fuzzing Approach for MQTT

```
Input: Protocol State $S$
1 while $stopping\_criterion == false$ do
2     $t \leftarrow select\_packet\_type(S)$;
3     $m \leftarrow generate\_packet(t)$;
4     $r \leftarrow feed\_input(m)$;
5     $S \leftarrow evaluate\_response(r)$;
6     $L \leftarrow monitor\_program(S)$
Output: $L$
```

3.2.1 Selecting the Packet Type

Network packets must follow a particular order to reach deep protocol states. For example, a *DISCONNECT* packet must be sent only if the MQTT client is in a *connected state*. The interactions must adhere to formal specifications of the protocol, transitioning to different states in the correct order. Protocol states are determined by control packets (See Appendix C, Table C.1 for further details). For example, if an MQTT client receives a *CONNACK* packet from the broker, then the client is connected.

`MQTTGRAM` uses an approach that selects and generates packets based on the current broker state. For example, at the beginning of the test run, a fuzzer based on the proposed approach is in a *disconnected state* because it has not established a connection with the broker. Thus, it performs a Transmission Control Protocol (TCP) handshake and sends a *CONNECT* packet to the broker. If `MQTTGRAM` receives a *CONNACK* packet from the broker, then it has successfully transitioned to a *connected state*.

3.2.2 Generating the Packets

Protocol fuzzers need to possess knowledge of both the input structure and states, maintaining execution consistency throughout the fuzzing campaign (Yurong Chen *et al.*, 2019). It is not enough to simply gain program knowledge through a grammar. The fuzzer needs to be state-aware (Kitagawa *et al.*, 2010), and generate packets based on the type of packets received from the broker. Moreover, the fuzzer needs to generate the necessary packets to reach deep protocol states.

Derivation of Hexadecimal Strings

Algorithm 2 presents the pseudocode for the derivation of hexadecimal strings from an MQTT grammar. The process of choosing a nonterminal and applying an expansion rule is adapted from (Zeller *et al.*, 2020) considering the MQTT standard.

Algorithm 2: Derivation of Hexadecimal String from an MQTT Grammar

```
Input: Packet Type $t$, Grammar $g$
1 while nonterminals from $t > 0$ do
2     $n \leftarrow choose\_nonterminal(t, g)$;
3     $e \leftarrow choose\_expansion\_rule(n, g)$;
4     $s \leftarrow apply\_expansion(e, n)$;
5 for field_lengths in $s$ do
6     $calculate(field\_lengths)$;
7 $p \leftarrow convert\_string\_to\_bytes(s)$;
8 $m \leftarrow calculate\_remaining\_length(p)$;
Output: $m$
```

The MQTT 3.1.1 standard states that several packet fields must be represented as UTF-8 encoded strings, such as usernames, passwords, and topic names. Each UTF-8 encoded string is prefixed with a two-byte length field. This is required in order to identify multiple UTF-8 encoded strings correctly. Thus, when there are no further expansions, Algorithm 2 calculates the length of each UTF-8 encoded string and remaining length (lines 5-8).

Figure 3.3 presents an example of Algorithm 2 when generating a *PUBLISH* packet.

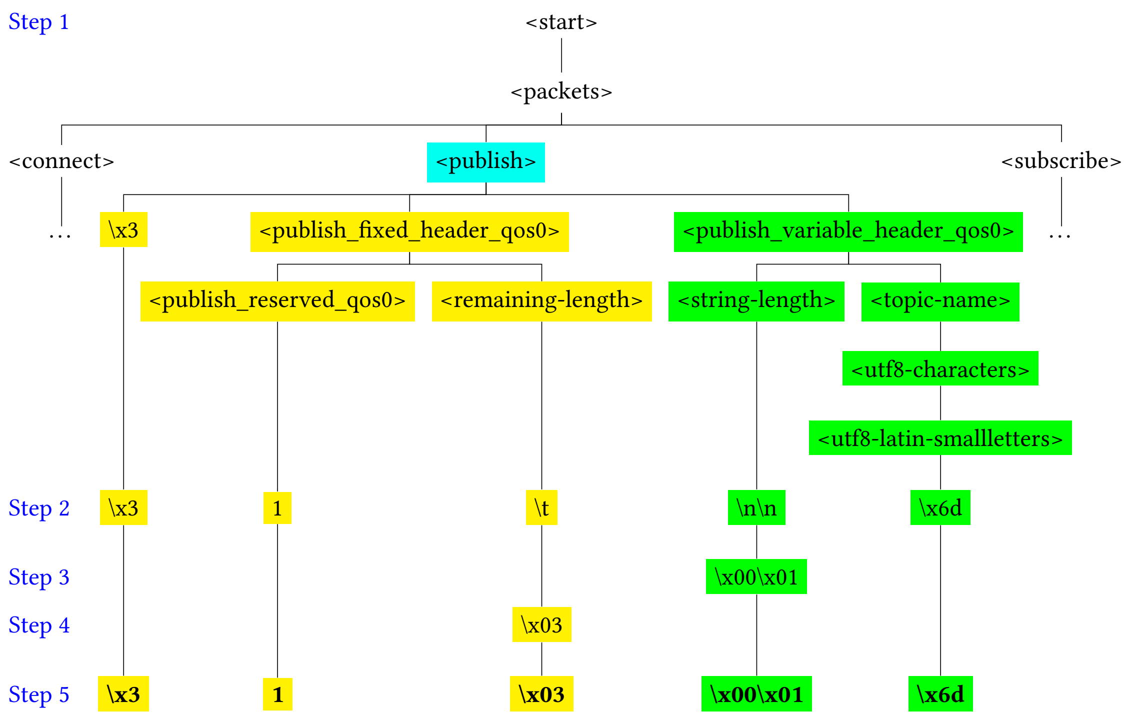


Figure 3.3: *Derivation Tree for a PUBLISH Packet in Hexadecimal Notation*

The steps performed by Algorithm 2 to generate the hexadecimal string that represents a *PUBLISH* packet, shown in Figure 3.3, are as follows.

Step 1: The derivation process begins with a start symbol `<start>`, which is expanded into the nonterminal symbol `<packets>`. The symbol `<packets>` has fourteen expansion alternatives, each one being a type of MQTT packet. In this case, the nonterminal symbol `<publish>` is chosen to be expanded. The symbol `<publish>` has four expansion rules. However, Figure 3.3 presents only one of these expansions rules (`\x3<publish_fixed_header_qos0><publish_variable_header_qos0>`) for simplicity purposes. The expansion rule shown in Figure 3.3 is for *PUBLISH* packets whose QoS level is set to `0`, and the payload is absent. The expansion rule is divided into three fields in Figure 3.3 to better illustrate the methodology. The first field `\x3` is a terminal symbol that consists of three characters: `\x` mean that digits are in hexadecimal; and `3` represents the value of a *PUBLISH* packet according to the MQTT 3.1.1 standard. The second field `<publish_fixed_header_qos0>` is expanded into two nonterminal symbols: `<publish_reserved_qos0>` and `<remaining_length>`. The symbol `<publish_reserved_qos0>` is substituted for `1`, which signifies that the *Retain Flag* in the packet is set to 1. The symbol `<remaining_length>` is substituted for `\t`, which is a temporary symbol that will be replaced with the remaining length in Step 4. The third field `<publish_variable_header_qos0>` is also expanded into two nonterminal symbols: `<string-length>` and `<topic-name>`. Similar to `<remaining_length>`, the symbol `<string-length>` is substituted for `\n\n`, which will be replaced with the actual length of `<topic-name>` in Step 3. The symbol `<topic-name>` is expanded into the nonterminal symbol `<utf8-characters>`, which currently has four expansion alternatives: `<utf8-numbers>`, `<utf8-latin-capitalletters>`, `<utf8-latin-smallletters>`, `<utf8-symbols>`. In this case, Algorithm 2 randomly chooses `<utf8-latin-smallletters>`, which is substituted for `\x6d`, representing the letter `m`. It is worth noting that the grammar is recursive, meaning nonterminal symbols such as `<utf8-latin-smallletters>` or `<topic-name>` can be expanded an infinite number of times, yielding complex inputs.

Step 2: When all nonterminals have been expanded, a hexadecimal string is produced.

Step 3: Using regular expressions, all UTF-8 encoded strings are retrieved by searching for `\n\n`, and their length is calculated.

Step 4: The remaining length of the packet is calculated, hence the importance of calculating the length of all UTF-8 encoded strings in Step 3.

Step 5: When all necessary field lengths are calculated, the derived output is a byte string that represents an MQTT packet.

3.2.3 Feeding the Packets

`MQTTGRAM` interacts directly with the broker rather than acting as a man-in-the-middle. This approach provides more control over the packets that are generated during the test run. Rather than requiring initial test cases, `MQTTGRAM` generates its own network packets to communicate with the broker successfully.

3.2.4 Evaluating the Response

`MQTTGRAM` sends mainly five types of packets to the broker: *PUBLISH*, *SUBSCRIBE*, *UNSUBSCRIBE*, *PINGREQ*, and *DISCONNECT*. For every packet sent, the last response from the broker is evaluated based on the TCP flag and the broker state. If the packet's TCP flag is set to Finish (FIN) or Reset (RST), `MQTTGRAM` reconnects to the broker automatically; otherwise `MQTTGRAM` analyzes the type of MQTT packet, and responds accordingly. For example, if the broker sends a *PUBLISH* packet, `MQTTGRAM` responds by sending a *PUBACK* packet or *PUBREC* packet when the QoS level is set to 1 and 2 respectively.

3.2.5 Monitoring the Program

The fuzzing process is monitored constantly for any crashes or errors until a stopping criterion has been satisfied. Logs are used to store information about the test run.

3.3 Performance Evaluation

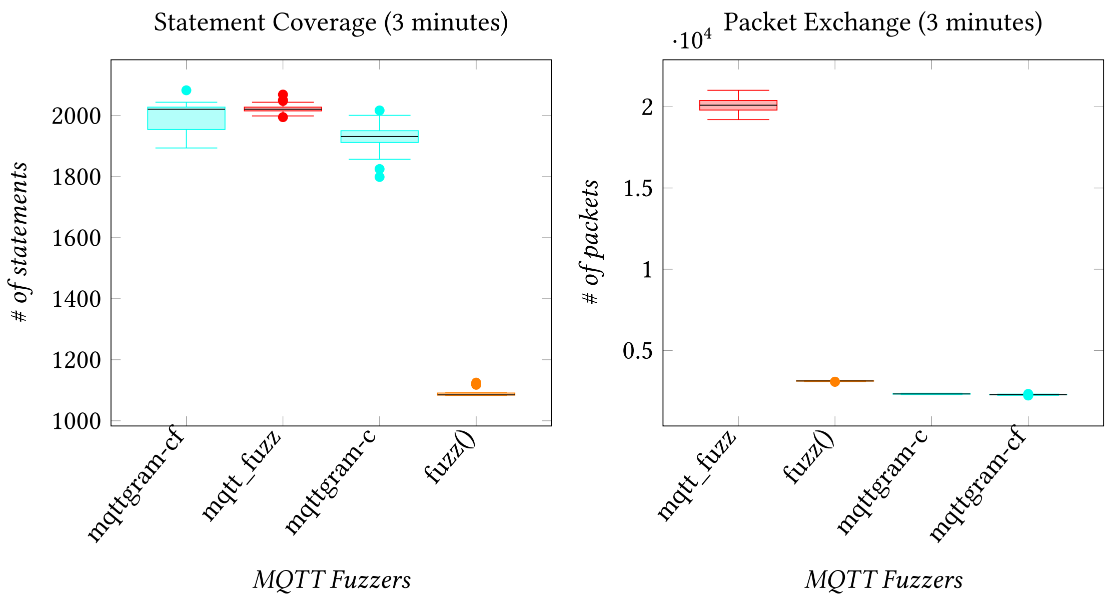
The performance of the proposed grammar-based approach is compared with that of a naive fuzzer (`fuzz()`), a mutation-based fuzzer (`mqtt_fuzz`), and a generation-based fuzzer (Sochor *et al.*, 2020b). `fuzz()` and `mqtt_fuzz` are among the most popular naive and mutation-based fuzzers, respectively, and thus were chosen for the experiments. The fuzzer by Sochor *et al.* (2020b) was chosen for its promising vulnerability-oriented approach, however it is proprietary, meaning it could not be evaluated on the testbed developed for the doctoral studies. As a result, the grammar-based approach was evaluated in the same manner as the fuzzer by Sochor *et al.* (2020b) for comparison purposes.

Two variants of `MQTTGRAM` were developed in order to evaluate how probabilistic settings for control packet types affect the performance of the proposed grammar-based approach. The first variant, `mqttgram-c`, sends MQTT packets to the broker in correct order, and packets sent to the broker have the same probability of being generated. The second variant, `mqttgram-cf`, sends MQTT packets in correct order, and occasionally out of order. Moreover, each *PUBLISH*, *SUBSCRIBE*, and *UNSUBSCRIBE* packet has a 25% chance of being generated; *PINGREQ* has a 15% chance, and *DISCONNECT* has a 10% chance. Considering these slight modifications, `mqttgram-c` covers only *correct* functionalities, whereas `mqttgram-cf` covers both *correct and failed* functionalities. Moreover, `mqttgram-cf`'s configuration of sending packets out-of-order and preferring packets with topic fields is based on existing MQTT vulnerabilities.

The effectiveness of the proposed grammar-based approach is evaluated using two metrics: (1) statement coverage and (2) input coverage, the latter of which is considered indispensable when developing grammar-based approaches (Havrikov and Zeller, 2019). Mosquitto and Moquette were chosen as the target systems because they rank among the most popular MQTT brokers (Hernández Ramos *et al.*, 2018; Sochor *et al.*, 2020b). Two separate experiments were conducted, each satisfying a different stopping criterion. For the first experiment, the fuzzers perform 3- and 30-minute test runs. For the second experiment, the fuzzers test the brokers until 500 and 8000 packets have been exchanged between both parties. The testbed shown in Figure 1.3, and explained in Section 1.2.2 was used for the performance evaluation. It is worth noting that Sochor *et al.* (2020b) chose Moquette as the target system to evaluate their fuzzer, hence its absence in figures based on Mosquitto.

3.3.1 Mosquitto

Figure 3.4a presents the statement coverage achieved by the fuzzers in 3 minutes. `fuzz()` has the lowest statement coverage, executing at most 1125 statements and at the very least 1083. `mqttgram-c` manages to have higher statement coverage than `fuzz()`, executing at most 2017 statements and at least 1799. Thus, `mqttgram-c` performs at most 59.91% better because it has knowledge of MQTT's specifications. `mqtt_fuzz` manages to execute at most 2069 statements, performing 83.91% and 2.58% better than `fuzz()` and `mqttgram-c` respectively. `mqttgram-cf` fared slightly better, achieving a coverage increase of at most 0.68% and 85.15% compared to `mqtt_fuzz` and `fuzz()` respectively.



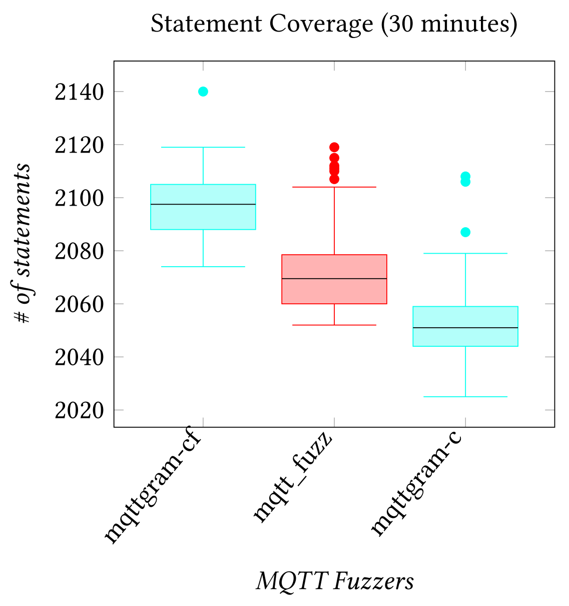
(a) **(b)**

Figure 3.4: *Results of 3-Minute Test Runs*

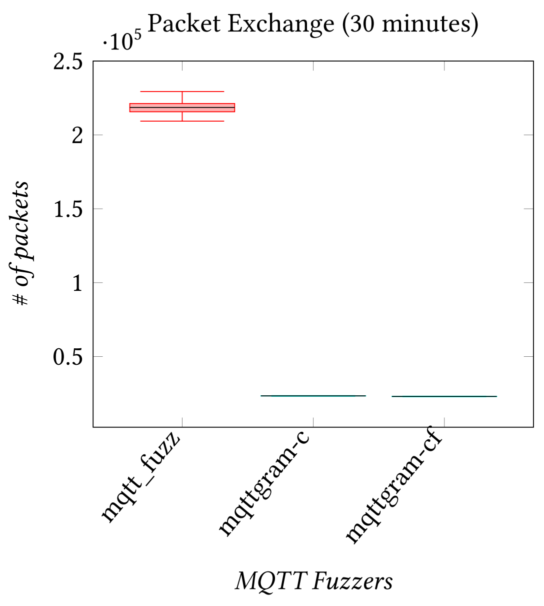
`mqtt_fuzz` manages to have better statement coverage overall because it exchanges a considerable amount of packets with the broker, as shown in Figure 3.4b. On average, `mqtt_fuzz` and Mosquitto exchange 20111 packets, approximately 544.79%, 765.36%, and 783.61% more than `fuzz()`, `mqttgram-c`, and `mqttgram-cf` respectively. Since `mqtt_fuzz` sends more packets to Mosquitto, there is a higher probability that more code paths are traversed during a short amount of time (3 minutes). However, `mqttgram-cf` is more effective than its counterpart, executing 2083 statements while exchanging only 2,258 packets. `mqttgram-cf` has higher statement coverage because it considers correct and failed functionalities of MQTT. Moreover, `mqttgram-cf` triggers more functionalities of MQTT because it has knowledge of its specifications. `fuzz()` manages to send more packets to Mosquitto than `mqttgram-c` and `mqttgram-cf` within the same time frame. This is because `fuzz()` generates random packets without considering the MQTT standard.

For simplicity purposes, the following figures do not present the results of `fuzz()` because it achieves low performance in terms of statement coverage.

Although `mqtt_fuzz` has the highest statement coverage overall in 3 minutes, a different outcome occurs in 30 minutes (Figure 3.5a). Among all MQTT fuzzers, `mqttgram-cf` has the highest statement coverage, executing 2140 statements at most, which is approximately up to 90%, 1.51%, and 0.99% more than `fuzz()`, `mqttgram-c`, and `mqtt_fuzz` respectively. It is worth noting that on average `mqttgram-cf` and Mosquitto exchange the lowest number of packets (Figure 3.5b), approximately 22995; thus confirming the effectiveness of the proposed grammar-based approach.



(a)



(b)

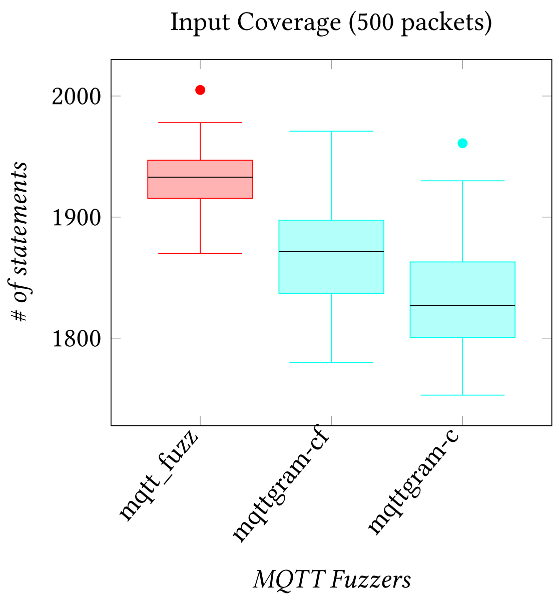
Figure 3.5: *Results of 30-Minute Test Runs*

Over time, both variants of `MQTTGRAM` have higher statement coverage because they possess knowledge of MQTT's packet format, thus triggering all possible behaviors. The remaining fuzzers have an average number of packets exchanged with the broker as follows: `mqtt_fuzz`: 218557; `mqttgram-c`: 23364; and `fuzz()`: 30993.

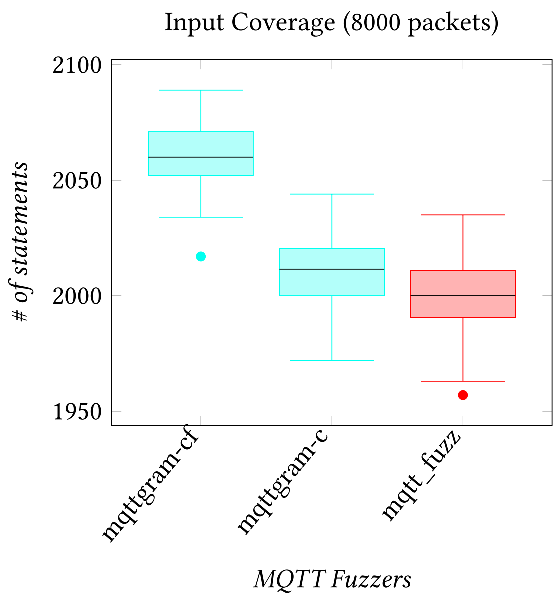
Figure 3.6a presents the input coverage achieved by the MQTT fuzzers when exchanging exactly 500 packets with the broker. `mqtt_fuzz` has the highest coverage performance, executing 2005 statements. `mqttgram-c`, `mqttgram-cf`, and `fuzz()` execute at most 1961, 1971, and 1118 statements respectively. Although variants of `MQTTGRAM` have lower coverage than their counterparts, exchanging 8000 packets with Mosquitto has a different outcome (Figure 3.6b). On average, `mqttgram-c` and `mqttgram-cf` execute 2009 and 2060 statements respectively. The results of both variants are higher than their counterparts, confirming that they test more functionality of MQTT effectively.

Moquette

This section presents a performance comparison between `MQTTGRAM` and the fuzzer proposed by Sochor *et al.*, 2020b, which also developed two variants of their approach.



(a)



(b)

Figure 3.6: *Results of 500- and 8000-Packet Test Runs*

The first variant generates packets that are not based on existing vulnerabilities of MQTT, whereas the second variant generates packets based on a list of twenty-five cyberattacks. `mqttgram-cf` is classified as being *vulnerability-oriented* in Table 3.1 because it is designed to send packets with topic fields much more frequently. This design choice is based on the fact that several implementation flaws in MQTT have been uncovered with topic-based packets (Di Paolo *et al.*, 2021).

Since Sochor *et al.* (2020b) measure statement coverage for each source code directory of Moquette, the performance of `MQTTGRAM` is evaluated in the same manner to enable a comparison between the two fuzzers. Table 3.1 presents the statement coverage achieved by the two variants of `MQTTGRAM` and the fuzzer proposed by Sochor *et al.* (2020b) during 30 minutes.

Source Code (Directory)	Fuzzed packets not based on existing vulnerabilities		Fuzzed packets based on existing vulnerabilities	
	Sochor et al. 2020	mqttgram-c	Sochor et al. 2020	mqttgram-cf
broker	57.8%	**66.34%**	58%	**67.57%**
broker.security	11.3%	**15%**	12.8%	**15%**
broker.subscriptions	59.0%	**73.52%**	63.9%	**73.92%**
broker.config	49.3%	**51%**	49.3%	**51%**
broker.metrics	**77.5%**	73%	**77.5%**	73%
persistence	**9.1%**	9%	**9.1%**	9%
interception	**32.3%**	30%	**32.3%**	30%
Logging	**62.5%**	43%	**62.5%**	43%
Total	50.0%	**56.76%**	51.4%	**57.24%**

Table 3.1: *Statement Coverage of Moquette Achieved by MQTT Fuzzers in 30 Minutes (Results by Sochor et al. (2020b) were copied directly from their research paper due to their fuzzer being proprietary)*

It is worth noting that the fuzzer proposed by Sochor *et al.* (2020b) is not publicly available. Thus, the performance of `MQTTGRAM` is compared with results shown in their research paper (Sochor *et al.*, 2020b). Moreover, results by Sochor *et al.* (2020b) are based on a single thirty-minute fuzzing campaign, whereas the results of `MQTTGRAM` in Table 3.1 are based on the average of a hundred test runs.

Table 3.1 highlights in bold the highest statement coverage for each directory of Moquette. Both variants of `MQTTGRAM` have the highest statement coverage in the `broker.security` directory. Although `mqttgram-c` is geared towards correct functionality of MQTT, it manages to outperform the vulnerability-oriented fuzzer by Sochor *et al.* (2020b). Moreover, although Sochor *et al.* (2020b) generated fuzzed packets based on twenty-five cyberattacks, `mqttgram-cf` outperforms their approach by considering only two patterns of existing MQTT vulnerabilities. This confirms that grammar-based approaches for MQTT are not only efficient, but have better chances of triggering more flaws in MQTT.

3.3.2 Takeaway from Experiments

There are three takeaways from the experiments. First, mutation-based approaches, such as `mqtt_fuzz`, are more suitable for short-lived fuzzing executions. Second, MQTT fuzzers must possess knowledge of the protocol standard to test brokers effectively over longer sessions. Third, `mqttgram-cf` demonstrated the possibility of using different grammar-based approaches to achieve better results. It is worth noting that no crashes were triggered during the test runs.

After developing and evaluating `MQTTGRAM`, the answer to **RQ1** is as follows:

RQ1: How can a grammar-based fuzzer for a pub/sub protocol such as MQTT be developed?

Network protocols support different types of packets, each usually consisting of a fixed header, a variable header, and a payload. For the grammar, production rules should be defined in accordance with the structure of a packet. For example, each type of packet should have its own designated nonterminal symbol (<publish>), which then should be substituted with three nonterminal symbols, each representing a layer of the packet (<fixed-header><variable-header><payload>). A production rule has to be created for each optional field. For example, suppose the payload of a packet is optional. Thus, two production rules will need to be created for each scenario: (<fixed-header><variable-header><payload>) and (<fixed-header><variable-header>). For variable-length fields, *recursive* production rules are needed to generate complex values. Among variable-length fields, subscription topics are one of, if not, *the* most important to test pub/sub protocols. A compromise has to be made for production rules to generate unexpected, *but* semantically-meaningful topics that activate and test message publishing features. A strategy to overcome this challenge is to limit the character set in order to increase the chances of generating the same topics across publication and subscription requests. However, the derivation process by itself is insufficient to test message publishing features because the fuzzer has to interact *correctly* with the broker in order to receive subscription messages. Thus, a response engine and a packet generator should operate collectively during a test run.

3.4 Threats to Validity

Hardware: Sochor *et al.* (2020b) failed to provide any information whatsoever regarding their testbed's hardware configuration, which may or may not differ from that of Figure 1.3. In terms of the former case, different hardware configurations may provide an unfair performance comparison between the fuzzer proposed by Sochor *et al.* (2020b) and its competitors. This threat to the validity of the experiments is minimized, however, by using the same stopping criterion (30 minutes), metric (statement coverage), and target broker (Moquette 0.13) chosen by Sochor *et al.* (2020b) for their research study.

Metrics: Due to the absence of crashes, the effectiveness of the fuzzers was measured and determined using statement coverage, which is a metric that indicates *how likely* an implementation flaw will be discovered during a test run. However, statement coverage provides *no guarantees* that a fuzzer will actually uncover an implementation flaw in a target broker.

Time: In this research study, the fuzzers test the brokers for up to 30 minutes, which is the same stopping criterion used by Sochor *et al.* (2020b) for their experiments. The reason for using the same stopping criterion is to provide a more fair and consistent comparison between results generated by Sochor *et al.* (2020b) and those generated by the testbed presented in Figure 1.3. However, the coverage performance of the fuzzers after 30 minutes is unknown, meaning that there is no way to guarantee that the number of statements will either be the same or improve over longer periods of time.

Repetitions: Experiment results generated by the testbed shown in Figure 1.3 are based on one hundred test runs, whereas those provided by Sochor *et al.* (2020b) are based on only one. The different number of test runs between both research studies is a potential threat to the validity of the performance analysis and comparison presented in Table 3.1.

3.5 Concluding Remarks

Existing fuzzing frameworks lack knowledge of MQTT's specifications, hindering their testing capabilities. As a result, several research papers have expressed interest in grammar-based approaches, however the literature lacks information on how to apply them to pub/sub protocols such as MQTT. This research aimed to address both of these limitations by presenting a grammar-based approach that aims for high code and state coverage. Based on our experiments, the grammar-based approach implemented in `MQTTGRAM` has higher statement coverage than existing MQTT fuzzers. Thus, an important contribution of this research is the confirmation that grammar-based approaches for pub/sub protocols are not only viable, but also effective and promising for testing purposes. Furthermore, the design considerations, architecture, methodology, and even challenges presented for this research study can help developers to build grammar-based fuzzers for other pub/sub protocols.

Chapter 4

Taxonomy and Coverage Evaluation of Fuzzing Techniques for the MQTT Protocol

While developing the new grammar-based fuzzing technique for MQTT, *four* additional research gaps were identified in the literature regarding pub/sub protocol fuzzing:

Gap 1: Most research studies focus on the fuzzers' bug-finding capabilities rather than their coverage performance Although bug-finding is an important metric during testing, it fails to provide sufficient feedback on how *thoroughly* the tests are performed by the fuzzers. Several test coverage metrics are unused or neglected in most research studies, such as statement coverage. For example, despite being among the most popular and accessible fuzzers, `mqtt_fuzz` was evaluated in terms of statement coverage only until recently (Araujo Rodriguez and Macêdo Batista, 2021). The literature also currently lacks information regarding the fuzzers' shortcomings in terms of feature and functionality testing. This poses the question as to whether developers and existing fuzzers, regardless of their testing technique, are considering the unique attributes of the pub/sub messaging pattern. The issue is further aggravated by proprietary fuzzers such as `Defensics`, which despite being popular, remains largely unstudied from a scientific perspective, with limited information regarding its testing or coverage capabilities. As a result, unknown testing capabilities currently hinder further advancements in the field of MQTT *and* pub/sub protocol fuzzing.

Gap 2: The lack of baseline results for comparison purposes is clearly evident across the literature, hindering possible opportunities for future work. For example, Sneha Suhitha Galiveeti and Pranitha Malae (2020) noted the lack of baseline results in the literature, having no choice but to avoid performance comparisons for their study. Zeng *et al.* (2020) compared their fuzzer with others unrelated to MQTT due to the lack of baseline results. For this thesis, it was necessary to first create baseline results of a naive- and mutation-based approach to demonstrate the advantages of `MQTTGRAM`, as shown in Chapter 3.

Gap 3: Fuzzer evaluation is conducted inconsistently across the literature. Aichernig *et al.* (2021) and Di Paolo *et al.* (2021) measure fuzzing effectiveness by the number of security inconsistencies found across several brokers, neglecting coverage metrics altogether. Casteur *et al.* (2020) use a scoring system to rank the effectiveness of each scenario generated by their fuzzer. At the beginning of the fuzzing campaign, scenarios are assigned an initial score, which is later incremented for each inconsistency found during testing. Inconsistent behavior is determined by several factors such as slow broker response times and error logs. The more inconsistencies found during testing, the higher the rank of each scenario. Top-ranked scenarios are therefore considered more promising and effective at testing MQTT implementations. Hernández Ramos *et al.* (2018) evaluate their proxy fuzzer by considering the following criteria: the time to process and mutate packets; the number of implementation flaws found during testing; and the CPU consumption of the host machine. Palmieri *et al.* (2019) present the number and types of messages intercepted by their fuzzer, as well as its threat detection and pub/sub capabilities. As a future work, Palmieri *et al.* (2019) propose a more in-depth analysis of the effectiveness of their framework in providing feedback to developers about the current broker configuration. Anantharaman *et al.* (2017) fail to provide any sort of explanation regarding their fuzzers' performance during testing. In contrast, Sochor *et al.* (2020b) deeply explain the issues identified across multiple brokers, as well as the number of unhandled exceptions and test failures throughout the experiments. Sochor *et al.* (2020b) also present their fuzzers' statement coverage. For this thesis, statement coverage was chosen for evaluation purposes, whereas Zeng *et al.* (2020) preferred path coverage, thereby hindering a performance comparison between the two research studies. At the time of writing, only the latter three research studies use traditional testing metrics to evaluate their proposals. The reason behind this issue is due to the lack of standardized methods or metrics in the literature to evaluate fuzzers for pub/sub protocols such as MQTT.

Gap 4: Lack of a performance comparison between MQTT fuzzers. This in turn raises uncertainty about the improvement of subsequent fuzzers compared to their predecessors. There is also a lack of awareness regarding the benefits and limitations of each fuzzing technique for MQTT. This situation stems from the fact that no research study has benchmarked existing MQTT fuzzers across a wide variety of testing and pub/sub metrics.

Analyzing and evaluating multiple fuzzing techniques under the same conditions provides opportunities to: (1) establish a necessary baseline for future research studies; (2) raise awareness about their testing and pub/sub capabilities; and (3) offer constructive feedback to their developers. This chapter therefore aims to answer the following research questions:

RQ2: What fuzzing techniques have been proposed for MQTT over the last few years?

RQ3: How effective are fuzzing frameworks for MQTT in terms of their testing and pub/sub capabilities?

For **RQ2**, a literature review is conducted in order to develop a taxonomy based on fuzzing techniques proposed specifically for MQTT brokers. The taxonomy presents a total of sixteen fuzzing frameworks found across the literature, more so than for any other IoT protocol. Table 2.3 classified MQTT fuzzers into four main categories based on their test case generation technique. The proposed taxonomy goes one step further, and classifies the MQTT fuzzers based on their distinguishing or innovative feature for testing purposes. The taxonomy therefore provides a more detailed overview of the current state of the art in terms of fuzzing techniques for MQTT.

In order to answer **RQ3**, at least one MQTT fuzzer from each category in the taxonomy is evaluated using three different types of criteria based on testing, pub/sub, and MQTT-specific metrics respectively. The first criterion (*testing*) is based on *statement coverage*, which is the most traditional, yet the most reliable metric to predict the quality of test suites (Gopinath *et al.*, 2014). The second criterion (*pub/sub*) is based on *pub/sub behavior*, which is a metric that is used to evaluate whether the MQTT fuzzers are testing *message publication*, which is the process in which the broker sends messages to interested subscribers. Message publication is the most important and representative feature of the pub/sub design pattern, meaning every pub/sub fuzzer should *at least* be capable of testing it regardless of whether they are designed for MQTT or not. The second criterion is based on a *generic* metric for pub/sub protocols, whereas the third criterion is based on features *specific* to MQTT. For the third criterion, the MQTT fuzzers are evaluated in terms of their testing capabilities for core features of MQTT: (1) QoS Levels; (2) Last Will and Testament; (3) Retained Messages; and (4) Persistent Sessions. The results of the second and third criteria are presented collectively as *Feature Coverage* in Section 4.3. The research findings attest that most fuzzing frameworks are incapable of testing message publications and the four core features of MQTT defined in the standard.

Overall, this chapter provides three main research contributions: (1) a taxonomical classification of fuzzing techniques for MQTT; (2) a performance comparison and discussion of fuzzing techniques proposed by several researchers for MQTT; and (3) a baseline for future studies to compare with. It is worth noting that MQTT is the *only* pub/sub protocol for which developers have a proposed a wide variety of fuzzing techniques in the literature at the time of writing. Thus, this chapter classifies and evaluates most, if not all, advancements in the field of pub/sub protocol fuzzing as well, despite focusing specifically on MQTT. The lessons learned from this research study can therefore help lay the foundation for effective pub/sub protocol fuzzing in general.

This chapter begins by explaining aspects that need to be considered by developers when designing MQTT fuzzers regardless of their testing strategy. These explanations are then followed by a taxonomical classification of techniques used by developers to fuzz MQTT and pub/sub protocols in general. The final section of this chapter presents a performance evaluation of each technique presented in the taxonomy. The design considerations presented in the earlier sections of this chapter will play a *key* role in the evaluation.

4.1 Design Considerations for MQTT Fuzzers

The most difficult, and possibly the most important, types of bugs to find in pub/sub brokers are those related to their message publishing features. These types of bugs are not only a major threat to the security of the IoT application, but also to its QoS. From a security standpoint, a bug can *intentionally* be exploited by a publisher to either crash the broker or an end device acting as a subscriber. Another potential outcome is the publisher uncovering a software weakness *unintentionally*, which can then be found and exploited by subscribers to perform unauthorized actions. The latter outcome is actually based on a real-world vulnerability found in an MQTT broker (CVE-2018-12546)[1]. From a user standpoint, publication-related bugs may lead to low-quality experiences when subscribers receive messages based on their topics of interest. In order to reduce these risks, features based on the unique characteristics of the pub/sub design pattern need to be tested thoroughly.

The main challenge of fuzzing MQTT implementations is that most of its pub/sub features can only be tested if the fuzzer performs a specific type of connection, subscription, *and* publication request. Certain features of MQTT also depend on user interactions from previous sessions. The fuzzer must therefore reconnect using an existing client ID to activate certain features at some point during testing. The complexity is further increased with the release of MQTT 5.0 (Andrew Banks and Ed Briggs and Ken Borgendale and Rahul Gupta, 2019), which introduces 27 user properties, each with its own specific syntax and format. As a result, an MQTT fuzzer has to be designed in such a way that it satisfies the necessary requirements to activate and test these features despite its random nature. Regardless of the version of MQTT, every fuzzer should *at least* strive to activate and test the following four pub/sub features defined in the standard.

QoS Levels

The delivery of messages to interested subscribers is guaranteed by specifying a QoS level:

- Messages set to *QoS level 0* are delivered to the subscriber *at most once*. The publisher does not receive an acknowledgment from the broker.
- Messages set to *QoS level 1* are delivered to the subscriber *at least once* until receiving an acknowledgment from the broker.
- Messages set to *QoS level 2* are delivered to the subscriber *exactly once* using a four-way handshake.

Last Will and Testament

The Last Will and Testament is a feature whereby subscribers are notified if a publisher disconnects from the network unexpectedly. The broker detects an unexpected disconnection if the publisher does not respond within a given time period. MQTT's Last Will and Testament feature can be considerably useful to inform the status of an IoT device if a network failure or loss of battery power occurs. Since environment settings can occasionally hinder device connectivity, this feature can help keep track of devices and their status. Figure 4.1 presents an example of a device that unexpectedly disconnects from the broker, which will then notify subscribers of the outcome.

[1] https://nvd.nist.gov/vuln/detail/CVE-2018-12546. Accessed on June 12th, 2023

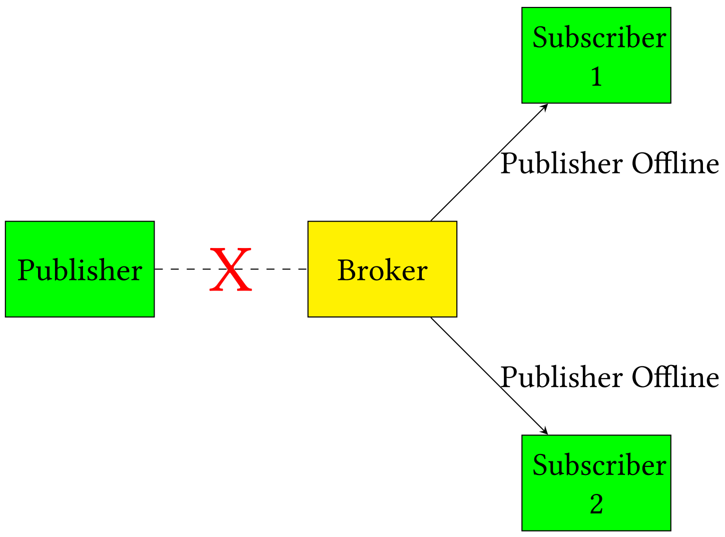


Figure 4.1: *Last Will and Testament Messages*

Publishers can specify their last will messages when connecting to the broker. The *CONNECT* packet has a *Will Flag* to activate this feature. If activated, publishers will need to specify the *Last Will Topic* and its corresponding message. Clients subscribed to this topic will be notified in the event of an unexpected disconnection.

Retained Messages

Retained Messages are messages delivered *immediately* to newly-subscribed MQTT clients, as shown in Figure 4.2.

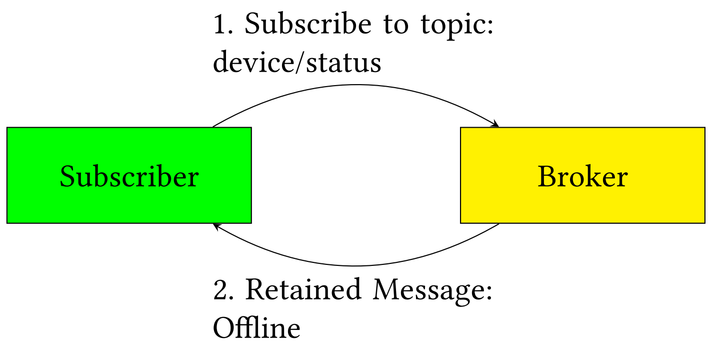

1. Subscribe to topic: device/status
Subscriber
Broker
2. Retained Message: Offline

Figure 4.2: *Retained Messages*

The main benefit of this feature is that it offers subscribers the ability to receive information automatically, rather than manually. Publishers specify these messages by setting the *Retain Flag* to True. Only one retained message is allowed per topic. However, retained messages can be updated when desired. If updated, messages are pushed automatically to subscribers.

Persistent Session

A Persistent Session is a feature where a subscriber's information is stored in the broker, as shown in Figure 4.3.

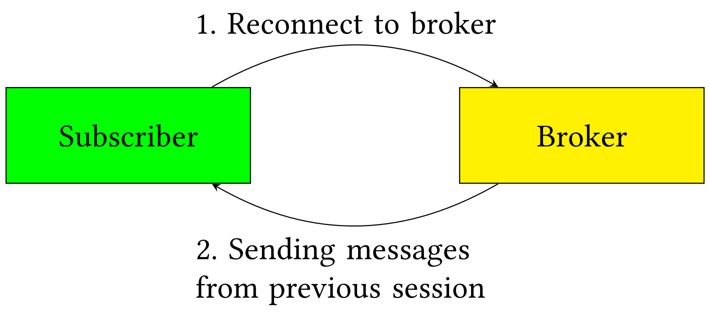


Figure 4.3: *Persistent Session*

If the subscriber disconnects from the broker, information such as subscriptions will be retained, meaning resubscribing is unnecessary in later sessions. Persistent sessions provide several benefits for IoT applications. First, persistent sessions can reduce workload for users. For example, resubscribing can be unmanageable if users are subscribed to a considerable number of topics. Second, persistent sessions can reduce inefficient network usage and overhead for constrained devices (Giambona *et al.*, 2018). Third, QoS 1 and 2 messages are queued until clients reconnect to the network. This can be useful if a device disconnects temporarily to preserve battery power.

4.2 Taxonomy

Figure 4.4 presents the proposed taxonomy of MQTT fuzzers, all of which are classified based on their *core* testing strategy.

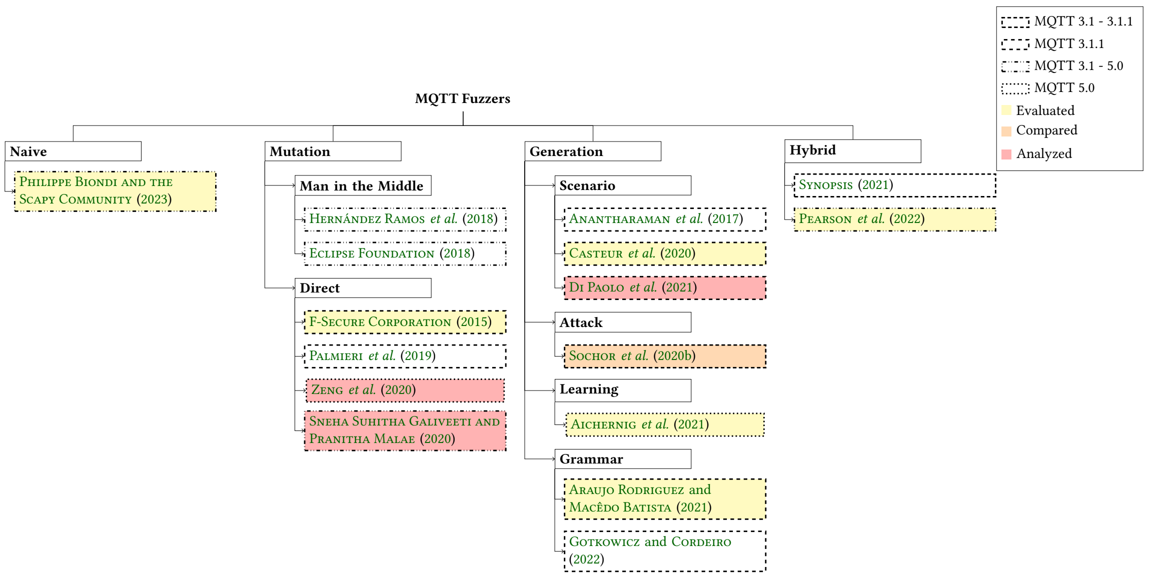


Figure 4.4: *Taxonomy of Fuzzing Techniques for MQTT*

The taxonomy uncovers that a wide variety of fuzzing-inspired approaches have been proposed for MQTT, ranging from simple techniques based on templates to more sophisticated algorithms based on Markov modeling and automata learning. In fact, more techniques have been proposed for MQTT than for any other protocol in the last few years. The MQTT fuzzers shown in the taxonomy are classified into four main categories: (1) Naive; (2) Mutation; (3); Generation; and (4) Hybrid. The four categories are based on the fuzzers' input generation capabilities. Mutation-based fuzzers are further classified by their type of interaction with the broker, being either direct or indirect, the latter of which is referred to as proxy or man-in-the-middle fuzzing. Generation-based fuzzers are usually interacting with the broker directly, and thus were classified by their packet-crafting technique.

The fuzzers shown in the taxonomy are further classified by the version(s) of MQTT supported for testing purposes. Dashed rectangles (⬚) indicate fuzzers that support only version 3.1.1 of MQTT, whereas dotted rectangles (⬚) indicate fuzzers that support only version 5.0. Fuzzers that support versions 3.1 and 3.1.1 are indicated by densely dashed rectangles (⬚), whereas fuzzers that support all three versions of MQTT (3.1, 3.1.1, and 5.0) are indicated by a rectangle with a dash-and-dot pattern (⬚).

After developing the taxonomy of MQTT fuzzers, the answer to **RQ2** is as follows:

RQ2: What fuzzing techniques have been proposed for MQTT over the last few years?

The proposed taxonomy presents sixteen MQTT fuzzers, most of which are classified as either a mutation- or generation-based approach. Mutation-based fuzzers are split into direct- and man-in-the-middle-based approaches, the former of which is more prevalent in the literature at the time of writing. Two main mutation-based approaches currently exist for MQTT: coverage-guided and basic mutational fuzzing. Generation-based fuzzers are more varied, consisting of four types: attack, learning, grammar, and scenario; the latter being the most popular option. `FUME` is the only fuzzer that supports all versions of the MQTT standard; whereas two fuzzers are specifically built for v5.0; one is designed for both v3.1 and v3.1.1; and the remaining twelve are only for v3.1.1.

4.3 Performance Evaluation

Now that the taxonomical classification has been developed, the main question left unanswered is whether the techniques found across the literature were designed considering the unique attributes of the pub/sub design pattern. Thus, the goal of this section is to determine the testing and pub/sub capabilities of each technique, thereby answering **RQ3**. The MQTT fuzzers, brokers, and metrics chosen for the performance evaluation are explained in the following sections.

MQTT Fuzzers

Figure 4.4 highlights in yellow the MQTT fuzzers that were evaluated on the testbed. At least one fuzzing technique from each category in the taxonomy is evaluated to provide a more in-depth comparison. In order to evaluate the scenario-based fuzzer developed by Casteur *et al.* (2020), its source code was modified for it to interact with brokers in virtual machines rather than in `Docker` containers. As a result, the following modifications were applied to the source code:

- **The TCP/IP layer is now managed for every packet** because the original framework used Scapy supplied sockets to interact with `Docker` containers;
- **The fuzzer now disconnects from the broker at the end of each test scenario.** The original framework does not perform disconnection requests because the test environment consisted of several brokers in `Docker` containers, each handling different test scenarios. In contrast, the testbed developed for this research study (Figure 1.3) consists of a single broker, meaning disconnection requests are necessary to successfully transition between different scenarios.

There are several fuzzers that could not be evaluated on the testbed due to being either proprietary (Anantharaman *et al.*, 2017; Sochor *et al.*, 2020b; Synopsis, 2021), partially automated (Hernández Ramos *et al.*, 2018; Eclipse Foundation, 2018; Palmieri *et al.*, 2019; Zeng *et al.*, 2020; Di Paolo *et al.*, 2021), or unfinished (Gotkowicz and Cordeiro, 2022). Despite these hindrances, two workarounds were performed in order to evaluate their effectiveness in some manner. First, the source code of less automated fuzzers (highlighted in red in Figure 4.4) was *analyzed* in order to slightly estimate their effectiveness. Second, if the source code is unavailable, then a fuzzer's performance from other research studies (highlighted in orange in Figure 4.4) is *compared* with those of its counterparts on the testbed. For example, the attack-based fuzzer by Sochor *et al.* (2020b) could not be evaluated on the testbed due to it being proprietary. In order to mitigate this limitation, the MQTT fuzzers were evaluated using the same metrics, tools, and broker chosen by Sochor *et al.* (2020b) for their experiments. This allows for a comparison between results from their paper (Sochor *et al.*, 2020b) and performances achieved by its counterparts on the testbed.

MQTT Brokers

Mosquitto and Moquette were selected as the target systems for the experiments. In particular, Mosquitto was chosen because it has proven to be the implementation that is most representative of the standard, offering support for most, if not all, features and versions of MQTT (Mladenov *et al.*, 2017; Tappler *et al.*, 2017; Aichernig *et al.*, 2021). Mosquitto's adherence to the standard therefore makes it a suitable target system to determine whether fuzzers are testing all features and functionalities of MQTT thoroughly.

Version 1.6.8 of Mosquitto was specifically chosen because of three reasons. First, Mosquitto 1.6.8 is still widely used despite being released in late 2019. Second, Mosquitto 1.6.8 is the most widely used and preferred version to evaluate different fuzzing techniques for MQTT (Sochor *et al.*, 2020b; Aichernig *et al.*, 2021; Araujo Rodriguez and Macêdo Batista, 2021). Third, certain fuzzers were designed specifically with version 1.6.8 in mind.

For example, AICHERNIG *et al.* (2021) chose version 1.6.8 of Mosquitto specifically in their case study to generate the necessary test cases and evaluate the performance of their fuzzer.

In addition to Mosquitto, Moquette 0.13 was chosen as the second target system because it is the same version used by SOCHOR *et al.* (2020b) to evaluate their proprietary fuzzer based on attack patterns. Using the same version therefore enables a performance comparison between open-source fuzzers and their attack-based counterpart. It is worth noting that Mosquitto supports versions 3.1, 3.1.1, and 5.0 of MQTT, whereas Moquette supports the former two. It was therefore impractical to test Moquette with the learning-based approach proposed by AICHERNIG *et al.* (2021) because it was specifically designed for MQTT 5.0.

Performance Metrics

The test runs are monitored constantly in case the broker crashes. When no bugs are found during testing, statement coverage is regarded as *the* ideal metric to measure the effectiveness of fuzzing frameworks (BOEHME *et al.*, 2021). This is because the higher the number of statements executed in the source code, the more likely the fuzzers will find broker errors. Thus, statement coverage was chosen as one of the performance metrics to measure the effectiveness of the tests performed by the fuzzers during 30 minutes. It is worth noting that it was impractical to monitor the statement coverage of the fuzzers *in real-time* due to their blackbox nature. In order to provide a more in-depth analysis of their performance *during* testing, statement coverage is measured after every 3 minutes (3, 6, 9, 12, 15, 18, 21, 24, 27, 30). Fuzzing campaigns are repeated 100 times in order to calculate the average and standard deviation for each increment. In addition to statement coverage, the fuzzers are evaluated based on their *Feature Coverage*, which refers to the pub/sub functionalities or *behaviors* that were covered during testing.

4.3.1 Statement Coverage

Testing MQTT implementations in depth is only achievable with high-coverage fuzzers. Figures 4.5 and 4.6 are each divided into several subfigures, all of which display the statement coverage achieved by MQTT fuzzers throughout 30 minutes. In order to display the results as clearly as possible, fuzzers with similar performance were arranged in the same row and in ascending order. As a result, the subfigures in each row have different y-axis labels. For simplicity purposes, each fuzzer is referred to by their name shown in the title of the subfigures. The learning-based approach by AICHERNIG *et al.* (2021) is referred to as `learner` from this point forward due to lacking a formal name. In the following sections, the name `MQTTGRAM` refers to both `mqttgram-c` and `mqttgram-cf`. Each fuzzing technique is assigned its own color.

Mosquitto

Among all MQTT fuzzers, `FUME` achieves the highest statement coverage in 30 minutes, executing at most 2311 statements. `mqttgram-cf`, `mqtt_fuzz`, and `mqttgram-c` execute 2140, 2120, and 2108 statements respectively, slightly less than `FUME`. `learner` and `Cy-berExploit` execute at most 1818 and 1396 statements respectively, underperforming

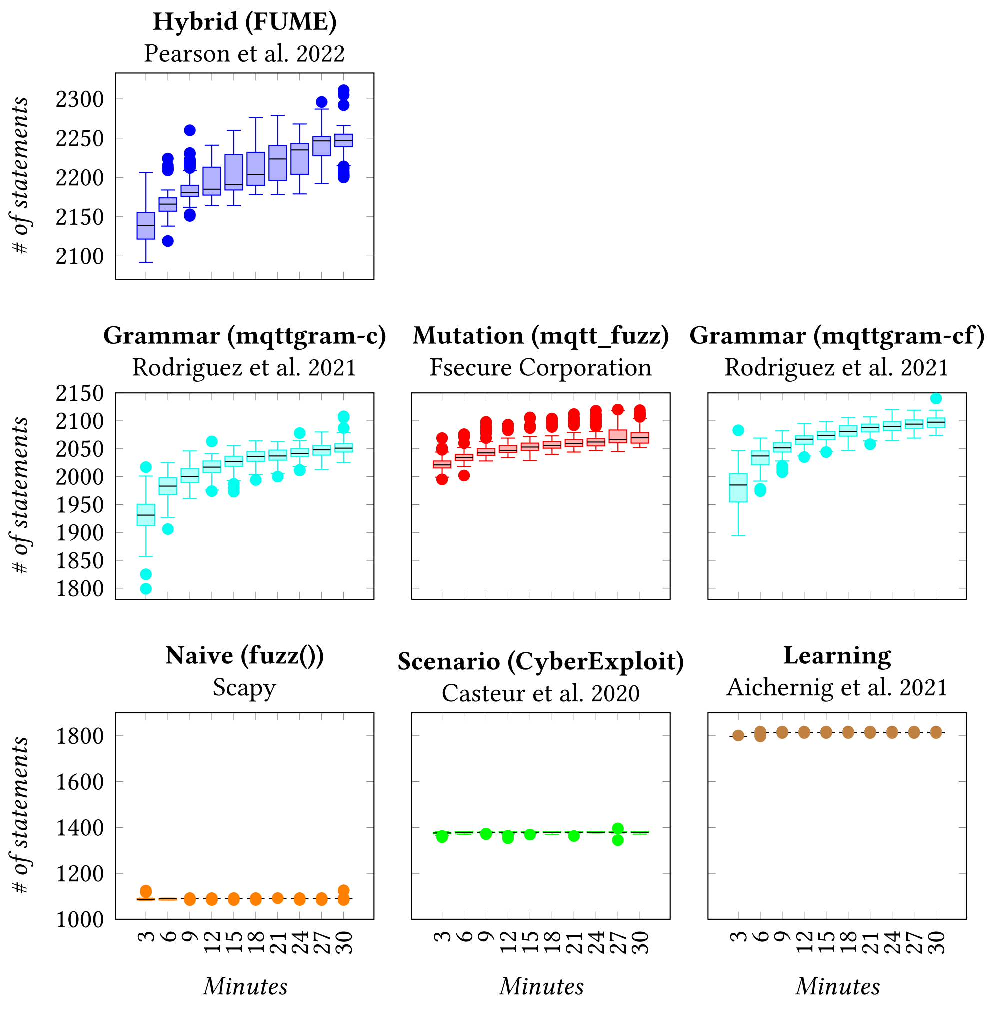


Figure 4.5: *Statement Coverage (Mosquitto 1.6.8)*

considerably compared to their counterparts. Unsurprisingly, `fuzz()` executes at most 1126 statements, ranking as the worst-performing fuzzer. The following paragraphs explain the statement coverage of each fuzzer more in depth. The explanations are in order from the worst- to best-performing fuzzer.

fuzz(): `fuzz()` executes on average between 1088 and 1091 statements in 30 minutes. `fuzz()` underperforms considerably because its test runs mostly consist of failed connection attempts, stemming from the fact that it generates packets in a completely random manner. Protocol states were largely unexplored, so much so that the `fuzz()` executed 0% of the statements in files unrelated to connection requests. In terms of connection files, the fuzzer executes approximately 6% of the statements.

CyberExploit: In contrast to `fuzz()`, `CyberExploit` connects successfully with the broker. However, `CyberExploit` ranks as the second-worst fuzzer based on statement coverage according to the research findings. Its coverage improves by up to 0.29% from 3 to 30 minutes, meaning it executes the same statements for most of the test run. The coverage performance of `CyberExploit` remains mostly static, executing on average between 1345 and 1383 statements in 30 minutes. Its underwhelming performance can be attributed to the following reasons. First, `CyberExploit` assigns the same values to most fields except for topics in *SUBSCRIBE* and *PUBLISH* packets. `CyberExploit` generates random topics of different lengths, ranging from 2 to 400 characters. Although random topic generation has been a successful technique for bug detection in MQTT implementations (Sochor *et al.*, 2020b), it is largely ineffective at reaching high statement coverage because fuzzers will rarely subscribe to *valid* topics. In order to effectively test a pub/sub protocol such as MQTT, topics should not only be syntactically valid, but also semantically meaningful. Crafting valid and meaningful topics will ensure that the core functionality of pub/sub protocols, message publication, is covered during testing.

Second, `CyberExploit` generates scenarios based on short-lived interactions with the broker. Scenarios are performed in a similar manner, usually beginning with a connection request to the broker, followed by either a subscription or publish request. The test scenarios consist of a small set of packets, meaning connection requests are performed 3x more frequently than its publish or subscribe counterparts.

Third, `CyberExploit` is incapable of generating test cases for several functionalities of MQTT. For example, several MQTT flags for optional features, such as username and password authentication, are disabled during the test run. Mandatory packet flags also lack variety, with several of them set to the default or same value in most test cases. For example, `CyberExploit` generates *CONNECT* packets with the same client ID, repeating the exact test case for 30 minutes. The root cause of this issue lies in the packet generator developed for `CyberExploit`, which is unaware of several features defined in the standard.

Fourth, `CyberExploit` is also incapable of generating both *UNSUBSCRIBE* and *PING* packets. MQTT fuzzers should be capable of generating *all* control packet types, especially those related to the *core* functionality of the pub/sub design pattern.

learner: Despite outperforming `CyberExploit`, `learner` has similar drawbacks that hinders it from executing more statements. First, `learner` is incapable of generating three control packet types: *PING*, *AUTH*, and *PUBLISH* (QoS 2). Second, similar to `CyberExploit`, `learner` connects to the broker in the same manner throughout the entire fuzzing campaign, reusing a predefined username for authentication purposes. Publish and subscription requests by `learner` are always performed using QoS 1. It is also worth noting that `learner` generates publication and subscription messages with the same topic at the beginning of the fuzzing campaign. Reusing the same topic triggers the broker into publishing messages to subscribers. Third, `learner` lacks support for all the user properties of MQTT 5.0, except *Session Expiry Interval* and *Topic Alias Maximum*, both of which were used within 30 minutes. Future fuzzing frameworks should support *all* the user properties of MQTT 5.0, covering different behaviors or features. Fourth, on several occasions, `learner` disconnects immediately after the broker accepts a connection request. As `learner` gains a better understanding of MQTT over time, immediate disconnections become less frequent. Similar to `CyberExploit`, `learner` requests up to 3x more connections than message publications or subscriptions. The connection requests are performed in the exact manner for 30 minutes, meaning several authentication mechanisms are left untested.

`learner` outperforms `CyberExploit` for several reasons. First, `learner` supports only MQTT 5.0, meaning it executes both version-specific and independent statements. Second, `CyberExploit` is incapable of triggering the broker into publishing messages, which is yet another important behavior left untested. Third, `learner` connects to the broker with a username and client ID, whereas `CyberExploit` uses only the latter.

Despite outperforming `CyberExploit`, `learner` rarely executes more statements over time. The largest increase in statement coverage (0.94%) occurs between 3 and 6 minutes. After approximately 4 minutes and 16 seconds, `learner` changes its testing strategy to one that is based solely on random topic generation. As a result, statement coverage rarely increases after 6 minutes. In that regard, `learner`, with its stale statement coverage, performs similar to `CyberExploit` when testing MQTT implementations. It is worth noting that `CyberExploit` occasionally sends packets out of order, whereas `learner` always follows the correct sequence.

mqtt_fuzz: `mqtt_fuzz` offers a substantial improvement over its scenario-, learning-, and naive-based counterparts, executing at most 2120 statements. On average, `mqtt_fuzz` executes between 2022 and 2073 statements in 30 minutes. `mqtt_fuzz` outperforms `CyberExploit` and `learner` because of the following reasons. First, `mqtt_fuzz` is capable of generating every type of control packet. Second, `mqtt_fuzz` performs connection requests using multiple client IDs and MQTT flags, the latter of which are all related to core features such as QoS, Last Will and Testament, and Persistent Sessions. Third, `mqtt_fuzz` occasionally uses nonrandom and predefined topics to trigger the broker into publishing messages. Fourth, since `mqtt_fuzz` is a mutation-based approach, test cases are generated from existing MQTT packets rather than from scratch. As a result, `mqtt_fuzz` exchanges a considerable amount of packets with the broker compared to its counterparts.

Despite offering a substantial improvement over its counterparts, `mqtt_fuzz` has several shortcomings that remain unaddressed. Most notably, `mqtt_fuzz` is incapable of generating valid *CONNECT* packets with usernames, passwords, and will retain fields. Another shortcoming is the constant reuse of test cases, meaning more time is spent on executing the same, rather than new, statements. At the time of writing, `mqtt_fuzz` also lacks support for MQTT 5.0.

MQTTGRAM: The grammar-based approaches presented in Chapter 3, `mqttgram-c` and `mqttgram-cf`, have a similar performance to `mqtt_fuzz`. On average, `mqttgram-c` executes from 1928 to 2052 statements in 30 minutes. `mqttgram-cf` outperforms `mqttgram-c`, executing from 1981 to 2096 statements on average. In terms of both grammar-based approaches, the standard deviation of their coverage results decreases as time progresses. The opposite occurs for `mqtt_fuzz`, which outperforms `mqttgram-c` mainly because it occasionally sends packets out of order to the broker, thereby testing both correct and incorrect functionalities of MQTT. The superior performance by `mqtt_fuzz` over `mqttgram-c` highlights the importance of testing both types of functionalities.

FUME: On average, `FUME` executes from 2138 to 2242 statements in 30 minutes. `FUME` executes more statements than its counterparts because it supports all major versions of MQTT, being the only framework to do so at the time of writing. Despite outperforming its counterparts, `FUME` also suffers from shortcomings with regard to pub/sub protocol testing. Most notably, there are two issues preventing it from effectively testing message publication. First, `FUME` generates invalid, rather than valid publish messages for most of the test run. As a result, the broker rejects most publish requests *immediately*, preventing `FUME` from reaching certain states or publishing messages to subscription topics. Second, for each test scenario, `FUME` connects to the broker, sends a small set of packets in both random and rapid succession, and then disconnects before receiving any acknowledgment or response whatsoever. This process is repeated until a stopping criterion has been satisfied. Each test scenario therefore consists of *short* interactions with the broker. As a result, the fuzzing campaigns consist mostly of connection rather than pub/sub-related requests, which *should* be the focus when testing network protocols such as MQTT.

Moquette

As stated previously, it was impractical to perform experiments with `learner` and `FUME` because Moquette lacks support for version 5.0 of MQTT at the time of writing. The results in Figure 4.6 follow mostly the same pattern as in Figure 4.5.

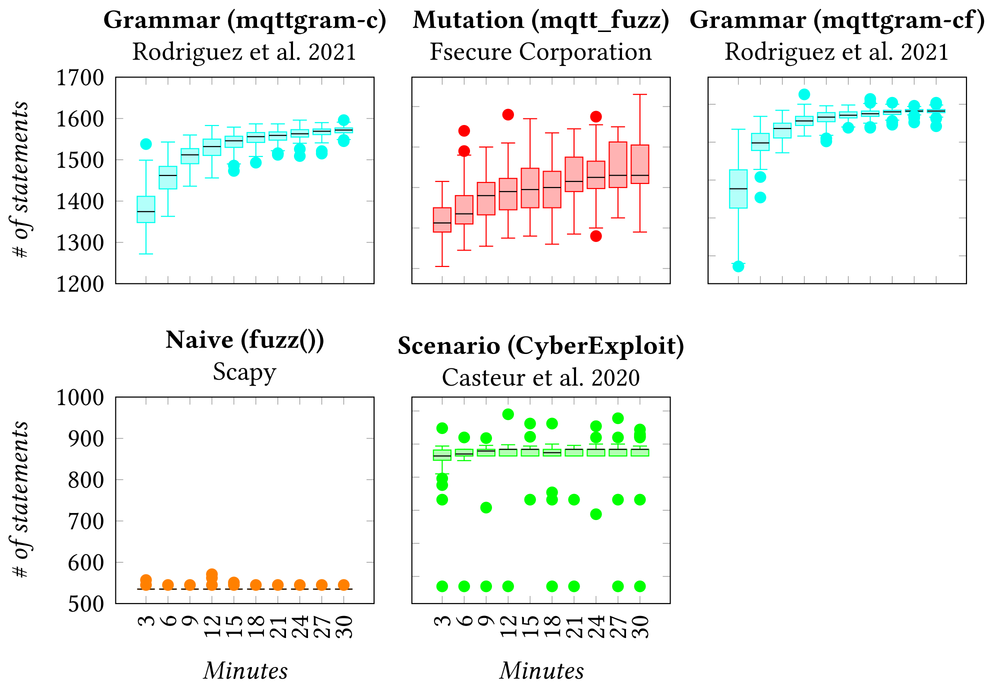


Figure 4.6: *Statement Coverage (Moquette 0.13)*

`mqttgram-cf` executes at most 1613 statements in 30 minutes, outperforming all of its counterparts. In contrast to results obtained in the previous study with Mosquitto, `mqttgram-c` executes more statements in Moquette than `mqtt_fuzz`. `mqttgram-c` and `mqtt_fuzz` execute at most 1596 and 1566 statements respectively. `CyberExploit` and `fuzz()` underperform considerably compared to their counterparts, executing at most 995 and 571 statements respectively. Similar to their performance in Mosquitto, both fuzzers rarely execute more statements over time.

All of the aforementioned MQTT fuzzers were further evaluated using the same metrics as Sochor *et al.* (2020b) in order to compare them with their attack-based counterpart, which is proprietary. Before going any further, it is important to explain three aspects of the experiments performed by Sochor *et al.* (2020b) to evaluate their fuzzer:

1. Sochor *et al.* (2020b) evaluated their fuzzer using Moquette instead of Mosquitto.
2. Sochor *et al.* (2020b) did not perform a single repetition of their experiments, meaning that their fuzzers' coverage performance is based on a result from a single test run, lacking sufficient evidence. In contrast, coverage performance by its counterparts are based on the average of 100 test runs.
3. Sochor *et al.* (2020b) developed two variants of their proprietary fuzzer, one of which is based on existing vulnerabilities. The explanations regarding the coverage performance by both of these variants may therefore be inaccurate due to their proprietary nature. For simplicity purposes, the variant based on existing vulnerabilities is referred to as *vulnerability-oriented*, whereas its counterpart is referred to as *vulnerability-unoriented*.

Table 4.1 presents the results of the attack-based approach by Sochor *et al.* (2020b) and its counterparts. Cells highlighted in blue indicate the highest coverage percentage for a particular directory. Table 4.1 classifies fuzzers considering both types of variants developed by Sochor *et al.* (2020b) in order to enable a more fair comparison. The following paragraphs discuss the coverage performances for each directory in depth.

Source Code (Directory)	**Fuzzed packets not based on existing vulnerabilities**					**Fuzzed packets based on existing vulnerabilities**	
	fuzz()	**CyberExploit**	**Sochor et al. 2020**	**mqtt_fuzz**	**mqttgram-c**	**Sochor et al. 2020**	**mqttgram-cf**
broker	21.00%	39.42%	57.80%	64.20%	**66.34%**	58.00%	**67.57%**
broker.security	12.00%	12.00%	11.30%	13.02%	**15.00%**	12.80%	**15.00%**
broker.subscriptions	8.00%	23.56%	59.00%	**73.86%**	73.52%	63.90%	**73.92%**
broker.config	**51.00%**	**51.00%**	49.30%	**51.00%**	**51.00%**	49.30%	**51.00%**
broker.metrics	44.00%	67.81%	**77.50%**	71.78%	73.00%	**77.50%**	73.00%
persistence	3.00%	3.00%	**9.10%**	9.00%	9.00%	**9.10%**	9.00%
interception	11.00%	25.65%	**32.30%**	28.04%	30.00%	**32.30%**	30.00%
Logging	43.00%	43.00%	**62.50%**	43.00%	43.00%	**62.50%**	43.00%
Total	19.21%	33.83%	50.00%	55.24%	**56.76%**	51.40%	**57.24%**

Table 4.1: *Statement Coverage of Moquette (30 Minutes) (Cells highlighted in blue indicate the highest coverage percentage for a particular directory.)*

broker: The `broker` directory contains files for client authorizations, session storage, queued/retained messages, among others. Coverage performance depends primarily upon a fuzzer's understanding of the states and packets defined in the standard. In that regard, both variants of `MQTTGRAM` outperform their counterparts within their respective categories. More specifically, `mqttgram-c`, `mqttgram-cf`, and `mqtt_fuzz` outperform the fuzzers developed by Sochor *et al.* (2020b), executing 66.34%, 67.57%, and 64.2% of the statements respectively. Unsurprisingly, `CyberExploit` and `fuzz()` execute only 39.42% and 21% of the statements respectively. Similar to `mqtt_fuzz`, their underwhelming performance is also due to the lack of test cases for certain functionalities of MQTT. The vulnerability-unoriented approach by Sochor *et al.* (2020b) executes 57.8% of the statements, whereas its vulnerability-oriented counterpart executes 58%. Although the latter fuzzer narrowly outperforms the former, both seem to be incapable of testing several features of MQTT compared to their grammar- and mutation-based counterparts.

The results in the `broker` directory provide a general overview of the fuzzers' coverage performance during testing. However, a more in-depth analysis is required in order to gain a better understanding of the fuzzers' shortcomings and coverage capabilities. Thus, the following paragraphs explain the fuzzers' coverage performance in specific subdirectories of the `broker` directory.

broker.security: Files in the `broker.security` directory are associated with authentication mechanisms, most notably Access Control Lists (ACL). ACL are used by Moquette to assign pub/sub permissions to users, therefore acting as network-based filters for topics. Moquette uses ACL to block interactions with unknown publishers or subscribers, improving network security as a result. Coverage performance in security-related files is relatively low for all fuzzers. Both variants of `MQTTGRAM` execute approximately 15% of the statements, the result of which is the highest among all fuzzers. `mqtt_fuzz` and the vulnerability-oriented approach by Sochor *et al.* (2020b) execute 13.02% and 12.8% of the statements respectively. `MQTTGRAM` outperforms its counterparts due to its use of usernames and passwords when connecting to the broker. In contrast, both `fuzz()` and `CyberExploit` are incapable of generating syntactically valid packets with usernames and passwords, executing only 12% of the statements. However, despite of this hindrance, they outperform the vulnerability-unoriented approach by Sochor *et al.* (2020b). The subpar performance of all fuzzers is caused by their disuse of ACL during testing.

broker.subscriptions: Files in the `broker.subscriptions` directory are necessary for subscription-related tasks, such as topic matching and message delivery, which play a *key* role in enabling pub/sub communication between devices. When testing pub/sub protocols such as MQTT, fuzzers should strive to execute as many statements as possible in subscription-related files, such as those located in this directory. This outcome is not only achieved by triggering the broker into publishing messages, but also by testing exceptional pub/sub behaviors. For example, in addition to triggering the broker into publishing messages, `mqtt_fuzz` tests exceptional behavior by sending packets out of order, and using incorrect levels of QoS. This allows `mqtt_fuzz` to slightly outperform `mqttgram-c`, which triggers only normal pub/sub behaviors. Similar to `mqtt_fuzz`, `mqttgram-cf` also tests exceptional behavior by sending packets out of order. However, despite performing less subscription requests than `mqtt_fuzz`, `mqttgram-cf` achieves the highest statement coverage at 73.92%. `mqttgram-cf` outperforms `mqtt_fuzz` because it generates topics that contain wildcard characters (`#` or `+`) in a manner that is prohibited by the formal specification of MQTT. `CyberExploit` underperforms considerably, executing approximately 23.56% of the statements. Its low coverage performance is because of its incapability to trigger the broker into publishing messages. The interaction between `CyberExploit` and the broker is therefore more similar to the traditional client-server approach than pub/sub, meaning that the core functionality of MQTT is neglected during testing. Unsurprisingly, `fuzz()` executes the fewest statements in 30 minutes. `fuzz()` is unable to connect to the broker successfully, hence the lack of topic subscriptions during testing.

broker.config: The `broker.config` directory contains configuration files that allow users to modify a wide variety of settings, such as port numbers. All fuzzers evaluated on the testbed have the same coverage performance in configuration-related files (51%) because Moquette was executed using default settings.

broker.metrics: The `broker.metrics` directory contains the necessary files to collect statistical information such as the number of clients connected to the broker. Both fuzzers by Sochor *et al.* (2020b) outperform their counterparts, executing 77.5% of the statements. As stated previously, it cannot be determined if their superior performance is due to Sochor *et al.* (2020b) modifying Moquette's source code or triggering an exceptional crash that generates more statistical information about the broker session. In terms of its counterparts, coverage performance seems to depend primarily on the fuzzers' knowledge of MQTT. Both variants of `MQTTGRAM` execute 73% of the statements, followed by `mqtt_fuzz`, `CyberExploit`, and `fuzz()` with 71.78%, 67.81%, and 44% respectively.

persistence: The `persistence` directory contains the necessary files to enable both persistent sessions and storage. When enabling the former, user-related information, such as subscriptions and queued messages, are stored in memory by default. However, Moquette deletes the information on shutdown, requiring users to create new sessions from scratch after restart. In order to mitigate this issue, Moquette offers an option called *persistent storage*, in which the information is stored in a database and *persists* regardless if the broker is offline or online. All fuzzers achieve subpar performance when executing statements in persistence-related files because Moquette was executed using default settings, meaning *persistent storage* is disabled during testing. Results indicate that their performance depends on the level of understanding of MQTT. Both fuzzers developed by Sochor *et al.* (2020b) achieve the highest coverage performance, executing 9.1% of the statements. These results hint that Sochor *et al.* (2020b) probably tested Moquette using default settings.

interception: Interceptors can be extended to monitor Moquette's incoming messages and notify about specific events. The source files of these interceptors can be found in the `interception` directory, which contains a subdirectory named `messages`. The former directory contains files associated with the *Interception Handler*, whereas the latter subdirectory contains the necessary files to notify about specific message events, such as normal or abrupt disconnections. Moquette disables packet interception by default, meaning files in the `messages` directory are neglected throughout the experiments. As a result, the coverage tool used for the experiments (`Cobertura`) reports 0% of statement coverage for all files in the `messages` directory. However, despite the lack of packet interception, statements from some files in the `interception` directory are executed, as shown in Table 4.1. It cannot be determined which statements are executed because `Cobertura` generates coverage reports with limited information. However, it should be highlighted that files associated with the *Interception Handler* import functions from broker-related files, such as those used for subscription, connection, and publish requests. Since no messages are intercepted during the fuzzing campaign, coverage performances in the `interception` directory are most likely associated with functions imported from broker-related files, or more specifically with the functionalities and features of MQTT covered during testing. This may be a valid observation because coverage performances are ranked in decreasing order from most to least knowledgeable fuzzer. Both variants of `MQTTGRAM` outperform all of their counterparts, executing 30% of the statements, followed by mqtt_fuzz, CyberExploit, and fuzz() with 28.04%, 25.65%, and 11% respectively. It cannot be determined if the superior performance of the proprietary fuzzer proposed by Sochor *et al.* (2020b) is due to it intercepting packets during testing. If that were the case, files in the messages directory would have been executed, thereby outperforming its counterparts. Another explanation for the fuzzer's superior performance may have to do with the possibility of Moquette's source code being extended or modified by the researchers to better intercept messages.

Logging: The Logging directory contains the necessary files for Moquette to perform log-related tasks. Default logging activities are performed by Moquette on the testbed, meaning coverage performance is the same across all fuzzing-inspired approaches, which achieve 43%. Both of the fuzzers proposed by Sochor *et al.* (2020b) outperform their counterparts, executing 62.5% of the statements. The superior performance of the fuzzers proposed by Sochor *et al.* (2020b) may be due to either: (1) a possible alteration of the source code to generate additional or more detailed logs about Moquette's behavior during testing; or (2) exceptional crashes. However, the exact reason cannot be determined due to the lack of information provided by Sochor *et al.* (2020b) about logging procedures for their experiments.

Summary: The last row of Table 4.1 presents the fuzzers' average performance considering the statement coverage of each subdirectory. Both mqttgram-c and mqttgram-cf execute 56.76% and 57.24% of the statements respectively, outperforming all of their counterparts. mqtt_fuzz executes 55.24% of the statements, followed by the vulnerability-oriented approach by Sochor *et al.* (2020b) with 51.4%, and its unoriented counterpart with 50.0%. The low coverage performance of the latter two fuzzers may be due to their incapability of triggering important functionalities during testing. CyberExploit and fuzz() are the worst-performing fuzzers, executing 33.83% and 19.21% of the statements respectively. Among all directories, broker, broker.security, and broker.subscriptions are the most important because their files are directly linked to MQTT's pub/sub functionalities. The grammar-based approaches presented in Chapter 3 test the contents of these directories more in depth, despite exchanging the fewest packets with the broker.

4.3.2 Feature Coverage

Thus far, only the statement coverage of each fuzzer has been discussed. A testing metric that also plays a crucial role in measuring the effectiveness of fuzzing frameworks is *feature coverage*. As its name suggests, feature coverage refers to the pub/sub features or functionalities tested by each fuzzer. However, before explaining about feature coverage, it is important to discuss *which* MQTT flags are enabled or disabled by each fuzzer throughout the test run. MQTT offers several flags for a wide variety of purposes, such as basic authentication, guaranteed message delivery, and persistent sessions, among others. Flags are directly tied to the functionality of a network protocol, meaning a fuzzer's packet generator should be designed with them in mind. Most flags are disabled by default, meaning the fuzzer must enable them by generating syntactically valid packets, otherwise the broker will close the connection immediately. Fuzzers should also attempt to explore several flag combinations in order to test several features simultaneously.

Tables 4.2 and 4.3 present a detailed summary of the flags used by MQTT fuzzers when performing connection and publish requests respectively. The first column presents the MQTT fuzzer, whereas the remaining columns indicate whether a specific flag value is used during the test run. Each flag value is represented by a circle in Tables 4.2 and 4.3. It is worth mentioning that most flags in network protocols are represented by a single bit, and can be set to a value of either *0* or *1*. There are exceptions, such as the QoS flag, which can be set to a third possible value of *2*. The first, second, and third circle (if any) therefore represent the value of 0, 1, and 2 respectively. The type of circle shown for each value indicates either correct 🟢#, incorrect 🟡#, or no usage 🔴#. For example, 🟢0🟡1 indicates that the first value (0) for a specific flag is used correctly by an MQTT fuzzer, whereas the second (1) is not. For simplicity purposes, results of `mqttgram-c` and `mqttgram-cf` are combined in a single row because both fuzzers enable and disable the same flags. As shown in Tables 4.2 and 4.3, most fuzzers except for `FUME` and both variants of `MQTTGRAM` are incapable of crafting syntactically valid packets when setting flags to certain values.

MQTT Fuzzer	User Name Flag	Password Flag	Will Retain	Will QoS	Will Flag	Clean Session
`mqtt_fuzz`	🟢0🟡1	🟢0🟡1	🟢0🟡1	🟢0🟡1🟢2	🟢0🟢1	🟢0🟢1
`CyberExploit`	🟢0🔴1	🟢0🔴1	🟢0🔴1	🟢0🔴1🔴2	🟢0🔴1	🔴0🟢1
Di Paolo *et al.* (2021)	🟢0🔴1	🟢0🔴1	🟢0🔴1	🟢0🔴1🔴2	🟢0🔴1	🔴0🟢1
`learner`	🔴0🟢1	🟢0🔴1	🟢0🔴1	🟢0🔴1🔴2	🟢0🔴1	🔴0🟢1
`MQTTGRAM`	🟢0🟢1	🟢0🟢1	🟢0🟢1	🟢0🟢1🟢2	🟢0🟢1	🟢0🟢1
`FUME`	🟢0🟢1	🟢0🟢1	🟢0🟢1	🟢0🟢1🟢2	🟢0🟢1	🟢0🟢1

Table 4.2: *Packet Generation - Connect Flags*
🟢#*: Correct usage of a flag value* | 🟡#*: Incorrect usage of a flag value* | 🔴#*: No usage of a flag value*

MQTT Fuzzer	DUP flag	QoS Level	Retain flag
`mqtt_fuzz`	🟢0🟢1🟢2	🟢0🟢1🟢2	🟢0🟢1🟢2
`CyberExploit`	🟢0🟡1	🟢0🟡1🟡2	🟢0🟡1
Di Paolo *et al.* (2021)	🟢0🔴1	🟢0🟢1🟢2	🟢0🔴1
`learner`	🟢0🟢1🟢2	🔴0🟢1🔴2	🟢0🔴1
`MQTTGRAM`	🟢0🟢1🟢2	🟢0🟢1🟢2	🟢0🟢1🟢2
`FUME`	🟢0🟢1🟢2	🟢0🟢1🟢2	🟢0🟢1🟢2

Table 4.3: *Packet Generation - Publish Flags*
🟢#*: Correct usage of a flag value* | 🟡#*: Incorrect usage of a flag value* | 🔴#*: No usage of a flag value*

Table 4.4 presents the features tested by each fuzzer within 30 minutes. The feature coverage of each fuzzer is determined by examining the packet logs. It is worth noting that Tables 4.2 and 4.3 are directly related to Table 4.4 because certain flags have to be enabled to test specific features. Each column name in Table 4.4 is based on a core pub/sub feature of MQTT. The symbol ✓indicates if a feature is tested by an MQTT fuzzer whereas the symbol × indicates the opposite. The symbol ✓* indicates that the fuzzer *would* have been capable of testing a feature if other clients had been connected to the broker during testing. The following paragraphs explain the results for each feature.

MQTT Fuzzer	Pub/Sub Behavior	All QoS Levels	Last Will and Testament	Retained Messages	Persistent Session
mqtt_fuzz	✓	✓	✓*	✓	✓
CyberExploit	×	×	×	×	×
Di Paolo *et al.* (2021)	×	✓	×	×	×
learner	✓	×	×	×	×
MQTTGRAM	✓	✓	✓*	✓	✓
FUME	✓	✓	✓*	✓	✓

Table 4.4: *Feature Coverage of MQTT Fuzzers (30 Minutes)*
✓: Tested successfully | ×: Tested unsuccessfully | ✓: Tested successfully if clients > 1*

Pub/Sub Behavior: In order to trigger the broker into publishing messages, a fuzzer must perform a subscription and publish request with the same topic. In that regard, CyberExploit and the fuzzer proposed by Di Paolo *et al.* (2021) fail to meet this requirement, generating long random topics that are never used more than once. It is worth noting that, in most cases, both mqtt_fuzz and learner are capable of triggering the broker into publishing messages *only* because of their use of predefined topics.

All QoS Levels: QoS-based functionality is fully tested by all MQTT fuzzers except CyberExploit and learner, which test only level 0 and 1 respectively.

Last Will and Testament: The will flag enables immediate notifications for when an MQTT client disconnects from the network. The will flag is never enabled by CyberExploit, learner, and the fuzzer proposed by Di Paolo *et al.* (2021) during the test run. As such, these three fuzzers are incapable of testing the Last Will and Testament feature of MQTT. Among all the core functionalities of MQTT, the Last and Will Testament is the most difficult to test thoroughly because it requires multiple clients connected to the broker. In that regard, none of the fuzzers manage to fully test this feature due to the lack of additional clients during testing. However, mqtt_fuzz, FUME, and both variants of MQTTGRAM would have been capable of fully testing this feature if other clients had also been connected to the broker. This is because of two reasons. First, all three fuzzers are capable of triggering the broker into publishing messages to subscribers. Second, the fuzzers subscribe to will topics occasionally during testing. The symbol ✓* in Table 4.4 therefore indicates that these fuzzers would have been capable of fully testing the Last Will and Testament feature if other clients had been connected to the broker.

Retained Messages: As shown in Tables 4.2 and 4.3, learner and the fuzzer proposed by Di Paolo *et al.* (2021) disable retain flags during testing. CyberExploit attempts, but ultimately fails, to generate valid packets that enable retain flags. As a result, learner, CyberExploit, and the fuzzer proposed by Di Paolo *et al.* (2021) are all unable to test the functionality of retained messages.

Persistent Session: CyberExploit, learner, and the fuzzer proposed by Di Paolo *et al.* (2021) enable the clean session flag for the entire test run, meaning user information is never stored in the broker.

After analyzing the performance of all the fuzzers evaluated on the testbed, the answer to **RQ3** is as follows:

RQ3: How effective are fuzzing frameworks for MQTT in terms of their testing and pub/sub capabilities?

`FUME` executes the most number of statements in MQTT implementations because it supports multiple versions of the standard, thereby being the most effective for testing purposes. In terms of pub/sub capabilities, most fuzzers proposed thus far support a single version of MQTT, meaning that message publishing features introduced in other releases are left untested. Existing learning-based techniques are incapable of understanding and testing the *core* functionalities of MQTT. Scenario-based approaches are mainly geared towards random topic generation, neglecting pub/sub functionality altogether during testing. Proxy fuzzers apply random mutations to packet fields selected by the user, unaware of necessary requirements for testing message publications. The Markov modeling approach incorporated into `FUME` supports multiple versions of MQTT, but lacks awareness of valid message sequences and state transitions. In fact, `FUME` struggles to craft valid publish packets, meaning that it tests pub/sub functionality on *rare* occasions. `MQTTGRAM` and `mqtt_fuzz` are more consistent in terms of testing message publications. However, `mqtt_fuzz` manages to test message publishing features *only* because of its use of predefined topics, meaning that its test cases lack variety. Overall, `MQTTGRAM` manages to generate more varied, but semantically-meaningful topics that activate and test message publishing features of the broker. Future research should address the aforementioned issues, combine techniques, and cover more pub/sub functionality during testing, the latter of which is neglected to some extent across *all* fuzzers proposed for MQTT thus far. The shortcomings presented in this chapter can raise awareness and motivate developers to better test pub/sub protocols such as MQTT in future work.

4.4 Concluding Remarks

MQTT Fuzzing has been evolving considerably in the last few years, quickly gaining prominence due to its necessity in the IoT. However, several issues have arisen that hinder its progression and future research studies. Most notably, the lack of baseline data and standardized pub/sub metrics in the literature has led to limited information regarding the strengths, weaknesses, and even improvements of each fuzzing technique over its predecessors. To mitigate these issues, a literature review was first conducted in order to create a taxonomical classification of *all* fuzzing techniques proposed for MQTT, providing developers a clear and more detailed overview of the current state of the art. Afterwards, each technique was benchmarked across a wide variety of testing metrics under equivalent conditions, further highlighting their benefits and shortcomings to developers for future research opportunities. As a result, developers can now compare their findings with the baseline results presented in this study to further improve their testing strategy. The findings presented in this chapter are further complemented by the results shown in Appendixes D and E, which delve deep into the fuzzers' input coverage and packet exchange capabilities respectively.

Chapter 5

Refinement of a Grammar-Based Fuzzing Technique for a Pub/Sub Protocol

The research findings presented in Chapter 4 indicate that *all* open-source fuzzers have shortcomings in regards to pub/sub protocol testing. Upon further investigation, it is found that developers neglect *three* essential elements for successful pub/sub fuzzing: (1) two-way communication capabilities; (2) topic awareness; and (3) multiversion support. The following paragraphs explain each element in more detail.

Two-way communication: According to the taxonomy shown in Figure 4.4, there are two main approaches to fuzzing a pub/sub broker. Both approaches differ in terms of the fuzzer's role during testing, which can either be a man in the middle or a normal client. In terms of the former role, the fuzzer intercepts and modifies messages in transit between the broker and the clients. In terms of the latter role, the fuzzer exchanges messages directly with the broker as if it were a normal client. Regardless of the role, the test architecture *should* support a request-response (or two-way) communication pattern between the broker and a client, otherwise the fuzzer will fail to trigger message publications. *Four* fuzzers fail to meet this requirement. `fuzz()` lacks a *complete* understanding of MQTT, thereby preventing it from sending valid requests and responses to the broker. `FUME` first sends a connection request, followed by several other messages in random order. All of the messages generated by `FUME` are sent within a single packet, after which it proceeds to end the connection. This means that `FUME` sends only *one* packet for each connection. Similarly, the fuzzer proposed by Di Paolo *et al.* (2021) sends messages without acknowledging to any request or response by the broker. `AFLNet-MQTT` is incapable of behaving as a publisher or subscriber because its architecture lacks a complete understanding of two-way communication with MQTT.

Multiversion: Most protocol implementations support multiple versions of the standard. Subsequent versions of the standard either add or remove features for message publications. For this research study, a fuzzer is classified as *multiversion* if it supports *at least* two versions of a protocol standard. At the time of writing, `FUME` is the *only* fuzzer in the literature that supports all three major versions of MQTT (3.1, 3.1.1, and 5.0). `AFLNet-MQTT`, `fuzz()`, and `Polymorph` have flexible architectures that enable them to test any implementation regardless of the version of MQTT. In contrast, the remaining fuzzers shown in the taxonomy (Figure 4.4) are designed for a specific version of MQTT.

Topic Awareness: Topic generation should be a central focus of pub/sub fuzzers. In fact, it is *the* element or requirement that sets it apart from fuzzers for other types of target systems. As stated previously, a pub/sub fuzzer must generate topics that strike a balance between semantically-meaningful and error-prone values. For this research study, a fuzzer is classified as *topic aware* if it is capable of generating random, but semantically-meaningful topics that trigger the broker into publishing messages. Five fuzzers are currently incapable of testing message publications because of different reasons. For example, `fuzz()` is unaware of the MQTT message format, whereas `AFLNet-MQTT` is incapable of acting as a genuine MQTT client. `Polymorph` mutates messages in transit between the broker and MQTT clients, lacking the necessary capabilities to generate semantically-meaningful topics. `CyberExploit` generates invalid topics throughout the entire test run, but is able to respond and acknowledge requests from the broker. The fuzzer proposed by Di Paolo *et al.* (2021) has the opposite problem, generating valid topics without acknowledging messages from the broker.

According to the research findings, *all* MQTT fuzzers were designed with either 1 or 2 elements in mind. However, *none* of the MQTT fuzzers available for testing purposes encompass *all* three elements. Thus, the research hypothesis for this study is:

> *When considering the three elements, effectiveness is higher than that of existing MQTT fuzzers.*

The research question that will be used to validate the research hypothesis is as follows:

> *RQ4: How effective is an MQTT fuzzer when considering three essential elements for pub/sub fuzzing: two-way communication capabilities; topic awareness; and multiversion support?*

In order to answer **RQ4**, the architecture and the algorithm of the original `MQTTGRAM` were modified to meet all three of these criteria. The modifications and improvements ultimately resulted in a new grammar-based fuzzer called `mqttgram-r`. Table 5.1 compares `mqttgram-r` with its counterparts.

5.1 Refinements

As stated previously, the main difference between `mqttgram-cf` and `mqttgram-c` is that the former fuzzer prioritizes topic-based messages during testing. `mqttgram-r` is based on `mqttgram-cf` because pub/sub fuzzers *should* in fact prioritize topic-based messages to trigger important publish operations of the broker.

The response engine and packet generator of the original `MQTTGRAM` satisfy only two

MQTT Fuzzers	Two-way	Multiversion	Topic Awareness
`fuzz()`	×	✓	×
`mqtt_fuzz`	✓	×	✓
`Polymorph`	✓	✓	×
`CyberExploit`	✓	×	×
`MultiFuzz`	✓	×	✓
`AFLNet-MQTT`	×	✓	×
Aichernig *et al.* (2021)	✓	×	✓
Di Paolo *et al.* (2021)	×	×	×
`MQTTGRAM`	✓	×	✓
`FUME`	×	✓	✓
`mqttgram-r` (This research)	✓	✓	✓

Table 5.1: *Classification of Fuzzers for Pub/Sub Brokers*

of the essential conditions for successful pub/sub fuzzing: two-way communication and topic awareness. The original packet generator supported only version 3.1.1 of MQTT. Figure 5.1 presents the refined architecture for `mqttgram-r`. The main difference between the architectures of `mqttgram-r` and the original `MQTTGRAM` is that the former supports versions 3.1.1 *and* 5.0 of MQTT. This means that, in contrast to its counterparts, `mqttgram-r` meets *all* three of the criteria shown in Table 5.1.

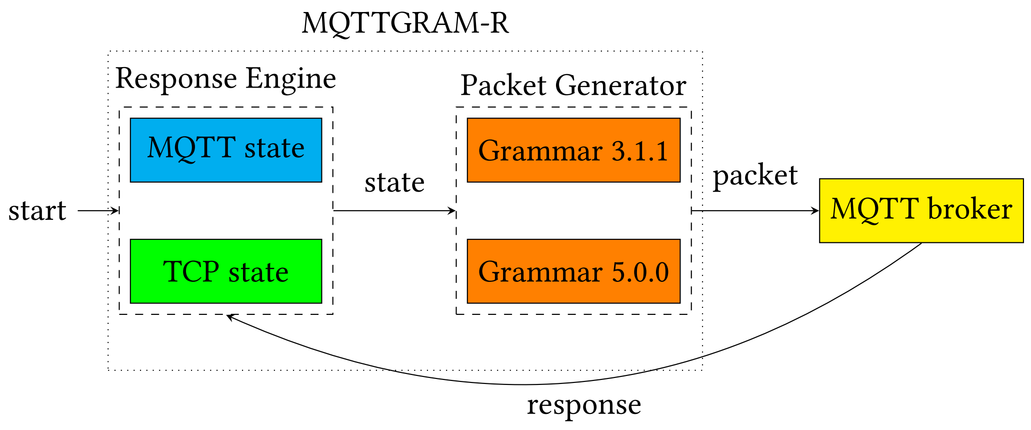


Figure 5.1: *Refined Architecture for MQTTGRAM-R*

`mqttgram-r` generates hexadecimal strings from *two* grammars based on MQTT 3.1.1 *and* 5.0 respectively. There are several notable differences between both versions, which in turn influenced the development of the grammar for MQTT 5.0. For example, the headers of MQTT packets vary across different versions of the standard. In fact, several MQTT 5.0 packets have reason codes, as part of their variable header, to indicate the result of an operation. The most notable difference or feature of MQTT 5.0, however, is the introduction of *user properties*, which are UTF-8 string key-value pairs defined by the user to set specific rules or settings such as session expiry intervals, topic aliases, maximum packet size, among others. A grammar based on MQTT 5.0 is developed that incorporates *all* changes made to the packet headers, including *all* 45 reason codes and 27 user properties introduced in the latest version of the standard. A simple example of our MQTT 5.0 grammar and its expansion rules is shown below:

$$
\begin{array}{lcl}
\langle \textit{start} \rangle & ::= & \langle \textit{packets} \rangle \\
\langle \textit{packets} \rangle & ::= & \langle \textit{publish} \rangle \\
\langle \textit{publish} \rangle & ::= & \langle \textit{fheader} \rangle \langle \textit{vheader} \rangle \langle \textit{properties} \rangle \\
 & | & \langle \textit{fheader} \rangle \langle \textit{vheader} \rangle \langle \textit{properties} \rangle \langle \textit{payload} \rangle \\
\langle \textit{properties} \rangle & ::= & \langle \textit{no-property} \rangle \mid \langle \textit{propertyN} \rangle \\
\langle \textit{no-property} \rangle & ::= & \text{`}\texttt{Number 0 in Hex notation}\text{'} \\
\langle \textit{propertyN} \rangle & ::= & \langle \textit{length} \rangle \langle \textit{id} \rangle \langle \textit{value} \rangle \\
\langle \textit{length} \rangle & ::= & \text{`}\texttt{length of id and value}\text{'} \\
\langle \textit{id} \rangle & ::= & \text{`}\texttt{id of property in Hex notation}\text{'} \\
\langle \textit{value} \rangle & ::= & \text{`}\texttt{value of property in Hex notation}\text{'} \\
\langle \textit{fheader} \rangle & ::= & \text{`}\texttt{Hexadecimal string of fixed header}\text{'} \\
\langle \textit{vheader} \rangle & ::= & \text{`}\texttt{Hexadecimal string of variable header}\text{'} \\
\langle \textit{payload} \rangle & ::= & \text{`}\texttt{Hexadecimal string of payload}\text{'}
\end{array}
$$

Figure 5.2: *Simple Example of the MQTT 5.0 Grammar in Backus-Naur Form*

Rather than developing it from scratch, the MQTT 5.0 grammar is adapted from its 3.1.1 counterpart used by the original MQTTGRAM. New and updated expansion rules were defined to describe the grammatical structure of MQTT 5.0 messages. The *main* difference between the MQTT 3.1.1 and 5.0 grammar is the latter's nonterminal symbol `<properties>`, which describes the necessary expansion rules to generate all 27 properties considering their length, ID, and values defined in the standard. The end result of the grammar is the concatenation of hex strings for the fixed header, variable header, payload, *and* properties, which together make up an MQTT 5.0 message.

Algorithm 3 presents the pseudocode of the proposed *multiversion* grammar-based approach for a pub/sub protocol, which is incorporated into `mqttgram-r`.

Algorithm 3: Multiversion grammar-based fuzzing approach for MQTT

```
   Input: Protocol State $S$, Protocol Version $V$
1  while $stopping\_criterion == false$ do
2      $t \leftarrow select\_packet\_type(S, V)$;
3      $m \leftarrow generate\_packet(t)$;
4      $r \leftarrow feed\_input(m)$;
5      $S \leftarrow evaluate\_response(r)$;
6      if $S == disconnected$ then
7          $V \leftarrow choose\_protocol\_version()$;
8      $L \leftarrow monitor\_program(S)$
   Output: $L$
```

The algorithms proposed in Chapter 3 were adapted for `mqttgram-r`. More specifically, Algorithm 3 is adapted from Algorithm 1, and receives two inputs instead of one: (1) a

Protocol State S and (2) a Protocol Version V, the latter of which can be either v3.1.1 or v5.0. Before establishing a connection with the broker, the algorithm *randomly* chooses between testing either version 3.1.1 or 5.0 of MQTT. V is then assigned the version number chosen by the algorithm. `mqttgram-r` then selects (line 2 in Algorithm 3), generates, and sends MQTT messages based on version V to the broker until a disconnection occurs, after which V is assigned a random value for the next connection (lines 6-7 in Algorithm 3). This process is repeated until a stopping criterion has been satisfied. In other words, `mqttgram-r` tests *only* one version of MQTT for each connection with the broker. This design choice is based on the fact that the broker *will* disconnect a fuzzer from the network unless both parties exchange messages that belong to the *same* version. Maintaining version consistency therefore leads to fewer connection requests, which in turn leads to a greater focus on publication or subscription messages during testing.

Algorithm 2 remains largely unchanged for `mqttgram-r`, the only difference being that the `calculate()` function (line 6) now calculates the lengths of user properties after the hexadecimal string has been produced.

With these changes, `mqttgram-r` mitigates certain shortcomings found in MQTT 5.x compatible fuzzers and presented in Chapter 4. For example, in contrast to `learner`, `mqttgram-r` supports *all* 27 properties introduced in MQTT 5.0. In contrast to `FUME`, `mqttgram-r` sends messages based on the same MQTT version to the broker for each connection. This in turn allows `mqttgram-r` to have infrequent disconnections from the broker, thereby increasing the probability of triggering message publications during testing.

5.2 Performance Evaluation

This section evaluates the performance of the proposed *multiversion* grammar-based approach, which is incorporated into `mqttgram-r`. For the experiments, Mosquitto 1.6.8 is selected as the target broker. `mqttgram-r` and its counterparts exchange messages with Mosquitto until a stopping criterion is satisfied. Two separate experiments were conducted, each with a different stopping criterion. In the first experiment, the fuzzers communicate with Mosquitto for 30 minutes. In the second experiment, the fuzzers communicate with Mosquitto until 8000 packets have been exchanged between both parties. For each stopping criterion, the average statement coverage achieved by the MQTT fuzzers in 100 test runs is calculated. For comparison purposes, `mqttgram-r` is also evaluated when testing only MQTT 5.0. This variant is referred to as `mqttgram5-cf` for the remainder of the chapter. Among the 10 open-source fuzzers available to developers, six are *completely* automated, whereas the remaining four require user intervention. In order to provide a more fair comparison, only automated fuzzers are evaluated for this research study. The testbed shown in Figure 1.3 was used for the performance evaluation.

Statement coverage should always be analyzed in conjunction with the important features or functionalities of the protocol. In the case of MQTT implementations, the most important files are those related to features of the pub/sub design pattern, such as message publications and topic subscriptions. In that regard, the fuzzers are evaluated by measuring the number of statements executed in pub/sub-related files of Mosquitto:

`handle_publish.c`, `handle_subscribe.c`, and `subs.c`. The number of statements executed in `handle_connect.c` is also measured in order to determine the degree to which connection requests are favored over their pub/sub counterparts.

5.2.1 handle_connect.c

Figure 5.3 presents the number of statements (as a percentage) executed by each fuzzer in 30 minutes, and after exchanging 8000 packets with the broker. Despite the two different stopping criteria, coverage percentages shown in Figure 5.3 vary slightly and are in the same decreasing order.

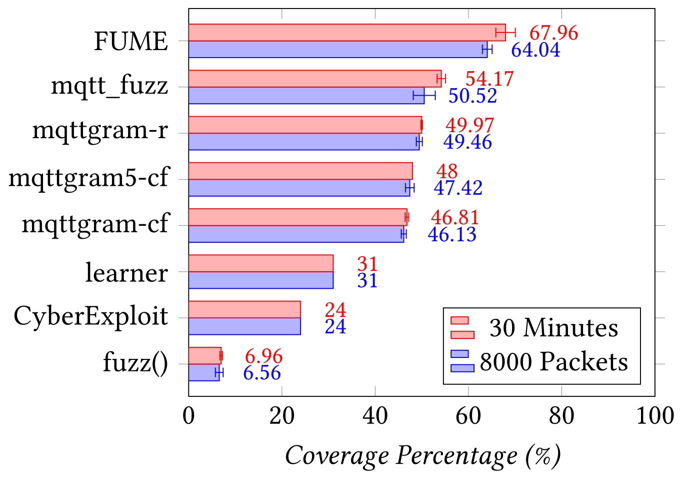


Figure 5.3: *Statement Coverage in `handle_connect.c`*

`FUME` achieves the highest coverage in 30 minutes, executing approximately 67.96% of the statements. Furthermore, `FUME` executes 64.04% of the statements after exchanging 8000 packets with Mosquitto, outperforming its counterparts by a wide margin. The outperformance of `FUME` is directly linked to the overabundance of connection requests performed during testing. This is due to the following three reasons. First, `FUME` performs multiple tasks, including connection requests, simultaneously, after which it disconnects from the broker and repeats the entire process until a stopping criterion has been satisfied. For each test scenario, the interaction between `FUME` and Mosquitto is considerably short, meaning the latter handles connection requests much more frequently than pub/sub-related operations. For each scenario, `FUME` sends packets unrelated to connection and disconnection requests in random order, which does not comply with the rules provided by the standard. As a result, Mosquitto closes the connection with `FUME` *immediately*, halting message publications or any other pub/sub functionality in that particular test scenario. Connections are closed within a short time frame, meaning `FUME` reconnects to the broker very frequently. Third, `FUME` generates many *PUBLISH* packets incorrectly, which causes the broker to close the connection. `FUME` then establishes a new connection with the broker to continue the tests.

Similar to `FUME`, `mqtt_fuzz` performs connection requests frequently. As a result, `mqtt_fuzz` executes approximately 54.17% of the statements in 30 minutes, outperforming most of its counterparts, except for `FUME`. This outcome also holds true when `mqtt_fuzz` and Mosquitto exchange 8000 packets, which results in 50.52% of the statements being executed. In contrast to FUME, mqtt_fuzz interacts with the broker *dynamically*, requesting and responding to messages accordingly. In order to accomplish this goal, mqtt_fuzz *correctly* generates and sends messages to the broker on *most* occasions. For example, mqtt_fuzz is incapable of generating test cases for username and password authentication, which cause Mosquitto to close the connection immediately. This in turn makes mqtt_fuzz reconnect more frequently to Mosquitto than most fuzzers, except for FUME. Connection requests are also more prevalent because mqtt_fuzz uses a mutation-based approach, which creates and sends test cases to Mosquitto faster than their generation-based counterparts. It is also worth noting that mqtt_fuzz performs disconnection requests at any given moment during testing. In that regard, the vast majority of disconnections mainly occur upon request of mqtt_fuzz rather than Mosquitto.

learner executes approximately 31% of the statements in 30 minutes *and* after exchanging 8000 packets with Mosquitto. Likewise, CyberExploit achieves the exact coverage performance when satisfying both conditions, executing approximately 24% of the statements. The coverage performance across both stopping conditions is identical because learner and CyberExploit perform exactly the same connection request for the entire test run. However, learner outperforms CyberExploit because of two reasons. First, learner performs more connection requests than CyberExploit. In fact, within the first four minutes of testing, learner performs *only* connection-related requests. The initial test period therefore plays a *key* role in the success of learner over CyberExploit. Second, learner uses a username and client ID to authenticate with the broker, whereas CyberExploit opts only for the latter. learner further differentiates itself from CyberExploit by performing connection requests with properties specific to MQTT 5.0. The aforementioned differences allow learner to outperform CyberExploit.

All variants of MQTTGRAM perform up to 4x fewer connection requests than their counterparts. Among all variants of MQTTGRAM, mqttgram-r achieves the highest coverage performance, executing approximately 49.97% of the statements in 30 minutes. mqttgram5-cf, mqttgram-cf, and mqttgram-c execute 48%, 46.81%, and 46.55% of the statements, respectively. Coverage performances are fairly similar after exchanging 8000 packets with the broker. mqttgram-r and mqttgram5-cf execute approximately 49.46% and 47.42% of the statements, respectively. mqttgram-cf and mqttgram-c achieve a nearly identical coverage performance, each executing 46.13% and 46.11% of the statements.

Among all fuzzers, fuzz() achieves the lowest coverage performance. fuzz() executes 6.96% and 6.56% of the statements in 30 minutes, and after exchanging 8000 packets with the broker, respectively.

5.2.2 handle_publish.c

Figure 5.4 presents the statement coverage percentage achieved by the MQTT fuzzers in the file handle_publish.c.

Despite executing the largest number of statements in handle_connect.c, FUME fails to outperform most fuzzers in handle_publish.c except for fuzz(), which executes no statements whatsoever. As a result, FUME achieves the second-lowest performance, execut-

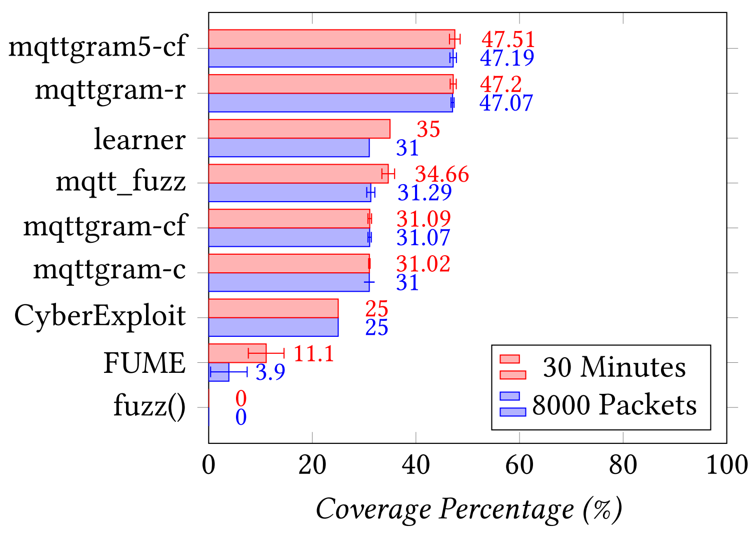


Figure 5.4: *Statement Coverage in* `handle_publish.c`

ing approximately 11.1% of the statements in 30 minutes, and only 3.9% after exchanging 8000 packets with Mosquitto. The low coverage performance can be attributed to the fact that most of the publish requests performed by `FUME` are invalid.

`CyberExploit` executes 25% of the statements within the first three minutes of testing, *and* before exchanging 500 packets with Mosquitto. Despite outperforming `FUME` within a short time frame, `CyberExploit` executed no more than 25% of the statements across all of its test runs. The lack of a coverage increase is due to `CyberExploit` performing the same publish request for most of the test run.

`mqttgram-cf` and `mqttgram-c` slightly outperform `CyberExploit`, executing 31.09% and 31.02% of the statements respectively in 30 minutes. `mqtt_fuzz` surpasses the coverage performance of `mqttgram-cf` and `mqttgram-c`, executing 34.66% of the statements. Despite using fewer Publish flags than its aforementioned counterparts, `learner` achieves a higher coverage performance (35%) because it executes statements specifically written for MQTT 5.0. Aside from `learner`, only `FUME`, `mqttgram5-cf`, and `mqttgram-r` are capable of executing statements specifically for MQTT 5.0. `mqttgram-r` and `mqttgram5-cf` outperform their counterparts by executing *at least* 12% more statements. More specifically, `mqttgram5-cf` executes 47.51% of the statements, whereas `mqttgram-r` executes 47.2%.

Although `learner` outperforms `mqtt_fuzz`, `mqttgram-c`, and `mqttgram-cf` in 30-minute test runs, a different outcome occurs after exchanging 8000 packets with Mosquitto. All of the aforementioned four fuzzers achieve a near identical performance. However, `mqttgram-cf` and `mqtt_fuzz` *slightly* outperform both `learner` and `mqttgram-c`, executing 31.07% and 31.29% of the statements, respectively. It is worth noting that `mqtt_fuzz` achieves a peak coverage performance of 34%, whereas `mqttgram-cf` executes at most 33% of the statements. However, their peak coverage performance is considerably surpassed by `mqttgram-r` and `mqttgram5-cf`, which execute 47.07% and 47.19% of the statements respectively. `mqttgram5-cf` achieves a peak coverage performance of 51%, whereas `mqttgram-r` achieves 50%.

5.2.3 handle_subscribe.c

Figure 5.5 presents the statement coverage of the MQTT fuzzers in `handle_subscribe.c`.

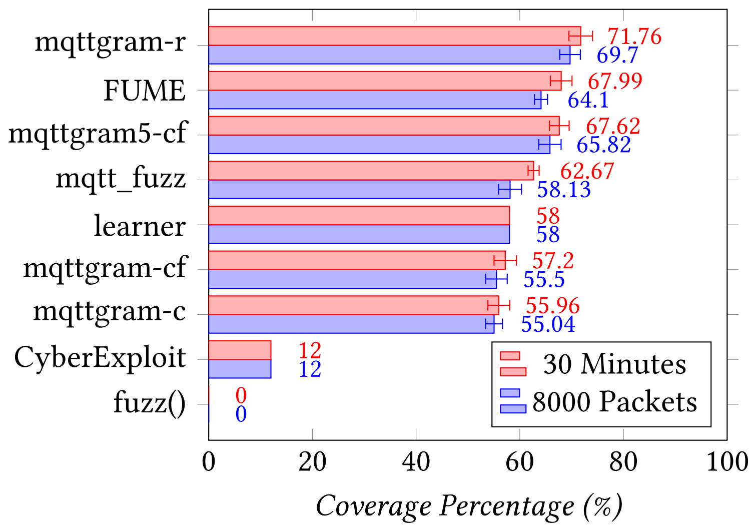


Figure 5.5: *Statement Coverage in* `handle_subscribe.c`

Among all fuzzers, `mqttgram-r` achieves the highest coverage performance, executing 71.76% of the statements in 30 minutes. This outcome is all the more surprising given that `mqttgram-r` exchanges at least 15x fewer packets than `FUME`, which executes 67.99% of the statements within the same time frame. This result sheds light on two common issues across existing MQTT fuzzers: (1) the abundance of repeated test cases and (2) the lack of domain knowledge, which in turn leads to the same statements being executed repeatedly regardless of how many packets are sent over time.

On average, `mqttgram5-cf` and `FUME` achieve a similar coverage performance despite the former supporting only MQTT 5.0 and exchanging the *fewest* packets with Mosquitto in 30 minutes. However, `FUME` manages to achieve a *peak* coverage performance of 75%, whereas `mqttgram5-cf` achieves 70%.

`mqtt_fuzz` achieves the fourth-best coverage performance, executing at most 64% of the statements. On average, `mqtt_fuzz` executes 62.67% of the statements, whereas `learner` executes 58%, which is also its *best* coverage percentage across 100 test runs. In fact, `learner` executes 58% of the statements in approximately 3 minutes, and remains the same for the remainder of the test run. It is worth noting that, at the time of writing, `mqttgram5-cf` and `learner` are the only fuzzers designed specifically for MQTT 5.0. However, between the two fuzzers, `mqttgram5-cf` is the most effective test suite for MQTT 5.0, outperforming `learner` by a margin of nearly 10%. Despite using Mosquitto to infer the message sequence and syntax of MQTT, `learner` underperforms considerably in terms of statement coverage.

The coverage performance between `mqttgram-c` and `mqttgram-cf` is nearly identical, averaging approximately 55.96% and 57.20% respectively in 30 minutes. However, their statement coverage *peaks* at 60% in 30-minute test runs, outperforming `learner` by 2%. It is worth noting that the performance of `mqtt_fuzz` surpasses that of `mqttgram-cf` and `mqttgram-c`. The reason behind this outcome is due to `mqtt_fuzz` performing subscription requests with both invalid and valid QoS levels, whereas its grammar-based counterparts use only the former type.

`CyberExploit` achieves the second-lowest performance, averaging and peaking at 12% of the statements. The reason for its low statement coverage is due to subscription requests being performed mostly in the same manner during testing. Most notably, `CyberExploit` uses the same identifier (0) and QoS level (0) for every subscription message it generates and sends to the broker. As a result, levels 1 and 2 of QoS are left untested. Subscription topics are the only exceptions to this rule, varying considerably across test cases.

`fuzz()` fails to execute any statement whatsoever in `handle_subscribe.c` because it is incapable of connecting successfully to the broker. As a result, the broker does not receive nor handle any subscription request from `fuzz()`.

In terms of the packet-based experiments, `mqttgram-r` achieves the highest coverage performance, outperforming its counterparts by a margin of *at least* 4%. On average, `mqttgram5-cf` and `FUME` execute 65.82% and 64.1% of the statements, respectively. Prior to 2000 packets, the statement coverage of `mqttgram5-cf` peaks at 68%, and afterwards increases to 70%, which is exactly the same result across all of its 30-minute test runs. The statement coverage of `FUME` peaks at 68% prior to exchanging 500 packets with Mosquitto, and remains the same for the remainder of the test run. Regardless of the stopping criterion, the coverage performance of both `mqttgram5-cf` and `FUME` are fairly similar, despite the latter supporting multiple versions of the standard.

The remaining six fuzzers, including `mqtt_fuzz`, achieve the same ranking when satisfying both stopping conditions. The statement coverage of `learner` peaks and remains at 58% during most of the fuzzing campaign. The considerable lack of increase in statement coverage signals that `learner` performs the same type of subscription request constantly. This reinforces the fact that developers are neglecting the *core* characteristics of the pub/sub design pattern when building MQTT fuzzers. `mqttgram-c` and `mqttgram-cf` achieve similar performance, executing 55.04% and 55.5% of the statements respectively. `CyberExploit` underperforms considerably when compared to its counterparts, executing at most 12% of the statements. Similar to `learner`, `CyberExploit` achieves peak performance very early during testing, meaning its subscription-related test cases lack variety. Unsurprisingly, `fuzz()` executed no statements whatsoever, as is the case in its 30-minute test runs.

5.2.4 subs.c

`subs.c` may very well be considered the *most* important file for Mosquitto because its purpose is to publish messages to interested subscribers. In that regard, `subs.c` is the file that is most associated with the *core* features of the pub/sub design pattern. MQTT fuzzers should therefore prioritize statement coverage in `subs.c`. Figure 5.6 reveals that the variants of `MQTTGRAM` are the only fuzzers capable of executing over 60% of the statements across *both* stopping conditions.

`mqttgram-r`, in particular, achieves the best performance among other variants of

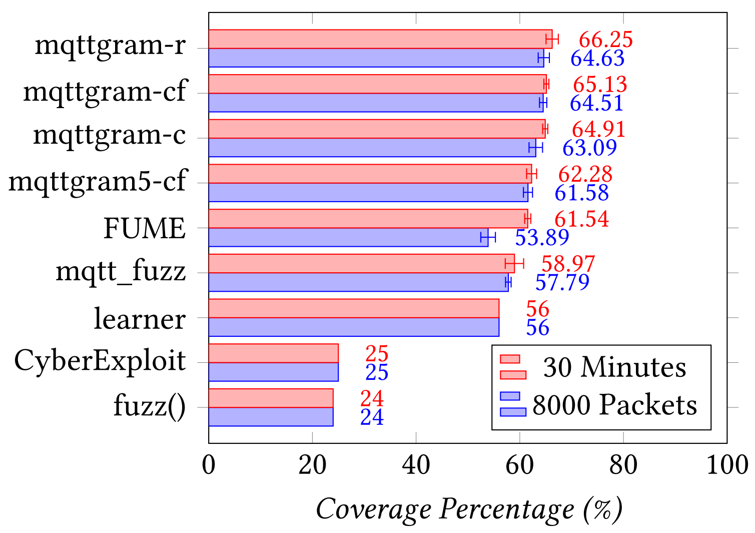


Figure 5.6: *Statement Coverage in* `subs.c`

`MQTTGRAM`, executing 66.25% of the statements in 30 minutes. `mqttgram-cf` and `mqttgram-c` execute 65.13% and 64.91% of the statements respectively. In fact, among all the variants of `MQTTGRAM`, `mqttgram-cf` triggers the *highest* average number of message publications in 30 minutes (319), followed by `mqttgram-r` (212), `mqttgram5-cf` (192), and `mqttgram-c` (178) respectively. The latter fuzzer triggers the *lowest* number of message publications because it is designed to generate topic-based packets less frequently than its counterparts (Araujo Rodriguez and Macêdo Batista, 2021). `mqttgram5-cf` triggers the second-lowest number of publications because its methodology for packet generation is more time consuming than that of its counterparts. This has to do with the fact that version 5.0 of MQTT packets adds more fields and user properties to the payload than past releases. For each MQTT 5.0 packet, `mqttgram5-cf` needs to randomly select a user property and define its corresponding value, the process of which affects the overall number of test cases generated and sent to the broker over time. `mqttgram-r` is affected by this issue to a lesser degree because it *occasionally* generates MQTT 3.1.1 packets, which demand less effort. However, despite triggering the second-highest number of message publications, `mqttgram-r` executes more statements in `subs.c` than `mqttgram-cf`. This result stems from the fact that `mqttgram-r` supports two versions of the standard, whereas `mqttgram-cf` supports only one. The superior performance of `mqttgram-r` serves as an indication of its aim and capabilities in triggering the broker into publishing messages using different parameters, whereas *all* of their counterparts fail in this regard.

For example, `FUME` triggers the broker into publishing *at least* 8x more messages (2769) to interested subscribers in 30 minutes than all variants of `MQTTGRAM`. Despite the large number of message publications, `FUME` executes 61.54% of the statements, slightly below the average performance of its grammar-based counterparts. This is surprising given the fact that `FUME` supports all major versions of MQTT, whereas its counterparts support one or two releases at most. Another surprising fact is the number of packets exchanged between `FUME` and Mosquitto. The higher the number of packets exchanged with the broker, the greater the chances of executing more statements and triggering additional message publications. In that regard, `FUME` exchanges 546,284.2 packets with

Mosquitto in 30 minutes, out of which only 268.6 (0.05%) are publish requests. The lack of message publications is further hindered by the fact that most publish requests performed during testing are invalid, hence its performance drop to 53.89% in 8000-packet test runs. As a result, `FUME` struggles to trigger Mosquitto into publishing messages to interested subscribers, meaning the *core* functionality of the pub/sub pattern is neglected to a certain degree during testing. Although `FUME` performs approximately 5745 subscription requests during the test run, these efforts also seem to be of little avail.

Among MQTT fuzzers, `mqtt_fuzz` performs the most subscription and publish requests, averaging 6868 and 4926 respectively in 30 minutes. This leads `mqtt_fuzz` to trigger 15012.1 message publications in 30 minutes, outperforming all of its counterparts by a wide margin. Despite the large number of message publications, `mqtt_fuzz` is slightly outperformed by `FUME` and `MQTTGRAM`-based fuzzers in terms of statement coverage, which averages approximately 58.97%. It is worth noting that `mqtt_fuzz` achieves a coverage performance of 58.02% in 3 minutes, meaning it increments its statement coverage by approximately 1% at the end of the test run.

`learner`, on the other hand, is incapable of increasing its coverage performance after 3 minutes, executing at most 56% of the statements. This is due to the fact that `learner` uses the same connection, publish, and subscription parameters for the entire test run. This is also the case for `CyberExploit`, which its coverage percentage never surpasses 25% after 3 minutes. In addition to the same parameters, `CyberExploit` and `learner` assign the same values to the majority of the fields in connection- and pub/sub-related packets, the sole exceptions being subscription topics and their corresponding messages. However, in contrast to `learner`, at no time during testing does `CyberExploit` trigger the broker into publishing messages. The lack of message publications causes `CyberExploit` to achieve the second-lowest coverage performance among MQTT fuzzers. Likewise, similar to `CyberExploit`, `fuzz()` executes 24% of the statements due to also being incapable of triggering message publications. It is worth noting that `fuzz()` achieves the same coverage percentage (24%) after exchanging 8000 packets with Mosquitto, as shown in Figure 5.6. `CyberExploit` executes 25% of the statements, which is also its same coverage percentage in 30-minute test runs.

A major performance difference shown in Figure 5.6 is with regards to `FUME`, which drops to 53.89% when executing 8000-packet test runs. The reason behind the performance drop has to do with the fact that `FUME` struggles to generate *valid* publish packets, requiring more time than its counterparts to execute certain statements. Unsurprisingly, `learner` achieves the same result as in 30-minute test runs, executing 56% of the statements. The coverage performance of `mqtt_fuzz` varies slightly across both stopping conditions, executing 57.79% of the statements in 8000-packet test runs. The variants of the `MQTTGRAM` are the only fuzzers capable of executing over 60% of the statements. `mqttgram-r` achieves the highest coverage performance (64.63%), followed by `mqttgram-cf` (64.51%), `mqttgram-c` (63.09%), and `mqttgram-5cf` (61.58%), respectively.

After evaluating the performance of `mqttgram-r`, the answer to **RQ4** is as follows:

RQ4: How effective is an MQTT fuzzer when considering three essential elements for pub/sub fuzzing: two-way communication capabilities; topic awareness; and multiversion support?

Chapter 4 identified `FUME` as the most effective MQTT fuzzer proposed in the literature thus far. However, `mqttgram-r` manages to outperform *all* of its state-of-the-art competitors, including `FUME`, in terms of standardized testing metrics such as code coverage, executing up to 12x more statements in pub/sub-related files. This result is all the more surprising given that `mqttgram-r` supports fewer versions of MQTT than `FUME`, and *still* manages to achieve the highest statement coverage. `mqttgram-r` and `FUME` execute *at most* 2321 and 2311 statements, respectively. On average, `mqttgram-r` executes from 2131 to 2276 statements in 30 minutes, whereas `FUME` executes from 2138 to 2242 statements. The original `MQTTGRAM` underperforms considerably compared to `mqttgram-r`, executing *at most* 2140 statements in 30 minutes. These results therefore confirm the research hypothesis, which stated that the effectiveness of an MQTT fuzzer is higher when considering the three essential elements.

5.3 Concluding Remarks

Chapter 4 determined that all fuzzers have issues regarding pub/sub protocol testing. This chapter therefore presented and evaluated a new fuzzer based on an architecture that developers can use as a reference to test MQTT or other pub/sub protocols. The open-source fuzzer introduced in this chapter outperforms *all* of its state-of-the-art-competitors in terms of pub/sub testing. Not only did this chapter present the new multiversion grammar-based approach for a pub/sub protocol, but it also reinforced the importance of the contributions presented in previous chapters of this thesis for the development of better testing tools. This chapter can therefore help raise awareness and motivate developers to better design their fuzzers considering the three essential elements for successful pub/sub fuzzing in future studies.

Chapter 6

Stress Test Evaluation of Fuzzing Techniques for MQTT Brokers

Centralized pub/sub architectures, such as the one shown in Figure 6.1, have been adopted for several smart city applications, including transportation systems, traffic control, and healthcare services.

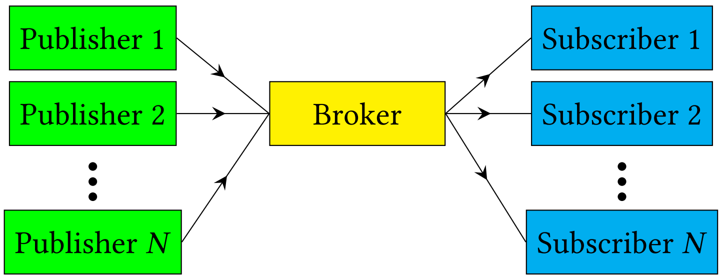


Figure 6.1: *Centralized Broker Architecture for Pub/Sub Messaging*

As previously stated, a major disadvantage of centralized architectures, when compared to their distributed counterparts, is that the broker most often becomes a performance bottleneck because it is the single entity responsible for data transmission and storage (Johnsen *et al.*, 2018). In the worst case scenario, a performance bottleneck leads to a Denial of Service (DoS), which has negative effects, especially in large-scale environments such as smart cities. For example, the lack of transport services is detrimental to citizens *and* city revenue; the absence of traffic control systems may increase the number of car accidents; and unavailable healthcare systems can delay urgent medical procedures or appointments.

DoS attacks can also be performed *intentionally* to either *flood* or *crash* the target system. Both of these outcomes usually occur by elevating the CPU and memory usage of the broker to such a degree that its functionality is affected. According to the MITRE Corporation (2006), uncontrolled resource consumption has a high probability of leading to an exploit. In fact, resource-related vulnerabilities rank within the top 25 most dangerous software weaknesses (MITRE Corporation, 2006). Furthermore, resource exhaustion is one of the most common types of DoS attacks in IoT according to the literature (Mrabet *et al.*, 2020).

The robustness of the broker therefore plays a *key* role in the success and reliability of smart city applications, which must be capable of providing high quality services under heavy workload. A DoS can be mitigated or avoided altogether if the robustness of the broker is tested *thoroughly* before deployment, thereby guaranteeing its reliability in real-world environments (Oliveira *et al.*, 2019). The MITRE Corporation (2006) lists fuzz testing as one of the three main detection methods for resource-exhaustion problems. However, in order to guarantee that the broker is robust and reliable enough against performance bottlenecks or issues in smart cities, a fuzzer should perform CPU- and memory-intensive tests (Săndescu *et al.*, 2018). Despite the wide range of broker fuzzers available, there is a lack of information in the literature regarding their capabilities to perform resource-exhaustion attacks during the test run.

This chapter therefore aims to answer the following research question:

> *RQ5: How effective are existing fuzzing strategies at impacting the CPU and memory usage of the broker during testing?*

Although there have been several publications about the broker's performance while under heavy workload (Mishra and Kertesz, 2021), none have evaluated the capabilities of existing fuzzing tools for *stress-testing* purposes. This is therefore the *first* research to investigate about the fuzzers' capabilities in regards to resource exhaustion. This chapter also highlights questionable design choices that prevent existing fuzzers from consuming more system resources.

6.1 State of the Art

At the time of writing, broker fuzzers proposed in the literature are mostly for MQTT, which research studies have demonstrated is extremely vulnerable to resource-exhaustion attacks (Kim *et al.*, 2017). Since 2016, *at least* ten vulnerabilities related to memory management have been triggered in MQTT brokers. Examples of memory-management vulnerabilities are CVE-2016-10523, CVE-2017-2894, CVE-2017-7651, CVE-2018-17614, CVE-2018-19417, CVE-2018-19587, CVE-2018-5879, CVE-2018-8531, and CVE-2019-12951. All of the aforementioned vulnerabilities were triggered by sending malicious or malformed packets to the broker, which is a common practice among cyberattackers. Despite these issues, resource-related metrics are barely used in the literature for comparing MQTT fuzzers. At the time of writing, only Hernández Ramos *et al.* (2018) evaluated their fuzzer by considering the CPU consumption of the broker.

Although none of the broker fuzzers presented in the previous chapters are designed specifically for resource-intensive purposes, it is important to evaluate their stress-testing capabilities because of three reasons. First, open-source *resource-guided fuzzers* designed specifically for MQTT brokers are nonexistent. A *resource-guided fuzzer* receives and analyzes resource-related feedback about the broker while fuzzing. Due to their nonexistence, developers have two choices: (1) develop their own resource-guided fuzzer from scratch; or (2) use and extend an existing framework to perform stress testing. Developers have thus far preferred the latter, as evidenced by the research studies conducted by Fehrenbach (2017) and Morelli *et al.* (2021), which propose to use or extend an open-source MQTT fuzzer to perform more complex resource-exhaustion attacks. Second, the tools proposed by Fehrenbach (2017) and Morelli *et al.* (2021) are proprietary, meaning developers have no choice but to select one of the state-of-the art fuzzing frameworks evaluated in this research study. As such, it is important for developers to be aware of the capabilities and shortcomings of each open-source fuzzer in order to select the most appropriate for testing purposes. Third, although there exists open-source resource-guided fuzzers such as `MEMLock` (Wen *et al.*, 2020) or `ResFuz` (L. Chen *et al.*, 2022), they are incompatible with network-based target systems such as brokers, meaning developers are more likely to use and extend the open-source fuzzers evaluated in this research study.

6.2 Performance Evaluation

This section evaluates six open source MQTT fuzzers (Philippe Biondi and the Scapy Community, 2023; F-Secure Corporation, 2015; Casteur *et al.*, 2020; Aichernig *et al.*, 2021; Araujo Rodriguez and Macêdo Batista, 2021; Pearson *et al.*, 2022). Mosquitto 1.6.8 and Moquette 0.13 were chosen as the target brokers because of their popularity in the literature (Hernández Ramos *et al.*, 2018; Bender *et al.*, 2021; Sochor *et al.*, 2020b). The MQTT brokers and fuzzers were evaluated using default settings. The CPU and memory usage of the brokers are monitored throughout the fuzzing campaigns. The more CPU- and memory-intensive inputs are sent to the brokers, the higher the probability of finding resource-exhaustion bugs. Fuzzing campaigns are repeated 100 times in order to calculate the average and standard deviation for each stopping criterion. Two separate experiments were conducted, each satisfying a different stopping criterion. For the first experiment, the fuzzers are executed until a certain time has elapsed (30 minutes). For the second experiment, the fuzzers are executed until a specific number of packets has been exchanged with the brokers (8000). Resource usage is measured after every three minutes and after 500, 1000, 2000, 4000, 6000, and 8000 packets. The fuzzers are referred to by either their designated name (if available) or main characteristic. Similar to the previous chapters, the fuzzer by Aichernig *et al.* (2021) is referred to as `learner` due to lacking a formal name. It is worth noting that Moquette lacks support for MQTT 5.0, hence the reason why it could not be tested with `learner` and `FUME`. The testbed shown in Figure 1.3 was used for the performance evaluation.

6.2.1 Mosquitto

Figure 6.2 presents the CPU usage of Mosquitto when fuzzing for 30 minutes. It is worth noting that the figures in this section present the results of only one variant of `MQTTGRAM` (`mqttgram-cf`) because it performs nearly identical to `mqttgram-c`.

Among all MQTT fuzzers, `FUME` consumes the most CPU resources on Mosquitto, followed by `mqtt_fuzz` and `learner` respectively. The CPU usage by `FUME` ranges from 1.05% to 1.23%, and peaks at 2.40%. `mqtt_fuzz` consumes at most 1.50% of the CPU, and normal usage ranges from 0.92% to 1.07%. `learner` uses up to 0.40% of the CPU, and average consumption is fairly consistent throughout 30 minutes, remaining mostly at

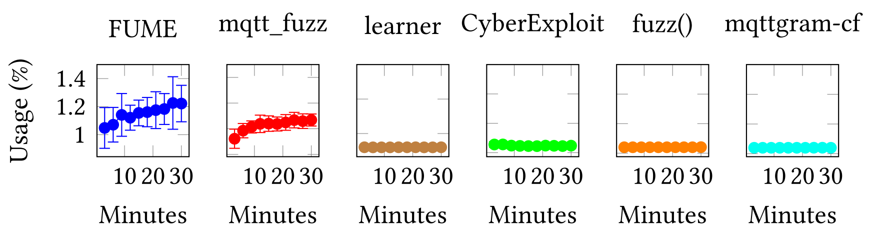


Figure 6.2: *Average CPU Usage of Mosquitto During 30 Minutes.*

0.30%. Peak CPU usage when testing with `fuzz()` and `CyberExploit` is slightly lower than its counterparts, reaching at most 0.30% and 0.20% respectively. Average CPU usage by both fuzzers is mostly consistent throughout 30 minutes, ranging from 0.10% to 0.14%. Finally, both variants of `MQTTGRAM` perform mostly the same, with `mqttgram-c` and `mqttgram-cf` using at most 0.10% and 0.20% respectively. Average CPU usage by both grammar-based approaches remains at 0.10% throughout most of the fuzzing campaign.

Based on the time-based experiments, *all* MQTT fuzzers are incapable of creating CPU-intensive scenarios that test the broker's performance under heavy workload. The results of the packet-based experiments, shown in Figure 6.3, further confirm this limitation.

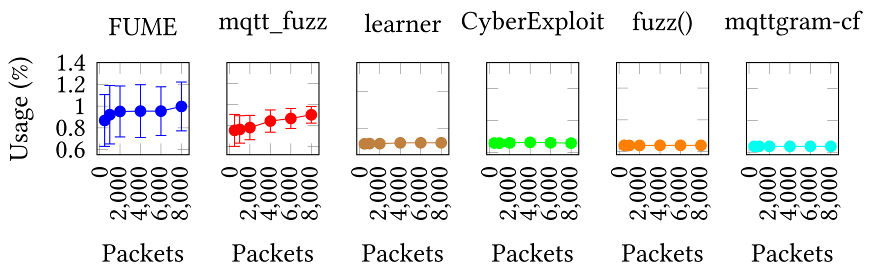


Figure 6.3: *Average CPU Usage of Mosquitto When Exchanging 8000 Packets.*

Figure 6.4 presents the memory usage of Mosquitto when fuzzing for 30 minutes.

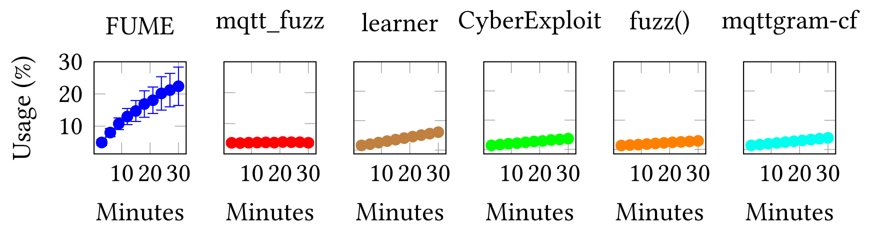


Figure 6.4: *Average Memory Usage of Mosquitto During 30 Minutes.*

`FUME` peaks Mosquitto's memory usage at 43.50%, outperforming *all* other state-of-the-art fuzzing techniques *combined*. The memory usage by `learner` peaks at 6.10%, followed by `mqtt_fuzz` at 5.80%, and `mqttgram-cf` at 4.90%, respectively. The memory usage by `FUME` ranges from 4.93% to 22.39%, increasing at a higher rate than those of its counterparts. The percentage increase may be directly linked to the network traffic during testing. For example, `FUME` exchanges 544,082 packets with Mosquitto in 30 minutes, outperforming all other fuzzers by a wide margin. In fact, `mqtt_fuzz` generates over 50% less network traffic (218,557) than FUME in the same time frame. Similarly, mqtt_fuzz exchanges over 50% more packets with the broker than learner (75,855). Despite outperforming learner, mqtt_fuzz consumes only from 3.71% to 4.04% of memory on average. In contrast, learner increases Mosquitto's memory usage from 1.59% to 6.08%. According to the results, a broker's memory consumption seems to increase at a higher rate when testing MQTT 5.0, as is the case of FUME and learner. The latter fuzzer consumes less memory at the beginning of the fuzzing campaign because its interactions with the broker are mostly short-lived, consisting solely of connection and disconnection requests. However, learner slightly covers more functionality over time by performing publish and subscribe requests, increasing Mosquitto's memory usage as a result.

Despite covering more functionality than learner, mqttgram-cf increases Mosquitto's memory usage only from 1.39% to 3.97% on average. Both mqttgram-c and CyberExploit consume at most 3.70% of Mosquitto's memory, and their average usage is nearly identical. The former's memory usage ranges from 1.32% to 3.57%, whereas the latter's from 1.33% to 3.65%. Among all fuzzers for MQTT brokers, fuzz() underperformed the most in terms of Mosquitto's memory usage, consuming at most 2.90%. Average memory usage by fuzz() ranges from 1.30% to 2.89% throughout 30 minutes. Despite covering less functionality than most of its counterparts, learner consumes more memory on Mosquitto than most fuzzers at the end of 30 minutes, except for FUME. More specifically, learner outperforms mqtt_fuzz, despite the latter exchanging considerably more packets with the broker than the former. In fact, all fuzzers compatible with MQTT 5.0 have the largest percent increase from 3 to 30 minutes. For example, mqtt_fuzz increases memory usage by up to 0.33% from 3 to 30 minutes, whereas learner increases memory usage by up to 4.50% in the same time frame.

Similarly, fuzz() uses the least amount of memory when exchanging up to 8000 packets with Mosquitto, as shown in Figure 6.5.

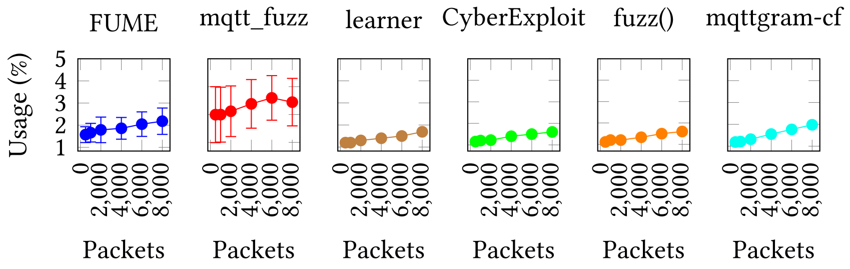


Figure 6.5: *Average Memory Usage of Mosquitto When Exchanging 8000 Packets.*

In fact, fuzzers that cover the least amount of functionality seem to consume fewer memory resources than their counterparts. For example, fuzz() and CyberExploit perform roughly the same, consuming at most 1.60% of Mosquitto's memory. The average memory usage by both fuzzers ranges from 1.11% to 1.60%. Despite learner ranking second-best in terms of memory usage at the end of 30 minutes, it ranks as the third lowest when exchanging up to 8000 packets, consuming at most 1.70% of memory. Average memory usage by learner ranges from 1.20% to 1.69%. mqttgram-c and mqttgram-cf perform slightly better than the aforementioned approaches, using at most 2.10% and 2.20% of memory respectively. More specifically, mqttgram-cf performs better than mqttgram-c overall, consuming from 1.20% to 2.13% of memory on average. Memory usage by mqttgram-c ranges from 1.19% to 1.98%. Among all fuzzers, mqttgram-cf has the largest percent increase (0.93%) when exchanging up to 8000 packets with Mosquitto, followed by mqttgram-c (0.78%). However, it is worth noting that learner outperforms both mqttgram-cf and mqttgram-c at the end of 30 minutes because it exchanges more packets with the broker than the aforementioned approaches, hence the importance of evaluating fuzzers based on the number of packets. Among all fuzzers, mqtt_fuzz has the highest average memory usage, which ranges from 2.99% to 3.60%. The minimum value (2.99%) is higher than all standout performances of nearly every fuzzer except for FUME, which consumes at most 4.80% of memory resources, whereas mqtt_fuzz uses at most 4.60%. Although FUME has the highest standout performance (4.80%) among all fuzzers, its average memory usage ranges from 1.57% to 2.18%, meaning it is slightly outperformed by mqtt_fuzz.

6.2.2 Moquette

All fuzzers manage to either maintain or increase Mosquitto's CPU usage during the test run. In contrast, Moquette's CPU usage gradually decreases over time, as shown in Figure 6.6.

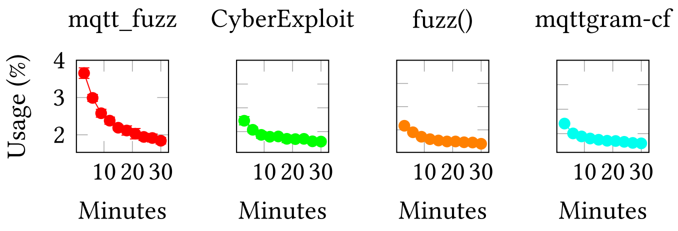


Figure 6.6: *Average CPU Usage of Moquette During 30 Minutes.*

For example, mqtt_fuzz consumes the highest amount of CPU on Moquette, reaching up to 4.00%. However, CPU usage decreases from 3.66% to 1.84% on average at the end of 30 minutes. Moquette's CPU usage also decreases when testing it with CyberExploit, lowering from 1.46% to 0.58%. Both variants of MQTTGRAM performed in a similar manner, consuming at most 1.50% of CPU usage, which decreases to roughly 0.60% at the end of the fuzzing campaign. Moquette's CPU usage peaks at 6.70% when exchanging 8000 packets with mqtt_fuzz, and gradually decreases over time, as shown in Figure 6.7.

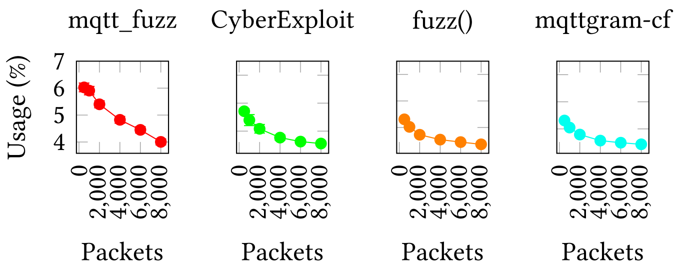


Figure 6.7: *Average CPU Usage of Moquette When Exchanging 8000 Packets.*

Moquette's memory usage is fairly similar to that of Mosquitto, as shown in Figure 6.8.

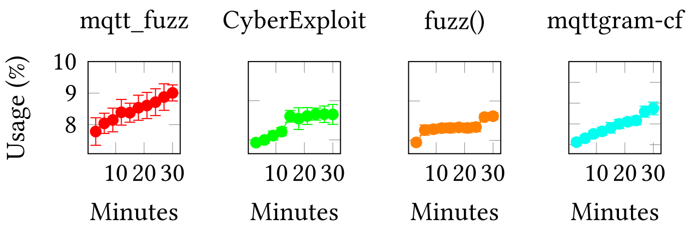


Figure 6.8: *Average Memory Usage of Moquette During 30 Minutes.*

In fact, fuzzers rank in the exact order across both brokers at the end of 30 minutes. For example, among 3.x compatible fuzzers, `mqtt_fuzz` consumes the most memory on both Mosquitto and Moquette. Due to the identical rank order at the end of 30 minutes, all explanations about Mosquitto's fuzzing campaigns also apply to those of Moquette. In fact, Moquette's memory usage throughout 30 minutes further confirms that most fuzzers, except for `FUME`, are incapable of performing memory-intensive tests for pub/sub brokers. The average memory usage by 3.x compatible fuzzers ranges from 5.90% to 9.00%, and peaks at 10.40%.

Fuzzers rank differently, however, when exchanging 8000 packets with Moquette, as shown in Figure 6.9.

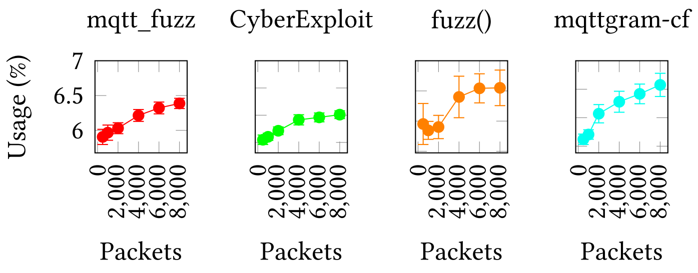


Figure 6.9: *Average Memory Usage of Moquette When Exchanging 8000 Packets.*

Unexpectedly, `fuzz()` outperforms other fuzzers in terms of average memory usage, which ranges from 5.95% to 6.55%. Both `fuzz()` and `mqttgram-cf` consume at most 7.50% of memory, whereas the remaining fuzzers use no more than 6.60%.

Overall, the fuzzers consume few CPU and memory resources on Moquette. These results support the major finding of this research study, which is that existing MQTT fuzzers are incapable of intensively testing both a broker's CPU and memory.

6.3 Discussion

Although fuzzers underperformed in terms of the brokers' CPU consumption, their results provide insight into two ineffective strategies to avoid for future work. First, sending a considerable amount of packets, as is the case of `mqtt_fuzz` and `FUME`, does not increase the CPU usage considerably. Second, performing publish requests with long topic names, as is the case of `FUME` and `CyberExploit`, also consumes few CPU resources on Mosquitto. Future work should be directed towards improving these strategies. For example, running multiple instances of fuzzers simultaneously could potentially increase the CPU usage of the broker. Future research could analyze the effectiveness of fuzzers when running multiple instances, exploring strategies that increase CPU resources and hinder the performance of the broker.

There are also several opportunities for future work considering the lessons learned from Mosquitto's memory usage while fuzzing. First, performing multiple requests simultaneously and successively seems to be an effective strategy to consume more of the broker's memory. In this chapter, *performing multiple requests simultaneously* refers to sending multiple requests in a single packet to the broker, whereas *performing multiple requests successively* refers to sending multiple packets one after the other without waiting for a response from the broker (See Appendix C, Figure C.4). Future work should attempt to develop fuzzers that apply both approaches to increase the broker's workload.

Second, storing significant amounts of user data on the broker should be performed in order to increase memory usage during testing. This task can be accomplished by disabling clean sessions *and* enabling retained messages when performing connection and publish requests respectively. Storing user sessions and topic messages can increase the broker's memory usage because multiple messages will have to be published by the broker when a client resumes communications or subscribes to a given topic. Furthermore, topic filters with wildcard characters, such as `#` or `+`, should be used to receive multiple publish messages from the broker.

Third, MQTT 5.0 sessions are more memory intensive than their older counterparts. This is evidenced by the following three observations. First, `learner` outperforms `CyberExploit` in terms of memory usage despite generating shorter topic names for both publish and subscribe requests. Second, `learner` exchanges fewer packets with the broker than `mqtt_fuzz`, but still manages to use more memory. Third, in contrast to `mqtt_fuzz`, `learner` stores neither user- nor subscription-related information in the broker. The reason for the outperformance of `learner` stems from the fact that MQTT 5.0 is a substantial upgrade over its older siblings, supporting a wide variety of features such as user properties or subscription options. Thus, most MQTT 5.0 packets possess more fields, meaning the broker must store additional subscription-related information. For example, *SUBSCRIBE* packets in MQTT 5.0 contain more fields for configuration options, such as scheduled message transmissions, all of which are stored on the broker. User sessions are therefore much more memory consuming, which explains why 5.x compatible fuzzers have the largest percent increase over time.

The memory consumption analysis of MQTT fuzzers also reveals different performance rankings for each type of stopping criterion. For example, `FUME` consumed the most memory at the end of 30 minutes, followed by `learner` and `mqtt_fuzz` respectively. However, when exchanging the same number of packets with Mosquitto, `mqtt_fuzz` ranks as the most memory-consuming fuzzer on average, whereas `FUME` and `learner` fell to second and third place respectively. The different performance rankings may indicate that certain strategies are more effective than others in terms of memory consumption. In fact, when fuzzers generate the same amount of network traffic (8000 packets), their limitations in terms of memory consumption become more noticeable. Considering the research findings presented in this paper, it is strongly recommend that developers incorporate resource-exhaustion techniques into their MQTT fuzzers.

After analyzing the resource-consumption of existing MQTT fuzzers, the answer to **RQ5** is as follows:

RQ5: How effective are existing fuzzing strategies at impacting the CPU and memory usage of the broker during testing?

The results confirm that current fuzzers are incapable of intensively testing both the broker's CPU and memory. Among existing fuzzers, `FUME` shows the most promise for resource-intensive testing, peaking the memory usage of the broker at 43.5%, which is more than 20% when compared to its counterparts.

6.4 Concluding Remarks

MQTT brokers are currently being deployed to large-scale scenarios such as smart cities. In that regard, the broker should be robust enough to handle requests from its citizens. Several fuzzers are made available to developers for testing-purposes. However, developers are unaware of the fuzzers' shortcomings in terms of resource-exhaustive testing. This chapter presented a performance evaluation of the most popular open-source fuzzers in the literature. Developers can use the guidelines presented in this chapter to either improve existing fuzzers or incorporate them into their own testing tool.

Chapter 7

Conclusions and Future Work

Fuzzing has made considerable progress across multiple domains. However, a research field that has been largely neglected is pub/sub protocol fuzzing, which is important to guarantee the reliability of message brokers deployed to the Internet of Things. The aim of this PhD research was therefore to study and develop effective fuzzing strategies for pub/sub protocols, aiming to contribute to the development of more robust applications in IoT and Smart Cities. This thesis therefore began by analyzing the research advancements and trends of pub/sub protocol fuzzing since its inception (Chapter 2). In that regard, the thesis focused primarily on MQTT, the *only* pub/sub protocol for which developers have proposed a wide variety of fuzzing techniques in the literature. Despite focusing specifically on MQTT, this research can serve as an initial step towards developing effective fuzzing strategies for pub/sub protocols in general, raising awareness and encouraging developers to better test brokers considering their message-publishing features and event-driven architecture.

It was evident after reviewing the literature that several research gaps needed to be filled in order to further advance the field of pub/sub protocol fuzzing. For example, information regarding established testing techniques such as *grammar-based fuzzing* for pub/sub protocols was mostly nonexistent in the literature, despite developers and researchers expressing interest. As a result, a new grammar-based approach for a pub/sub protocol (MQTT) was proposed and incorporated into a new fuzzer called `MQTTGRAM` [1], which developers can now use as a reference for testing purposes (Chapter 3).

`MQTTGRAM` joined several other fuzzers in providing a different testing strategy to developers and researchers, leading to a promising, yet complicated situation. On the one hand, developers now have several different and *varied* options at their disposal to test MQTT, but on the other hand the sheer number of techniques hinders decision-making in choosing the most appropriate or effective for a given situation. This hindrance will also have a negative impact on future studies, which will be unable to discern promising research directions or advancements in the field of pub/sub protocol fuzzing. As a result, a taxonomical classification (Chapter 4, Figure 4.4) and performance benchmark of fuzzing techniques for MQTT were presented in this thesis to clarify inquiries regarding their effectiveness. Due to

[1] https://github.com/luisgar1990/MQTTGRAM. Accessed on May 17th, 2023

the sheer amount of fuzzing techniques proposed for MQTT, one could have easily assumed that developers have a wide range of options to test their brokers' pub/sub functionalities. However, upon further investigation, the research findings indicated that *all* fuzzers have shortcomings regarding pub/sub protocol testing (Chapter 4). The root of the problem stems from the fact that *all* techniques were proposed without considering three essential elements for testing message-publishing features: (1) Two-way communication; (2) Topic awareness; and (3) Multiversion support. The algorithm and architecture of `MQTTGRAM` were refined to meet the three criteria (Chapter 5) [2], outperforming *all* state-of-the-art fuzzing techniques in terms of statement coverage, which is an established metric to measure the quality of test suites. In addition to test metrics, the fuzzers were evaluated based on their stress-testing capabilities in order to incentivate future studies in that field (Chapter 6). The testbed [3] used for the doctoral studies is also freely available for future work.

7.1 Future Work

Considering that pub/sub fuzzers are mostly for MQTT at the time of writing, the research findings presented in this thesis highlight the *current* state of both MQTT and pub/sub protocol fuzzing in general. This section, however, focuses more on the lessons learned and future research directions to move *both* fields forward.

7.1.1 Improvements to Existing Fuzzing Techniques

Learning-based fuzzing

Automatic knowledge acquisition using learning-based algorithms has been extensively researched to mitigate development and configuration efforts for fuzzers. However, the main shortcoming of learning-based fuzzers is that their knowledge is based more on protocol implementations rather than formal specifications. This approach also comes at the risk of putting more effort and time into *learning* the protocol rather than actually *testing* it, as evidenced by the subpar performance of `learner`. Developing a successful learning-based algorithm tailored specifically to pub/sub protocols such as MQTT is a challenge that has yet to be mitigated. Future work should focus on improving learning-based algorithms, and `learner` specifically, in two areas. First, in its current state, the learning-based algorithm for `learner` is incapable of understanding several core pub/sub functionalities of MQTT. The algorithm needs to better infer the syntax rules and message sequence from a given MQTT implementation. Second, `learner` takes approximately 4 minutes to generate interesting test cases as it interacts with the broker. `learner` should therefore be improved to gain knowledge of MQTT either quicker, or *before* rather than during testing.

[2] https://github.com/luisgar1990/MQTTGRAM-R. Accessed on May 17th, 2023

[3] https://github.com/luisgar1990/mqtt-testbed. Accessed on May 17th, 2023

Scenario-based fuzzing

Generating different types of scenarios is a useful, promising, and suitable technique to test specific functionalities of a target system. Pub/sub protocols, in particular, tend to be more *scenario-oriented* than other network-based systems due to their feature-rich and requirement-heavy nature. For example, there are *at least* three possible scenarios related to message publication that are worth considering when testing pub/sub protocols. First, a broker will discard publish messages if there are no interested subscribers. Second, a broker will send topic messages *immediately* to connected subscribers. Third, the broker will *retain* and send topic messages *after* the subscriber reconnects to the network. Existing scenario-based fuzzers fail to generate the latter two scenarios, meaning the broker discards topic messages throughout the entire test run. The fuzzer proposed by Di Paolo *et al.* (2021) is currently incapable of performing subscription requests, whereas `CyberExploit` is unable to trigger the broker into publishing messages. Another common misstep found across MQTT fuzzers is their short-lived test scenarios, each consisting of a single pub/sub packet. Scenario-based fuzzers must be designed around the idea that a message will be published only if there is *at least* one interested subscriber. For each test scenario, the fuzzer should at least perform a valid subscription request, and then publish a message to an existing topic. For future work, scenario-based fuzzers should therefore be more tailored to the pub/sub design pattern.

Mutation-based fuzzing

A mutation-based fuzzer should trigger the broker into publishing messages regardless of how a packet is modified. Mutation-based fuzzing, in the context of pub/sub protocols, must therefore be performed carefully, otherwise the broker will very rarely send messages to interested subscribers. For example, a broker publishes messages only to existing topics. Mutating a single character in an existing topic could potentially generate a new value that may be inconsistent with prior subscription requests. As a result, the mutated message will be discarded by the broker, preventing it from reaching subscribers. Proxy fuzzers, in particular, are more prone to this issue because they mutate packets in transit without considering user subscriptions or sessions.

Coverage-guided fuzzing with mutation testing is an approach considered less effective for network protocols (Yurong Chen *et al.*, 2019). In fact, coverage-guided fuzzers such as `AFLNet` and its variant `AFLNet-MQTT` are incapable of behaving as genuine MQTT clients because their current architecture is unsuitable for pub/sub communications (Zeng *et al.*, 2020; Sneha Suhitha Galiveeti and Pranitha Malae, 2020). According to Sneha Suhitha Galiveeti and Pranitha Malae (2020), the architecture of their fuzzer hinders its coverage performance significantly, becoming a major issue when testing MQTT implementations. At the time of writing, only `MultiFuzz` attempts to mitigate the shortcomings of the architecture through the use of message-aware mutation operators. Future work should continue mitigating limitations of the architecture in order to better support the pub/sub design pattern.

Another major issue is the time-consuming nature of coverage-guided approaches to discover new code paths during testing, as evidenced by the performance evaluation of `MultiFuzz` (Zeng *et al.*, 2020) and `AFLNet-MQTT` (Sneha Suhitha Galiveeti and

Pranitha Malae, 2020). This task is far more complex for network-based fuzzers, which have to discover coverage-increasing test cases, while still maintaining an active connection with the broker. Future work should attempt to develop *fast* coverage-guided approaches capable of supporting several versions of MQTT.

Hybrid-based fuzzing

Combining mutation- and generation-based techniques seems promising for future research because it allows developers to take advantage of their strengths during the test run. However, in order to effectively leverage the strengths of both mutation- and generation-based techniques, a hybrid-based fuzzer has to be much more aware of messages *and* states than its counterparts. The main challenge lies in *carefully* choosing between mutation- or generation-based techniques during testing. Otherwise, the fuzzer will make poor decisions regarding the type of packet generation that is most appropriate for a given situation. In the context of pub/sub protocols, there are multiple factors to consider when making a decision, such as subscriptions or user sessions. Thus, a hybrid-fuzzer for MQTT has to be *smart* enough to choose the technique that will enable it to reach pub/sub states in a more effective and efficient manner. `FUME` fails to meet this requirement because it is unaware of most state transitions, except those necessary to connect to and disconnect from the broker. Future work should focus on improving both the finite state machine from which `FUME` is modeled by, and the decision-making process for the most appropriate packet generation technique during testing.

Grammar-based fuzzing

Future work should combine grammar-based fuzzing with multiple techniques presented in the taxonomy. For example, the grammar can be used to generate vulnerability-oriented packets. Coverage-guided fuzzing should also be used with the MQTT grammars in order to gain feedback during testing, and thus attempt to generate packets that traverse through undiscovered code paths.

7.1.2 Development of Built-In Fault Detection Mechanisms

Most MQTT fuzzers lack fault detection mechanisms, requiring external debugging tools to monitor the behavior of the broker during testing. For example, this thesis uses `AddressSanitizer` as a tool to detect run-time errors or memory leaks in Mosquitto throughout the fuzzing campaign. Casteur *et al.* (2020), Di Paolo *et al.* (2021), and Sochor *et al.* (2020b) analyze system logs after each test run for any sort of indication regarding crashes or unhandled exceptions. The `Polymorph` fuzzing framework by Hernández Ramos *et al.* (2018) consists of five modules, none of which monitor exceptions. The repository description of `mqtt_fuzz` states that brokers should be compiled using debugging tools such as `AddressSanitizer` or `gdb` to detect potential flaws during testing. It is impractical to determine if `Defensics` monitors exceptions during testing because its source code is unavailable. Future work should focus on developing fuzzers that are able to detect faults in the broker. At the time of writing, `MultiFuzz`, `AFLNet-MQTT`, `FUME` and `learner` are the only fuzzers that possess built-in fault detection mechanisms.

7.1.3 Development of a Resource-Intensive Fuzzer for MQTT Brokers

A resource-intensive fuzzer should be developed considering the lessons learned from the research study presented in Chapter 6. For future work, additional experiments should also be conducted with other broker-side implementations such as HiveMQ, VerneMQ, and RabbitMQ. A simple traffic generator should be developed in order to provide baseline results against which to compare the stress-testing capabilities of existing and subsequent fuzzers.

7.1.4 Development of Fuzzers Based on Hybrid and Machine Learning Approaches

Although promising, the fuzzing techniques proposed for MQTT thus far are either underdeveloped or unsuitable for pub/sub protocols, as evidenced by the research findings presented in the previous chapters. Future work should delve deeper into two promising techniques for pub/sub protocols. First, hybrid-based approaches that incorporate elements of both grammar-based and mutation-based fuzzing should be further studied for pub/sub protocols. Second, fuzzing techniques based on machine learning should also be further explored.

7.1.5 Performance Evaluation Over Longer Test Runs

It is worth clarifying that the broker was constantly monitored during the test runs in the case of an unexpected crash. However, *none* of the fuzzers were capable of crashing the broker within 30 minutes. Future work should attempt to evaluate the fuzzers over longer test runs in order to further identify shortcomings and areas of improvement.

7.1.6 Maintenance of MQTT Fuzzers

Most, if not all, research proposals lack information regarding their fuzzers' flexibility to evolve in lockstep with MQTT itself. For example, in its current form, `learner` is *only* applicable to MQTT 5.0, meaning it requires adjustments for future versions. The emergence of `FUME` in early 2022 further diminishes the relevance, longevity, and necessity of `learner` due to the former's *built-in knowledge* of the message syntax for version 5.0. Among other examples, Sochor *et al.* (2020b) developed an attack-based fuzzer that, while promising, requires further maintenance as more types of implementation flaws emerge. The *simple* mutations performed by `mqtt_fuzz` to a given packet will be less effective as MQTT implementations become more robust over time, requiring further improvement. `FUME` supports all major versions of MQTT, extending its lifespan even further. However, no information is given regarding its flexibility to evolve as new versions of MQTT are released. The effectiveness of proxy fuzzers, proposed by Hernández Ramos *et al.* (2018) and Eclipse Foundation (2018), is mostly unaffected by new version releases because they simply mutate packets that are transmitted from one endpoint to another, lacking packet generators or any sort of knowledge regarding state transitions. Future work should attempt to propose *flexible* approaches that can *easily* evolve over time.

7.1.7 Expand the Research Scope to Include Other Pub/Sub Protocols

MQTT is *the* most popular pub/sub protocol in terms of the number of fuzzing techniques. However, future work should focus on advancing the state of the art by studying fuzzers for other pub/sub protocols such as AMQP, DDS, and XMPP. Most importantly, future work should adapt existing fuzzing strategies for MQTT to other pub/sub protocols, analyzing their strengths and weaknesses more in depth.

Appendix A

Usage of MQTT in IoT Applications

MQTT is used for several technologies, including Facebook Messenger, Amazon Web Services, Arduino, and Mongoose OS (Maggi *et al.*, 2018). MQTT is also currently being integrated into several IoT-based applications, such as home automation systems; health monitoring systems; Intelligent Transportation Systems (ITS); and electricity metering systems.

A.1 Home Automation Systems

Future smart cities must integrate home automation systems into their infrastructure (Schiefer, 2015). A home automation system connects lighting, heating, ventilation, and electronic devices, which interact intelligently to automate domestic tasks. Over the last few years, home automation systems have grown in terms of popularity. Open source home automation software such as *HomeAssistant* [1], *HomeGear* [2], *Domoticz* [3], and *OpenHab* [4] are compatible with MQTT, allowing users to integrate custom-made or publicly available brokers [5].

A.2 Health Monitoring Systems

Over the last few years, the healthcare industry has shown interest in using IoT technologies to improve services (Casino *et al.*, 2015). Health monitoring systems use sensors to collect information, such as a patient's pulse rate, which is then transferred to hospitals for further analysis. Health monitoring systems provide significant advantages over traditional

[1] https://www.home-assistant.io/. Accessed on March 23rd, 2023

[2] https://homegear.eu/. Accessed on March 23rd, 2023

[3] https://www.domoticz.com/. Accessed on March 23rd, 2023

[4] https://www.openhab.org/. Accessed on March 23rd, 2023

[5] https://www.home-assistant.io/integrations/mqtt/. Accessed on March 23rd, 2023

healthcare methods. In fact, studies have confirmed the benefits of MQTT in the healthcare sector (Yi *et al.*, 2016; Georgi and Le Bouquin Jeannès, 2017). For example, MQTT offers real-time communication, which is necessary for efficient monitoring systems (Georgi and Le Bouquin Jeannès, 2017). Real-time communication allows medical practitioners to access data immediately and continuously. The ease of access to medical data reduces frequent visits of senior citizens; increases health awareness; and minimizes healthcare costs (Khan *et al.*, 2019).

A.3 Intelligent Transportation Systems

ITS offer services that improve the overall transport and traffic management. MQTT has emerged as a popular and effective protocol for bus-tracking systems because of its reliability and scalability. Several research papers propose real-time bus-tracking systems using MQTT to transfer the bus' location to an external server for further analysis (Sharad *et al.*, 2016; Lohokare *et al.*, 2017; Pianez *et al.*, 2017; Rutke, 2019). Users can monitor the bus' location with a website or mobile application. These recent research studies confirm the popularity and interest of MQTT for ITS.

A.4 Electricity Metering Systems

Smart Grids are applications that distribute and generate energy efficiently (Engel, 2013). A Smart Grid has three primary objectives: distribute energy efficiently; provide information and feedback to clients; and offer secure and integrated services (Curiale, 2014). A key component of Smart Grids is *Smart Electricity Metering*, which is used to capture information related to energy consumption, and transfer it to the service provider. Miškuf *et al.* (2017) propose an MQTT-based metering system that measures and analyzes energy consumption, highlighting the benefits of MQTT in electricity metering systems.

Appendix B

Comparison Between MQTT and Other IoT Protocols

This section highlights the differences between MQTT and other IoT protocols. The explanation of each protocol is in chronological order.

B.1 HTTP

The Hypertext Transfer Protocol (HTTP) emerged in 1991 for the World Wide Web. It is based on the client-server model and runs on top of the Transmission Control Protocol (TCP). The size of the header and message depends on the web server or programming technology (Naik, 2017). Unlike MQTT, HTTP is power inefficient and lacks QoS. Despite its popularity, HTTP's slow performance and large memory footprint makes it unsuitable for IoT environments (Naik, 2017).

B.2 XMPP

XMPP was introduced in 1999, and designed originally for instant messaging. However, it has also been used as a pub/sub messaging protocol for IoT. XMPP runs on top of TCP and is standardized by the Internet Engineering Task Force (IETF) [1]. An advantage of XMPP is its built-in support for Transport Layer Security (TLS), offering more security by default. Unlike MQTT, XMPP lacks levels of QoS, being less flexible and more prone to packet loss in unreliable networks as a result (Dizdarević *et al.*, 2019). XMPP's message size is larger than MQTT, hindering its performance in constrained networks (Dizdarević *et al.*, 2019). In fact, a current challenge is optimizing XMPP for low-powered devices (Dizdarević *et al.*, 2019; Wang *et al.*, 2017).

[1] https://tools.ietf.org/html/rfc6120. Accessed on March 23rd, 2023

B.3 AMQP

AMQP was introduced in 2003, and also runs on top of TCP. Similar to MQTT, AMQP is standardized by the Organization for the Advancement of Structured Information Standards (OASIS) [2], and its control packets are divided into three fields. The *Frame Header* is required for every packet. However, unlike MQTT, the frame header has a size of eight bytes. The remaining two fields, *Extended Header* and *Frame Body*, are optional, and their size depends on the broker or programming technology. Despite offering three levels of QoS (Dizdarević *et al.*, 2019), AMQP's main drawback is its large code footprint, which makes it unsuitable for constrained devices (Dizdarević *et al.*, 2019). Unlike MQTT, AMQP lacks features such as Last Will and Testament, Retained Messages, and Persistent Sessions.

B.4 DDS

DDS is a publish-subscribe messaging protocol introduced in 2004 by the Object Management Group (OMG). DDS's distinguishing feature is its decentralized broker architecture (Al-Fuqaha *et al.*, 2015), which enables peer-to-peer communications between the network clients (Dizdarević *et al.*, 2019). In contrast to MQTT and AMQP, DDS offers 23 levels of QoS (Al-Fuqaha *et al.*, 2015). However, the main drawback of DDS is its high bandwidth consumption compared to MQTT (Yuang Chen and Kunz, 2016).

B.5 CoAP

The Constrained Application Protocol (CoAP) is based on the client-server model for M2M communications (Maggi *et al.*, 2018), and emerged in 2010 as a lightweight alternative to HTTP. Unlike MQTT, CoAP runs on top of the User Datagram Protocol (UDP), meaning it has low latency, but is more prone to packet loss. Message delivery is even more unreliable when considering that CoAP offers limited support for QoS. In contrast to MQTT, CoAP lacks levels of QoS, relying only on acknowledgment signals for message delivery confirmation. For added security, CoAP supports protocols such as the Datagram Transport Layer Security (DTLS) (Halabi *et al.*, 2018).

B.6 Summary

Table B.1 presents a brief comparison of IoT protocols.

Among all protocols presented in Table B.1, MQTT is the preferred choice by IoT developers because of two reasons (Eclipse Foundation, 2022). First, it is lightweight compared to traditional protocols such as HTTP. A study by Yuang Chen and Kunz (2016) further confirms that MQTT consumes less bandwidth than CoAP and DDS. Second, it can be used for real-time communication, which is appropriate for smart city applications such as home automation systems, health monitoring systems, and intelligent transportation

[2] http://docs.oasis-open.org/amqp/core/v1.0/amqp-core-overview-v1.0.html. Accessed on March 23rd, 2023

Protocol	**QoS**	**Transport**	**Fixed Header**
HTTP	No	TCP	Undefined
XMPP	No	TCP	Undefined
AMQP	3 Levels	TCP	8 Bytes
DDS	23 Levels	TCP	Undefined
CoAP	Limited	UDP	4 Bytes
MQTT	3 Levels	TCP	2 Bytes

Table B.1: *Comparison of IoT Protocols*

systems (Jaloudi, 2019). Home automation systems tend to provide better support for MQTT than XMPP and AMQP. For example, *HomeAssistant* and *Domoticz* have extensive support for MQTT; limited support for XMPP; and no support for AMQP. *HomeGear* has built-in support for MQTT; and no support for XMPP and AMQP.

It is worth noting that among all pub/sub protocols discussed in this section, MQTT is considered *the* most popular for IoT (Zeng *et al.*, 2020). Testing MQTT in depth is therefore necessary considering its popularity and benefits over its counterparts.

Appendix C

MQTT Packets

MQTT clients and brokers communicate with one another using *control packets*. The delivery of these control packets is guaranteed by specifying a QoS level. Certain control packets require a specific level of QoS to be delivered. Table C.1 presents all of MQTT's control packets.

Control Packet Type	**Description**
CONNECT	Connection request
CONNACK	Connection acknowledgment
PUBLISH	Publish a message
PUBACK	Publish acknowledgment (QoS 1 & 2)
PUBREC	Publish received (QoS 2)
PUBREL	Publish release (QoS 2)
PUBCOMP	Publish completed (QoS 2)
SUBSCRIBE	Subscribe request
SUBACK	Subscribe acknowledgment
UNSUBSCRIBE	Unsubscribe request
UNSUBACK	Unsubscribe acknowledgment
PINGREQ	Ping request
PINGRESP	Ping received
DISCONNECT	Disconnect message
AUTH	Authentication Exchange (MQTT 5)

Table C.1: *MQTT Control Packets*

C.1 Structure

An MQTT control packet is divided into three fields: the fixed header; the variable header; and the payload, as shown in Figure C.1.

- **Fixed Header**: The size of the fixed header is only two bytes, thereby enabling lightweight messaging for resource-constrained devices. The bits 7-4 of the fixed

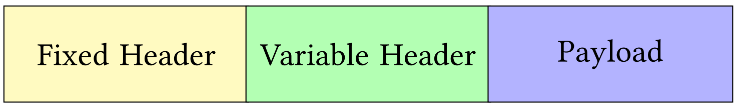


Figure C.1: *Structure of An MQTT Control Packet*

header consist of the type of packet being sent. The remaining bits (3-0) of the first byte are reserved for flags specific to each packet. For example, if a *PUBLISH* packet is sent to the broker, then the four bits are reserved for three flags: (1) duplicate messages (DUP); (2) QoS level (QoS); and (3) retained messages (RETAIN); as shown in Table C.2. All of the aforementioned features of MQTT, such as retained messages, will be further explained in the following sections. The second byte represents the number of bytes remaining, considering the variable header and the payload.

Bits	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**
Byte 1	Control Packet Type				DUP	QoS		RETAIN
Byte 2	Remaining Length							

Table C.2: *Fixed Header Format of the PUBLISH Packet*

- **Variable Header**: The variable header is optional, being absent in MQTT control packets such as *PINGREQ*, *PINGRESP*, and *DISCONNECT*. The variable header varies depending on the packet type. For example, the variable header of the *PUBLISH* packet contains the *topic length* and *topic name*, whereas the variable header of the *SUBSCRIBE* packet contains a *message identifier*.

- **Payload**: The payload is also optional, and varies depending on the packet type. For example, the payload of the *PUBLISH* packet contains the topic message that will be sent to interested subscribers. In contrast, the payload of the *CONNECT* packet contains user-related information such as the ID, username, and password.

C.2 Transmission

Figure. C.2 and C.3 present sequence diagrams of MQTT using the control packets. Both figures present different types of scenarios involving a publisher, subscriber, and broker. Figure C.2 presents interactions related to the core functionality of the pub/sub design pattern, whereas Figure C.3 presents other scenarios.

The scenarios of Figure C.2 are as follows.

1. **Connection Request:** Both the publisher and subscriber request to connect to the broker by sending a *CONNECT* packet. The broker acknowledges the connection as successful by responding with a *CONNACK* packet.

2. **Pub/sub with QoS 0:** The subscriber sends a *SUBSCRIBE* packet, specifying the topic of interest (*a*) and QoS level (0). The broker acknowledges the subscription as successful by sending a *SUBACK* packet. Afterwards, the publisher sends a message about that particular topic to the broker, which then redirects the message to the

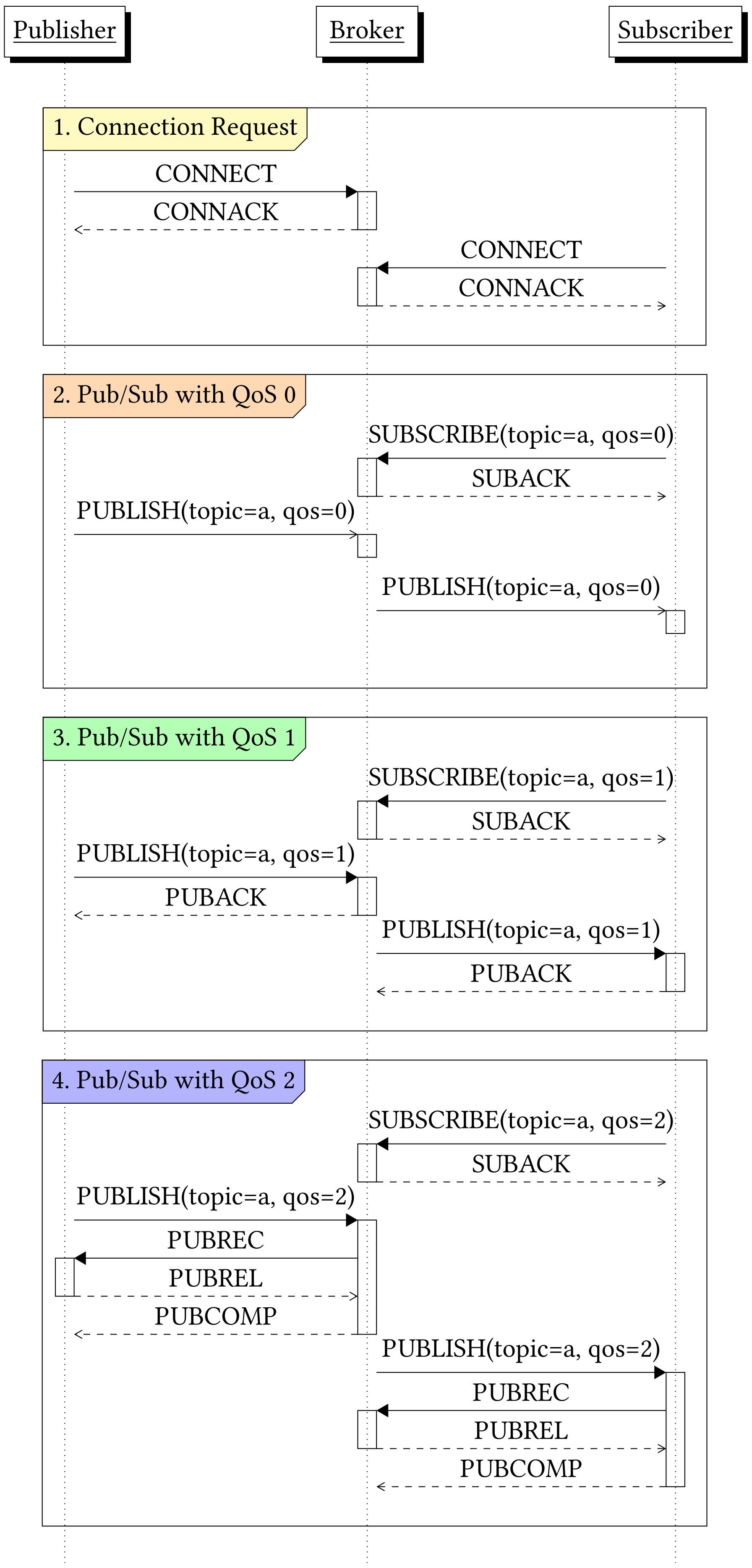


Figure C.2: *Pub/Sub Messaging Sequence on MQTT*

interested subscriber. Messages set to QoS level 0 are delivered to the subscriber *at most once*. The publisher does not receive an acknowledgment from the broker.

3. **Pub/Sub with QoS 1:** This interaction is based on messages set to QoS level 1. In such a case, messages are delivered to the subscriber *at least once* until receiving an acknowledgment from the broker (*PUBACK*).
4. **Pub/Sub with QoS 2:** If subscriptions are set to QoS level 2, then messages are delivered to subscribers *exactly once* using a four-way handshake.

The scenarios of Figure C.3 are as follows.

5. **Connection Request with AUTH (MQTT 5.0):** MQTT 5.0 supports enhanced user authentication through the use of *AUTH* packets, which can be exchanged between MQTT clients and brokers. The *AUTH* packets contain data based on the authentication method established in the *CONNECT* packet. Exchanging both *CONNECT* and *AUTH* packets adds an extra layer of security because the former only enables a basic authentication using usernames and passwords.
6. **Unsubscribe request:** MQTT clients can cancel topic subscriptions via *UNSUBSCRIBE* messages. The broker acknowledges unsubscribe requests as successful by responding with an *UNSUBACK* packet.
7. **PING utility:** Ping messages are used to verify the status of MQTT clients and brokers. Once a *PINGREQ* packet is sent out, a *PINGRESP* packet is expected. Undelivered responses could signal network connection issues.
8. **Disconnection Request:** Publishers and subscribers can close the network connection with the broker by delivering *DISCONNECT* packets.

Similar to HTTP, MQTT supports *pipelined connections*, which means that multiple requests or responses can be sent over a single transmission. Due to their asynchronous nature, MQTT messages can also be sent successively without waiting for an immediate response from the broker or clients. Figure C.4 presents an example of simultaneous and successive messages.

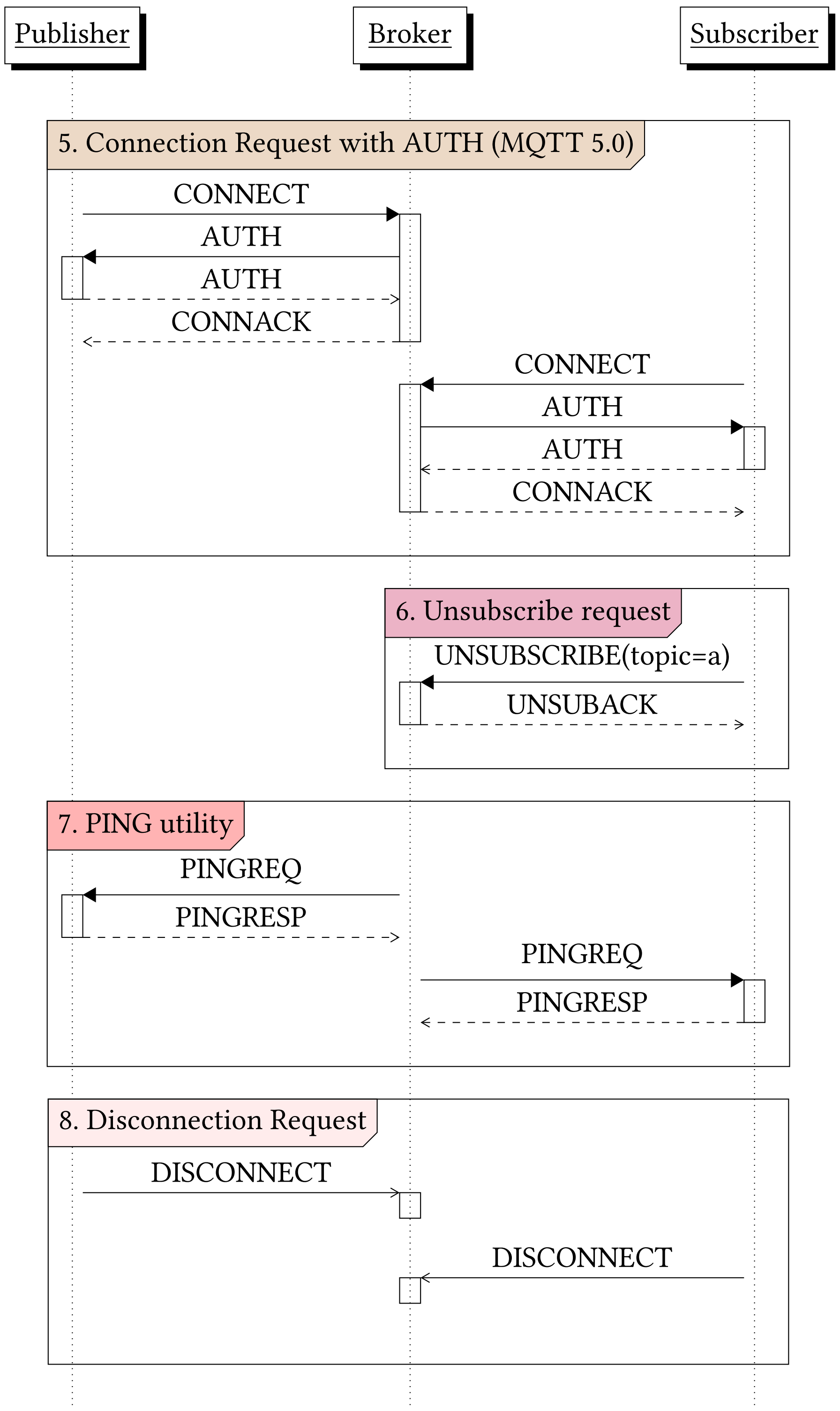


Figure C.3: *Message Sequence for AUTH, UNSUBSCRIBE, PING, and DISCONNECT Packets*

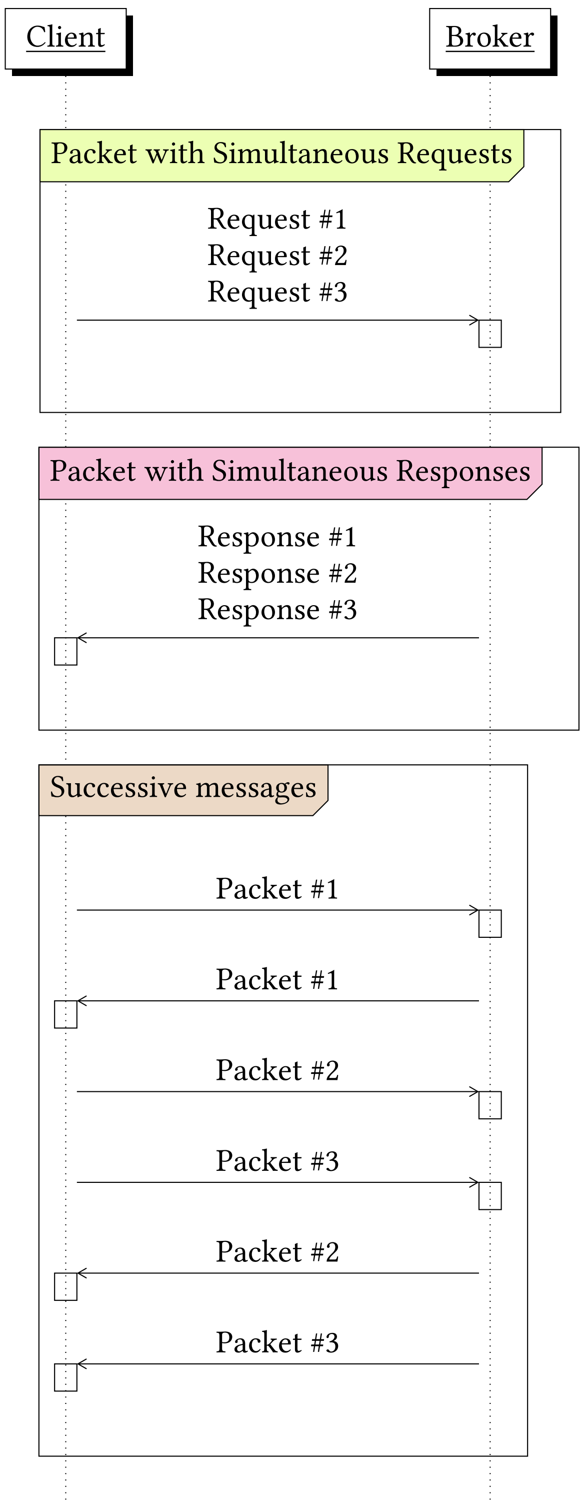


Figure C.4: *Simultaneous and Successive Messages*

Appendix D

Input Coverage of Fuzzing Techniques for the MQTT Protocol

Input coverage refers to the statement coverage achieved by an MQTT fuzzer after exchanging a specific number of packets with the broker. The input coverage achieved by all MQTT fuzzers was evaluated after exchanging 500, 1000, 2000, 4000, 6000, and 8000 packets. The input coverage of each fuzzer was evaluated because of the following reasons. First, grammar-based fuzzers are more aware of the input structure than their counterparts, making it necessary to analyze the *quality* of their test cases during the fuzzing campaign. Second, mutation-based approaches usually inject more test cases into target systems than their counterparts. This is largely due to mutation-based approaches using predefined test cases rather than generating new ones from scratch. The significant advantage of mutation-based approaches makes it necessary to measure the statement coverage after exchanging the same number of packets with the broker, thereby evaluating the fuzzers based on the quality, rather than quantity of the test cases. Third, an analysis of the input coverage will also provide a better understanding of how many packets are required by each fuzzer to execute a specific number of statements in the source code. The following sections present the input coverage by each MQTT fuzzer for Mosquitto and Moquette.

D.1 Mosquitto

Figure D.1 presents the input coverage of each MQTT fuzzer.

As expected, `fuzz()`, `learner`, and `CyberExploit` underperform because of their aforementioned shortcomings. `fuzz()` executes at most 1119 statements, and its coverage performance increases up to 0.37% during the test run. Although `learner` has higher input coverage than `fuzz()` and `CyberExploit`, its coverage performance varies the least, executing from 1793 to 1797 statements on average. The input coverage by `learner` increases up to 0.16% after exchanging 500 packets with Mosquitto. `CyberExploit` also

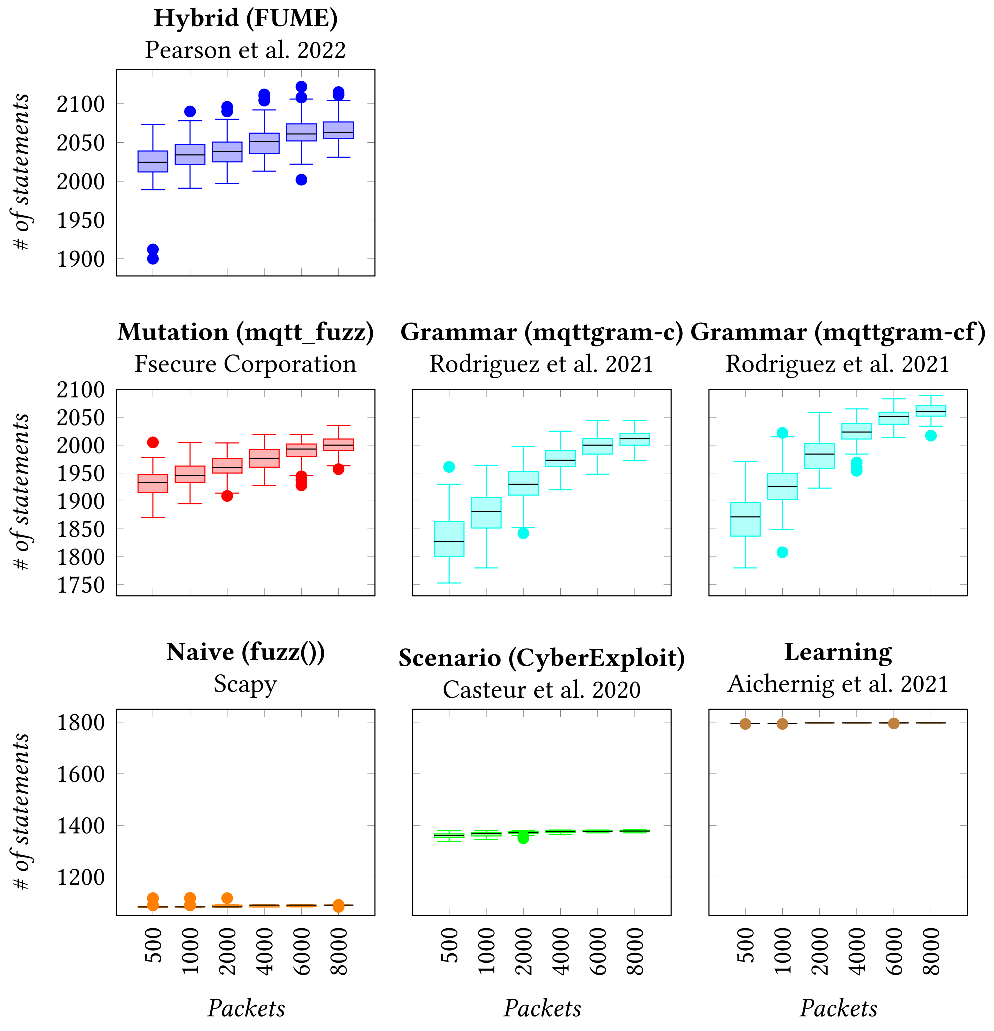


Figure D.1: *Input Coverage (Mosquitto 1.6.8)*

outperforms `fuzz()`, executing at most 1383 statements. The coverage performance by `CyberExploit` increases up to 1.39% during testing.

Among all fuzzers, `learner` increases input coverage the *least* during testing. This outcome is attributed to two main reasons. First, and as previously explained, `learner` reuses several packets and values constantly, rather than generating different test cases to execute more functionality and statements in the source code. Second, `learner` requires time to infer the message syntax and sequence of a network protocol, hindering its input coverage considerably at the beginning of the fuzzing campaign. For example, prior to exchanging 8000 packets with Mosquitto, `learner` alternates between two values for subscription topics until gaining a better understanding of the message syntax. However, regardless of the stopping criterion, `learner` struggles to execute more statements because it is currently incapable of inferring *key* features of network protocols for testing purposes.

As more packets are exchanged with the broker, the more statements are expected to be executed by an MQTT fuzzer. However, as shown in Figure D.1, the number of statements rarely increases when testing with all three aforementioned fuzzers. After exchanging 500 packets with Mosquitto, `learner` executes only three additional statements, whereas `fuzz()` and `CyberExploit` execute four and nineteen respectively. This lack of increase during testing further confirms that the test cases generated by these fuzzers are of low quality. In contrast, the techniques used by `FUME`, `mqtt_fuzz`, and `MQTTGRAM` prove to be very well aware of MQTT's specifications, generating test cases of higher quality than its counterparts. The coverage performance of these fuzzers follows expected patterns, increasing at a steady pace over time.

On average, `mqtt_fuzz` executes from 1931 to 1998 statements after exchanging 500 packets with Mosquitto. The input coverage by `mqtt_fuzz` increases up to 3.46% during the test run, peaking at 2035 statements. `mqttgram-c` outperforms the peak input coverage achieved by `mqtt_fuzz`, executing 2044 statements before 6000 packets are exchanged with Mosquitto. `mqttgram-cf` outperforms both `mqttgram-c` and `mqtt_fuzz`, executing 2089 statements before 2000 packets. The input coverage of `mqttgram-cf` and `mqttgram-c` increases by up to 10.21% and 9.78% respectively, percentages of which are the highest among all MQTT fuzzers. The performance increase of `mqttgram-c` and `mqttgram-cf` serve as an indication of the quality of their test cases. On average, `mqttgram-cf` is *slightly* outperformed by `FUME`, despite the fact that the latter supports all major versions of MQTT, whereas the former supports only 3.1.1. On average, `FUME` executes from 2024 to 2066 statements after exchanging 500 packets with Mosquitto. However, the peak input coverage achieved by `FUME` is 2122 statements, outperforming all of its counterparts. `FUME` is therefore a better option to test MQTT implementations because it executes more statements with few test cases and low bandwidth consumption.

D.2 Moquette

Figure D.2 presents the input coverage of each MQTT fuzzer.

The results follow the same pattern as in Figure D.1, with `fuzz()` and `CyberExploit` performing poorly in terms of input coverage. `fuzz()` and `CyberExploit` execute at most 545 and 986 statements respectively. `mqtt_fuzz` outperforms both `fuzz()` and `CyberExploit`, executing at most 1531 statements. On average, the input coverage by `CyberExploit`, `mqtt_fuzz`, and `fuzz()` increases up to 3.53%, 1.15%, and 0.18% respectively. These coverage performances further highlight the lack of varied and full-featured test cases by most fuzzers except for both variants of `MQTTGRAM`. In fact, the input coverage by `mqttgram-c` and `mqttgram-cf` increases up to 14.44% and 18.14% respectively after exchanging 500 packets with Moquette. In addition to their considerable performance increase during testing, `mqttgram-c` and `mqttgram-cf` achieves the highest input coverage, executing at most 1558 and 1594 statements respectively.

Table D.1 presents the fuzzers' average coverage performance after exchanging exactly 8000 packets with Moquette. However, the results by Sochor *et al.* (2020b) in Table D.1 are based on on a single 30-minute test run due to their fuzzer being proprietary. Nevertheless, in spite of the small discrepancy, results are fairly similar with those in Table 4.1. Both variants of `MQTTGRAM` outperform their counterparts when exchanging the same number of packets with Moquette.

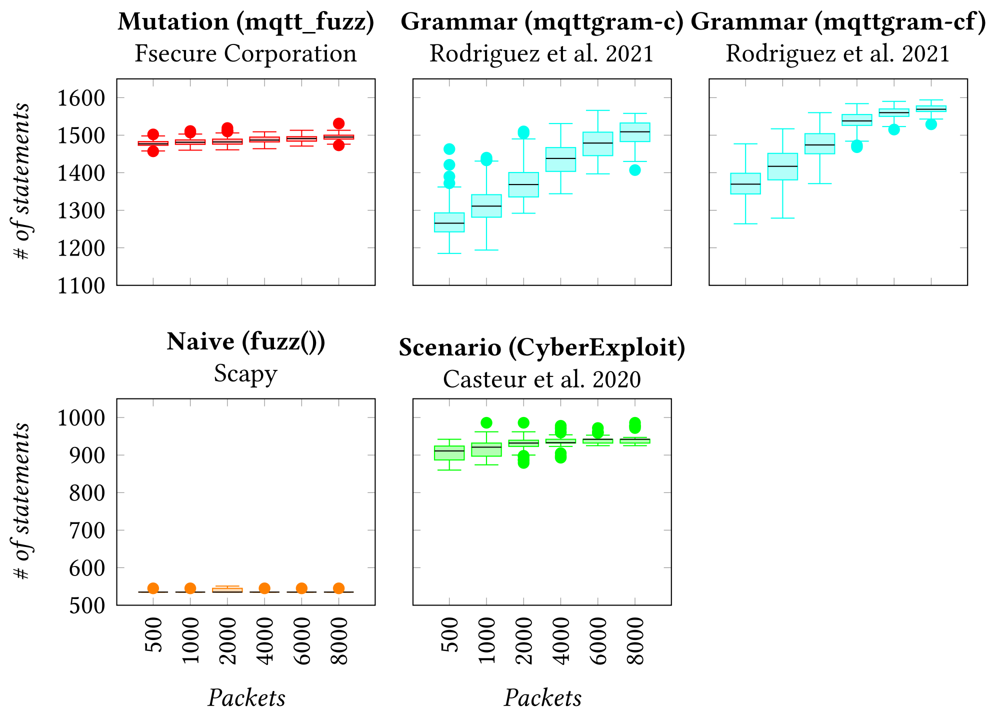


Figure D.2: *Input Coverage (Moquette 0.13)*

Source Code (Directory)	Fuzzed packets not based on existing vulnerabilities					Fuzzed packets based on existing vulnerabilities	
	Scapy	**Casteur et al. 2020**	**Sochor et al. 2020**	**mqtt_fuzz**	**mqttgram-c**	**Sochor et al. 2020**	**mqttgram-cf**
broker	21.00%	39.63%	57.80%	62.39%	**62.42%**	58.00%	**66.29%**
broker.security	12.00%	12.00%	11.30%	13.00%	**15.00%**	12.80%	**15.00%**
broker.subscriptions	8.00%	24.01%	59.00%	**71.93%**	71.65%	63.90%	**73.32%**
persistence	3.00%	3.00%	**9.10%**	9.00%	9.00%	**9.10%**	9.00%
interception	11.00%	26.00%	**32.30%**	28.00%	30.00%	**32.30%**	30.00%
broker.config	**51.00%**	51.00%	49.30%	**51.00%**	**51.00%**	49.30%	**51.00%**
broker.metrics	44.00%	68.00%	**77.50%**	71.10%	73.00%	**77.50%**	73.00%
Logging	43.00%	43.00%	**62.50%**	43.00%	43.00%	**62.50%**	43.00%
Total	19.23%	34.02%	50.00%	53.96%	**54.31%**	51.40%	**56.67%**

Table D.1: *Input Coverage of Moquette (8000 packets)*

Appendix E

Packet Exchange of Fuzzing Techniques for the MQTT Protocol

Figure E.1 presents the number of packets exchanged between the MQTT fuzzers and Mosquitto 1.6.8 in 30 minutes.

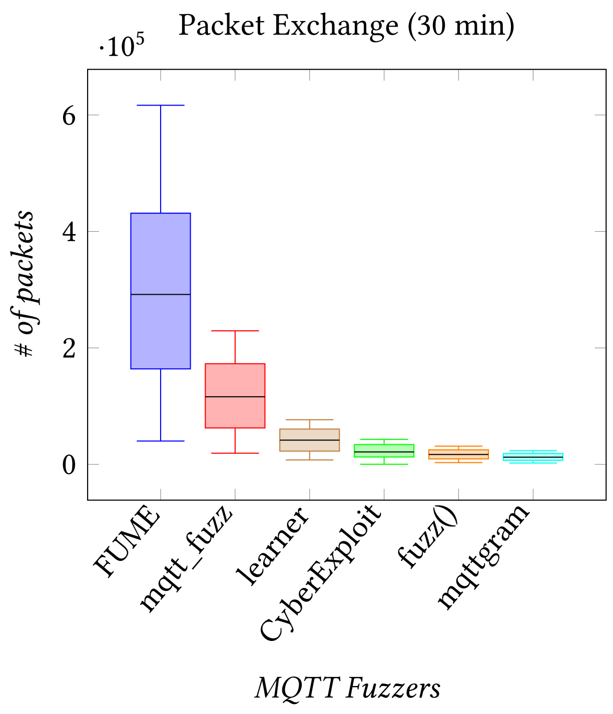


Figure E.1: *Packets Exchanged with Mosquitto 1.6.8 in 30 Minutes*

For simplicity purposes, results of `MQTTGRAM` shown in Figure E.1 are only from `mqttgram-c` because its performance is nearly identical to `mqttgram-cf`, the latter of which exchanges the *lowest* number of packets with the broker.

As shown in Figure E.1, FUME exchanges at least 2x more packets than its counterparts because of the following reasons. First, FUME performs multiple requests in a single packet due to MQTT supporting asynchronous communications. For each session, FUME sends most packets over a single TCP connection. All packets except for *CONNECT* are sent in random order to the broker. Connection requests are performed first to avoid immediate rejection by the broker. After sending multiple requests in a single packet, FUME receives a message from the broker acknowledging the connection as successful. FUME then reconnects to the broker intentionally to repeat the process until a stopping criterion is satisfied. Thus, the test run mostly consists of short-lived interactions with the broker.

mqtt_fuzz exchanges up to 9x more packets with Mosquitto than most fuzzers, except for FUME, because it slightly modifies predefined test cases rather than generating new ones from scratch. The latter approach is performed by the remaining four fuzzers shown in Figure E.1, hence their low network traffic during testing. learner exchanges more packets than the last three fuzzers because it generates smaller values for subscription topics in the test cases. CyberExploit generates subscription topics of considerable, but acceptable length. In contrast to learner and CyberExploit, fuzz() generates values of arbitrary length for several fields, including subscription topics. MQTTGRAM exchanges the fewest packets with the broker because of its *careful* generation-based approach.

In order to gain a better understanding of how quickly these fuzzers generate network packets, Figure E.2 presents the average time elapsed until exchanging 8000 packets with Mosquitto.

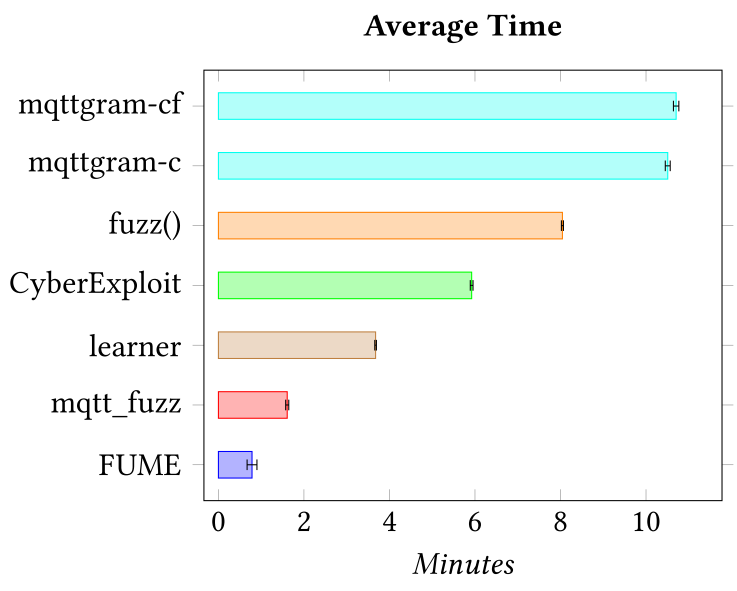


Figure E.2: *Average Time to Exchange 8000 Packets*

Developing fast packet generators brings several benefits to the testing phase, most notably frequent communications between the fuzzer and the broker. As a result, there is a higher probability of uncovering more bugs or reaching deeper states of the protocol within a short period of time. These benefits are overshadowed, however, if packets sent in rapid succession to the broker are of low quality. Thus, the effectiveness of MQTT fuzzers cannot be solely analyzed nor determined by the amount of time spent generating the necessary network packets (Figure E.2). Standardized metrics such as statement, input, and feature coverage must be analyzed alongside with Figure E.2 to determine both the effectiveness *and* efficiency of MQTT fuzzers. As expected, all variants of `MQTTGRAM` are the most time consuming because their aim is to *carefully* and *correctly* craft the network packets. More specifically, `mqttgram-cf` and `mqttgram-c` exchange 8000 packets in 642 and 630 seconds respectively. `mqttgram-cf` generates more topic-based packets than `mqttgram-c`, the task of which is time consuming due to the complexity and length of the message fields. `fuzz()` took roughly 8 minutes, whereas `CyberExploit` took 6 minutes. `CyberExploit` takes less time because it generates all the necessary network packets prior to testing an MQTT implementation. In contrast, `fuzz()` generates network packets *during* the fuzzing campaign, thereby having a longer response delay when it interacts with the broker. Furthermore, `fuzz()` assigns longer values than `CyberExploit`, resulting in larger packets that are more time consuming to generate. `learner` took slightly less than 4 minutes because of its *mapper component*, which rapidly translates abstract data into concrete data and vice versa for packet generation. The authors cited the complexity of generating MQTT packets as a motivation to develop the *mapper component*. Since the process of translating abstract data into concrete data is less complex than crafting entire packets from scratch, `learner` takes less time to exchange 8000 packets with the broker than its generation-based counterparts. `mqtt_fuzz` and `FUME` take the least amount of time, exchanging 8000 packets in approximately 1 and 2 minutes respectively. `mqtt_fuzz` is a much *simpler* (F-Secure Corporation, 2015) fuzzer than `FUME`, using only mutation-based approaches to craft the test cases. `FUME`, on the other hand, uses both mutation- and generation-based approaches, adding an extra layer of complexity to its testing capabilities. However, `FUME` takes less time to exchange 8000 packets than *mqtt_fuzz* because of its *triage algorithm*, which, according to the official repository description, uses *simple* alterations to craft the test cases. `mqtt_fuzz`, on the other hand, uses `Radamsa`, which applies various types of heuristics to modify the inputs, and can therefore take a longer time to generate the test cases.

Figure E.3 presents the number of packets exchanged with Moquette 0.13 in 30 minutes. Results are mostly similar to those achieved with Mosquitto. Unsurprisingly, `mqtt_fuzz` exchanges at least 7x, 6x, and 4x more packets than `MQTTGRAM`, `fuzz()`, and `CyberExploit` respectively. However, as explained in the previous sections, both variants of `MQTTGRAM` manage to outperform its counterparts in terms of statement coverage, despite exchanging the fewest packets with Moquette.

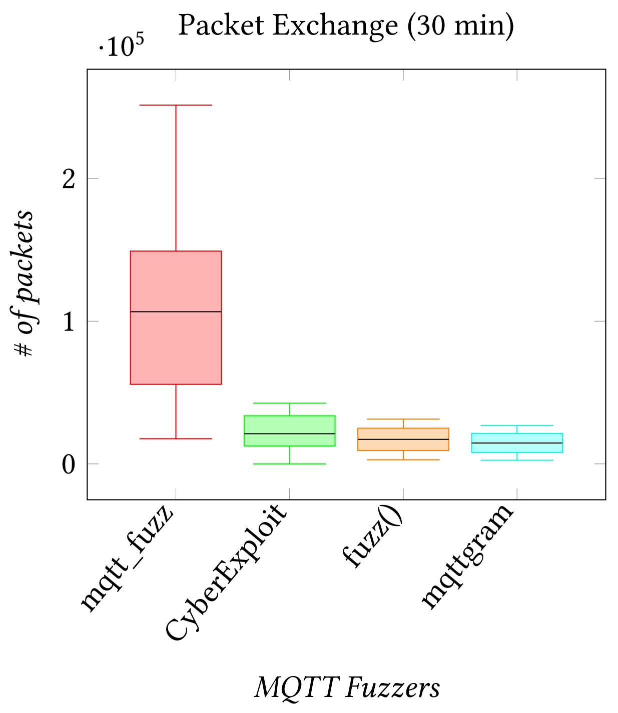


Figure E.3: *Packets Exchanged with Moquette 0.13 in 30 Minutes*

References

[Aichernig *et al.* 2021] Bernhard K. Aichernig, Edi Muškardin, and Andrea Pferscher. "Learning-Based Fuzzing of IoT Message Brokers". In: *Proceedings of the IEEE Conference on Software Testing, Verification and Validation.* 2021, pp. 47–58. doi: 10.1109/ICST49551.2021.00017 (cit. on pp. 9, 21, 24, 26, 38, 42, 44, 45, 59, 73).

[Alghamdi *et al.* 2018] Khalid Alghamdi, Ali Alqazzaz, Anyi Liu, and Hua Ming. "IoTVerif: An Automated Tool to Verify SSL/TLS Certificate Validation in Android MQTT Client Applications". In: *Proceedings of the ACM Conference on Data and Application Security and Privacy.* New York, NY, USA: Association for Computing Machinery, 2018, pp. 95–102. isbn: 9781450356329. doi: 10.1145/3176258.3176334 (cit. on p. 16).

[Aljaafari *et al.* 2020] Fatimah Aljaafari, Lucas C. Cordeiro, and Mustafa A. Mustafa. "Verifying Software Vulnerabilities in IoT Cryptographic Protocols". *CoRR* (2020). doi: 10.48550/arXiv.2001.09837 (cit. on p. 16).

[Anantharaman *et al.* 2017] P. Anantharaman, M. Locasto, G. F. Ciocarlie, and U. Lindqvist. "Building Hardened Internet-of-Things Clients with Language-Theoretic Security". In: *Proceedings of the IEEE Security and Privacy Workshops.* 2017, pp. 120–126. doi: 10.1109/SPW.2017.36 (cit. on pp. 16, 17, 21, 23, 38, 42, 44).

[Andrew Banks and Ed Briggs and Ken Borgendale and Rahul Gupta 2019] Andrew Banks and Ed Briggs and Ken Borgendale and Rahul Gupta. *MQTT Version 5.0 Oasis Standard.* https://docs.oasis-open.org/mqtt/mqtt/v5.0/mqtt-v5.0.html. [Online; accessed 22-March-2023]. 2019 (cit. on p. 40).

[Andrew Banks and Rahul Gupta 2014] Andrew Banks and Rahul Gupta. *MQTT Version 3.1.1 Oasis Standard.* http://docs.oasis-open.org/mqtt/mqtt/v3.1.1/os/mqtt-v3.1.1-os.html. [Online; accessed 22-March-2023]. 2014 (cit. on p. 27).

[Antunes *et al.* 2010] João Antunes, Nuno Neves, Miguel Correia, Paulo Verissimo, and Rui Neves. "Vulnerability discovery with attack injection". *IEEE Transactions on Software Engineering* 36.3 (2010), pp. 357–370. issn: 00985589. doi: 10.1109/TSE.2009.91 (cit. on p. 11).

[Araujo Rodriguez 2021] Luis Gustavo Araujo Rodriguez. *Adding support for version 5.0 of the MQTT protocol.* https://github.com/secdev/scapy/pull/3292. [Online; accessed 14-June-2023]. 2021 (cit. on p. 10).

[Araujo Rodriguez 2020] Luis Gustavo Araujo Rodriguez. *MQTTSubscribe now supports multiple topic subscriptions in the payload.* https://github.com/secdev/scapy/pull/2759. [Online; accessed 14-June-2023]. 2020 (cit. on p. 10).

[Araujo Rodriguez and Macêdo Batista 2020] Luis Gustavo Araujo Rodriguez and Daniel Macêdo Batista. "Program-Aware Fuzzing for MQTT Applications". In: *Proceedings of the ACM SIGSOFT International Symposium on Software Testing and Analysis.* Virtual Event, USA: Association for Computing Machinery, 2020, pp. 582–586. isbn: 9781450380089. doi: 10.1145/3395363.3402645 (cit. on pp. 2, 3, 16, 18, 22).

[Araujo Rodriguez and Macêdo Batista 2021] Luis Gustavo Araujo Rodriguez and Daniel Macêdo Batista. "Towards Improving Fuzzer Efficiency for the MQTT Protocol". In: *Proceedings of the IEEE Symposium on Computers and Communications.* 2021, pp. 1–7. doi: 10.1109/ISCC53001.2021.9631520 (cit. on pp. 3, 7, 9, 37, 42, 44, 67, 73).

[Araujo Rodriguez, Selvatici Trazzi, *et al.* 2018] Luis Gustavo Araujo Rodriguez, Julia Selvatici Trazzi, Victor Fossaluza, Rodrigo Campiolo, and Daniel Macêdo Batista. "Analysis of Vulnerability Disclosure Delays from the National Vulnerability Database". In: *Proceedings of the Workshop on CyberSecurity in Connected Devices at the Brazilian Symposium on Computer Networks and Distributed Systems.* São José dos Campos: SBC, 2018. url: https://sol.sbc.org.br/index.php/wscdc/article/view/2394 (cit. on pp. 2, 17).

[Bender *et al.* 2021] Melvin Bender, Erkin Kirdan, Marc-Oliver Pahl, and Georg Carle. "Open-Source MQTT Evaluation". In: *Proceedings of the IEEE Annual Consumer Communications & Networking Conference.* 2021, pp. 1–4. doi: 10.1109/CCNC49032.2021.9369499 (cit. on p. 73).

[Boehme *et al.* 2021] Marcel Boehme, Cristian Cadar, and Abhik Roychoudhury. "Fuzzing: Challenges and Reflections". *IEEE Software* 38.3 (2021), pp. 79–86. doi: 10.1109/MS.2020.3016773 (cit. on pp. 12, 14, 45).

[Casino *et al.* 2015] Fran Casino, Edgar Batista, Constantinos Patsakis, and Agusti Solanas. "Context-aware recommender for smart health". In: *Proceedings of the International Smart Cities Conference.* 2015, pp. 1–2. doi: 10.1109/ISC2.2015.7366176 (cit. on p. 87).

[Casteur *et al.* 2020] G. Casteur *et al.* "Fuzzing attacks for vulnerability discovery within MQTT protocol". In: *Proceedings of the International Wireless Communications and Mobile Computing.* 2020, pp. 420–425. doi: 10.1109/IWCMC48107.2020.9148320 (cit. on pp. 9, 21, 23, 25, 26, 38, 42, 44, 73, 84).

[C. Chen *et al.* 2018] Chen Chen *et al.* “A systematic review of fuzzing techniques”. *Computers & Security* 75 (2018), pp. 118–137. ISSN: 0167-4048. DOI: https://doi.org/10.1016/j.cose.2018.02.002 (cit. on p. 25).

[J. Chen *et al.* 2018] Jiongyi Chen *et al.* “IoTFuzzer: Discovering Memory Corruptions in IoT Through App-based Fuzzing”. In: *Network and Distributed Systems Security Symposium.* 2018. DOI: 10.14722/ndss.2018.23159 (cit. on pp. 11, 12, 16).

[L. Chen *et al.* 2022] Liqian Chen *et al.* “Estimating Worst-case Resource Usage by Resource-usage-aware Fuzzing”. In: *Fundamental Approaches to Software Engineering.* Cham: Springer International Publishing, 2022, pp. 92–101. ISBN: 978-3-030-99429-7. DOI: 10.1007/978-3-030-99429-7_5 (cit. on p. 73).

[Yuang Chen and Kunz 2016] Yuang Chen and Thomas Kunz. “Performance evaluation of IoT protocols under a constrained wireless access network”. In: *Proceedings of the International Conference on Selected Topics in Mobile Wireless Networking.* 2016, pp. 1–7. DOI: 10.1109/MoWNet.2016.7496622 (cit. on p. 90).

[Yurong Chen *et al.* 2019] Yurong Chen, Tian lan, and Guru Venkataramani. “Exploring Effective Fuzzing Strategies to Analyze Communication Protocols”. In: *Proceedings of the ACM Workshop on Forming an Ecosystem Around Software Transformation.* London, United Kingdom: Association for Computing Machinery, 2019, pp. 17–23. ISBN: 9781450368346. DOI: 10.1145/3338502.3359762 (cit. on pp. 14, 28, 83).

[Curiale 2014] Mauro Curiale. “From smart grids to smart city”. In: *Proceedings of the Saudi Arabia Smart Grid Conference.* 2014, pp. 1–9. DOI: 10.1109/SASG.2014.7274280 (cit. on p. 88).

[Di Paolo *et al.* 2021] Edoardo. Di Paolo, Enrico Bassetti, and Angelo Spognardi. “Security assessment of common open source MQTT brokers and clients”. In: *Proceedings of the CEUR Workshop of the Italian Conference on Cybersecurity.* 2021. URL: https://ceur-ws.org/Vol-2940/paper40.pdf (cit. on pp. 9, 21, 23, 24, 26, 34, 38, 42, 44, 54, 55, 57–59, 83, 84).

[Dizdarević *et al.* 2019] Jasenka Dizdarević, Francisco Carpio, Admela Jukan, and Xavi Masip-Bruin. “A Survey of Communication Protocols for Internet of Things and Related Challenges of Fog and Cloud Computing Integration”. *ACM Computing Surveys* 51.6 (2019), 116:1–116:29. ISSN: 0360-0300. DOI: 10.1145/3292674. URL: http://doi.acm.org/10.1145/3292674 (cit. on pp. 89, 90).

[Eceiza *et al.* 2021] Maialen Eceiza, Jose Luis Flores, and Mikel Iturbe. “Fuzzing the Internet of Things: A Review on the Techniques and Challenges for Efficient Vulnerability Discovery in Embedded Systems”. *IEEE Internet of Things Journal* 8.13 (2021), pp. 10390–10411. DOI: 10.1109/JIOT.2021.3056179 (cit. on p. 18).

[Eclipse Foundation 2018] Eclipse Foundation. *Eclipse IoT-Testware.* https://iottestware.readthedocs.io/en/development/smart_fuzzer.html. [Online; accessed 23-March-2023]. 2018 (cit. on pp. 20–22, 25, 42, 44, 85).

[Eclipse Foundation 2022] Eclipse Foundation. *The Eclipse Foundation Releases 2022 IoT & Edge Developer Survey Results.* https://newsroom.eclipse.org/news/announcements/eclipse-foundation-releases-2022-iot-edge-developer-survey-results%C2%A0. [Online; accessed 23-March-2023]. 2022 (cit. on p. 90).

[Engel 2013] Dominik Engel. "Privacy and Security Challenges in the Smart Grid User Domain". In: *Proceedings of the ACM Workshop on Information Hiding and Multimedia Security.* ACM, 2013, pp. 85–86. isbn: 978-1-4503-2081-8. doi: 10.1145/2482513.2482966. url: http://doi.acm.org/10.1145/2482513.2482966 (cit. on p. 88).

[F-Secure Corporation 2015] F-Secure Corporation. *A simple fuzzer for the MQTT protocol.* https://github.com/F-Secure/mqtt_fuzz. [Online; accessed 16-May-2023]. 2015 (cit. on pp. 20–22, 25, 42, 73, 105).

[Fehrenbach 2017] Patrik Fehrenbach. *Messaging Queues in the IoT under pressure.* https://blog.it-securityguard.com/wp-content/uploads/2017/10/IOT_Mosquitto_Pfehrenbach.pdf. [Online; accessed 16-May-2023]. 2017 (cit. on p. 73).

[Al-Fuqaha *et al.* 2015] Ala Al-Fuqaha, Mohsen Guizani, Mehdi Mohammadi, Mohammed Aledhari, and Moussa Ayyash. "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications". *IEEE Communications Surveys & Tutorials* 17.4 (2015), pp. 2347–2376. doi: 10.1109/COMST.2015.2444095 (cit. on p. 90).

[Georgi and Le Bouquin Jeannès 2017] Nawras Georgi and Régine Le Bouquin Jeannès. "Proposal of a health monitoring system for continuous care". In: *Proceedings of the International Conference on Advances in Biomedical Engineering.* 2017, pp. 1–4. doi: 10.1109/ICABME.2017.8167548 (cit. on p. 88).

[Giambona *et al.* 2018] Riccardo Giambona, Alessandro E. C. Redondi, and Matteo Cesana. "MQTT+: Enhanced Syntax and Broker Functionalities for Data Filtering, Processing and Aggregation". In: *Proceedings of the ACM International Symposium on QoS and Security for Wireless and Mobile Networks.* ACM, 2018, pp. 77–84. isbn: 978-1-4503-5963-4. doi: 10.1145/3267129.3267135. url: http://doi.acm.org/10.1145/3267129.3267135 (cit. on p. 42).

[Godefroid *et al.* 2017] Patrice Godefroid, Hila Peleg, and Rishabh Singh. "Learn&Fuzz: Machine learning for input fuzzing". In: *Proceedings of the IEEE/ACM International Conference on Automated Software Engineering.* 2017, pp. 50–59. doi: 10.1109/ASE.2017.8115618 (cit. on pp. 3, 25).

[Gopinath *et al.* 2014] Rahul Gopinath, Carlos Jensen, and Alex Groce. "Code coverage for suite evaluation by developers". In: *Proceedings of the International Conference on Software Engineering*. Hyderabad, India: Association for Computing Machinery, 2014, pp. 72–82. isbn: 9781450327565. doi: 10.1145/2568225.2568278. url: https://doi.org/10.1145/2568225.2568278 (cit. on pp. 9, 39).

[Gotkowicz and Cordeiro 2022] Maksymilian Gotkowicz and Lucas Cordeiro. "Grammar-Aware MQTT Fuzzing: A New Fuzzing Strategy for the Security Testing of MQTT Broker Applications". A Third Year Project Report for the Degree of Bachelor of Science. University of Manchester, 2022. url: https://ssvlab.github.io/lucasccordeiro/supervisions/bsc_thesis_maks.pdf (cit. on pp. 42, 44).

[Halabi *et al.* 2018] Dana Halabi, Salam Hamdan, and Sufyan Almajali. "Enhance the security in smart home applications based on IOT-CoAP protocol". In: *Proceedings of the International Conference on Digital Information, Networking, and Wireless Communications*. 2018, pp. 81–85. doi: 10.1109/DINWC.2018.8357000 (cit. on p. 90).

[Havrikov and Zeller 2019] Nikolas Havrikov and Andreas Zeller. "Systematically Covering Input Structure". In: *Proceedings of the IEEE/ACM International Conference on Automated Software Engineering*. 2019, pp. 189–199. doi: 10.1109/ASE.2019.00027 (cit. on p. 31).

[Hernández Ramos *et al.* 2018] Santiago Hernández Ramos, M. Teresa Villalba, Raquel Lacuesta, and Syed H. Ahmed. "MQTT Security: A Novel Fuzzing Approach". *Wireless Communications and Mobile Computing* 2018 (2018). issn: 1530-8669. doi: 10.1155/2018/8261746 (cit. on pp. 3, 9, 21, 22, 25, 26, 31, 38, 42, 44, 72, 73, 84, 85).

[Husnain *et al.* 2022] Muhammad Husnain *et al.* "Preventing MQTT Vulnerabilities Using IoT-Enabled Intrusion Detection System". *Sensors* 22.2 (2022). issn: 1424-8220. doi: 10.3390/s22020567 (cit. on pp. 2, 18).

[Jaloudi 2019] Samer Jaloudi. "MQTT for IoT-based Applications in Smart Cities". *Palestinian Journal of Technology and Applied Sciences* 2 (2019). [Online; accessed 22-June-2023]. url: https://web.archive.org/web/20200212031109/https://zenodo.org/record/2582892/files/1.pdf (cit. on p. 91).

[Johnsen *et al.* 2018] Frank T. Johnsen, Lars Landmark, Mariann Hauge, Erlend Larsen, and Øivind Kure. "Publish/subscribe versus a content-based approach for information dissemination". In: *Proceedings of the IEEE Military Communications Conference*. 2018, pp. 1–9. doi: 10.1109/MILCOM.2018.8599786 (cit. on p. 71).

[Khan *et al.* 2019] Imran Khan *et al.* “Healthcare Monitoring System and transforming Monitored data into Real time Clinical Feedback based on IoT using Raspberry Pi”. In: *Proceedings of the International Conference on Computing, Mathematics and Engineering Technologies.* 2019, pp. 1–6. doi: 10.1109/ICOMET.2019.8673393 (cit. on p. 88).

[Kim *et al.* 2017] Jun Young Kim, Ralph Holz, Wen Hu, and Sanjay Jha. “Automated Analysis of Secure Internet of Things Protocols”. In: *Proceedings of the Annual Computer Security Applications Conference.* Orlando, FL, USA: Association for Computing Machinery, 2017, pp. 238–249. isbn: 9781450353458. doi: 10.1145/3134600.3134624 (cit. on p. 72).

[Kitagawa *et al.* 2010] Takahisa Kitagawa, Miyuki Hanaoka, and Kenji Kono. “Asp-Fuzz: A State-Aware Protocol Fuzzer based on Application-Layer Protocols”. In: *Proceedings of the IEEE Symposium on Computers and Communications.* 2010, pp. 202–208. doi: 10.1109/ISCC.2010.5546704 (cit. on p. 28).

[Kwon *et al.* 2021] Soonhong Kwon, Sang-Jin Son, Yangseo Choi, and Jong-Hyouk Lee. “Protocol fuzzing to find security vulnerabilities of RabbitMQ”. *Concurrency and Computation: Practice and Experience* 33.23 (2021), pp. 1–14. doi: https://doi.org/10.1002/cpe.6012 (cit. on p. 22).

[J. Li *et al.* 2018] Jun Li, Bodong Zhao, and Chao Zhang. “Fuzzing: a survey”. *Cybersecurity* 1 (Dec. 2018). doi: 10.1186/s42400-018-0002-y (cit. on pp. 12, 14).

[Y. Li *et al.* 2021] Yabin Li *et al.* “Generating Highly Structured Inputs: A Survey”. In: *Proceedings of the IEEE International Conference on Data Science in Cyberspace.* 2021, pp. 466–473. doi: 10.1109/DSC53577.2021.00075 (cit. on p. 14).

[Liang *et al.* 2018] Hongliang Liang, Xiaoxiao Pei, Xiaodong Jia, Wuwei Shen, and Jian Zhang. “Fuzzing: State of the Art”. *IEEE Transactions on Reliability* 67.3 (2018), pp. 1199–1218. doi: 10.1109/TR.2018.2834476 (cit. on p. 14).

[Liljedahl 2019] Fredrik Liljedahl. “Exploring the Possibilities of Robustness Testing CoAP Implementations Using Evolutionary Fuzzing”. Master’s dissertation. KTH Royal Institute of Technology, 2019. url: https://www.diva-portal.org/smash/get/diva2:1383128/FULLTEXT01.pdf (cit. on p. 11).

[Lohokare *et al.* 2017] Jay Lohokare, Reshul Dani, Sumedh Sontakke, and Rahul Adhao. “Scalable tracking system for public buses using IoT technologies”. In: *Proceedings of the International Conference on Emerging Trends Innovation in ICT.* 2017, pp. 104–109. doi: 10.1109/ETIICT.2017.7977019 (cit. on p. 88).

[Luo *et al.* 2018] Jian-Zhen Luo, Chun Shan, Jun Cai, and Yan Liu. “IoT Application-Layer Protocol Vulnerability Detection using Reverse Engineering”. *Symmetry* 10.11 (2018), p. 561. doi: 10.3390/sym10110561 (cit. on pp. 2, 12).

[Maggi *et al.* 2018] Federico Maggi, Rainer Vosseler, and Davide Quarta. *The Fragility of Industrial IoT's Data Backbone.* [Online; accessed 22-June-2023]. Trend Micro, 2018. URL: https://documents.trendmicro.com/assets/white_papers/wp-the-fragility-of-industrial-IoTs-data-backbone.pdf (cit. on pp. 16, 87, 90).

[Makhshari and Mesbah 2021] Amir Makhshari and Ali Mesbah. "IoT Bugs and Development Challenges". In: *Proceedings of the IEEE/ACM International Conference on Software Engineering*. 2021, pp. 460–472. DOI: 10.1109/ICSE43902.2021.00051 (cit. on p. 2).

[Manès *et al.* 2019] Valentin Jean Marie Manès *et al.* "The Art, Science, and Engineering of Fuzzing: A Survey". *IEEE Transactions on Software Engineering* (2019). DOI: 10.1109/TSE.2019.2946563 (cit. on pp. 12, 14).

[Melo and Geus 2017] Bruno Melo and Paulo Geus. "Robustness Testing of CoAP Server-side Implementations through Black-box Fuzzing Techniques". In: *Proceedings of the Brazilian Symposium on Information and Computational Systems Security*. Brasília: SBC, 2017, pp. 533–540. DOI: 10.5753/sbseg.2017.19528 (cit. on p. 21).

[Michael Zalewski 2013] Michael Zalewski. *American Fuzzy Lop.* https://lcamtuf.coredump.cx/afl/. [Online; accessed 23-March-2023]. 2013 (cit. on p. 14).

[Miller *et al.* 1990] Barton P. Miller, Louis Fredriksen, and Bryan So. "An Empirical Study of the Reliability of UNIX Utilities". *Communications of the ACM* 33.12 (1990), pp. 32–44. ISSN: 0001-0782. DOI: 10.1145/96267.96279 (cit. on pp. 2, 12).

[Mishra and Kertesz 2021] Biswajeeban Mishra and Attila Kertesz. "Stress-Testing MQTT Brokers: A Comparative Analysis of Performance Measurements". *Energies* 14.18 (2021). ISSN: 1996-1073. DOI: 10.3390/en14185817 (cit. on p. 72).

[Miškuf *et al.* 2017] Martin Miškuf, Erik Kajáti, and Iveta Zolotová. "Smart metering IoT solution based on NodeMCU for more accurate energy consumption analysis". *International Journal of Internet of Things and Web Services* 2 (2017). URL: https://www.iaras.org/iaras/filedownloads/ijitws/2017/022-0017(2017).pdf (cit. on p. 88).

[MITRE Corporation 2006] MITRE Corporation. *CWE-400 Uncontrolled Resource Consumption.* https://cwe.mitre.org/data/definitions/400.html. [Online; accessed 27-September-2022]. 2006 (cit. on pp. 71, 72).

[Mladenov *et al.* 2017] Kristiyan Mladenov, Stijn Van Winsen, Chris Mavrakis, and KPMG Cyber. "Formal verification of the implementation of the MQTT protocol in IoT devices". Master's dissertation. University of Amsterdam, 2017. URL: https://rp.os3.nl/2016-2017/p42/report.pdf (cit. on p. 44).

[Morelli *et al.* 2021] Umberto Morelli, Ivan Vaccari, Silvio Ranise, and Enrico Cambiaso. “DoS Attacks in Available MQTT Implementations: Investigating the Impact on Brokers and Devices, and Supported Anti-DoS Protections”. In: *Proceedings of the International Conference on Availability, Reliability and Security.* Vienna, Austria: Association for Computing Machinery, 2021. isbn: 9781450390514. doi: 10.1145/3465481.3470049 (cit. on p. 73).

[Mrabet *et al.* 2020] Hichem Mrabet, Sana Belguith, Adeeb Alhomoud, and Abderrazak Jemai. “A Survey of IoT Security Based on a Layered Architecture of Sensing and Data Analysis”. *Sensors* 20.13 (2020). issn: 1424-8220. doi: 10.3390/s20133625 (cit. on p. 72).

[Munea, Lim, *et al.* 2016] Tewodros Legesse Munea, Hyunwoo Lim, and Taeshik Shon. “Network Protocol Fuzz Testing for Information Systems and Applications: a Survey and Taxonomy”. *Multimedia Tools and Applications* 75.22 (2016), pp. 14745–14757. doi: https://doi.org/10.1007/s11042-015-2763-6 (cit. on pp. 2, 12, 14).

[Munea, Luk Kim, *et al.* 2017] Tewodros Legesse Munea, I. Luk Kim, and Taeshik Shon. “Design and Implementation of Fuzzing Framework Based on IoT Applications”. *Wireless Personal Communications* 93.2 (2017), pp. 365–382. issn: 1572834X. doi: 10.1007/s11277-016-3322-9 (cit. on pp. 2, 12).

[Naik 2017] Nitin Naik. “Choice of effective messaging protocols for IoT systems: MQTT, CoAP, AMQP and HTTP”. In: *Proceedings of the IEEE International Systems Engineering Symposium.* 2017, pp. 1–7. doi: 10.1109/SysEng.2017.8088251 (cit. on p. 89).

[Natella and Pham 2021] Roberto Natella and Van-Thuan Pham. “ProFuzzBench: A Benchmark for Stateful Protocol Fuzzing”. In: *Proceedings of the ACM SIGSOFT International Symposium on Software Testing and Analysis.* Virtual, Denmark: Association for Computing Machinery, 2021, pp. 662–665. isbn: 9781450384599. doi: 10.1145/3460319.3469077 (cit. on p. 15).

[Newman and Al-Nemrat 2021] Benjamin Newman and Ameer Al-Nemrat. “Making the Internet of Things Sustainable: An Evidence Based Practical Approach in Finding Solutions for yet to Be Discussed Challenges in the Internet of Things”. In: *Digital Forensic Investigation of Internet of Things (IoT) Devices.* Springer International Publishing, 2021, pp. 255–285. isbn: 978-3-030-60425-7. doi: 10.1007/978-3-030-60425-7_11 (cit. on p. 18).

[Oliveira *et al.* 2019] Davi L. de Oliveira *et al.* “Performance Evaluation of MQTT Brokers in the Internet of Things for Smart Cities”. In: *Proceedings of the International Conference on Smart and Sustainable Technologies.* 2019, pp. 1–6. doi: 10.23919/SpliTech.2019.8783166 (cit. on p. 72).

[OWASP 2021] OWASP. *OWASP Top 10.* https://owasp.org/Top10/. [Online; accessed 23-March-2023]. 2021 (cit. on p. 2).

[Palmieri *et al.* 2019] Andrea Palmieri, Paolo Prem, Silvio Ranise, Umberto Morelli, and Tahir Ahmad. “MQTTSA : A Tool for Automatically Assisting the Secure Deployments of MQTT brokers”. In: *IEEE World Congress on Services*. Vol. 2642-939X. IEEE, 2019, pp. 47–53. isbn: 9781728138510. doi: 10.1109/SERVICES.2019.00023 (cit. on pp. 9, 16, 21, 22, 38, 42, 44).

[Pearson *et al.* 2022] Bryan Pearson, Yue Zhang, Cliff Zou, and Xinwen Fu. “FUME: Fuzzing Message Queuing Telemetry Transport Brokers”. In: *Proceedings of the IEEE Conference on Computer Communications*. 2022, pp. 1699–1708. doi: 10.1109/INFOCOM48880.2022.9796755 (cit. on pp. 21, 24, 26, 42, 73).

[Pham *et al.* 2020] Van-Thuan Pham, Marcel Böhme, and Abhik Roychoudhury. “AFLNET: A Greybox Fuzzer for Network Protocols”. In: *Proceedings of the IEEE International Conference on Software Testing, Validation and Verification*. 2020, pp. 460–465. doi: 10.1109/ICST46399.2020.00062 (cit. on pp. 13, 15, 22).

[Philippe Biondi and the Scapy Community 2023] Philippe Biondi and the Scapy Community. *Usage – Scapy 2.5.0 documentation – Fuzzing*. https://scapy.readthedocs.io/en/latest/usage.html#fuzzing. [Online; accessed 14-May-2023]. 2023 (cit. on pp. 20, 21, 25, 42, 73).

[Pianez *et al.* 2017] Gabriel Dornellas Pianez, Thiago Teodoro Peres, and Wânderson de Oliveira Assis. *Smart Cities Mobility - Um projeto de automação voltado para otimizaccão da logística de transporte público urbano por meio de GPS e rede de comunicação*. Tech. rep. 2017. url: https://maua.br/files/122017/smart-cities-mobility-um-projeto-automacao-voltado-para-otimizacao-logistica-transporte-publico-urbano-por-meio-gps-rede-comunicacao-261731.pdf (cit. on p. 88).

[Praveen *et al.* 2023] Meghna Praveen, Ali Raza, and Maheen Hasib. “Open-Source Security Testing Tools for IoT Protocols - MQTT and Zigbee”. In: *Proceedings of the Advances in Science and Engineering Technology International Conferences*. 2023, pp. 01–06. doi: 10.1109/ASET56582.2023.10180709 (cit. on p. 2).

[Rutke 2019] Julio Cezar Rutke. “Uma abordagem baseada em visão computacional com internet das coisas para contagem de passageiros em transporte publico urbano”. Master’s Thesis. Universidade do Estado de Santa Catarina, 2019. url: https://www.udesc.br/arquivos/cct/id_cpmenu/1024/Disserta__o_merged_comCAPA_15571594468679_1024.pdf (cit. on p. 88).

[Săndescu *et al.* 2018] Cristian Săndescu, Octavian Grigorescu, Răzvan Rughiniş, Răzvan Deaconescu, and Mihnea Calin. “Why IoT security is failing. The Need of a Test Driven Security Approach”. In: *Proceedings of the RoEduNet Conference: Networking in Education and Research*. 2018, pp. 1–6. doi: 10.1109/ROEDUNET.2018.8514135 (cit. on pp. 2, 18, 72).

[Schiefer 2015] Michael Schiefer. “Smart Home Definition and Security Threats”. In: *Proceedings of the International Conference on IT Security Incident Management IT Forensics*. 2015, pp. 114–118. doi: 10.1109/IMF.2015.17 (cit. on p. 87).

[Sharad *et al.* 2016] S. Sharad, P. Bagavathi Sivakumar, and V. Anantha Narayanan. "The smart bus for a smart city — A real-time implementation". In: *Proceedings of the IEEE International Conference on Advanced Networks and Telecommunications Systems*. 2016, pp. 1–6. doi: 10.1109/ANTS.2016.7947850 (cit. on p. 88).

[Sneha Suhitha Galiveeti and Pranitha Malae 2020] Sneha Suhitha Galiveeti and Pranitha Malae. *MQTT fuzzing using AFLNET*. https://github.com/SuhithaG/MQTT-fuzzing-using-AFLNET. [Online; accessed 23-March-2023]. 2020 (cit. on pp. 14, 15, 21, 23, 37, 42, 83).

[Sochor *et al.* 2020a] Hannes Sochor, Flavio Ferrarotti, and Rudolf Ramler. "An Architecture for Automated Security Test Case Generation for MQTT Systems". In: *Database and Expert Systems Applications*. Springer International Publishing, 2020, pp. 48–62. isbn: 978-3-030-59028-4. doi: 10.1007/978-3-030-59028-4_5 (cit. on pp. 21, 23).

[Sochor *et al.* 2020b] Hannes Sochor, Flavio Ferrarotti, and Rudolf Ramler. "Automated Security Test Generation for MQTT Using Attack Patterns". In: *Proceedings of the 15th International Conference on Availability, Reliability and Security*. Virtual Event, Ireland: Association for Computing Machinery, 2020. isbn: 9781450388337. doi: 10.1145/3407023.3407078 (cit. on pp. 3, 9, 25, 26, 31–36, 38, 42, 44, 45, 47, 50–53, 73, 84, 85, 101).

[Synopsis 2021] Synopsis. *Defensics Fuzz Testing*. https://www.synopsys.com/software-integrity/security-testing/fuzz-testing.html.. [Online; accessed 29-September-2021]. 2021 (cit. on pp. 21, 24, 42, 44).

[Tappler *et al.* 2017] Martin Tappler, Bernhard K. Aichernig, and Roderick Bloem. "Model-Based Testing IoT Communication via Active Automata Learning". In: *Proceedings of the IEEE International Conference on Software Testing, Verification and Validation*. 2017, pp. 276–287. doi: 10.1109/ICST.2017.32 (cit. on p. 44).

[Thantharate *et al.* 2019] Anurag Thantharate, Cory Beard, and Poonam Kankariya. "CoAP and MQTT Based Models to Deliver Software and Security Updates to IoT Devices over the Air". In: *Proceedings of the International Conference on Internet of Things and IEEE Green Computing and Communications and IEEE Cyber, Physical and Social Computing and IEEE Smart Data*. 2019, pp. 1065–1070. doi: 10.1109/iThings/GreenCom/CPSCom/SmartData.2019.00183 (cit. on p. 18).

[Vinzenz and Oka 2021] Nico Vinzenz and Dennis Kengo Oka. "Integrating Fuzz Testing into the Cybersecurity Validation Strategy". In: *SAE WCX Digital Summit*. SAE International, Apr. 2021. doi: https://doi.org/10.4271/2021-01-0139 (cit. on p. 12).

[Wang *et al.* 2017] Heng Wang, Daijin Xiong, Ping Wang, and Yuqiang Liu. "A Lightweight XMPP Publish/Subscribe Scheme for Resource-Constrained IoT Devices". *IEEE Access* 5 (2017), pp. 16393–16405. doi: 10.1109/ACCESS.2017.2742020 (cit. on p. 89).

[Wen *et al.* 2020] Cheng Wen *et al.* “MEMLOCK: Memory Usage Guided Fuzzing”. In: *2020 IEEE/ACM 42nd International Conference on Software Engineering (ICSE)*. 2020, pp. 765–777. doi: 10.1145/3377811.3380396 (cit. on p. 73).

[Yi *et al.* 2016] Ding Yi, Fan Binwen, Kong Xiaoming, and Ma Qianqian. “Design and implementation of mobile health monitoring system based on MQTT protocol”. In: *Proceedings of the IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference*. 2016, pp. 1679–1682. doi: 10.1109/IMCEC.2016.7867503 (cit. on p. 88).

[Zaddach *et al.* 2014] Jonas Zaddach, Luca Bruno, Aurélien Francillon, and Davide Balzarotti. “Avatar: a framework to support dynamic security analysis of embedded systems’ firmwares”. In: *Proceedings of the Network and Distributed System Security Symposium*. 2014. doi: 10.14722/NDSS.2014.23229 (cit. on p. 11).

[Zanella *et al.* 2014] Andrea Zanella, Nicola Bui, Angelo Castellani, Lorenzo Vangelista, and Michele Zorzi. “Internet of Things for Smart Cities”. *IEEE Internet of Things Journal* 1.1 (2014), pp. 22–32. doi: 10.1109/JIOT.2014.2306328 (cit. on p. 1).

[Zeller *et al.* 2020] Andreas Zeller, Rahul Gopinath, Marcel Böhme, Gordon Fraser, and Christian Holler. “Fuzzing with Grammars”. In: *The Fuzzing Book*. [Online; accessed 12-June-2023]. CISPA Helmholtz Center for Information Security, 2020. url: https://www.fuzzingbook.org/html/Grammars.html (cit. on p. 28).

[Zeng *et al.* 2020] Yingpei Zeng *et al.* “MultiFuzz: A Coverage-Based Multiparty-Protocol Fuzzer for IoT Publish/Subscribe Protocols”. *Sensors* 20.18 (2020). issn: 1424-8220. doi: 10.3390/s20185194. url: https://www.mdpi.com/1424-8220/20/18/5194 (cit. on pp. 3, 9, 14–16, 21, 22, 26, 37, 38, 42, 44, 83, 91).

[Zhao 2020] Danyang Zhao. “Fuzzing Technique in Web Applications and Beyond”. 1678 (2020), p. 012109. doi: 10.1088/1742-6596/1678/1/012109. url: https://doi.org/10.1088/1742-6596/1678/1/012109 (cit. on p. 14).

[Zhu *et al.* 2022] Xiaogang Zhu, Sheng Wen, Seyit Camtepe, and Yang Xiang. “Fuzzing: A Survey for Roadmap”. *ACM Computing. Surverys* 54.11s (2022). issn: 0360-0300. doi: 10.1145/3512345. url: https://doi.org/10.1145/3512345 (cit. on p. 14).