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Communication protocols form the bedrock of our interconnected world, yet vulnerabilities within their implementations pose significant security threats. Recent developments have seen a surge in fuzzing-based research dedicated to uncovering these vulnerabilities within protocol implementations. However, there still lacks a systematic overview of protocol fuzzing for answering the essential questions such as what the unique challenges are, how existing works solve them, etc. To bridge this gap, we conducted a comprehensive investigation of related works from both academia and industry. Our study includes a detailed summary of the specific challenges in protocol fuzzing, and provides a systematic categorization and overview of existing research efforts. Furthermore, we explore and discuss potential future research directions in protocol fuzzing. This survey serves as a foundational guideline for researchers and practitioners in the field.

$\label{eq:ccs} \mbox{CCS Concepts:} \bullet \mbox{General and reference} \rightarrow \mbox{Surveys and overviews}; \bullet \mbox{Networks} \rightarrow \mbox{Protocol testing and verification}; \bullet \mbox{Software and its engineering} \rightarrow \mbox{Software testing and debugging}.$

Additional Key Words and Phrases: Protocol, Fuzz Testing, Security

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1 INTRODUCTION

Communication protocols, such as TCP (Transmission Control Protocol) [16], TLS (Transport Layer Security) [40], Bluetooth [139], etc., serve as the cornerstone of communication by defining the rules for message exchange between parties. As these protocols underpin publicly accessible services, their security is paramount and the vulnerabilities contained can lead to severe consequences. A stark illustration of this is the Heartbleed vulnerability in OpenSSL, an implementation of the TLS protocol. Upon its disclosure, Heartbleed was found to affect over 17% of servers worldwide [105, 119, 155], demonstrating the extensive impact a single vulnerability can have. Moreover, recent statistical analyses signal an upward trend in high-risk software vulnerabilities within network services [62], underscoring the increasing risks to network security. Given this context, the development of automated methods to detect vulnerabilities in network protocol implementations is not just beneficial but essential for the safeguarding of modern network services.

Fuzzing, as a software testing technique, was brought to the forefront by an empirical study conducted by Miller et al. in 1990 [103]. This method involves the generation of a large number of random, mutated testcases aimed at triggering abnormal runtime behaviors within a software program. Due to its simplicity and scalability, fuzzing has proven to be highly effective at uncovering a wide array of bugs, leading to its widespread adoption [41, 82–85, 94, 176–179, 182, 184]. However, fuzzing protocol implementations, as opposed to general software like command-line tools [97, 117, 161], introduces additional challenges. These complexities are largely due to the peculiarities associated with effectively testing the intricate communication logic that protocols entail, ranging from methodological considerations to tool-specific requirements. In response to these challenges, there is a notable trend towards creating advanced fuzzing methods tailored explicitly for protocol testing [15, 18, 39, 53, 55, 89, 100, 116, 142]. Despite this progress, there still remains a significant gap in research dedicated to systematically examining the distinctive challenges inherent to this field, thoroughly summarizing the existing solutions and discussing future directions. To fill this gap, we extensively discussed and analyzed protocol fuzzing specifics in the following content of this article.

1.1 Motivation

The main motivations for this survey are as follows:

- Protocols are the essential rules that dictate how our devices and applications communicate, making them both pervasive and critically important. Because these protocols are everywhere, ensuring they are secure against potential threats is of utmost importance. Fuzzing plays a key role in finding and fixing security issues within these systems. In light of this, building the first end-to-end guide covering the overview and specifics of protocol fuzzing is highly valuable for both researchers and those in the tech industry.
- Protocol fuzzing presents unique challenges that set it apart from general application fuzzing, grounded in the intricacies of the communication protocols themselves. Firstly, there's the need to adhere to strict rules that dictate not just the structure of the messages but also the strict sequence and context in which these messages are sent and received [1, 2, 40, 126]. This makes the testing process complex as it requires an in-depth grasp of how these communication protocols operate and change over time. Secondly, protocols are built to address various attributes beyond simple message exchange. They must account for factors like timing and how multiple messages or actions can happen simultaneously, which introduces more variables into the mix when testing for security issues [68, 73, 75]. Thirdly, the widespread use of protocols across different technology levels and systems adds another layer of complexity. They are embedded everywhere, from hardware up to

Research Area Type Name					
Cubar Sagurity	Conferences	ACSAC, CCS, CODASPY, DSN, ICDCS, ICICS, NDSS, SP, USENIX, WiSec, Blackhat*, DEFCON*, RSA*			
Cyber Security Journals TDSC, TIFS		TDSC, TIFS			
System Architecture	Conferences	ASPLOS, ATC, DAC, Eurosys, Mobisys, OSDI			
System Architecture	Journals	TC			
Communication	Conferences	INFOCOM, MobiCOM, NSDI, SIGCOMM			
Communication	Journals	TMC, TNSM, TON			
Software Engineering	Conferences	ASE, FSE, ICSE, ICST, ISSTA			
sortware Engineering	Journals	TOSEM, TSE			

Table 1. Selected influentia	conferences and journals
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*: industrial conferences.

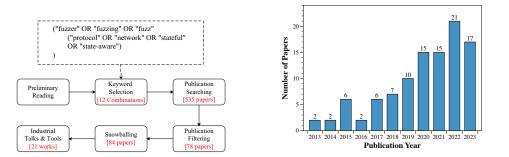


Fig. 1. Search criteria.

Fig. 2. Distribution of papers along publication years.

the software applications we interact with daily, leading to diverse testing scenarios and discovering potential vulnerabilities in every layer [46, 53, 55, 56, 91, 130, 165]. Given these realities, it becomes imperative to establish a comprehensive understanding of protocol-specific challenges.

• Many protocol fuzzing works have been completed but no systematic review on protocol fuzzing has been conducted thus far. Although some survey articles [85, 94, 185] about traditional software fuzzing are available, they cannot provide a systematic overview of the current status and future directions based on existing works solving protocol-specific challenges.

1.2 Research Questions

This survey aims to provide an overview of the protocol-specific challenges, the corresponding solutions, and the future directions. Specifically, this survey answers the following questions:

- RQ1: What are the differences between traditional fuzzing and protocol fuzzing?
- RQ2: How do existing works address the challenges in protocol fuzzing?
- **RQ3:** What are the potential future directions?

In Section 3, we provide an in-depth examination of the distinctive differences between protocols and traditional fuzzing targets to answer RQ1. Then, in Sections 4 to 6, we detail the techniques used in existing protocol fuzzers to answer RQ2. Lastly, RQ3 are discussed in Section 7.

1.3 Collection Strategy

In this survey, we focus on stateful network protocols and the various techniques that are directly related to the fuzz testing of their implementations. To collect the relevant publications, we followed

the procedures depicted in Fig. 1. First, we performed a preliminary reading and summarized 12 different keyword combinations that can be used to search related works. Then, searching these keyword combinations in Google Scholar, we collected 535 publications published from 2013 to 2023. After that, we manually filtered out the papers irrelevant to protocol fuzzing or not published in the influential publications listed in Table 1. At this time, the number of papers was reduced to 78. Note that all preprint papers were kept to remove publication bias [169]. And a paper is relevant if its key contribution is in the scope of protocol fuzzing or that paper is a bug detection tool and has picked at least one protocol implementation as its evaluation target. The latter criteria is based on the heuristic that likely a bug detection tool have proposed protocol specific techniques if it uses protocol implementations as its evaluation targets. Next, we performed snowballing and inverse snowballing to obtain a more comprehensive view. Six more papers were added in this procedure. Finally, we applied the above collection process to the released talks of several mainstream industrial security conferences such as BlackHat. 21 industrial works were added, including 18 related talks and three open-source protocol fuzzers with more than 50 stars on Github. The ascending trajectory of publications, as illustrated in Fig. 2, underscores the burgeoning research interest in protocol fuzz testing, affirming its emergence as a focal point within the field.

The rest of the paper is organized as follows. Section 2 introduces the background knowledge of protocol fuzzing. Section 3 introduces the main differences between general fuzzing targets and protocols, then summarize the major enhancements of existing protocol fuzzers. The next three sections detail the existing techniques for each key component of protocol fuzzing. Section 4 discusses the progress in input generator component. Section 5 introduces the techniques for improving the executor component. Section 6 manifests the taxonomy of oracles used in the bug detector component. Section 7 offers future directions.

2 BACKGROUND

2.1 Communication Protocols

A communication protocol is a set of rules that enables the exchange of information between two or more entities within a communication system, utilizing any form of physical quantity variation. The implementation of a communication protocol generally involves multiple phases [35]. First, the protocol is conceptually designed, which includes defining the rules, behaviors, and functions it will perform based on the protocol's needs, taking into account factors such as efficiency, reliability, scalability, and security. The outcome of the design phase is a **specifications**. Then, during the development phase, the protocol design is translated into concrete **implementations**. This can be in the form of software, hardware or a combination of both. Once developed, the protocol undergoes rigorous testing to confirm that it adheres to the protocol specifications and meets performance and reliability requirements. Among them, fuzzing, which this paper focuses on, is a commonly used technology for testing protocol implementations. Eventually, the protocol implementation will be deployed in a real-world environment.

In addition to the fundamental task of data exchange, protocols encompass a myriad of other functionalities critical to communication, introducing new layers of complexity [96]. This includes tasks such as routing, detection of transmission errors, managing timeouts and retries, confirmations, flow control, and sequence control. As a typical example, TCP (Transmission Control Protocol) [16] contains the following functionalities for guaranteeing optimal communication:

• Acknowledgment: Acknowledgment is a mechanism to confirm the receipt of data packets. This process is crucial for ensuring the reliability of data transmission, as it allows the sender to know whether the data has reached its intended destination. In TCP, when a data packet is received, the recipient sends back an acknowledgment to the sender to confirm receipt.

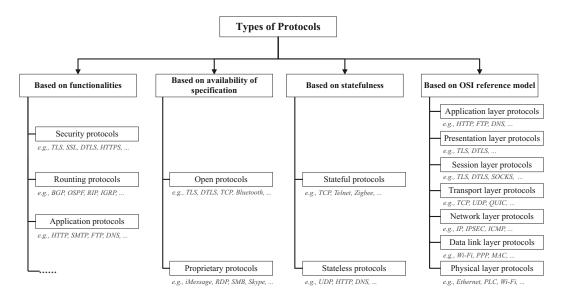


Fig. 3. Types of protocols.

- **Sequence control:** Sequence control ensures that data packets are received and processed in the order they were sent. TCP segments are sequenced with a sequence number.
- Error handling: Error handling involves detecting and correcting errors that occur during data transmission. TCP includes error-checking features. Every TCP segment contains a checksum field, which is used to check for data integrity. If a segment is found to be corrupted (*i.e.*, the data does not match the checksum), it is discarded, and TCP will handle retransmission.

Each of these functionalities embodies a set of strategies and implementations that collectively ensure the efficacy and reliability of communication protocols. The intricate integration of these functions demonstrates the sophisticated nature of protocol design and its pivotal role in modern communication systems.

2.2 Types of Protocols

Protocols can be classified from various perspectives, such as functionality, the accessibility of their specifications, and their alignment with the layers of the OSI network reference model.

From a functional standpoint, protocols exhibit a broad spectrum of varieties, each tailored to fulfill unique operational objectives. For instance, security protocols are primarily designed to ensure the integrity and confidentiality of data, exemplified by TLS [40] and DTLS (Datagram Transport Layer Security) [126]. Routing protocols, such as BGP (Border Gateway Protocol), are dedicated to efficiently managing the routes that data packets traverse across the network. Furthermore, application protocols, like HTTP (Hypertext Transfer Protocol) for web services and SMTP (Simple Mail Transfer Protocol) for email, are specialized to enable specific functionalities at the application layer.

When considering the availability of protocol specifications, a distinction is drawn between *open protocols* and *proprietary protocols*. *Open protocols*, like TCP, have publicly accessible specifications, allowing for widespread scrutiny and implementation. In contrast, *proprietary protocols* such as Microsoft's RDP (Remote Desktop Protocol) [102], are governed by individual entities, with

	General Fuzzing Targets	Protocol Implementations	
Communication Complexity	Low	High	
Testing Environment	Unconstrained	Constrained	

Table 2. Comparison between traditional fuzzing target and protocol

specifications that are not fully public. The availability of protocol specifications is crucial for various stages of fuzzing, such as crafting inputs, constructing state machines, and detecting bugs. It is important to clarify that the classification into *open* and *proprietary* pertains solely to the availability of specifications, and is independent of the accessibility of source codes for protocol implementations.

Regarding the statefulness, protocols are bifurcated into stateful and stateless categories. Stateful protocols, such as TLS [39, 142] and TCP [69], necessitate multiple interaction rounds. Stateless protocols, like UDP and HTTP, do not maintain state information across requests.

Based on the OSI network reference model, protocols can be classified into seven distinct layers: physical, data link, network, transport, session, presentation, and application. The protocol layers each solve a distinct class of communication problems. Among them, the lower-level protocols have higher coupling with physical hardware. It is pertinent to note that not every protocol aligns precisely with a single layer in the OSI model. For example, TLS/DTLS contains the functionality of the session and representation layers; the Wi-Fi protocol contains the main functionality of the physical and data link layers [2, 28]. Given varying interpretations of protocol layering in numerous sources, we categorize these protocols based on their primary functions.

3 PROTOCOL FUZZING OVERVIEW

3.1 Differences between protocol fuzzing and traditional fuzzing

In this subsection, we delve into the unique challenges associated with protocol fuzzing as identified in the literature, addressing RQ1. Table 2 encapsulates two primary distinctions between protocol implementations and general fuzzing targets. These differences not only highlight the specificities of protocol fuzzing but also correspond to a set of inherent challenges.

3.1.1 High communication complexity. The high complexity of communication can be discussed in the following two aspects.

Respecting Semantic Constraints In Communication. Protocols serve as the backbone for facilitating communication between different systems by providing a standardized set of rules for message exchange. This communication is inherently complex, often involving a multi-round process where multiple steps must be sequentially executed for the exchange to be successful. Such protocols inherently demand implementations that are stateful, with each stage of communication building upon the previous one [1, 2, 40, 126]. In testing scenarios, this means that deeper layers of the protocol implementation cannot be tested until the earlier constraints are satisfactorily met - these are the strict semantic constraints inherent in communication protocols. Semantic constraints come in two primary forms: intra-message and inter-message constraints. Intra-message constraints pertain to the structure and content of individual messages, ensuring that data fields are syntactically correct and semantically meaningful within the context of that message. Taking TCP as an example, in a TCP segment, there are several critical fields such as the source port, destination port, sequence number, acknowledgment number, data offset, and control flags (like SYN, ACK) [96]. Each of these fields must adhere to specific formats and rules. Inter-message constraints, on the other hand, govern the relationship and sequence of multiple messages, requiring that they adhere to the established protocol sequence and context for the conversation to progress [35]. For instance, the establishment of a TCP connection involves a "three-way handshake" process: the client first sends a SYN message, followed by the server responding with a SYN-ACK message, and finally, the client sends an ACK message to complete the connection. Violations of either type of constraints during communication can result in the fuzzing nonprogressive [69, 116, 142, 158, 187].

Testing Different Properties of Communication Process. Besides basic message exchange functionality, protocols need to guarantee a series of extra features that forming a more secure or reliable communication such as timing requirements, authentication, confidentiality, and concurrency[68, 73, 75]. Effectively testing these attributes in the implementation requires a more complex form of testing that goes beyond typical application fuzzing which mainly focuses on altering structured inputs to find issues [94, 185]. Each attribute may require the significant modification or even redesign of the fuzzing framework, including the developments of specialized input generator, feedback mechanisms, and oracles to facilitate effective testing [31, 56, 66, 72, 92, 99, 138, 142, 158, 187]. For instance, in the context of crafting a fuzzer aiming at detecting traffic amplification attacks within protocol implementations [78], an oracle is needed to identify disproportional request-to-response data volume ratios, indicative of an amplification factor. Concurrently, input generator needs to be adeptly redesigned to generate specific variations of protocol messages that can maximize the potential amplification factor. Moreover, the amplification factor can be used as a feedback to further enhance the search performance of fuzzing.

3.1.2 Constrained Testing Environment. Protocol fuzzing usually faces a constrained testing environment due to the tight coupling between protocols and the hardware. Firstly, numerous protocols are designed either for communications between low-level physical devices or for communications happened in specialized sectors, such as the protocols reside in the lower layers of the OSI refernce model, *i.e.*, the physical and data link layers [1, 2, 5, 28, 139], or protocols designed for specific sectors like automotive [14, 109, 189], industial control system (ICS) [21, 181], eletricity grids, and aviation systems. In these cases, the testing throughput will be limited by the hardware dependencies, such as the lack of auotmation [113, 145], the bottleneck for scalable fuzzing [21, 130], etc. Besides, these physical dependencies also limit the application of advanced fuzzing techniques. This is because many advanced fuzzing techniques require greybox or whitebox testing information from the test target, which cannot be satisfied due to the lack of program analysis frameworks on these specific hardware [133, 188, 189].

3.2 Summary of Existing Protocol Fuzzers

We have analyzed current protocol fuzzing research and encapsulated these efforts into a technical framework for protocol fuzzers, as depicted in Fig. 4. Note that the existing fuzzing works still follow the high-level concepts of general fuzzing but propose specific enhancements in these subcomponents to solve protocol-specific challenges. We first discuss the general concepts and functionalities of these components in this section, and then detail the specific enhancements existing works made in following sections (Sections 4 to 6).

A general fuzzer consists three basic components, namely input generator, executor and bug collector. In one iteration of fuzzing, **input generator** first produces a testing input to **executor**. Then **executor** executes the PUT with the given input and collects runtime information for the other two components. Finally the **bug collector** checks the runtime information to determine whether the input has triggered a bug.

Input generator. Ideally, this component is responsible for generating inputs to expose vulnerabilities inside PUTs as effective as possible. To realize this, protocol fuzzers usually implement input generator with three main subphases including communication model construction, scheduling and testcase construction. *Communication model construction* phase is responsible for learning the

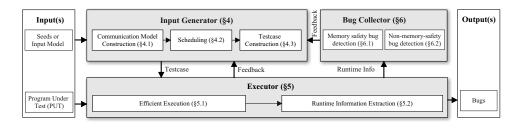


Fig. 4. Summarized Workflow of Existing Protocol Fuzzers.

semantic constraints of the protocol to provide knowledge for the other phases. With protocol domain specific knowledge, *scheduling* phase decides all the scheduling configurations used in the next iteration of input generation, with an intention to expose more bugs. *Testcase construction* phase is responsible for producing testcase according to the scheduler's instructions.

Executor. In pursuit of an ideal executor for protocol fuzzing, contemporary research has concentrated on two critical aspects: *Efficient Execution* and *Runtime Information Extraction*. The former explores the development of an efficient, automated, and scalable testing environment, enhancing the execution of protocol testing. The latter focuses on creating an analysis environment that extracts essential runtime information, thereby informing and improving the input generation and bug detection processes.

Bug collector. The primary objective of the bug collector component is to enhance both the variety of detected bug types and the accuracy of these detections. The component is finely tuned to meticulously identify a broad spectrum of vulnerabilities, ranging from *memory-safety bugs* like buffer overflows to more subtle *non-memory-safety* bugs such as logic errors and specification violation.

4 INPUT GENERATOR

In this section, we will introduce in detail how the existing works improve the input generator to solving the unique challenges in protocol fuzzing. As shown in Table 3, we summarize the techniques used by existing works in designing the three key phases in input generator. The covered works are selected from our paper set as long as their main techniques are directly related to the input generator. Besides the statistics of the mentioned three phases for these works, the table also lists their feedback information. According to Fig. 4, the feedback information can be provided by the executor or the bug collector. We only discuss how feedback information is used in input generator but leave the feedback collection related details for Section 5.2.

Years	Work	Т	Target	СМС	Scheduling	Construction Level	Feedback
2013	BED [137]		General	Manual	Sequential	Р	State
2013	Tsankov et al. [157]	•	General	Manual	-	P & S	-
2014	Peach[42]	•	General	Manual	Sequential	Р	State
2015	Pulsar[57]	•	General	TAPL	SCHS	Р	State
2015	Beurdouche et al.[18]	•	TLS	Manual	Random	S	State
2015	Ruiter et al.[39]		TLS	TAAL	Random	S	State
2016	TLS-Attacker[142]		TLS	Manual	Random	P & S	-
2016	Driller[147]	0	General	-	SPMS	Р	Code Cov
2017	Fan et al.[45]		General	TAPL	-	P & S	-

Table 3. Protocol fuzzers and their optimization solutions used in input generator.

Table 3 Protocol fuzzers and their optimization solutions used in input generator. (Continued)

Years	Table 3 Protocol fuzzo Work	T	Target	СМС	Scheduling	Construction Level	Feedback
2017	WiFuzz[158]		Wi-Fi	Manual	Sequential	P & S	-
2018	TCPWN[69]		TCP	Manual	Sequential	P & S	State
2018	IoTFuzzer[27]		IoT [107]	-	-	Р	-
2018	Danial et al.[38]		OpenVPN	Manual	Random	S	-
2018	DELTA[79]		OpenFlow	Manual	-	P & S	-
2019	SeqFuzzer[181]		ICS	TAPL	-	Р	State
2019	Polar[90]		ICS	-	SPMS	Р	Code Cov
2019	IoTHunter [171]	•	IoT	TAAL	Sequential	Р	Code Cov
2019	MoSSOT [138]		SSO[60]	Manual	Sequential	P & GUI Ops	-
2019	Chen et al. [30]		General	-	SPHS	Р	State & Code Cov
2019	Fuzzowski[128]	0	General	Manual	-	Р	State & Code Cov
2020	Walz et al.[159]		TLS	-	Random	Р	-
2020	DTLS-Fuzzer[48, 49]		DTLS	TAAL	Random	S	State
2020	AFLNET [116]	0	General	TAAL	SRHS	Р	State & Code Cov
2020	SweynTooth [56]		BLE[139]	Manual	SPHS	P & S	State & #Bugs
2020	Frankenstein [130]	0	Bluetooth	Manual	Random	P & S	State & Code Cov
2020	Peach * [91]	0	ICS	-	-	Р	Code Cov
2020	aBBRate [115]		TCP	Manual	Sequential	S	State
2020	IJON [12]	0	General	PAL	Random	Р	State & Code Cov
2020	FuSeBMC [6]	0	General	-	Sequential	Р	Code Cov
2020	DPIFuzz [124]		QUIC[67]	Manual	Random	P & S	-
2020	Zou et al.[186]		General	-	-	Р	-
2021	ICS ³ Fuzzer [46]		ICS [36, 43]	PAL	SCHS	P & GUI Ops	State
2021	StateAFL [106]	0	General	PAL	SPHS &	P	State & Code Cov
					SRHS		& # of Bugs
2021	TCP-Fuzz [187]	0	TCP	Manual	Random	P & S & Syscall	State Transition
2021	Snipuzz[47]	•	IoT	-	-	Р	-
2021	Z-Fuzzer[125]	0	Zigbee	-	-	P & Interrupt	Code Cov
2021	PAVFuzz[189]	0	AV [14]	Manual	Sequential	Р	Code Cov
2021	Aichernig et al.[4]		IoT	TAAL	-	Р	-
2017	Owfuzz[22]		Wi-Fi	Manual	-	Р	State
2022	Meng et al.[99]	0	General	Manual	PG	Р	State
2022	Greyhound[55]		Wi-Fi	Manual	SPHS	P & S	State & # of Bugs
2022	SGFuzz[15]		General	PAL	SRMS	Р	State & Code Cov
2022	Braktooth[53]	0	Bluetooth	TAAL	SPHS	Р	State Transition
2022	L2Fuzz[113]		Bluetooth	Manual	Sequential	Р	State Cov
2022	AmpFuzz[78]		UDP	-	-	Р	BAF
2022	FUME [114]	•	MQTT[107]	-	-	Р	Response Fresh- ness
2022	Garbelini et al.[54]	•	4G/5G	TAPL	-	P & S	-
2023	FeildFuzz[21]		Codesys	-	-	Р	Code Cov
2023	BLEEM[89]		General	TAAL	SRHS	P & S	State
2023	Tyr[32]	•	Blockchain	Manual	SRHS	Р	State & Code Cov
2023	CHATAFL[100]	0	General	LLM	LLM	Р	State & Code Cov
2023	EmNetTest[8]	0	General	Manual	Sequential	P & S	State
2023	DYFuzzing[7]	0	General	Manual	SPMS	P & S	Code Cov & # of
							Bugs
2023	FuzzBD[76]		USBPD	Manual	-	Р	State
2023	Mallory[101]	0	DS	TAAL	SPMS	P & S	Event Trace

○: Whitebox Fuzzer; ●: Blackbox Fuzzer; ①: Greybox Fuzzer; T: Taxonomy; CMC: Communication Model Construction; General: The fuzzer is not designed for a specific type of protocol; DS: Distributed System; PAL: Program-Analysisassisted Learning; TAAL: Traffic-Analysis-based Active Learning; TAPL: Traffic-Analysis-based Passive Learning; SRMS: State Rarity-preferred Monolithic Scheduling; SPHS: State Performance-preferred Hierarchical Scheduling; SCHS: State Complexity-preferred Hierarchical Scheduling; SPMS: State Performance-preferred Monolithic Scheduling; SRMS: State Rarity-preferred Hierarchical Scheduling; PG: Property-Guided; -: Not implemented; GUI Ops: GUI Operations; BAF: Bandwidth Amplification Factor; P: Packet level construction; S: Sequence level construction.

4.1 Communication Model Construction

To empower a traditional fuzzer with semantic constraint knowledge, most existing works model the communication as state machines or their variants to guide fuzzing. A state machine is a data structure that describes the internal state transitions of a protocol implementation. State machines are intrinsically the supergraphs of directed graphs, such as Deterministic Finite Automaton (DFA) or Mealy machine [39, 48, 55, 56, 125, 130, 142, 160]. The nodes and edges in the state machine represent the internal state of the entity and the transitions caused by receiving or sending a message, respectively. By referring to the state machine, protocol fuzzers can be aware of the current target state, and can generate testcases according to the message types that are acceptable in the current state, thereby improving the effectiveness of testcases. Note that a protocol implementation may have multiple communication models, as it may behave differently depending on its working mode or configurations. For example, a Wi-Fi device can be configured to run in AP-mode, STA-mode, or P2P-mode [22, 166] and a SIP implementation can be configured as a client, server, or proxy [110], each of them react differently to requests, thus having a different communication model. Most existing works treat these implementations running in different configurations as different targets: they construct one communication model for one given configuration.

In this section, we provide a taxonomy of the existing works based on their communication model construction methods. As shown in Fig 5, they are divided into two categories: (*i*) top-down approaches, and (*ii*) bottom-up approaches.

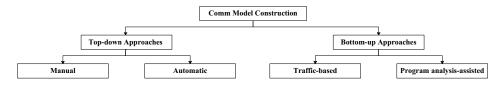


Fig. 5. Taxonomy of communication model construction techniques.

4.1.1 Top-Down Approaches. Top-down approaches construct the communication model of the protocol by learning from the textual description of the protocol, such as the specifications or documents. Top-down approaches require protocol specifications as input, thus mostly used by open protocols. Benefiting from global protocol knowledge of the specifications as well as the precisely defined states and transitions, communication models constructed by top-down approaches are relatively complete and accurate. It is worth noting that the constructed communication model may still differ from the implementation's. This is because developers may customize or extend the design described in the specification according to the practical situation. Such a difference may affect the final fuzzing performance. Methodologically, there are **manual** and **automatic** ways to construct a communication model from protocol documents.

Manual Construction (labeled as "*manual*" in Table 3 column 4): Most existing works construct a communication model manually with considerable domain expertise [7, 8, 18, 55, 56, 63, 69, 70, 77, 113, 115, 128, 130, 138, 142, 187]. For example, Garbelini *et al.* [56] and GREYHOUND [55] construct

a holistic state machine of Bluetooth Low Energy (BLE) and Wi-Fi by referring to the core design of protocol specifications [1, 2, 28, 139] to guide fuzzing. Though manually constructing a state machine is an error-prone and labor-intensive task, the benefit here is that human experts can flexibly customize (tailor or extend) the state machine to maximize its effect toward the work's goal. For example, to detect the state machine bugs caused by incorrect multiplexing between different protocol modes, e.g., different protocol versions, extensions, authentication modes, or key exchange methods, Beurdouche et al. [18] manually construct a composite state machine including all valid state transitions across protocol modes. That composite state machine is then used to generate deviant traces as testcases to discover invalid state transitions. Similarly, FuzzBD [76] is meticulously designed to accommodate the unique dual-role characteristic inherent in the USB Power Delivery (USBPD) protocol, where each device simultaneously functions as both a power source and a power sink. By integrating the state machines of these two roles, FuzzBD is capable of supporting seamless on-the-fly power role switching during the fuzzing process. Different from the above-discussed works, some works choose to learn partial information of a state machine for guidance. Zou et al. propose TCP-Fuzz, a novel approach that incorporates 15 dependency rules manually extracted from RFC documents. These rules encompass various dependencies, including packet-to-packet, syscall-to-packet, and syscall-to-syscall interactions. Utilizing these rules, TCP-Fuzz adeptly generates testcases by concurrently producing the interdependent packets and syscalls. A further exemplar is L2Fuzz [113]. The authors construct a map delineating the valid commands pertinent to each of the 19 states identified in the protocol. This mapping facilitates the generation of testcases that are specifically tailored to produce commands acceptable in the current state, thereby enhancing the relevance and effectiveness of the testing process. There are also some works addressing the problem that the communication models between the specification and implementation are not completely equal. Using heterogeneous Single-Sign-On (SSO) platforms as an example, MoSSOT [138] constructs a state machine of a regular SSO process first, then analyzes the practical SSO network traffics of different SSO platforms to learn the implementation details such as key parameters in each action. These implementation details refine the state transition conditions in the state machines of different SSO platforms.

Automatic Construction: To automate the error-prone and labor-intensive process of manual communication model construction, some works automatically retrieve semantic constraint from protocol specification [13, 111]. For example, RESTler [13] learns the message dependency relationships based on the return types from Swagger specification, which is a structural specification format describing the RESTful API endpoints, methods, parameters and return types. Pacheco *et al.* propose to use Natural Language Processing (NLP) to extract a finite state machine (FSM) from the protocol specifications [111]. Note that these two papers are not listed in Table 3 since these works are not building stateful protocol fuzzers. Another work that uses automatic state machine construction is CHATAFL [100], which leverage the emerging technology large language model to infer the current state of the target and generating suitable state transfer packets.

4.1.2 Bottom-Up Approaches. Bottom-Up approaches provide another solution for communication model reconstruction. These approaches utilize the observable information of a protocol implementation to reconstruct the communication model. Since they do not rely on textual documentation or specifications, they are suitable for proprietary protocols. Different from top-down approaches which have clear definitions of protocol states in the documents, the definitions of states in bottom-up approaches are purpose-specific and may vary among use cases, methods, and implementations. For example, AFLNET [116] determines a protocol state according to the status code of the PUT's response. Another example is StateAFL [106], which clusters the memory layout of long-lived memory as different states. From the learning source's point of view, these methods can be divided

into two categories, namely **traffic-analysis-based approaches** and **program-analysis-assisted approaches**.

Traffic-Analysis-Based approaches: The traffic-analysis-based methods focus on reconstructing the protocol communication model purely from the observed network traffic traces [39, 48, 90, 116, 162, 181]. This kind of approach is easy to operate and works well in cases that the program execution cannot be traced, *e.g.*, cannot obtain the firmware containing the target program. The traffic-analysis-based communication model construction approaches can be *passive* or *active*.

- Passive learning (labeled as "TAPL" in Table 3 column 4) methods mainly rely on a set of pre-collected network traces of the PUT with other entities to infer the communication model [45, 57, 172, 181]. The learning algorithms proposed by existing works can be divided into two categories: statistics-based and neural-network-based algorithms. For the former category, Pulsar [57] builds a second-order Markov Model by computing the probability of the occurrence of the adjacent messages in the network trace corpus and then minimizes this Markov model into a DFA. After a message has been received, Pulsar matches it to one of the states in the inferred DFA to select a valid response template for building a new testcase. For the latter category, Fan et al. [45] and SeqFuzzer[181] use LSTM to learn the grammar and temporal features of stateful protocols. Specifically, they employ LSTM as the encoder and decoder of the sequence-to-sequence (seq2seq) model [154]. Seq2seq model is an encoder-decoder model structure that can handle input and output sequences of different lengths. The encoder LSTM model learns the features of the protocol via captured network traces, while the decoder LSTM model is used to generate fuzzing inputs. Passive network trace-based state machine learning methods are easy to operate and fast-running. However, the quality of the constructed state machine depends on the coverage of captured traffics. In practice, it is hard to capture a comprehensive set of message types and sequences, causing the constructed communication model lacking part of uncaptured states or state transitions.
- Active learning (labeled as "TAAL" in Table 3 column 4) methods involve learning the communication model during the fuzzing process. These approaches can be categorized based on whether the global state set is predefined. The first category does not define the global state set in advance, *i.e.*, meaning it does not predetermine the number and nature of possible states in the state machine. This approach employs automata active learning algorithms to discern the state machine of the target. The learning algorithms rely on user-defined input/output alphabets and mappers between alphabets and concrete messages. Starting from an empty state machine, these algorithms iteratively propose and refine the model by interacting with the target protocol implementation, ceasing only when no counterexamples to the learned state machine are found. Most works in this category [4, 38, 39, 48, 49, 98, 131] utilize Angluin's L^* algorithm, defining input alphabets based on protocol specifications and translating these into actual messages using message templates. Conversely, the second category predefines the complete state set to circumvent the complexities of automata learning algorithms. Typically, this approach defines the state set through a rule-based method, learning transitions between states by mutating known messages. In essence, the potential states (nodes) of the state machine are predetermined, and the focus is on discovering and incorporating state transitions (edges). For example, AFLNET [116] uses response message status codes to determine the current protocol state, mutating real message sequences to uncover transitions. Bleem [89] utilizes the Scapy library to parse messages and abstracts them into various message types by retaining all fields of the enumeration type. This strategy is based on empirical observations from over 50 protocols supported by Scapy, where

different enumeration field values typically signify distinct packet or frame types. Bleem then uses these abstracted message traces to construct a guiding graph for fuzzing. Another instance is Braktooth [53], which defines eight rules mapping messages to states based on message characteristics. It operates as a proxy between the PUT and a standard protocol stack, mutating communications to explore additional state transitions. Similarly, Garbelini *et al.*[54] establish mapping rules to identify states and learn the state machine using capture traces (*i.e.*, pcap files).

Program-Analysis-Assisted Approaches (labeled as "PAL" in Table 3 column 4): Compared with traffic-analysis-based approaches, program-analysis-assisted approaches additionally use internal execution information to construct the communication model. In general, the internal execution information includes the results of static and dynamic program analysis, which requires not only the access to the program but also the availability of analysis frameworks such as program instrumentation tools. Based on the type of the used internal execution information, existing works can be divided into execution-trace-based and state-variable-based. Execution-Trace-Based approaches recognize different internal execution states according to the execution trace of the target. For example, ICS³Fuzzer[46] dynamically instruments the target supervisory software to collect the trace. By comparing the identity of execution traces, ICS³Fuzzer can distinguish whether the PUT is in a different state. The *state-variable-based* approaches detect protocol state transitions by tracking the value changes of state variables during input processing [15, 106, 120, 148]. These approaches are based on a simple observation that most protocol implementations use certain variables to store the current state. Therefore, they identify these variables as state variables and use their values to distinguish different states. For example, StateAFL [106] identifies possible state variables by identifying long-lived data structures in memory snapshots. Similarly, STATEINSPECTOR [148] identifies state variables by locating memory regions in heap memory that kept the same values in the execution of each message sequence. Differently, SGFuzz [15] identifies state variables through regular expressions by automatically extracting all *enum* type variables that are assigned at least once. The insight behind this approach is based on the investigation that most protocol implementations use enum-type state variables.

4.2 Task Scheduling

In the realm of recent protocol fuzzing research, the scheduling phase has been distinctly categorized based on the methodology employed for handling state-related complexities. This classification leads to two primary categories: *Hierarchical Approaches* and *Monolithic Approaches*. Hierarchical approaches decompose the scheduling process into two discrete phases: intra-state scheduling, which focuses on testing within a single state, and inter-state scheduling, which manages the transition between states. These phases are implemented separately, allowing for nuanced control over the fuzzing process. In contrast, monolithic approaches employ a single, unified scheduling phase, which integrates state-related information as a coefficient within the scheduling algorithm. Besides state-related information, many works utilize other categories of information for scheduling purposes. However, the scheduling algorithms based on these categories of information are generally universal and have been well-discussed in the literature [94, 185]. Therefore, we did not delve into detailed discussions about them.

Hierarchical Approaches. In this paradigm, the scheduler employs a two-step algorithm: (1) selection of a state for fuzzing using a state scheduling algorithm, followed by (2) application of a general scheduling algorithm to optimize fuzzing within that state. The heuristics used by the scheduling process mainly fall into three categories, namely *rarity-preferred* (SRHS in Table 3 column 5), *performance-preferred* (SPHS in Table 3 column 5), and *complexity-preferred* (SCHS

Scheduling Type	Infomation	Hierarchical	Monolithic
Rarity-preferred	State exercised times	[106, 116, 152]	[15]
Performance-preferred	Contribution to new code coverage, Contribution to new state coverage, Contribution to new bugs	[30, 55, 56, 106, 116]	-
Complexity-preferred	Count of connected basic blocks, Depth of state, Mutation opportunities	[46, 57]	-
Others	Distance from the key statement	-	[99]

Table 4. Categories of scheduling related information

in Table 3 column 5), as detailed in Table 4. Rarity-preferred heuristics allocate more resources to seldomly exercised states, hypothesizing that these states harbor more undiscovered adjacent states or code logics [19, 106, 116, 152]. Performance-preferred heuristics prioritize states demonstrating higher code coverage or bug discovery rates [30, 55, 56, 106, 116]. Additionally, some works utilize complexity-preferred heuristics, favoring states with greater complexity (*i.e.*, connected to more basic blocks) or deeper states (*i.e.*, further from the initial state) [46, 57]. For example, ICS³Fuzzer [46] inclines to choose the deeper states and those states that exercise more basic blocks. As a generation-based fuzzer, Pulsar [57] calculates the weight of all states that are reachable from the current state, and then selects the state that has the max weight to be tested next. In detail, the weight of a state is calculated as the sum of all mutable fields in a fixed number of transitions. However, as all these state selection algorithms are implemented and evaluated separately on different platforms and targets, it is hard to make a fair comparison and achieve conclusive findings. Liu et al. [87] evaluate the three existing state selection algorithms of AFLNet [116] including a rarity-preferred algorithm, an algorithm that randomly selects states, and a sequential state selection algorithm. They find that these algorithms achieved very similar results in terms of code coverage. They attribute the reasons to the coarse-grained state abstraction of AFLNET and the inaccurate estimation of the state productivity. Therefore, they propose the AFLNETLEGION algorithm [87] to address these issues, which is based on a variant of the Monte Carlo tree search algorithm [86].

Monolithic Approaches. In a monolithic manner, state-related information is calculated as a coefficient of the original scheduling algorithm used in the seed scheduling. For example, SGFuzz [15] divides the states into rare states and normal states according to the exercised times. When assigning energy to seeds, it calculates the proportion of the rare states that are exercised by each seed and adds this proportion as one of the parameters on the basis of the original power scheduling algorithm. In a similar way, SGFuzz assigns more energy to the seeds containing state transitions that correspond to the expected protocol behaviors. This is because SGFuzz expects that these valid state transitions are easier to be mutated to other invalid state transitions, thus incurring error handling logic. Similarly, LTL-Fuzzer [99] also schedules the entire seed. It prioritizes the seeds that are closer to the target code locations during the execution.

4.3 Testcase Construction

The construction strategy used in the protocol fuzzing can be categorized into *packet-level* and *sequence-level*.

4.3.1 Packet-Level Construction Strategy (labeled as "Packet" in Table 3 column 6). Packet-Level construction strategies of protocol fuzzers basically inherit the strategies of general fuzzers, such as bit flip, set zero, etc. In this paragraph, more consideration is given to the construction strategies that leverage protocol-specific characteristics for *reducing input space* or *improving the effectiveness of triggering bugs*. For the former purpose (*i.e., reducing input space*), SPIDER[80] leverages the domain-specific insight that most of the Openflow messages trigger new system events in existing SDN controllers that affect state computation and resource footprints. Based on the insight, SPIDER can

directly generate event sequences rather than generating Openflow messages, which significantly narrows down the input space. Also, L2Fuzz [113] divides the L2CAP packet format into the field that can be mutated and keeps the other fields unchanged to generate testcases that are less likely to be rejected. IPSpex [183] combines network traffic and execution traces of network packet construction to extract ICS protocol message field semantics. The strategies targeting the later purpose (*i.e., improving the effectiveness of triggering bugs*) are mostly heuristics summarized from practices. For example, EmNetTest [8] systematically generates validly constructed packets with invalid header fields or truncated headers. The insight behind this strategy is gained from a comprehensive study of 61 reported vulnerabilities in Embedded Network Stacks (ENS). Similar strategies are mentioned in many industry conference works. BadMesher [121] adopts several domain-specific strategies such as setting the length field to margin values, and randomly deleting some fields, to improve the effectiveness of triggering bugs in Wi-Fi mesh devices. Yen et al. [170] find that some strategies such as mutating the ID field to a non-existing ID, changing to port number or length field to a boundary value (e.g., 0xFF/0x00), and changing IP to some random addresses, can be quite effective in fuzzing Data Distribution Service (DDS) protocol. Similarly, BrokenMesh [167] adopts some strategies like mutating the packet count or the length field in fuzzing the Bluetooth Mesh protocol.

4.3.2 Sequence-Level Construction Strategy (labeled as "Sequence" in Table 3 column 6). Protocol fuzzers may adopt some sequence-level construction strategies. These strategies proactively construct message sequences that deviate from the regular protocol state machine, expecting to trigger more non-memory-safety bugs of the PUT. **Generation-based fuzzers** and **mutation-based fuzzers** operate differently in sequence-level construction.

- (1) **Generation-Based Fuzzers**: These fuzzers construct message sequences leveraging established protocol knowledge, such as standard state machines and inter-message dependency relationships. Notable examples include works [18, 124, 142, 158] that generate aberrant message traces by applying strategies like the addition or removal of random protocol messages to valid sequences derived from standard state machines. Projects like Sweyntooth [56], Greyhound [55], and Braktooth [53] meticulously monitor state transitions of PUT and strategically inject valid packets at incorrect states to elicit anomalies, in accordance with the state machine model. Recent research by Fiterau-Brostean *et al.*[50] proposes a novel method for detecting state machine bugs by inputting a catalogue of finite automatons which indicate certain types of state machine bugs, as well as a model of the PUT's. It can then analyze the models and produces testcases that expose the bug.
- (2) **Mutation-Based Fuzzers**: These fuzzers predominantly employ simple yet effective strategies to mutate the message sequences of seeds. This includes techniques such as packet shuffling, random insertion, or deletion. For instance, AFLNET [116] constructs message sequences by maintaining a pool of messages from network traces that can be integrated into or substituted for existing seeds. AFLNET further employs a blend of byte-level and sequencelevel operators, including replacement, insertion, duplication, and deletion of messages, to craft the message sequences. Similarly, DYFuzzing [8] mutates seeds and applies Dolev-Yao (DY) attacker strategies. Frankenstein [130] reorganizes known message sequences to enhance code coverage. He *et al.* [63] propose a unique fuzzer for the 5G non-access-stratum (NAS) protocol, which extracts packets from captures into a structured message table. This fuzzer then applies differentiated mutation strategies to various key fields, thereby significantly enhancing the intelligence and precision of the message mutation process. It is important to note that mutation-based fuzzers must judiciously manage the correlation of specific fields in message sequences, such as session numbers, counters, or timestamps. Indiscriminate

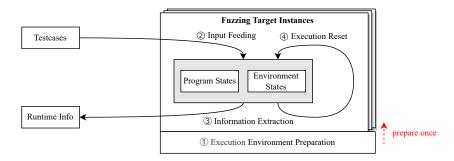


Fig. 6. Detailed workflow of executors in protocol fuzzing.

mutations in these fields could render the input ineffective and lead to early rejection. To address this challenge, AFLNET [116] modifies the code of the PUT to use a fixed session number, thereby ensuring the effectiveness of the fuzzing process.

5 EXECUTOR

In this section, we will introduce the key improvements of protocol fuzzers on the executor in detail. As shown in Fig. 6, an executor in protocol fuzzing normally includes four key processes. First, the executor needs to prepare an executable execution environment for PUT (①. Execution Environment Preparation), and then send input to PUT through the input feeding mechanism (②. Input Feeding), extract runtime information during the input processing (③. Information Extraction), and reset the execution state and environment state to a specific state after the execution of the current iteration is completed (④. Execution Reset).

In Table. 5, we summarize the key techniques and improvements in efficient execution (including (1), (2), (4)) and runtime information extraction ((3)) of the existing protocol fuzzing works. The works in the table are selected from the collection of papers because they are directly related to the executor.

5.1 Efficient Execution

In protocol fuzzing, there are commonly two directions to improve the fuzzing efficiency: 1) establishing an execution environment that enables **parallel testing** (① in Fig. 6); 2) **minimizing the execution cost** of each iteration of testing (② and ④ in Fig. 6).

5.1.1 Scalability Improvement. Scalable fuzzing, in this context, refers to the capacity to create multiple testing environments for parallel fuzzing. This is crucial in protocol fuzzing, where many fuzzing targets are closely bounded to hardware. The traditional approach for parallel testing of purchasing multiple physical devices can be economically burdensome and inefficient. For protocol fuzzing, since many fuzzing targets depend on specialized execution environments, concurrent testing of these targets can only be carried out by purchasing multiple physical devices, which leads to high economic costs and waste.

Emulation emerges as a key solution for scalable fuzzing. It offers a virtual execution environment for the PUT, reducing the dependency on specialized hardware and facilitating the creation of numerous parallel testing instances. This capability significantly enhances scalability, allowing for extensive fuzzing operations across multiple environments. Some of the protocol fuzzers leverage the existing emulation solutions to scale the fuzzing process (labeled as "*CUVM*" in Table. 5 column 4)[69, 115, 134, 138, 152].

Year	Work	Work T Target Efficient Execution						Runtime Info Extraction		
Ical	WOIK	1	Target	Env Prep	Input Feeding	Execution State Reset	Execution Env Reset	Runtime Info	Monitoring Method	
2014	Gorenc et al.[58]	٠	SMS/MMS[44]	HIL	OTA	VMSR	DR	-	-	
2017	WiFuzz [158]	٠	Wi-Fi	HIL	OTA	RM	-	State	Resp	
2018	TCPWN[69]	•	TCP	CUVM	Socket (MiTM)	-	-	State	Resp	
2019	SeqFuzzer[181]	٠	ICS	HIL	Socket (P2P)	-	-	-	-	
2019	MoSSOT[138]	•	SSO	CUVM	Socket (MiTM)	VMSR	VMSR	State	Resp	
2019	Chen et al.[30]	0	General	-	File	PSR	-	State & Code Cov	SSI	
2019	Fw-Fuzz[52]	•	General	-	Socket (P2P)	ProcR	-	Code Cov	SDI	
2019	Park et al.[112]	●	RDP[102]	-	Virtual Channels	-	-	Code Cov	SDI	
2020	Exploiting Dissent[160]	٠	TLS	-	Socket (P2P)	ProcR	-	State	Resp	
2020	DTLS-Fuzzer[48]	٠	DTLS	-	Socket (P2P)	MR	-	State	Resp	
2020	AFLNET[116]	0	General	-	Socket (P2P)	MR	UPSR	State & Code Cov	Resp & SSI	
2020	SweynTooth[56]	٠	BLE	HIL	OTA	ProcR	-	State	Resp	
2020	Frankenstein[130]	0	Bluetooth	SE	Shared memory	VMSR	-	Code Cov	SDI	
2020	Peach *[91]	0	ICS	-	Socket (P2P)	ProcR	UPSR	Code Cov	SSI	
2020	aBBRate[115]	•	TCP	CUVM	Socket (MiTM)	-	-	State	Resp	
2020	BaseSAFE[93]	0	LTE	SE	Shared-Memory	PSR	-	Code Cov	SDI	
2020	ToothPicker[64]	0	Bluetooth	HIL	FHPI	ThrdR	-	Code Cov	SDI	
2021	ICS ³ Fuzzer[46]	•	ICS	-	Socket (P2P)	ProcR	-	Exec Traces	SDI	
2021	StateAFL[106]	0	General	-	Socket (P2P)	PSR	UPSR	State & Code Cov	SSI	
2021	TCP-Fuzz[187]	Ō	TCP	-	Socket (P2P)	-	-	Branch Cov	SSI	
2021	Snipuzz[47]	•	IoT	HIL	Socket (P2P)	MR & PhyR	-	Code Cov	Resp	
2021	Z-Fuzzer[125]	0	Zigbee	SE	Socket (P2P)	ProcR	-	Code Cov	SDI	
2021	PAVFuzz[189]	Ō	AV	-	Socket (P2P)	ProcR	UPSR	Code Cov	SSI	
2021	Schepers et al.[133]	•	Wi-Fi	-	Virtual Interface	-	-	Code Cov	SSI	
2021	Wu et al.[164]	•	EV Fast Charging	HIL	CAN Bus (MiTM)	-	-	-	-	
2022	Meng et al.[99]	0	General	-	Socket (P2P)	PSR	-	Property-Guided	SSI	
2022	Greyhound[55]	0	Wi-Fi	HIL	OTA	ProcR	-	State	Resp	
2022	SGFuzz[15]	0	General	-	Shared-Memory	-	-	State & Code Cov	SSI	
2022	Braktooth [53]	0	Bluetooth	HIL	OTA	ProcR	-	State	Resp	
2022	SNPSFuzzer[81]	Ū.	General	-	Socket (P2P)	PSR	UPSR	Code Cov	SSI	
2022	Nyx-net[134]	0	General	CUVM	File	VMSR	VMSR	Code Cov	HA/SSI	
2022	SnapFuzz[9]	0	General	-	UDS	PSR	IMFR	Code Cov	SSI	
2022	AmpFuzz[78]	Ū.	UDP	-	Socket (P2P)	-	-	BAF & Code Cov	Resp & SSI	
2022	L2Fuzz[113]	•	Bluetooth L2CAP	HIL	OTA	-	-	State	Resp	
2022	Song et al.[145]	•	SOME/IP[14]	HIL	CAN Bus	-	-	State	Resp	
2022	Charon[188]	Ō	ICS	-	Socket (MiTM)	-	-	State & Code Cov	Resp & SSI	
2023	FieldFuzz[21]	•	Codesys v3	CUVM	Socket	RM	-	Code Cov	Resp	
2023	BLEEM[89]	•	General	-	Socket (MiTM)	RM	-	State	Resp	
2023	NS-Fuzz[120]	Ō	General	-	Socket (P2P)	PSR	UPSR	State & Code Cov	SSI	
2023	HNPFuzzer[51]	Õ	General	-	Shared-Memory	PSR	UPSR	State & Code Cov	Resp & SSI	

Table 5. Protocol fuzzers and their optimization of executor.

○: Whitebox Fuzzer; ●: Blackbox Fuzzer; ①: Greybox Fuzzer; T: Taxonomy; HIL: Hardware-In-the-Loop; General: The fuzzer is not designed for a specific type of protocol; CUVM: Commonly Used Virtual Machine; SE: Specialized Emulation; OTA: Over-the-air; UDS: Unix Domain Socket; MiTM: Man-in-The-Middle-based packet injection; VMSR: Virtual Machine-level Snapshot and Recovery mechanism; ProcR: Process Restart; PhyR: Physical Reset; ThrdR: Thread Restart; DR: Database Reset; PSR: Process-level Snapshot and Recovery mechanism; UPSR: User-Provided Script Reset; HA: Hardware-Assisted mechanism; EOB: Externally-Observable-Behavior-based method; SDI: Software Dynamic Instrumentation; SSI: Software Static Instrumentation; BAF: Bandwidth Amplification Factor; -: Not implemented; RM: Reset Message; IMFR: In-Memory Filesystem Reset; Resp: Resp: Responses.

However, two difficulties hinder the usage of emulation in protocol fuzzing. The first is the availability of the protocol implementation binary as many firmware images are not publicly available. Second, compared to the diversity of hardware, existing emulators can only support a small fraction of them. These difficulties lead to a lot of work still performing fuzzing in a hardware-in-the-loop way (labeled as *"HIL"* in Table. 5 column 4) [47, 55, 56, 58, 90, 113].

There are also some works addressing these issues according to the characteristics of different devices (labeled as *"SE"* in Table. 5 column 4). For the first challenge, the existing works obtain the target binaries by intercepting Over-The-Air (OTA) firmware updates, or extracting using vendor-specific command or debugging ports. For example, Frankenstein [130] leverages the *Patchram* mechanism, a Broadcom vendor-specific command that can be used to temporarily patch breakpoints to the ROM, to take the memory snapshot of a physical Bluetooth chip and emulate it in an unmodified version of QEMU. To address the second question, the existing work often uses

an approach called rehosting to partially emulate the functionality of the physical hardware. For example, BaseSafe [93] selectively rehosts several parser functions of signaling messages leveraging Unicorn engine, which is a popular CPU emulator [122].

5.1.2 Execution Cost Reduction. Another direction to improve fuzzing efficiency is to optimize the intermediate execution steps in each iteration. Below we present the progress of existing works toward this direction, which mainly focus on three sub-procedures: **input feeding** (2) in Fig. 6) and **execution reset** (④ in Fig. 6), specifically.

Input Feeding. Input feeding mechanism acts as a pipeline between the input generator and the PUT to pass the testcase to the PUT for parsing and execution. According to the Inter-Process Communication (IPC) mechanisms that the communication between Fuzzer and PUT rely on, the existing approaches can be roughly divided into four categories, namely *OTA-based*, *socket-based*, *shared-memory-based*, and *file-based* approaches. *OTA-* and *socket-based* approaches are mostly used when the fuzzer and PUT cannot be deployed on the same physical device. The latter two approaches can be used to speed up input feeding when PUT and the fuzzer can be deployed on the same device.

- *OTA-Based Input Feeding* (labeled as "*OTA*" in Table. 5 column 5). In general, OTA-based input feeding mechanisms are mostly used in the scenario of fuzzing the implementations of protocols that are typically closed in nature and tightly integrated with hardware components, such as Wi-Fi [55, 141, 158], Bluetooth (including classic Bluetooth and BLE) [53, 56, 113], LTE [93], 4G/5G [54, 63] and SMS/MMS protocols [58]. In this approach, PUT and the fuzzer need to be deployed in adjacent physical spaces and communicate with each other on specific frequency bands. Thus, OTA-based fuzzers require the use of radio-frequency transceiver devices with receive and transmit functions, such as a Software-Defined Radio (SDR), to handle signals over a wide tuning range. OTA-based fuzzing provides the capability of testing the entire protocol stack including the physical layer. However, OTA-based approaches are the slowest among the above-mentioned approaches. Therefore, many wireless protocol fuzzers try to use other input feeding mechanisms to have a better performance, which will be introduced in the following.
- Socket-Based Input Feeding (labeled as "Socket" in Table. 5 column 5). Socket-based input feeding mechanisms are mostly used in protocol implementations based on TCP/IP infrastructures. In common cases under these approaches, fuzzer and PUT communicate with each other through IP addresses, via socket mechanisms including TCP socket and UDP socket. The socket-based approaches include two deployment modes, one is point-to-point (P2P) communication between the fuzzer and PUT [9, 27, 48, 81, 99, 106, 116, 159, 187]. The fuzzer can play the role of a client or server depending on the role of the PUT. The other deployment mode is Man-in-the-middle (MiTM), in which the fuzzer acts as a proxy between two communication parties and performs mutation or injection to the normal communication traffic [69, 115]. The MiTM-based input feeding is mostly used in the scenario where the protocol involves certain contextual information (checksum, packet sequences, etc.) that cannot keep valid by mutating static seeds. However, both modes need to address two challenges. First, socket communication is quite heavy and involves lots of context switches. Existing works improve the efficiency of the socket-based input feeding mechanisms by avoiding the use of these expensive network functions. For example, SnapFuzz [9] replaces the original internet socket with UNIX domain socket [34], a lightweight IPC mechanism that does not have the routing, checksum calculation operations that IP sockets have. Second, it's hard for the fuzzer to determine whether the PUT has already finished processing the previous message and is ready to receive the next message. The PUT may reject the messages coming too early when

the target is not ready, thus causing the fuzzer to desynchronize from its state machine. To solve this issue, Fiterau-Brostean *et al.* [48] and AFLNET [116] set static time intervals to wait for the PUT to initialize, process requests, and send responses. However, static timers are too coarse-grained and can waste a lot of time waiting for the timeout, thus slowing down the fuzzing process. SnapFuzz [9] and AMPFuzz [78] develop a more fine-grained method to inspect the state of the socket. Specifically, they use the function call to related network system calls such as *recv()*, *recvfrom()* as a sign of ready to receive the next message. They monitor all these function calls through binary rewriting and compile-time code instrumentation, and then notify the fuzzer to send the next iteration of input.

- *File-Based Input Feeding* (labeled as *"File"* in Table. 5 column 5). File-based input feeding leverages static or dynamic instrumentation techniques to replace heavy network operations with file operations to achieve a performance boost. For example, Yurong *et al.* [30] transform socket communication to file operations using preloading customized libraries [175] under the circumstance that the source code of target is not available. Similarly, Nyx-net [134] injects a library into the target to hook the network functions of the target connection to obtain their associated file descriptors and injected fuzzing input to the right place.
- *Shared-Memory-Based Input Feeding* (labeled as *"Shared-Memory"* in Table. 5 column 5). Shared-Memory-Based input feeding writes the fuzzing input to the address of shared memory and hooks the related functions to read the testcase from shared memory [17, 51, 93, 130]. For example, BaseSafe [93] executes each generated testcase in a forked copy of the target process, and the input for each run is copied to the appropriate address in the corresponding child process. Similarly, Frankenstein [130] creates a virtual modem to inject custom packets. The fuzzed input are written to the receive buffer in RAM that is mapped to the hardware receive buffer using direct memory access (DMA). Also, HNPFuzzer [51] emulate network functions based on shared memory to short the time consumption due to message transmission between fuzzer and PUT.
- *Others.* There are also works that rely on specialized communication channels to feed fuzzing inputs. For example, to fuzz the client of the Remote Desktop Protocol (RDP), Park *et al.* leverage the virtual channel, an abstraction layer in RDP that is used for transporting data, to actively send fuzzing input from the server to the client [112]. Song *et al.* use a media converter to convert the traffic between Automotive Ethernet and standard Gigabit Ethernet and fuzz the SOME/IP protocol stack of the electronic control unit (ECU) [145], which is a control communication protocol between ECUs.

Execution Reset. After each iteration of execution, it is necessary to reset the PUT to a specified state and wait for the next iteration of fuzzing. This is because each testcase may affect both the internal execution states of the PUT (*e.g.*, global variables) or influence the execution environment (*e.g.*, file system, databases). Execution without reset makes the PUT behave more non-deterministicly, making it harder to reproduce the bugs. For example, when fuzzing an FTP server, a testcase may cause a file to be created under the shared folder. If the shared folder is not reset, the FTP server will report an error if the following testcase tries to create a file with the same name, which means that the same testcase results in different behavior of PUT.

The reset of execution includes three key steps, which are *reset time selection, execution state reset* and *execution environment reset*. First of all, the executor needs to judge whether the current iteration is over (*1. reset time selection*) before execution reset. After confirming that the current iteration of execution has finished, the executor needs to separately reset the runtime state of PUT (*2. execution state reset*) and its impact on the external execution environment such as the file

system and database (*3. execution environment reset*). Below we summarize the progress of existing works in these three key steps separately.

1. Reset Time Selection. The reset time selection has a significant influence on the performance of fuzzing. Early reset may cause the target to terminate when it is still doing some tasks that may be vulnerable, and late reset may affect the efficiency of the test. A common approach is to set a fixed time interval before resetting the execution. For example, AFLNET [116] allows the user to manually configure the time delays before restarting the PUT. However, this approach is relatively coarse-grained, and it is hard to determine an appropriate time interval. In order to precisely control when to reset the execution, some works use program analysis to find the location that indicates the end of the execution of an iteration, and instrument the target program to terminate at these code locations [9, 78, 120, 134]. For example, AMPFuzz [78] performs static analysis and injects termination calls to the code branches that do not contain message-sending APIs. In addition, some works choose not to perform an execution reset after each fuzzing iteration for performance boost. For example, Charon [188] leverage a program status inferring module to infer the time point at which the PUT has finished processing the packet, thereby detecting the coverage of specific inputs and avoid the need to repeatedly restart the PUT to collect feedback. Similarly, SGFuzz [15] doesn't restart the PUT in every iteration. However, it performs a post-analysis to eliminate the uon-deterministic. Specifically, it collects all the inputs on which the PUT has been executed and minimizes the input list to a minimal message sequence that can trigger the bug.

2. Execution State Reset. Execution state reset is responsible for resetting the context of the running PUT process to a specified state, including the data in registers and memory, etc. Existing execution state reset mechanisms can be divided into three categories, namely *message-based reset*, *process restart*, and *snapshot & recovery*.

Message-based reset (labeled as *"MR"* in Table. 5 column 6) operates by dispatching a specific type of message that compels the PUT to terminate the ongoing session and revert to its initial state [21, 48, 158]. For instance, when fuzzing the Wi-Fi Access Point (AP), WiFuzz use a deauthentication message to reset its state [158]. Message-based reset is easy-to-use, but it only supports a limited set of protocols as not every protocol is designed with a reset message. Moreover, it can only reset the explicit protocol state of the PUT, but the implicit state of the test target, such as the global variables, and the memory allocated but never freed, cannot be reset with this approach.

Another commonly used approach to reset the execution state is to *kill the target process and restart* (labeled as "*ProcR*" in Table. 5 column 6) [27, 46, 91]. However, it is a relatively heavy operation for fuzzing, as the restart of the program involves multiple expensive pre-processing steps, such as loading the program into memory, dynamic linking etc., resulting in inefficiencies.

The *snapshot & recovery* mechanism has been integrated into fuzzing. This approach involves checkpointing PUT at a specific runtime state and then resetting it back to that checkpoint after each fuzzing iteration. This method effectively bypasses the repeated execution of resource-intensive initialization operations, thereby enhancing fuzzing efficiency. Protocol fuzzing, in particular, derives significant benefits from snapshot technology. Protocols are predominantly stateful, implying that the input often comprises multiple prefix messages that guide the PUT to a designated state before introducing the crafted message. It's common for testcases to share the same prefix message sequences, especially when a specific state requires repeated exploration. Implementing snapshot technology in the protocol fuzzing process eliminates redundant executions associated with parsing these shared packet sequences, thereby markedly boosting fuzzing efficiency. The snapshot methodologies employed in current protocol fuzzing research can be broadly categorized into two types: *process-level snapshots* and *virtual machine-level snapshots*.

- Process-Level snapshot mechanisms (labeled as "PSR" in Table. 5 column 6) rely on system call capabilities provided by the operating system to realize their functionality. Generally, based on the APIs used, existing methods can be categorized into two types: fork-based and ptrace-based. Fork-based snapshot mechanisms are widely used in several well-known general-purpose fuzzers, including AFL[174]. Specifically, AFL inserts a piece of fork-server code into the PUT program binary, which is executed before the *main()* function. Following a signal from the AFL fuzzing side, the fork-server generates a child process via the fork()function, and this child process continues with the *main()* function. Since the fork-server has already loaded all kinds of resources, each child process only needs to execute the main function's code, thereby bypassing the costly pre-processing steps and enhancing efficiency. This mechanism has been adopted by many protocol fuzzers for state resetting [9, 51, 81, 90, 93, 106, 116, 120]. Additionally, some works have extended the original forkserver mechanism in AFL to allow for conditional multiple initializations at different code points, enabling the fuzzer to conveniently switch between various states of the protocol and thus boosting the fuzzing process [9, 30]. ptrace-based snapshot mechanisms, such as CRIU and DMTCP, leverage debugging API *ptrace()* to collect all the process context information and save it as image files [81]. In the restoration process, these snapshot mechanisms read the dumped image files and recreate the process using syscalls such as fork() or clone(). Unlike the fork-based snapshot, which requires predetermined snapshot conditions (*i.e.*, the location of the fork-server call) before execution, ptrace-based snapshots can checkpoint at any state during runtime.
- *Virtual-Machine-Level snapshot mechanisms* (labeled as "*VMSR*" in Table. 5 column 6) utilize the capabilities of virtual machine hypervisors to capture snapshots of the entire virtual machine at a specific time point, typically facilitated through a hypercall [134, 138]. When hypercalls are invoked, the program running within the virtual machine exits the VM context and transfers control to the hypervisor. Although the hypervisor-based approach is user-friendly, requiring no instrumentation, it is somewhat less efficient and more space-consuming due to its large granularity. To enhance the practicality of using virtual machine-level snapshots in protocol fuzzing, Nyx-net [134] implements an incremental snapshot approach to reduce the overhead associated with creating and removing snapshots. Specifically, Nyx-net establishes a root snapshot in a pristine state, and each execution iteration commences from this root snapshot. In subsequent fuzzing iterations, Nyx-net generates incremental snapshots based on the root snapshot following the execution of an input message. Consequently, Nyx-net has a great performance boost on the testcases that share the same prefix message sequences.

3. Execution Environment Reset. The reset of the execution environment primarily involves resetting the filesystem or database that may be affected by the PUT. Many fuzzers require users to provide a cleanup script to revert all changes [51, 81, 106, 116, 120], necessitating substantial manual effort to analyze the PUT's potential impact on the external environment. To address this issue, Snapfuzz [9] leverages a custom in-memory filesystem, wherein modifications are automatically discarded after the completion of a fuzzing iteration. Furthermore, the hypervisor-based snapshot mechanism. Besides, the hypervisor-based snapshot mechanism (VMSR in Table. 5 column 7) [134], which captures the state of the entire virtual machine, can reset both the execution state and the environment simultaneously.

5.2 Runtime Information Extraction

In general, the runtime information extraction methods used in existing works can be divided into three categories according to their generality.

Hardware-Assisted methods (labeled as "*HA*" in Table 5 column 9) capitalize on the unique capabilities inherent to certain specialized hardware devices to glean runtime information. A prime example of this method is demonstrated by Nyx-net [134], which employs Intel Processor Trace (Intel PT). This feature, unique to certain high-end Intel CPUs, allows for the detailed recording of software execution aspects, such as control flow paths, thus enabling the comprehensive collection of in-depth coverage information.

Software-Based methods leverage the capability of the software execution environment, *e.g.*, compiler, operating system, virtual machine hypervisor etc., to obtain the runtime information. Instrumentation is the most commonly used method for realizing runtime information extraction, which inserts information collection function calls into the program at specific code point. Program instrumentation can be either static (labeled as *"SSI"* in Table 5 column 9) or dynamic (labeled as *"SDI"* in Table 5 column 9) [46, 64, 112]. The former happens before the PUT runs, and can be performed at compile-time [15, 81, 90, 91, 99, 106, 116, 125, 134, 187] or by directly rewriting the binary [9]. The latter happens while the PUT is running, leveraging tools such as DynamoRIO [112] or Frida [64] to inject hooking functions at specific code points to collect runtime information.

Externally-Observable-Behavior-Based methods are the most general class of methods, as it doesn't rely on any support of the execution environment and can be used in a blackbox manner. There are various externally observable behaviors, such as the output of the program (labeled as "*Resp*" in Table 5 column 9) and the side-channel information such as power consumption and response time. The heuristics behind these observable behavior-based methods are that the differences in these behaviors can represent the PUT is under different states or having gone through different execution paths. Specifically, AFLNET [116] and Fieldfuzz [21] identify different protocol states according to the status code in the response messages. Snipuzz [47] and FUME [114] adopt a heuristic that different response messages mean different execution paths. Thus, they keep the input that can cause a different response as a seed for subsequent mutation testing, expecting to increase the coverage. Aafer *et al.* [3] use the execution logs of the Android system as a feedback to refine the input generation grammars as the developers usually add log statements to indicate the detailed information about the input validation. By observing the side channel information such as the system status, power consumption, and response time, Flowfuzz [140] determines whether the hardware switches have gone through different execution paths.

6 BUG COLLECTOR

To address the challenges in protocol fuzzing, existing works design both memory-safety bug oracles and non-memory-safety bug oracles according to various information sources.

6.1 Memory-Safety Bug Oracles

Memory-Safety bugs include stack overflow, heap overflow, Use-After-Free (UAF) etc., which can lead to crashes. Existing technologies mostly observe their running status through different channels to determine whether a memory-safety bug is triggered. From the information source point of view, there are five types of the commonly used oracles for detecting memory-safety bugs, namely process fatal signals and sanitizers, crash logs and debug information, error-signaling messages, timeout and liveness checks and abnormal physical behaviors.

6.1.1 Fatal Signals and Sanitizers. have been extensively utilized as a pivotal mechanism for bug detection in a plethora of contemporary studies [15, 90, 91, 106, 118, 125, 130, 142, 187]. Predominantly, memory-safety bugs manifest through the overwriting of data or code pointers with invalid values, leading to critical process disruptions such as segmentation faults or process terminations, thereby generating fatal signals like SIGSEGV, SIGABRT, and others. Fuzzers can

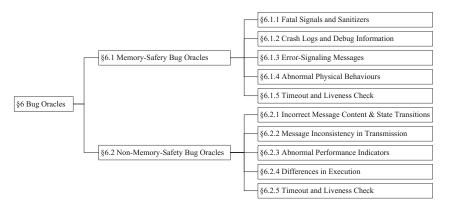


Fig. 7. Taxonomy of bug oracles in protocol fuzzing.

detect faults by checking whether the PUT process is dying from these signals. Addressing the subset of memory-safety bugs that do not immediately precipitate program crashes, fuzzers employ sanitizers. Sanitizers are bug detection tools, specifically engineered to identify and highlight unsafe or undesirable memory access patterns. Upon identifying such anomalies, sanitizers are designed to terminate the PUT, thereby signaling the presence of a potential bug [135, 136, 143, 146]. Sanitizers can be enabled at compile-time[15, 90, 91, 106, 125, 130, 142, 187] or enabled dynamically at runtime [93].

6.1.2 Crash Logs and Debug Information. Some works determine whether the PUTs are crashed by analyzing the system logs or debug information [21, 46, 53, 56, 113, 121, 163]. These system logs and debug information can be obtained by various channels. Specifically, ICS³Fuzzer leverages the Windows EventLog Service to detect crash events on Windows systems [46]. Swentooth [56] and Braktooth [53] propose to collect the startup messages or crash messages in the system logs leveraging the debug ports exposed by respective Bluetooth development boards. Startup message is an indicator of program crashes, as the Bluetooth devices have a watchdog program to reset the Bluetooth SoC when finding it is unresponsive. Wang *et al.* [163] leverage NLP technology to process the logs and detect unintended behavior of PUT. Differently, L2Fuzz [113] and FieldFuzz [21] identify crashes by checking whether a crash dump was generated.

6.1.3 Error-Signaling Messages (labeled as "ESM" in Table 6 column 5). Many protocols use special responses or status codes to indicate internal errors, therefore can be used for bug detection. For example, L2Fuzz detects Bluetooth L2CAP vulnerabilities by checking whether the packet received contains an error-signaling message such as Connection Failed, Connection Aborted, Connection Reset, and Connection Refused [113]. These error messages indicate that the PUT may be crashed. OWFuzz uses the Deauth/Disassoc frames, management frames of the Wi-Fi protocol to terminate the communication, as an indicator of anomaly during fuzzing Wi-Fi protocol stacks [22].

6.1.4 Abnormal Physical Behaviors (labeled as "APB" in Table 6 column 5). The abnormal physical behavior of the target device, *e.g.*, startup sound, can also be used as a bug oracle. For example, when fuzzing the Bluetooth sound device, Braktooth uses the event of repeated startup sound as a bug oracle [53]. This is because Bluetooth devices will be restarted by the watchdog program when an error occurs and a startup sound will be played during the booting process. Differently, PCFuzzer [88] leverages an oscilloscope to collect the physical signal of the output module to monitor the target's status.

v	Work		Tourset	Bug Detector			
Year			Target	Memory-Safety Bug Oracles	Non-Memory-Safety Bug Oracles		
2013	Tsankov et al.[157]	•	General	Sanitizer	-		
2015	Doona[95]	•	General	Fatal Signals	-		
2015	Pulsar[57]	•	General	Timeout	-		
2015	Ruiter et al.[39]	0	TLS	-	Manual		
2015	Beurdouche et al.[18]	•	TLS	Timeout	Incorrect State Transitions		
2016	TLS-Attacker[142]	•	TLS	Sanitizer	Incorrect State Transitions		
2017	WiFuzz[158]	•	Wi-Fi	Timeout	Incorrect Content & State Transitions		
2018	TCPWN[69]	•	TCP	-	Abnormal Performance Indicators		
2018	IoTFuzzer[27]	•	IoT	Liveness Check	-		
2019	SeqFuzzer[181]	•	ICS	-	Incorrect Content & State Transitions		
2019	ACT[152]	0	TCP	-	Abnormal Performance Indicators		
2019	MoSSOT[138]	•	SSO	Fatal Signals	Incorrect State Transitions		
2020	Exploiting Dissent[160]	•	TLS	-	DE		
2020	SweynTooth[56]	•	BLE	Crash Logs / Timeout	Incorrect State Transition		
2020	aBBRate[115]	•	TCP	-	Abnormal Performance Indicators		
2020	DPIFuzz[124]	•	QUIC	Sanitizer	DE		
2020	BaseSAFE[93]	0	LTE	Sanitizer	-		
2021	ICS ³ Fuzzer[46]	•	ICS	Crash Logs	-		
2021	TCP-Fuzz[187]	0	TCP	Fatal Signals	Inconsistency in Transmission & DE		
2021	Snipuzz[47]	•	IoT	Liveness Check	-		
2021	PAVFuzz[189]	0	AV	Fatal Signals	-		
2021	Aichernig et al.[4]	•	MQTT	-	DE		
2021	Roitburd et al.[127]	•	AnyConnect[33]	Liveness Check	-		
2021	Owfuzz[22]	•	Wi-Fi	Liveness Check & ESM	-		
2021	BadMesher[121]	•	Wi-Fi Mesh	Fatal Signals & Liveness Check	-		
2022	Meng et al.[99]	0	General	Fatal Signals	Incorrect State Transitions		
2022	Greyhound[55]	0	Wi-Fi	Fatal Signals / Timeout	Incorrect State Transitions		
2022	Braktooth[53]	0	General	Crash Logs & APB	-		
2022	L2Fuzz[113]	•	Bluetooth L2CAP	Crash Logs & Liveness Check & ESM	Incorrect State Transitions		
2022	AmpFuzz[78]	0	UDP	-	Abnormal Performance Indicators		
2022	BrokenMesh[167]	•	BLE Mesh	Timeout	-		
2022	PCFuzzer[88]	•	PLC	Liveness Check & APB	-		
2023	FieldFuzz[21]	•	Codesys v3	ESM & Crash Logs & Timeout	-		
2023	Tyr[32]	0	Blockchain	-	Incorrect State Transitions		
2023	LOKI[92]	•	Blockchain	Fatal Signals	Incorrect State Transitions		
2023	Wang et al.[163]	•	General	Crash Logs	-		
2023	DYFuzzing[7]	0	General	Sanitizer	Incorrect Content & State Transitions		
2023	ResolFuzz[20]	0	DNS	-	DE		

Table 6. Protocol fuzzers and their oracles

○: Whitebox Fuzzer; ●: Blackbox Fuzzer; ①: Greybox Fuzzer; T: Taxonomy; General: The fuzzer is not designed for a specific type of protocol; -: Not detectable; ESM: Error-Signaling Messages; APB: Abnormal Physical Behaviors; DE: Differences in Execution.

6.1.5 Timeout and Liveness Checks. As most memory-safety bugs result in process crashes, fuzzers can detect these bugs by liveness detection. A common way to check the liveness of a target is to set a static timeout for a response [22, 27, 47, 55, 57, 121, 145]. If the response message from the target is not received by the time, it is determined that the target process is dead. This method is suitable for environments with limited debugging techniques, such as unable to obtain process signals or debug logs. However, setting a fixed timeout is a relatively coarse-grained method, which may introduce false positives due to network fluctuations or excessive load on the target. Some works propose several active liveness checks to mitigate the false positive issues. For example, Snipuzz [47] resends input sequences for multiple times to reduce false positives. IoTFuzzer [27], OWFuzz [22], and BadMesher [121] use heartbeat messages (*e.g.*, ICMP messages) to infer the status of the PUT.

6.2 Non-Memory-Safety Bug Oracles

Non-Memory-Safety bugs are bugs that are caused by non-memory access reasons and violate some expected properties, such as logical bugs, RFC violations, or performance influential bugs. Non-Memory-Safety bugs are challenging to be identified because they have no uniform observable behavior. Detecting non-memory-safety bugs usually requires the user to define the oracle according to the properties destroyed by the target. Depending on the properties that are checked, these oracles can be roughly divided into four categories, namely *incorrect message content & state transitions, inconsistency in transmission, abnormal performance indicators*, and *differences in execution*. We will describe these techniques in detail in the following subsections. It should be noted that although there are various ways to identify possible non-memory-safety bugs, most of these methods can only report suspicious behaviors of the PUT, which still require experts' manual verification to determine impact and exploitability.

6.2.1 Incorrect Message Content & State Transitions. Incorrect Message Content checks whether the content of the responses violate some semantic constraints. Incorrect State Transitions verifies whether the state transitions are valid or allowed. In most cases, these rules are extracted from protocol specifications or designed with expert knowledge. These rules can be in different forms, such as canonical state machines [18, 142], linear-temporal properties [99], constraints of response messages [55, 56, 92], etc. For example, Beurdouche et al. [18] manually construct a standard state machine from the specification and then use this state machine as a ground truth to identify deviant behaviors of the PUT. Utilizing this method, a logical bug was identified in a TLS implementation JSSE[18]. This flaw permitted attackers to bypass all messages pertaining to key exchange and authentication, subsequently enabling them to initiate unencrypted communication. Given a lineartime temporal logic property that a protocol implementation needs to satisfy, LTL-Fuzzer [99] leverages directed greybox fuzzing to direct the fuzzing towards specific location that can affect the property, and checks whether the property is held during each execution iteration. Besides, Sweyntooth [56] and Greyhound [55] check whether the received response packet is in the expected type set of the current protocol state. Any mismatched message types are labeled as anomaly. Loki [92] extracts rules from the PBFT consensus protocol paper [24], which are used as oracles to detect non-memory-safety bugs in blockchain implementations. For example, Loki identified a bug in Hyperledger Fabric [10] that can be used to confirm illegal transactions.

6.2.2 Message Inconsistency in Transmission. Some works check whether there are non-memorysafety bugs that can lead to integrity break of the protocol. Specifically, as the correct data transfer is one of the basic properties of TCP protocol, TCP-Fuzz [187] designed a data checker on both the sender-side and receiver-side to check the violation of this property. Whenever a message is sent or received, the data checker checks whether the sent message and the received message are identical.

6.2.3 Abnormal Performance Indicators. Some works aim to find network attack strategies that can affect the performance of the PUT, and these works judge the effectiveness of attack strategies by monitoring whether some performance indicators of PUT are beyond the normal range. For example, to find the amplification DDoS attack strategies in UDP services, AMPFuzz [78] uses the bandwidth amplification factor (BAF) [129] of each request and response pairs, which is the ratio of the sum of the lengths of all response messages to the length of the attack request, as an indicator to find the message that can maximize the consumption of throughput. TCPWN [69] and ABBrate [115] aim to find the attack strategies against the implementations of TCP congestion control that can increase or decrease the congestion window in a model-guided approach. To detect whether the inputs indeed influence the congestion control mechanism, TCPWN obtains the window size from system logs and compares it with an expected baseline.

6.2.4 Differences in Execution (labeled as "DE" in Table 6 column 6). Differential testing involves comparing the execution behaviors of different implementations of the same protocol to investigate potential security impacts. This method is scalable due to its independence from code instrumentation. For instance, TCP-Fuzz [187] contrasts the outputs of multiple TCP implementations to identify discrepancies. Yang *et al.* [168] employ differential testing to uncover consensus bugs in Ethereum that could lead to fork attacks. They generate a sequence of transactions as inputs and observe the responses of two Ethereum clients, specifically implemented in Golang and Rust. However, a significant challenge in this domain is ascertaining which implementation diverges from the protocol's expected behavior, and determining whether observed behavioral differences stem from errors or under-specifications in the protocol's RFC. As such, most works adopting differential testing [20, 168, 187] integrate a subsequent manual inspection phase to differentiate actual vulnerabilities from innocuous discrepancies.

To augment the bug-finding efficiency, some studies compare the PUT with an already welltested or formally verified implementation, referred to as a 'reference stack' [187]. For instance, TCP-Fuzz [187] employs classical and extensively tested kernel-level TCP stacks, such as Linux TCP or FreeBSD TCP, as a reference to test newer TCP stacks. In such scenarios, if inconsistencies are reported, it strongly suggests the presence of bugs in the newer protocol implementations. This methodology not only identifies discrepancies but also provides a framework for evaluating the correctness of various protocol implementations.

6.2.5 *Timeout and Liveness Checks.* Timeout and liveness checks can also be used to detect infinite loops [22, 27, 47, 55, 57, 121, 145]. The detection methods are similar to those introduced in Section 6.1.5.

7 DIRECTIONS OF FUTURE RESEARCH

So far, we have discussed state-of-the-art protocol fuzzers. In this section, we will answer RQ3 by discussing the research trends and current challenges of fuzzing techniques based on what we have surveyed.

7.1 Towards Perfect Communication Model Construction

The current methods for constructing communication models are far from perfect, often resulting in either incomplete or inaccurate knowledge acquisition, or requiring extensive manual effort. Specifically, as introduced in Section 4, existing methodologies for constructing communication models can be broadly categorized into top-down and bottom-up approaches. Bottom-up methods are proposed to learn the communication models specific to particular protocol implementations [15, 39, 46, 48, 90, 106, 116, 120, 148, 162, 181], rather than the canonical communication model of the protocols themselves. However, for top-down approaches, the majority of existing works still rely heavily on manual processes to construct state machines from protocol specifications [18, 55, 56, 63, 69, 70, 77, 113, 115, 128, 130, 138, 142, 187]. This manual construction is not only labor-intensive but also prone to errors.

Existing research [71, 111] has embarked on exploring the automatic extraction of partial FSMs from protocol specifications using NLP techniques. This exploration has preliminarily validated the feasibility of automating the extraction of protocol communication models. However, this method currently falls short of extracting canonical communication model from protocol specifications due to ambiguities and unspecified behaviors in specifications, thus precluding a complete one-to-one translation between the text and the communication model.

To resolve this, machine learning model based approaches can be explored for better model construction. Considering the recent remarkable progress of LLM (Large Language Model) [29],

one promising direction is to develop LLM-based solution for more precise model construction. Another possible direction is to combine the other information sources (such as the code of protocol implementations, code commit or comment information during development, program analysis results, etc.) to help understand the content of the specification better.

7.2 Towards Multi-Dimension Testing Perspectives

Existing research focuses more on changing the content of packets or the order of packet sequences. This approach, while effective to a certain extent, overlooked the fact that protocols have multidimensional testing perspective, e.g., variables such as message latency [68], cache state [73], configurations [37, 180], and concurrency level [75], as highlighted in Section 3.1. These attributes play a crucial role in deciding the behavior of the target system. To effectively test these attributes within protocol implementations, it is necessary to create detailed models that accurately represent each attribute, including message latency, cache state, configuration parameters, and concurrency levels. Additionally, specific oracles and mutators can be designed to evaluate the correctness of the protocol behavior under various scenarios that encompass these multidimensional aspects. This direction is interesting and can help establish a more comprehensive evaluation of the protocol's resilience and robustness.

7.3 Fuzzing Characterized Protocol Targets

A significant and under-explored future research direction is the fuzzing of characterized protocol targets. Current research has not comprehensively covered various protocols, especially for those with distinct characteristics and importance. The following three areas are particularly noteworthy:

1. Domain-Specific Protocols. Proprietary domain protocols, such as those used in satellite communication [153], unmanned aerial vehicle (UAV) communication [61], and Robot Operating System (ROS) [108], typically possess a high knowledge threshold and a relatively closed nature. These protocols play a crucial role in many infrastructures, making their security research paramount. Presently, fuzzing research for these protocols is relatively scarce, presenting an opportunity for the academic community to improve testing effectiveness and security through the development of new fuzzing techniques and tools.

2. Hardware-Implemented Protocols. Another direction is hardware protocol which designs fuzzers for testing protocols implemented on hardware such as FPGAs [156]. These hardware implementations often exhibit different error characteristics compared to those at the software level, necessitating the development of new approaches to more effectively identify and exploit potential vulnerabilities.

3. Multi-Party Protocols. Another possible direction of protocol fuzzing is to support multiparty protocols. In general, protocols have many communication mode, such as peer-to-peer mode [69, 115, 159], server-client (master-slave) mode [27, 46, 158], and multi-party mode [149]. Existing protocol fuzzers focus more on the first two modes by acting as a client/server to test the other [27, 46, 158], or playing a role as a peer node to test the PUT [69, 115, 159]. The multi-party protocols have not been studied. For example, a node can play a role as the computing node, consensus node or management node in a blockchain network [10], each of which is responsible for a different task. The correct execution of a smart contract protocol requires the cooperation of these roles. How to efficiently test these multi-party protocols is a interesting but challenging question.

7.4 Combining with Other Vulnerability-Finding Techniques

Beyond fuzzing, there exists a plethora of vulnerability-finding techniques, such as symbolic execution [11, 26, 132, 144, 150, 151] and model checking [25, 59, 65, 74, 104]. While the combination of these techniques with fuzzing has been explored in general contexts [147, 173], their applications

in protocol fuzzing remains relatively under-explored [144]. This presents a promising future research direction, especially considering the fact that the combined approaches still faces the unique testing challenges for complex communications defined in protocols. Intuitively, future research can improve existing vulnerability-finding techniques to better solve protocol-specific challenges. Moreover, many protocols are accompanied by high-quality learning sources, such as detailed specifications. Future research can explore ways to effectively utilize these valuable sources to inform and enhance the combined approaches.

7.5 Shift-Left Protocol Fuzzing

Though there are certain research efforts focusing on the integration of general-purpose fuzzing techniques into the development cycle – such as with tools like libFuzzer, OSS-Fuzz, and research into fuzzing within CI/CD integration testing [123] - few studies have specifically dedicated themselves to bridging the gaps between protocol fuzzing and the development process. Protocol fuzzing is distinct from general software fuzzing; it entails rigorously testing the various protocols that allow for communication and data exchange between different software systems and components. Protocol targets generally have a more complex development workflow than that of general software targets. This complexity arises from their need to precisely follow set standards and specifications to ensure interoperability across diverse systems, leading to unique challenges in integration and testing. These challenges necessitate a tailored approach to fuzzing that understands and adapts to the intricacies of protocol development. Therefore, a shift-left approach to protocol fuzzing is needed, which would integrate protocol-specific fuzzing techniques earlier in the software development lifecycle. This can involve the exploration of designing techniques from the developer's perspective and HCI (Human-Computer Interaction) [23] techniques can also be considered if necessary. By doing so, it can surface vulnerabilities and issues at an earlier stage where they can be addressed more easily and cost-effectively, ensuring a more robust and secure software ecosystem for protocol implementations.

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