

SPARROW: A Novel Covert Communication Scheme Exploiting Broadcast Signals in LTE, 5G & Beyond

Reza Soosahabi

ATI Research Center, Keysight Technologies Inc., Austin, TX 78731

Email: reza.soosahabi@keysight.com

arXiv:2108.12161v1 [cs.CR] 27 Aug 2021

Abstract—This work¹ proposes a novel framework to identify and exploit vulnerable MAC layer procedures in commercial wireless technologies for covert communication. Examples of covert communication include data exfiltration, remote command-and-control (CnC) and espionage. In this framework, the SPARROW schemes use the broadcast power of incumbent wireless networks to covertly relay messages across a long distance without connecting to them. This enables the SPARROW schemes to bypass all security and lawful-intercept systems and gain ample advantage over existing covert techniques in terms of maximum anonymity, more miles per Watts and less hardware. The SPARROW schemes can also serve as an efficient solution for long-range M2M applications. This paper details one recently disclosed² vulnerability in the common random-access procedure in the LTE and 5G standards. This work also proposes a rigorous remediation for similar access procedures in current and future standards that disrupts the most sophisticated SPARROW schemes with minimal impact on other users.

Index Terms—security, 5G, LTE, exploit, covert communication, data exfiltration, M2M, hashing

I. INTRODUCTION

Covert communication can be a suitable term for referencing a wide array of security threats, such as data exfiltration, remote command-and-control (CnC) and espionage. The parties engaging in covert communication strive to stay anonymous and circumvent security and lawful-interception systems that actively inspect the incumbent means of communication. The rapid adoption of connectivity solutions has made covert communication schemes an integral part of most advanced security threats [2]. The published literature on covert communication schemes can be logically split between two dominant viewpoints: exploiting existing software protocols and designing new radio access solutions.

The first viewpoint includes data exfiltration and CnC techniques that are well-known topics in the cybersecurity community. Data exfiltration involves covertly extracting and communicating sensitive information from a compromised system. Exemplary CnC implementations include malicious software or hardware agents that are configured to covertly communicate across an Internet protocol (IP) network. These

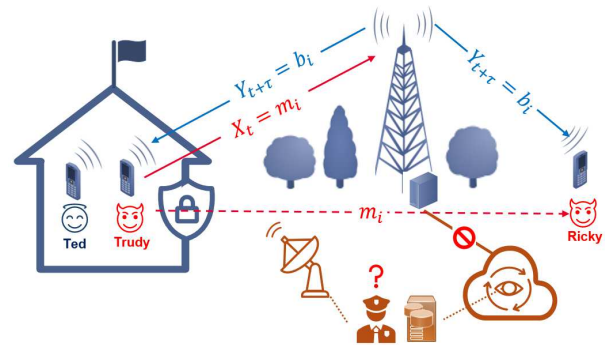


Fig. 1: SPARROW exploitation model in Scenario 1.

techniques usually involve exploiting application or network protocols to tunnel messages between two hosts connected to the Internet. Famous examples include ICMP and DNS tunneling [3] [4]. To counter such threats, the cybersecurity industry constantly monitors emerging techniques and adopts countermeasures to detect and block them. Once disclosed, these techniques rapidly lose their potency as vulnerable systems and security devices install software updates that implement the countermeasures.

On the other hand, designing radios for covert communication has long been of research interest in the wireless community. Covert communication devices usually access the radio spectrum without a license acquisition and generally employ low-power, ad-hoc radios that use PHY-layer technologies such as spread-spectrum. Low power commercialized ad-hoc technologies such as LoRA and ham radios can be engineered for covert communication, but unlike commercial radios, these systems usually sacrifice transmit power and data-rate in favor of defeating spectrum monitoring and jamming systems [5]. These power and data-rate limitations, along with a lack of access to elevated antennas or high transmission power, significantly reduces the operation range of these devices, particularly in indoor-to-outdoor communication scenarios [6].

To counter this type of security threat, spectrum monitoring and intelligence systems are constantly evolving to disrupt and locate the radios used for covert communication. Drawing upon elements of these previous approaches, this work introduces a novel and elegant methodology for identifying and mitigating covert communication referred to herein as exploit-

¹This work will be submitted to the IEEE for possible publication. Copyright may be transferred without notice, after which this version may no longer be accessible.

²CVD-2021-0045 acknowledged on GSMA coordinated vulnerability disclosure program website [1]

ing radio infrastructure. Section II presents a comprehensive framework to identify and exploit vulnerable procedures in MAC protocols of Wireless Carrier Networks (WCN), such as cellular and satellite communication. It shows how WCN user devices can be co-opted and transformed into SPARROW devices that exploit the broadcast power of a WCN radio access node for the purposes of covert communication. Figure 1 illustrates the implicit communication channel between SPARROW devices and a victim cellular station, which acts as an unwitting message relay.

Section III details a new responsibly disclosed security vulnerability example, which involves LTE/5G random-access procedures. This vulnerability enables SPARROW mobile devices to exchanged short messages within a cell without connecting to the cellular network. The SPARROW devices can be made identical to other user devices as far as size and transmit power concerned. Detailed in Section IV, the SPARROW covert communication scheme can be shown to outperform existing covert techniques in terms of: maximum anonymity, operation range and hardware footprint. These techniques can bypass all current security and lawful-interception systems, as well as all current spectrum monitoring and intelligence systems. This enables SPARROW attack techniques to be used in a wide variety of covert communication scenarios. Nevertheless, it will be appreciated that these techniques can also be used in good faith with the consent of incumbent network operators in scenarios such as connection-less M2M communication and disaster recovery efforts.

Random-access procedures, which facilitate wireless link establishment, are common in many wireless MAC protocols and, in fact, the vulnerable one in 5G/LTE has been implemented in the standards for over a decade. This fact was one of the primary motivations for developing a rigorous remediation scheme capable of hardening random-access procedures with respect to SPARROW threats in current and future wireless standards. Section V explores possible remediation strategies and makes the case to move forward with a novel *entropy-leveraging* strategy which involves the use of content obfuscation in unprotected broadcast messages. Section VI provides the mathematical foundation to analyze this entropy-leveraging strategy and understand the inherent trade-off between protection and performance. This section culminates with the analysis of two simple examples of the entropy leveraging scheme and their respective limitations in combating more sophisticated SPARROW attack schemes. Section VII proposes an enhanced entropy leveraging scheme called ELISHA (entropy-leveraged irreversible security hashing algorithm), which is used to efficiently disrupt most advanced SPARROW attacks with minimal impact on the network performance for other users. This minimally disruptive performance is achieved through a novel combination of cryptographic hash functions and random bit operations. A rigorous analysis of this advanced technique and the associated efficacy and overheads is provided to support the consideration and potential adoption of the disclosed SPARROW mitigation approach(es) by the relevant wireless standard setting organizations. The numerical results presented in Section VIII illustrate how to optimize the design parameters in an ELISHA-based mitigation scheme to

achieve desired levels of protection against SPARROW attacks while concurrently preserving user performance. Finally the concluding remarks are presented in Section IX along with acknowledgment notes.

II. GENERAL EXPLOITATION MODEL

This section provides an overview of Wireless Carrier Networks (WCNs) architectures and their associated resources. Also provided is a novel methodology that can be used to identify weaknesses in the MAC layer protocols utilized in these networks, which can be exploited by malicious actors to leverage a WCN's broadcast resources for SPARROW covert communication.

A. Overview of WCNs

WCN is the general term adopted in this work to reference technologies such as cellular (3G/LTE/5G), WiMAX and Satellite Internet. WCNs are deployed by service providers (operators) to offer secure wireless data connectivity to a large number of users in wide geographical areas, often via a subscription model. WCNs differ from end-user wireless technologies, such as wireless local area networks (WLANs), in several key aspects including: resources, architecture and user control.

A WCN can often be broken into two components: the Radio Access Network (RAN) and the Core Network (CN). The RAN consists of a network of radio access nodes (cellular stations in cellular terminology), which provide wireless connectivity between user devices and the CN. The CN hosts servers, which manage RAN operation and connect user devices to other networks, such as the Internet. The standard governing a WCN typically involves several protocol layers, collectively called control-plane, which define the interaction of user devices with the RAN and CN components. The control-plane procedures are abstracted away from user applications, which are only concerned with data connectivity to the Internet (data-plane). Related to the scope of this work, the Medium Access Control (MAC) protocol layer defines the interaction of a single radio access node with the user devices in its coverage area.

To enhance signal radiation, the radio access nodes can have antennas mounted on tall structures or be installed on satellites. It enables them to clearly communicate with user devices miles away over radio frequency (RF) signals that are otherwise blocked by terrestrial clutter, such as foliage and buildings. High transmit power, licensed spectrum and higher altitudes are luxuries available to WCNs compared to other technologies, such as WLAN, that offer limited coverage indoors or under terrestrial clutter. Nowadays, it is hard to find a neighborhood without WCN service coverage. Nevertheless, these WCN operators must comply with numerous government regulations concerning their resources, infrastructure, and the users' activity.

In most WCNs, the user devices have to authenticate with a CN entity (e.g. AAA servers) before accessing any of the network services. In addition to user-credential registries, there are CN servers constantly collecting user activity metadata,

such as service usage, location, etc.. The metadata are then consumed internally by the WCN operator or shared with government authorities in compliance with Lawful Intercept (LI) regulations [7]. It should be noted that the MAC layer protocols implemented by WCNs prohibit the user devices from engaging in untraceable peer-to-peer wireless communications, which this work aims to prove is currently still possible.

B. Exploitation Scenario

For the ease of illustration, a generic unidirectional covert communication scheme formulated for the following hypothetical scenario exploiting cellular technology. It can be extended to other WCN technologies without loss of generality:

Scenario 1. *Trudy intrudes a cyber air-gaped facility under heavy surveillance and wishes to send a set of covert messages to her counterpart Ricky with a passive receiver outside. To maintain their cover, both agents cannot connect to any IP networks. They also cannot use any ad-hoc radios due to spectrum surveillance and insufficient signal range. However, both are equipped with low-power radio devices that can interact with a nearby cellular station. Trudy programs its device to exploit the vulnerability in its MAC layer protocol to implicitly relay messages to Ricky without authenticating with the carrier's network.*

MAC layer protocol procedures can be expressed as a flow of messages exchanged between each user device and a WCN radio access node. In this case, Trudy and Ricky are assumed to have constructed a *code-book* for their communication scheme. This code-book consists of a set of possible messages (codewords) that Trudy can transmit to Ricky. Let $\mathcal{M} = \{m_1, m_2, \dots, m_{2^M}\}$ denote the code-book including a set of 2^M distinct MAC layer messages, where each m_i encodes M -bits of information. The messages in \mathcal{M} can trigger the set of distinct response messages $\mathcal{B} = \{b_1, b_2, \dots, b_{2^M}\}$ from the cellular station. Let the random variable $X_t \in \mathcal{M}$ stand for the message Trudy sends at time slot t . The cellular station response to X_t can be modeled with another random variable $Y_{t+\tau} \in \mathcal{B}$, where τ is the time lapse from the moment Trudy intends to send X_t until the cellular station broadcasts the response message.

Proposition 1. *The MAC layer protocol of a WCN is deemed vulnerable to covert communication in Scenario 1 if any of its procedures allows forming \mathcal{M} and \mathcal{B} of the uplink and the downlink messages satisfying all of the following conditions:*

- 1) **Passive Reception:** *The downlink broadcast messages in \mathcal{B} can be decoded by any passive scanning device within the radio access node signal range without a connection establishment or prior knowledge of PHY channel state information.*
- 2) **Bijectivity:** *For $1 < i \leq 2^M$, Receiving downlink message b_i at time $t + \tau$ is almost surely result of sending m_i in uplink at time t , i.e.*

$$\begin{aligned} Pr(X_t = m_i | Y_{t+\tau} = b_i) &= Pr(Y_{t+\tau} = b_i | X_t = m_i) \\ &= 1 - o(1) \end{aligned}$$

- 3) **Anonymous Uplink:** *Sending messages in \mathcal{M} does not reveal transmitter's identity to the WCN.*
- 4) **Stateless Uplink:** *The protocol does not mandate any correlation between consecutive uplink messages in \mathcal{M} ,*

$$Pr(X_t = m_i | X_{t-\Delta t} = m_j) = Pr(X_t = m_i), \Delta t > \tau$$

The condition for passive reception guarantees anonymity for Ricky implying that the cellular station broadcasts messages with the most basic modulation and coding scheme at the PHY layer. The second condition requires sufficiently strong bijective correlation between the messages in Trudy's code-book and their resulted downlink broadcast messages. It would be ideal to have a deterministic bijectivity discovered in the protocol standard documentation. Although, the same cellular station is serving other users who may confuse Ricky by accidentally triggering broadcast messages in \mathcal{B} . Since the presence of Ricky is unknown to the cellular station, he cannot rely on the reliability mechanisms built in most wireless standards. It is recommended the codewords in \mathcal{M} having integrity-check features to minimize degradation of bijectivity due to conditions caused by other users' activities and PHY layer noise.

Fig. 1 depicts how the vulnerability outlined in Proposition 1 leads to the execution of Scenario 1. Trudy and Ricky decide their optimal code-book and the target cellular station. Then Trudy transmits a codeword m_i at a time that triggers distinct broadcast signal b_i from the cellular station received by Ricky. This notifies Ricky about the transmission of m_i from Trudy according to the bijectivity condition. Thus, a virtual low power covert communication channel (dotted red line) is established from Trudy to Ricky. This channel takes advantage of the relatively high broadcast transmit power of the cellular station. It also allows Trudy to bypass network security devices, LI mechanisms in the operator network, and spectrum monitoring systems. The anonymous uplink condition could be relaxed in some other scenarios. If required, it limits the search space for \mathcal{M} to the early control messages that devices exchange with cellular station before authentication and data connection. Assuming Ricky is able to correctly decode the messages in near real-time, the stateless uplink condition allows Trudy to send a message in every τ seconds. Therefore, they can achieve data rates in order of $\frac{M}{\tau}$ bits per seconds.

III. SPARROW SCHEME IN LTE & 5G

This section shows a simple example of a SPARROW attack scheme, which exploits the random-access (RA) procedure in the LTE and 5G protocol standards (defined in section 5.1.5 of 3GPP specification documents TS36.321 [8]). It leads to a realization of Scenario 1 using the resources of any currently deployed LTE or 5G cellular stations (world wide). Adopting the 3GPP standard terminology moving forward, *e/gNB* refers to an LTE or 5G target cellular station, specifically the serving *sector* of the cellular station covering both Ricky and Trudy. Any user device interacting with an *e/gNB* is called a *UE* (User Equipment). This procedure has been present in the 3GPP standard since the early releases of LTE (Release 8) and may possibly be used in other non LTE/5G wireless technologies, as well.

A. Normal RA Procedure

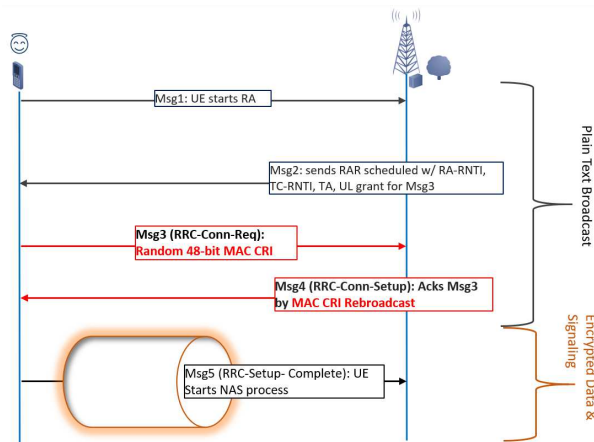


Fig. 2: Random-access (RA) procedure in LTE/5G including the contention resolution.

Figure 2 illustrates the initial messages exchanged between a UE trying to connect to an e/gNB for the first time. The first four messages ($Msg1$ to $Msg4$) are of particular interest, as they do not involve any authentication or encryption. Regardless of its type or registration identity, any UE can send $Msg1$ and $Msg3$ to any e/gNB that responds with $Msg2$ and $Msg4$ in the basic transmission mode (like broadcast SRBs). Thus, $Msg2$ and $Msg4$ are passively receivable a cell coverage area.

After downlink synchronization and decoding system information broadcast, a visiting UE starts RA by sending $Msg1$ that contains a randomly selected RACH preamble sequence identified by RAPID (RACH preamble ID). There is a limited set of RACH preambles allocated to each cell. Upon receiving $Msg1$, the e/gNB allocates a RA-RNTI (RA radio network temporary identity) to UE which is directly computed from $Msg1$ transmission time-slot. It then uses RA-RNTI to signal $Msg2$ to the UE which is actively decoding DCI blocks (downlink control information) associated with its pre-computed RA-RNTI. The pseudo-random property of RACH-preambles enables an e/gNB to estimate TA (timing advanced). The UE has to synchronize its uplink according to TA for any subsequent messages. The e/gNB releases RA-RNTI and allocates TC-RNTI (temporary cell RANTI) to the UE. It includes TA, TC-RNTI and some other configuration messages in $Msg2$ sent to the UE.

The UEs without prior network connection have to engage in a procedure known as contention resolution involving $Msg3$ and $Msg4$. To confirm the successful reception of $Msg1$, the UE transmits a randomly-generated Contention Resolution Identity (CRI) in $Msg3$ according to sections 6.1.3.3-4 in [8]. More precisely, CRI is 48-bits datum containing 40-bits of randomly selected bits. The e/gNB acknowledges $Msg3$ by broadcasting the received CRI value in $Msg4$ which is signaled via TC-RNTI sent in $Msg2$. The UE compares the CRI value in $Msg4$ against its randomly selected value. If they match, it assumes RA successful and proceeds with the next steps to connect to the network. Otherwise, the

UE has to back off and retry RA procedure. Per section 5.1.4 in [8], a UE can freely re-attempt RA after a randomly selected backoff time. However, there is no practical way for the e/gNB to enforce the backoff value. Consequently a UE can always select a minimum value between consecutive RA attempts. The purpose of contention resolution is further detailed in Section V-A.

B. Exploiting RA Procedure

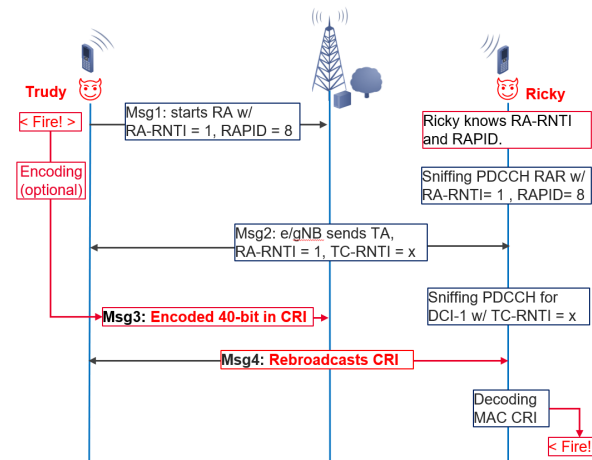


Fig. 3: SPARROW scheme exploiting RA procedure in LTE/5G.

According to Proposition 1, the $Msg3$ and $Msg4$ meet all of the conditions for a SPARROW scheme to work. The codebook \mathcal{M} can be any collection of 40-bits binary data in $Msg3$ CRI. Transmitting $Msg3$ does not require a network connection or revealing Trudy's identity. Upon receiving $Msg3$, the victim e/gNB broadcasts the same CRI in $Msg4$ implying $\mathcal{B} = \mathcal{M}$. As illustrated in Figure 3, a passively scanning device can recover CRI from $Msg4$. To be more specific, Ricky and Trudy have a prior agreement on RAPID and RA-RNTI. Ricky then passively scans and decodes DCI values with the expected RA-RNTI for $Msg2$. Upon receiving a matching $Msg2$, it extracts its TC-RNTI content to detect and decode the subsequent $Msg4$. Trudy can use all or portion of 40-bit CRI content to encode its data. She also can employ some integrity check mechanism to help Ricky filter out $Msg4$ transmissions belonging to other UEs in the cell.

C. Implementation³

Trudy can break longer messages into chunks of 40-bits (or less) and transmit them in consecutive attempts. There are resources providing an average estimate of RA-procedure duration times (from $Msg1$ to $Msg4$) including [10] expecting it to be around $30ms$ in typical LTE deployments. Taking this estimate and accounting for additional $10ms$ of back-off between multiple attempts, Ricky and Trudy can achieve near $1kbps$ throughput in this scheme. The offered throughput

³A proof-of-concept has been implemented and verified using Keysight UXM5G[®] and UeSIM[®]. Its video recording has been responsibly disclosed to GSMA and included in the presentation at [9].

suits IoT and M2M (machine-to-machine) applications that currently use low-power technologies such as LoRA [6]. However, SPARROW scheme can achieve longer range in cluttered environment without any direct access to RF spectrum. Section IV expands further into its features and the applications.

It will be appreciated that the RA procedure is agnostic to the PHY layer frequency band. However, the lower frequency bands in LTE and 5G WCNs better suits the objectives of Scenario 1. As far as RA concerned, the cell range depends on the PRACH preamble zero-correlation-zone configuration (N_{cs}) of the e/gNB (illustrated in section 24.8 of [11]). For typical outdoor LTE macro cells, N_{cs} is set to 9 or larger values that enables UEs to perform RA as far as 5 miles from the cell. 5G-NR (new radio) standards enable utilizing higher frequency bands above 6 GHz (FR2) that rely on beam-forming and multiple-antenna transmission modes. Nevertheless, the underlying RA procedure PHY layer is still very similar to LTE in sub-6 GHz (FR1) and therefore, more promising.

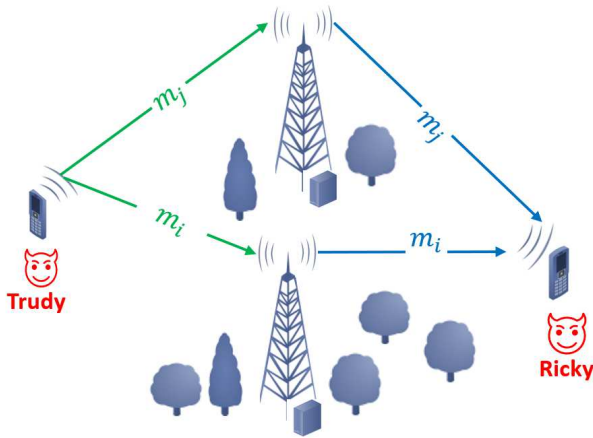


Fig. 4: Exploiting overlapping cells (sectors) for throughput enhancement.

Depending on the application, SPARROW UEs (Ricky and Trudy) can exploit multiple cells for throughput or operational range enhancements. Figure 4 shows how two cells can be exploited to achieve parallel covert communication channels. With the exception of very rural environments, UEs within the range of a few miles can be covered by multiple overlapping LTE or 5G sectors, which can be exploited for more throughput or a reverse link from Ricky to Trudy.

Figure 5 depicts a more interesting case involving a relay UE to extend the operational range beyond a single cell coverage. Relay UEs are placed in the handover (coverage overlap) region between adjacent cells. These relays can be configured to act as a proxy for Ricky, receiving a message in one cell and transmitting it in another adjacent cell. The SPARROW UEs are effectively low-power cellular modems that can operate off of rechargeable batteries. Thus a rechargeable relay UE can operate from any inconspicuous location in between cells. One can create a wide-area IoT mesh using relay UEs communicating via SPARROW.

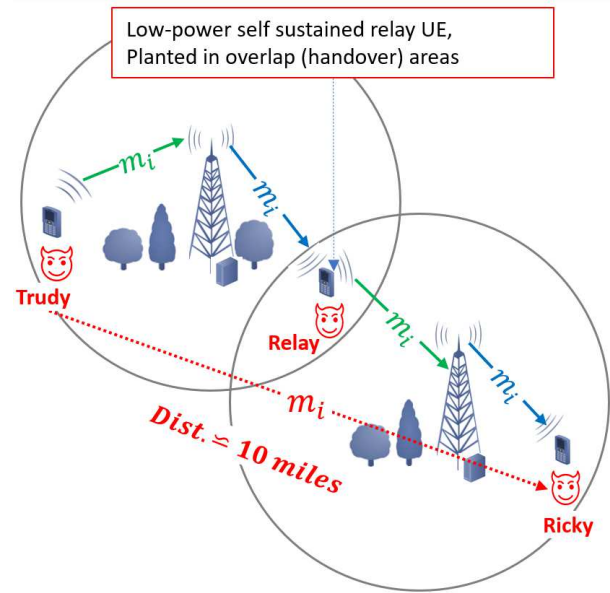


Fig. 5: Exploiting adjacent cells (sectors) for range enhancement with a relay.

IV. SPARROW IMPACT & APPLICATIONS

Targeting cellular stations or other WCNs access radio nodes vulnerable to Proposition 1, the SPARROW devices outperform known covert communication techniques based on the following key objectives:

- **Maximum Anonymity:** Unlike network protocol tunneling schemes, they do not need any network access while operating. This eliminates SPARROW device's exposure to network security and lawful intercept systems. While in disguise of other wireless user devices, they can also circumvent spectrum scanners and jamming that typically pose challenges to radio devices made for covert communication.
- **More Miles per Watts:** SPARROW devices exploit the RF coverage of cellular stations or non-terrestrial technologies. As shown in Section III, they can send information several miles apart while being at low altitudes in a RF-obstructed environment. The SPARROW UEs can achieve up to 5 miles while transmitting at commercial UE power level ($\sim 0.2W$). They offer data rates within the range of LoRA technology that are low-power narrow-band radios operating in regulated sub-GHz bands. Operating at similar power levels ($\sim 0.5W$), operational range of LoRA radios significantly degrades as low as 1.5 miles when deployed in a RF-obstructed environment [6].
- **Less Hardware:** SPARROW UEs have very small hardware footprint that can be deployed anywhere. They can be manufactured in the form of USB modems, or utilize modified open source LTE/5G code libraries installed on low-cost SDRs (software-define radios) [12]. They can autonomously operate on batteries or harvest energy from the environment. Thus, they deserve to be named after Sparrows!

It is worth mentioning that the operational range of SPARROW UEs has the potential to dramatically increase with the emergence of new satellite-based technologies such as 5G-NTN [13] should the same vulnerable contention resolution procedure remain in the standard. Bypassing most of known measures against covert-communication, the SPARROW scheme can remain a potential threat until the standards patch the MAC protocol procedures subject to Proposition 1. Prominent threat scenarios include:

- **Data Exfiltration:** as outlined in Scenario 1, SPARROW attack schemes can be an effective alternative to known data exfiltration techniques by leveraging vulnerabilities in existing network access protocols. Made in a small form factor, SPARROW devices can easily be used to smuggle data out of restricted facilities.
- **Command & Control:** SPARROW devices can anonymously communicate with remote malicious IoT devices to trigger unwelcome events using apparently benign WCN radio signals.
- **Clandestine Operations:** agents can anonymously communicate with SPARROW devices in hostile areas without broadcasting noticeable signals or directly accessing the incumbent networks.

Having the consent of the incumbent network operators, SPARROW scheme can also be used in good faith scenarios such as:

- **Connection-less M2M Communication:** Some M2M (machine-to-machine) application require extremely low latency and power consumption. The SPARROW scheme can compliment the existing solutions such as [14] that enables the devices to communicate via encoding information in LTE *Msg1* and *Msg2*.
- **Disaster Recovery:** SPARROW devices can be used to take advantage of partially functional access radio nodes to exchange critical messages in disaster situations without requiring authentication or back-haul connection to a core network.

V. SPARROW REMEDIATION STRATEGIES

The contention resolution procedure facilitated by *Msg3* and *Msg4*, which was exploited in Section III, plays an essential part of cellular RA procedure and may have analogues in other WCN protocol standards. Therefore, the presented remediation strategies focus on thwarting their exploitation while preserving their role in contention resolution procedure. This is a more challenging problem than offering a generic remediation to the generic scheme in Section II. After explaining the constraints of contention resolution mechanism, it will be clear that the remediation strategies will be limited.

A. Contention Resolution Mechanism

There are a limited number of RACH-preambles (e.g. 64 for LTE) available at each cell for random selection by UEs attempting to access the network. Depending on duplexing configuration mode, there is a limited set of PRACH resources associated with RA-RNTIs. Most low-frequency

LTE/5G bands operate in FDD mode (frequency division duplexing) where there is only 10 PRACH resources [11]. Consequently, there is always a real possibility that multiple UEs end up with the same RA-RNTI and that the random preambles cause a resource contention event. In most cases, the cellular station can only decode a single preamble transmission and is oblivious of any underlying contention event. To avoid any subsequent uplink interference between the UEs, the cellular station needs a mechanism to immediately signal the UE with successful *Msg1* to proceed and all other unsuccessful UEs to back off and retry RA. In this early stage of RA, there are no unique identities assigned to the UEs and the contending UEs follow the same protocol procedure in isolation. Going back to *Msg3* and *Msg4* in Figure 2, the only plausible resolution is having each UE to test the success of *Msg1* by sending a purely random N -bits within CRI in *Msg3*. Then the cellular station most likely receives *Msg3* from the UE with successful *Msg1* and acknowledges it with rebroadcasting its CRI in *Msg4*. Since the cellular station does not have any knowledge of distance or channel conditions of all contending UEs, it transmit *Msg4* similar to other cell broadcast messages which are receivable everywhere in its coverage area. The value N also has to be large enough ($N = 40$ in current 3GPP standards) to minimize the probability of identity collision, otherwise the contention may drag beyond RA procedure. Contention is ultimately resolved when each UE compares CRI in *Msg4* against what they transmitted in *Msg3*.

B. Strategy Paths

Before presenting the proposed strategy of this work, it is worth enumerating the following strategies that can have significant performance overhead, risks, or offer limited protection against SPARROW in contention resolution procedure:

- **Preset UE Identities:** To prevent broadcasting arbitrary UE-assigned identities, one shall propose having a unique pre-defined CRI per UE similar to MAC address in WLAN. This value can also be derived from secure keys stored in SIM device and verifiable by the network. This way the cellular station only broadcasts CRI in *Msg4* if its source is verified. This strategy risks UE privacy by exposing a new attack surface for unauthorized user tracking similar to IMSI-catching techniques [15]. It also does not prevent or protect against SPARROW UEs that employ a precomputed communication code-book of valid CRI values.
- **Detect & Block:** The victim cellular station may notice exploitation by monitoring the random-access activity patterns in the cell. However, the cell station does not have a reliable way of differentiating uplink messages from SPARROW UEs. The SPARROW UEs can adopt various evasion techniques, such as slowing their activity, routinely changing their CRI code-book and using different random access initial resources. Thus, this strategy can risk the cellular station service availability without offering quantifiable levels of protection.

The remainder of this work focuses on the *entropy-leveraging* remediation strategy. Compared to other strategies, it can practically prevent exploitation with minimal performance impact and no collateral security risks. In the context of Proposition 1, it aims at mitigating the deterministic bijectivity condition between *Msg3* and *Msg4*. The contention resolution procedure in a vulnerable MAC protocol should be modified as follows:

- **Entropy-Leveraging:** This strategy allows the UEs to randomly select the CRI content in *Msg3*. However, it requires the cellular station to obfuscate the content received in *Msg3* with a random pattern before broadcasting it in *Msg4*. The *Msg4* broadcast has two components the obfuscated message and some helper information, i.e. a *hint*. Each UE should process the received *Msg4* and their *Msg3* by a decision function defined in the standard to determine the next RA step. The hint plays an essential role in the decision function. It is designed to ensure the intended UE proceeds while the contending others back off. On the other hand, the obfuscated content of *Msg4* should prevent the SPARROW UEs to form stable code-books \mathcal{M} and \mathcal{B} .

VI. ANALYSIS OF ENTROPY-LEVERAGING STRATEGY

This section is dedicated to analyzing potential remediation schemes following the entropy-leveraging strategy. It first seeks to quantify its impact on the contention resolution performance and explores the theoretical trade-off between the remediation objectives: disrupting SPARROW scheme while preserving contention resolution performance. Section VII then details the elements needed to build a practically optimal scheme.

A. Formulation

Expanding the notation in Section II and Scenario 1, the following steps detail contention resolution process in a entropy-leveraging scheme:

- 1) **Uplink Message:** The random N -bits identities selected by contending UEs form a set of independent identically distributed (i.i.d) random variables with a uniform distribution on support set $U_N = \{0, 1, 2, \dots, 2^N - 1\}$. Lets $X_i \sim \mathcal{U}(2^N)$ be the discrete random variable denoting *Msg3* transmitted by the i -th contending UE in the cell. Analyzing a single exchange, the time has been omitted for brevity. On the other hand, random variable X' denotes Trudy's *Msg3* transmission from codebook $\mathcal{M} \subset U_N$.
- 2) **Obfuscated Broadcast:** The cellular station receives only one of the *Msg3* transmissions that is denoted by $X \in \{X_1, X_2, X'\}$. The cellular station cannot detect the source of X . It then derives *Msg4* modeled by random variable $Y = [B(X), h]$, where B is the broadcast obfuscation function defined in the standard along with the hint value h . In order to facilitate contention resolution, the cellular station includes h in the *Msg4* broadcast, where h is a parameter that is intended to help UEs make correct RA decisions. Depending on the desired level of protection, there could be multiple pre-defined choices

of B in the standard where a cellular station announces its choice in the periodic broadcast signals or *Msg2*. This will ensure the UEs adjust their decision functions accordingly to process *Msg4*.

- 3) **Downlink Processing:** Any choice for B should be accompanied with a well-defined UE decision function $D = D(Y, X_i) \in \{0, 1\}$, where 0 and 1 are respectively interpreted as RA success or failure commands for the i -th UE. Given Y , an ideal choice of D should almost surely evaluate to 1 for no more than one of the contending UEs. The decision function should also have the following property to eliminate the possibility of a live-lock where all UEs arrive at failed RA decision.

$$Pr(D(Y, X_i) = 1 | X = X_i) = 1 \quad (1)$$

Knowing the choice for B and code-book \mathcal{M} , Ricky attempts to recover X' from *Msg4* by devising an estimation function. Let $X'' = E(Y)$ be the random variable representing Ricky's estimated codeword. According Proposition 1, Ricky should design $E(Y)$ to minimize its estimation error probability, $Pr(X'' \neq X')$. It also has to keep the code-book small enough to distinguish between broadcast triggered by Trudy and other UEs. There is always a chance to have another UE in the cell randomly select $X_i \in \mathcal{M}$.

As described in Section V-A, the performance of contention resolution process requires low *identity collision probability* to ensure only one of the contending UEs succeeds in RA. In practice, having more than two UEs simultaneously attempting RA using the same preamble is a rare event that may occur while a cellular station recovers from a maintenance outage. Thus, moving forward, the contention scenarios is considered to only involve two UEs as the most probable scenario, i.e. $i \in 1, 2$. The identity collision probability, P_C for this scenario defined as follows:

$$P_C \triangleq Pr(D(Y, X_2) = 1 | X = X_1) \quad (2)$$

Here we assume both UEs can decode *Msg4* error free. Considering the uniform i.i.d property of X_i , the expression in (2) can be further expanded to

$$P_C = \sum_{\substack{i, j \in U_N \\ i \neq j}} \frac{Pr(D(Y, i) = 1 | X_2 = i, X = j)}{2^{2N}} + \frac{1}{2^N} \quad (3)$$

It implies that 2^{-N} is the minimum achievable value for P_C when $B(X)$ is an injective function. For instance, the current state of the standard described in Section III retrofits in this model with $B(X) = X$ and the identity check decision function $D(X_i, Y) = \delta(X - X_i)$.

B. Trade-Off Bounds

Introducing any obfuscation function should mitigate the achievable error-free data rate for SPARROW UEs while maintaining low P_C . The data rate of SPARROW UE depends on their strategy in selection of code-book \mathcal{M} and the estimation function $E(Y)$ to overcome channel entropy introduced by $B(X)$. Theoretically, it is desired to minimize SPARROW

UE's maximum achievable data rate called *channel capacity* in the context of information theory. SPARROW UEs may achieve the channel capacity by employing sophisticated forward error-correcting (FEC) code-books in the long run. The channel capacity may not be achievable in practice, but certainly highlights the inherent trade-off between protection and performance. Given $X = X'$, the channel capacity for SPARROW UEs is the maximum mutual information quantity as defined below:

$$I(X; Y) = H(X) - H(X|Y) \quad (4)$$

where $H(\cdot)$ denotes Shannon entropy. So, the remediation schemes should aim at designing $B(X)$ so that $H(X|Y)$ is maximized. On the other hand, applying Fano's inequality to the expression in (3), it can be shown that $H(X|Y)$ directly contributes to a lower bound on P_C [16]. Hence, the entropy-leveraging strategy is bound to a trade-off between the contention resolution performance (low $H(X|Y)$) and blocking the SPARROW UEs (high $H(X|Y)$).

The same trade-off can also be derived from a more intuitive viewpoint. The SPARROW UEs send $Msg3$ similarly to the other UEs in the cell. There is also a noticeable correlation between the ways they process $Msg4$ in the entropy-leveraging strategy. Ricky optimizes the estimation function $E(Y)$ to processes $Msg4$ to recover Trudy's message among all the candidates in the code-book \mathcal{M} . Now consider the rarest contention resolution situation where 2^M normal UEs are in contention and each happen to pick a distinct $Msg3$ identities from \mathcal{M} . To resolve the contention, $D(Y, X_i)$ should evaluate to 1 only for the intended UE and 0 for the rest of them. Thus, the collective outcome of $D(Y, X_i)$ serve the same purpose as $E(Y)$ in this hypothetical scenario leading to a very tight trade-off to design the broadcast obfuscation function $B(X)$ to disrupt the functionality for $E(Y)$ while preserving the resolution condition for $D(Y, X_i)$.

In reality, we consider the contention scenario between as few as two UEs that will relax the trade-off. Also, this trade-off does not account for the fact that \mathcal{M} should be small enough to reduce the chance of the $Msg4$ intended for other UEs being misinterpreted by Ricky as legitimate messages from Trudy. The channel capacity derivation in (4) does not account for the minimum viable information needed per attempt for synchronized reception. Ricky will need to reliably identify messages sent from \mathcal{M} in every attempt. In this context, the presented trade-off implies that the entropy-leveraging schemes impact the performance of contention resolution rather than dismissing their feasibility.

Remark. *It is worth noting that using Cryptographic Hash Functions (CHF) to obfuscate $Msg4$ will not serve as a proper remediation since $H(X|Y) = 0$. Even with random salting, $Msg4$ has to include the salt as the hint for the normal UEs to repeat the same computation with their $Msg3$ in the downlink processing step. For any given \mathcal{M} , Ricky can compute the hash value for all of its elements (preimage table) that forms \mathcal{B} of all possible $Msg4$ bijectively correlated to \mathcal{M} . Using CHF will only imposes some modest computational complexity to Ricky.*

C. Solution Examples

Examples of entropy-leveraging scheme should involve reducing $H(X|Y)$ in (4). The following simple schemes are inspired by known binary noisy channel models in communications theory [17]:

- **K-errors:** Similarly to a Binary Symmetric Channel (BSC), the cellular station induces bit errors at K random positions of the UE identity X in $Msg3$. Each time it generates a random N -bits error mask $e_K \in U_N$ with Hamming weight (number of set bits) K that is used to derive the $Msg4$ broadcast message:

$$Msg4: Y = [B(X) = X \oplus e_K, h = K] \quad (5)$$

where \oplus denotes bit-wise XOR operator. The value of K should be previously signaled to UEs or included as a hint to facilitate the decision function of the normal UEs:

$$UE_i: D(Y, X_i) = \delta(K - d_H(B(X), X_i)) \quad (6)$$

implying that each UE computes the Hamming distance $Msg4$ with its $Msg3$ denoted by $d_H(\cdot, \cdot)$ and compares the results against K .

- **K-erasures:** Inspired by Binary Erasure Channel (BEC), the cellular station omits bits at K random positions of the UE identity X in $Msg3$. Each time it generates a random N -bits erasure mask $e_K \in U_N$ with Hamming weight (number of set bits) K that is used to derive the $Msg4$ broadcast message:

$$Msg4: Y = [B(X) = X \circ e_K, h = e_K] \quad (7)$$

where \circ denotes bit-wise bit erasure operator producing $N - K$ remaining from X . It is worth to note that the size of $Msg4$ is $2N + K$ that depends on K as depicted in diagram in Figure 6. The contending UEs will need e_K as a hint to extract corresponding bits from their $Msg3$ in their decision function:

$$UE_i: D(Y, X_i) = \delta(X_i \circ e_k - B(X)) \quad (8)$$

The value of K in both schemes does not have to be random for each message and it can be selected to balance the trade-off between remediation and contention resolution performance.

Using (3), it is straightforward to derive the identity collision probability for each scheme as:

$$\text{K-errors: } P_C = \frac{\binom{N}{K}}{2^N}, \quad \text{K-erasures: } P_C = \frac{2^K}{2^N} \quad (9)$$

These are plotted for different values of K in Figure 7. For both schemes it can be shown that the SPARROW channel capacity is inversely related to P_C conforming to the design trade-off in Section VI-B.

$$I(X; Y) = -\log_2(P_C) \quad (10)$$

SPARROW UEs can use FEC codes which is a well-studies topic in these scenarios. For example, to circumvent the K-erasures schemes, Trudy can retransmit the messages multiple times to increase the chance Ricky recovering all of its randomly erased bits. To survive a K-errors scheme, Trudy can construct a code-books with minimum hamming distances

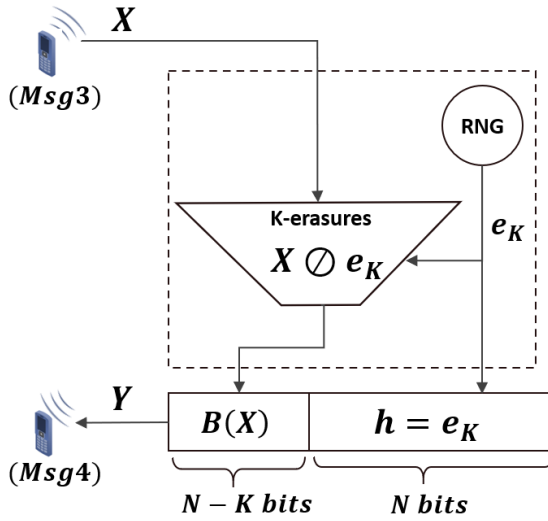


Fig. 6: K-erasures transformation of $Msg3$ to $Msg4$.

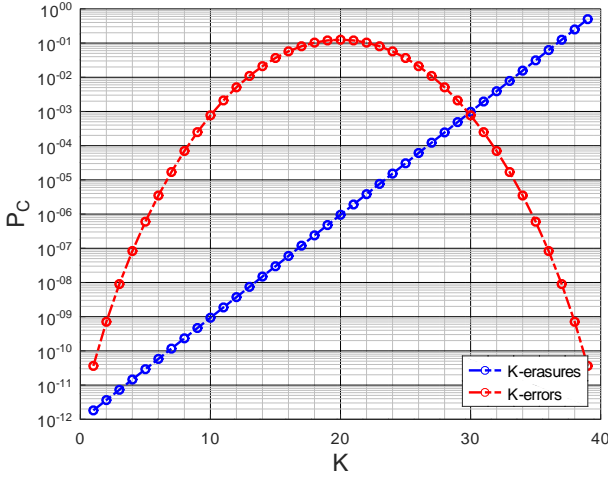


Fig. 7: Comparing identity collision probabilities (P_C) for K-erasures and K-errors schemes with $N = 40$

larger than K whose code words can still be uniquely distinguishable by Ricky despite the errors. This can be impractical if the K-errors scheme employs $K = N/2$. It will be appreciated that this is not a good choice for contention resolution performance since it leads to large $P_C \approx 0.1$ as shown in Figure 7. After all, the subpar effectiveness of these schemes in blocking SPARROW UEs versus their impact on the contention resolution performance still does not make them very attractive.

VII. ENTROPY-LEVERAGED IRREVERSIBLE SECURITY HASHING ALGORITHM (ELISHA)

The effectiveness of the schemes in Section VI-C can be significantly improved by preventing SPARROW UEs from employing FEC code-books. The entropy-leveraging scheme proposed herein achieves this goal by taking advantage of irreversible properties of randomly salted (nonced) CHF.

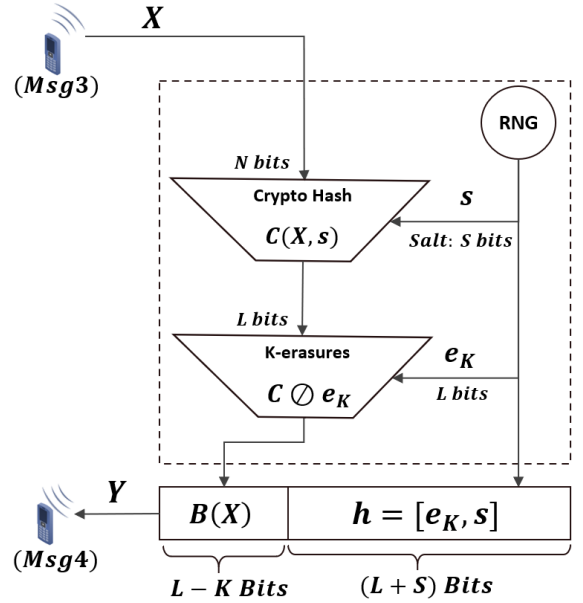


Fig. 8: ELISHA transformation of $Msg3$ to $Msg4$.

A. Design Architecture

Compared to previous schemes, ELISHA applies random bit-erasures (or bit-errors) to a CHF digest of the $Msg3$. Figure 8 illustrates the elements of ELISHA broadcast obfuscation function built based on the K-erasure scheme. Moving forward, this will serve as the reference model for the ease of analysis. The received N -bits identity in $Msg3$ is processed through a CHF denoted by $C(X, s)$ with an optional randomly generated salting nonce s (S -bits size) to produce an L -bits hash digest. The CHFs are designed to maintain bijectivity (unique output for unique inputs) and be computationally irreversible. Here the salting refers to mixing the input with a random s before computing the hash, so the same input produces a different hash digest every time. There are a variety of choices for $C(X, s)$, ranging from sophisticated SHA family to simpler MD family that usually result in $L > N$. The choice of $C(X, s)$ should be communicated to UEs in prior broadcast messages. Choosing the right CHF involves other practical considerations that are beyond the scope of this work.

The CHF output then undergoes a K-erasures process to generate the obfuscated broadcast message of size $L - K$. The cellular station uses a randomly-generated L -bits erasure mask e_K of Hamming weight K (K set bits) every time.

$$Msg4: Y = [B(X) = C(X, s) \odot e_K, h = [e_K, s]] \quad (11)$$

Both s and e_K are encoded in the hint section of $Msg4$ resulting to a broadcast message of total size in order of $2L + S - K$ bits. The increase in broadcast message size can be addressed during the implementation, although it is insignificant for most modern wireless technologies operating with large transmission bandwidths. The i -th contending UE computes $B(X_i)$ using the hint information and proceeds if it

equals to $B(X)$ value received in $Msg4$:

$$UE_i: D(Y, X_i) = \delta(C(X_i, s) \odot e_K - B(X)) \quad (12)$$

Using $C(X_i, s)$ with negligible hash collision probability, the impact of this scheme on contention resolution performance is similar to the K-erasures scheme in (9). It can be shown that the identity collision probability depends on the choice of L and K as follows

$$ELISHA: P_C \approx \frac{2^K}{2^L} \quad (13)$$

B. Remediation Strength

As discussed in Section VI-C, Trudy and Ricky seek to construct the code-book \mathcal{M} of $Msg3$ identity messages with FEC properties to recover their messages through K-erasures (or K-errors) and approach the maximum theoretical bit rate in (10). However with ELISHA scheme, they will lose their ability to employ FEC coding schemes as described in the following remark.

Remark. Given any choice of SPARROW code-book $\mathcal{M} = \{m_1, m_2, \dots, m_{2^M}\}$, the salted cryptographic hash function $C(X, s)$ maps its elements to a random set of L -bits binary string $C_{\mathcal{M}} = \{c_1, c_2, \dots, c_{2^M}\}$ at each attempt, where $c_i = C(m_i, s)$. The irreversible property of $C(X, s)$, makes it computationally infeasible to exert any control over the elements in $C_{\mathcal{M}}$, including FEC properties against bit-erasure (or bit-error). Exploiting the scheme illustrated in Figure 8, communicating M bits of information per attempt requires almost all elements in $C_{\mathcal{M}}$ to produce 2^M unique $B(X)$ output symbols through K-erasures process. Let

$$P_D \triangleq 1 - \Pr(c_i \odot e_K \neq c_j \odot e_K | i \neq j)$$

denote the SPARROW communication disruption rate (probability) due to symbol aliasing. The value of P_D is imposed to Ricky and Trudy regardless of their choice of \mathcal{M} . They have to sacrifice their bit rate, which is determined by M , to barely reach $P_D \ll 1$ for any reliable communication.

Another advantage of ELISHA is the ability to derive the protection metric P_D based on the design parameters. This derivation can be later used to balance the trade-off between low P_C and high P_D depending on the cell load and required level of protection against SPARROW. Calculating P_D relied on the fact that $C_{\mathcal{M}}$ is a collection of random L -bits strings that lose K bits at randomly selected positions through K-erasures process. The entire U_L space (all possible L -bits strings) is randomly divided into 2^{L-K} cut-sets that each contain 2^K strings that produce the same K-erasures output symbols. The definition of P_D indicates the complement event of selecting 2^M elements from U_L where each appears in a distinct cut-set. This can be computed as

$$P_D = 1 - \frac{\binom{2^{L-K}}{2^M} 2^{K2^M}}{\binom{2^L}{2^M}} \quad (14)$$

that can be further reduced to

$$ELISHA: P_D = 1 - \prod_{i=0}^{2^M-1} \left(\frac{2^L - i2^K}{2^L - i} \right) \quad (15)$$

VIII. NUMERICAL RESULTS

Computing P_D in (15) is challenging for large values of L and M and may require numerical approximations. Thus all the following results are computed for $L = 40$. This can also represent a practical example of ELISHA with $N = 40$. One may use random-permutation as a proven collision-free alternative to a randomly salted CHF. It randomly permutes its input string producing an output of the same size. Considering $N!$ possible permutations, it requires at least $O(N \log N)$ additional bits to encode the permutation parameter as a hint in $Msg4$.

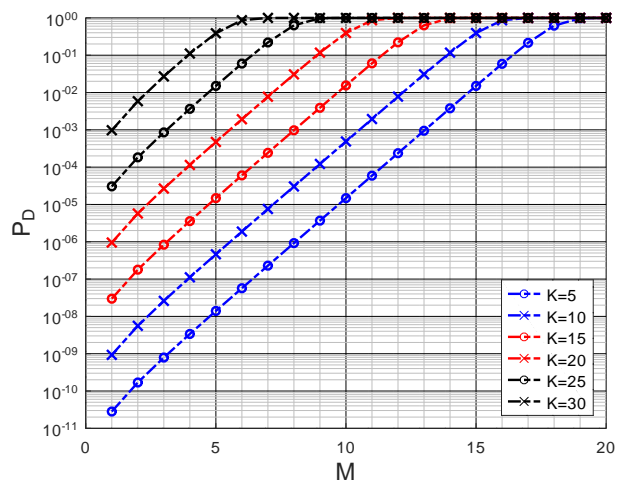


Fig. 9: SRARROW blocking probability (P_D) v.s. the number of bits erased (K)

Figure 9 indicates how increasing M rapidly increases P_D particularly for large K . It demonstrates how ELISHA forces SPARROW UEs to cut their data rate to an impractical level to achieve reliability. For $K \geq 20$, they significantly lose the ability to reliably communicate a single byte that is desired for Ricky to somehow distinguish Trudy's messages from other cell activity.

Figure 10 demonstrates the key design trade-off as expected: imposing higher P_D to SPARROW UEs will result in higher P_C . Setting a desired P_C will determine K from (13). The current standard provides SPARROW UEs with $M = N = 40$, $P_D = 0$ and keeps $P_C \approx 10^{-12}$ which is more than sufficient to ensure successful contention resolution even in a massive cell reboot event. For $P_D = 0.1$ as the maximum tolerable disruption by SPARROW UEs, they have to operate at much lower data rate with $M = 16$ at a slight expense of $P_C \approx 10^{-10}$. It is appreciated that all of the graphs reach a plateau around $P_C \approx 10^{-5}$ where P_D approaches 1 (impossible communication). The maximum tolerable P_C can vary depending on the cell traffic and the level of desired protection against SPARROW.

Figure 11 demonstrates the strength of ELISHA in abating the throughput of SPARROW UEs defined by M that is

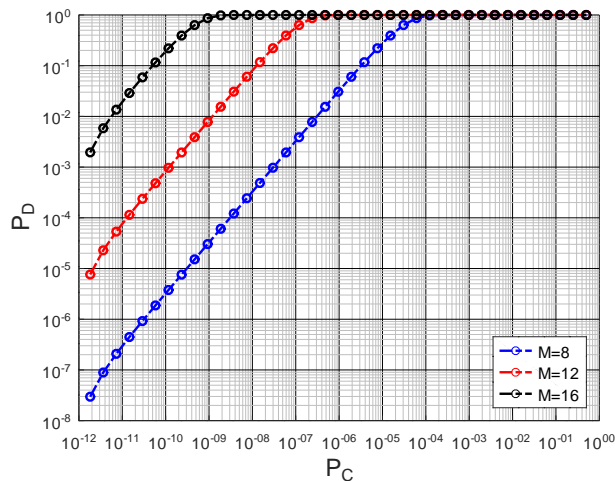


Fig. 10: Trade-off between SRARROW disruption rate (P_D) and identity collision probability (P_C).

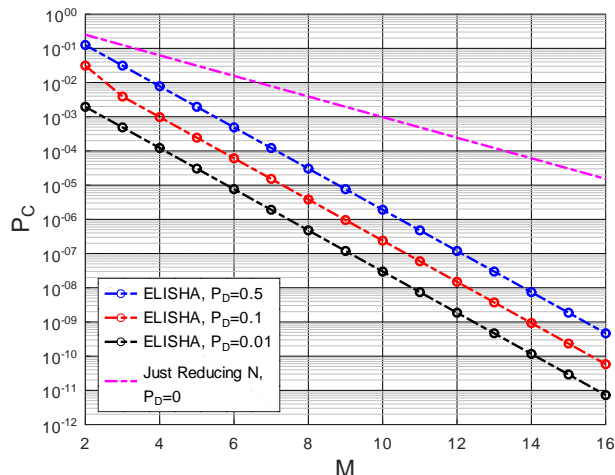


Fig. 11: Trade-off between SRARROW UE data rate (M) and identity collision probability (P_C).

plotted versus P_C for fixed P_D values. Three disruption rate levels are considered for SPARROW UEs: $P_D = 0.01$ (manageable), $P_D = 0.1$ (almost intolerable), $P_D = 0.5$ (impossible to operate). One can see that reducing M at each of the disruption rate levels requires an increase in P_C . This simply corroborates the design trade-off from the data rate point of view. Looking at $P_D = 0.5$ graph, ELISHA makes it impossible for SPARROW UEs to even send a single byte ($M = 8$) at $P_C \approx 10^{-5}$. Given the inherent trade-off in any entropy-leveraging scheme, one may argue for a simpler solution: just reducing N , the number of identity bits in $M \text{sg}3$. The SPARROW UEs have to use smaller codewords of size $M = N$ bits and the only cost would be direct P_C increase. The purple dotted line in Figure 11 shows the performance of such a system. However the results confirm the advantage of ELISHA over such a scheme in terms of much more protection (lower M) for the same sacrificed performance (increased P_C).

The presented results seems to indicate that ELISHA is an efficient solution to protect contention resolution procedures in LTE/5G and other technologies against SPARROW

exploitation schemes. Instances of ELISHA can be potentially adopted in the WCN protocol standards as a secure contention resolution option that is enabled on access radio nodes in vicinity of targets sensitive to covert communication.

IX. CONCLUSION

This work proposed a novel framework to identify and exploit vulnerable MAC layer procedures in commercial wireless technologies for covert communication. In this framework, the SPARROW schemes use the broadcast power of incumbent wireless networks to covertly relay messages across a long distance without connecting to them. This enables the SPARROW schemes to bypass all security and lawful-intercept systems and gain ample advantage over existing covert techniques in terms of maximum anonymity, longer range and less hardware. This paper detailed CVD-2021-0045 disclosed through GSMA coordinated vulnerability disclosure program [1]. This vulnerability has been in the common random-access procedure in the LTE and 5G standards for a long time. Hence, this work investigated remediation strategies tailored for this procedure including ELISHA which is a rigorous remediation that can suit other protocols as well. It can effectively disrupt the most sophisticated SPARROW schemes with a manageable system performance overheads.

Researchers are encouraged to investigate the SPARROW vulnerability conditions, outlined in Proposition 1, in other wireless MAC protocols or other aspects of LTE/5G. Also the framework can be expanded beyond just the broadcast signals to include other measurable implicit changes in the cell operation state that can be controlled by one SPARROW device and detected by another one. Finally, it is recommended to incorporate this framework in security evaluation of the emerging non-terrestrial wireless standards such as 5G-NTN that can be potentially exploited for very long range covert communication.

ACKNOWLEDGMENTS

I would like to thank these individuals at Keysight Technologies who assisted with disclosure and presentation of this work: Chuck McAuley for presentation at [9], Befekadu Mengesha and Lucal Mapelli for PoC implementation in [9] [1], Pete Marsico for technical editing, and finally Steve McGregor and Chris Moore for supporting this research.

REFERENCES

- [1] GSM Association. (2021) GSMA mobile security research acknowledgements. [Online]. Available: <https://www.gsma.com/security/gsma-mobile-security-research-acknowledgements/>
- [2] M. Li, W. Huang, Y. Wang, W. Fan, and J. Li, "The study of APT attack stage model," in *2016 IEEE/ACIS 15th International Conference on Computer and Information Science (ICIS)*. IEEE, 2016, pp. 1–5.
- [3] A. Singh, O. Nordström, C. Lu, and A. L. Dos Santos, "Malicious ICMP tunneling: Defense against the vulnerability," in *Australasian Conference on Information Security and Privacy*. Springer, 2003, pp. 226–236.
- [4] Y. Wang, A. Zhou, S. Liao, R. Zheng, R. Hu, and L. Zhang, "A comprehensive survey on DNS tunnel detection," *Computer Networks*, p. 108322, 2021.
- [5] N. Hou and Y. Zheng, "Cloaklora: A covert channel over LoRa PHY," in *2020 IEEE 28th International Conference on Network Protocols (ICNP)*. IEEE, 2020, pp. 1–11.

- [6] R. Oliveira, M. Luís, and S. Sargento, “LoRa connectivity analysis for urban coverage in real mobile environments,” in *2021 Telecoms Conference (ConfTELE)*. IEEE, 2021, pp. 1–6.
- [7] I. Brown, “Lawful interception capability requirements,” *Computers & Law, Aug/Sep*, 2013.
- [8] 3GPP, “LTE; E-UTRA; medium access control (MAC) protocol standard,” 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 36.321, 04 2015, version 12.5.0.
- [9] (2021) DEF CON 29 - Reza Soosahabi, Chuck McAuley - SPARROW: A Novel Covert Communication Scheme. DEFCON Conference. [Online]. Available: <https://www.youtube.com/watch?v=oaLio9HwW-g>
- [10] N. Maskey, S. Horsmanheimo, and L. Tuomimäki, “Latency analysis of LTE network for M2M applications,” in *2015 13th International Conference on Telecommunications (ConTEL)*. IEEE, 2015, pp. 1–7.
- [11] C. Johnson, *Long term evolution in bullets*. Johnson Northampton, 2012.
- [12] I. Gomez-Miguelez, A. Garcia-Saavedra, P. D. Sutton, P. Serrano, C. Cano, and D. J. Leith, “srsLTE: An open-source platform for LTE evolution and experimentation,” in *Proceedings of the Tenth ACM International Workshop on Wireless Network Testbeds, Experimental Evaluation, and Characterization*, 2016, pp. 25–32.
- [13] F. Rinaldi, H.-L. Maattanen, J. Torsner, S. Pizzi, S. Andreev, A. Iera, Y. Koucheryavy, and G. Araniti, “Non-terrestrial networks in 5G & beyond: A survey,” *IEEE Access*, vol. 8, pp. 165 178–165 200, 2020.
- [14] R. P. Jover and I. Murynets, “Connection-less communication of IoT devices over LTE mobile networks,” in *2015 12th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*, 2015, pp. 247–255.
- [15] S. F. Mjølunes and R. F. Olimid, “Easy 4G/LTE IMSI catchers for non-programmers,” in *International Conference on Mathematical Methods, Models, and Architectures for Computer Network Security*. Springer, 2017, pp. 235–246.
- [16] S. Verdú *et al.*, “Generalizing the fano inequality,” *IEEE Transactions on Information Theory*, vol. 40, no. 4, pp. 1247–1251, 1994.
- [17] A. Makur, “Information capacity of BSC and BEC permutation channels,” in *2018 56th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*. IEEE, 2018, pp. 1112–1119.