Enhancing Channel Shortening Based Physical Layer Security Using Coordinated Multipoint

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Abstract—Wireless networks have become imperative in all areas of human life. As such, one of the most critical concerns in next-generation networks is ensuring the security and privacy of user data/communication. Cryptography has been conventionally used to tackle this, but it may not be scalable (in terms of key exchange and management) with the increasingly heterogeneous network deployments. Physical layer security (PLS) provides a promising alternative, but struggles when an attacker boasts a better wireless channel as compared to the legitimate user. This work leverages the coordinated multipoint concept and its distributed transmission points, in conjunction with channel shortening, to address this problem. Results show significant degradation of the bit-error-rate experienced at the eavesdropper compared to state-of-the-art channel shortening-based PLS methods.

Index Terms—5G, 6G, channel shortening, coordinated multipoint (CoMP), OFDM, physical layer security.

I. INTRODUCTION

Wireless communication has pervaded all aspects of human existence. The recent pandemic has further cemented its importance, with different facets of our daily lives including (but not limited to) education, retail, banking, healthcare all depending heavily on reliable wireless communication for their continuity despite the challenging restrictions worldwide [1]. While this ubiquitous availability of wireless signals is desirable from a communication (and sensing) perspective, it is becoming increasingly challenging to ensure the privacy of confidential data and information when it is being transmitted openly into the environment [2]. This broadcast nature of wireless communication renders it susceptible to threats such as eavesdropping, jamming, and spoofing. In eavesdropping, the attacker tries to intercept and interpret the ongoing communication between legitimate nodes. In jamming, the attacker’s target is to disrupt the communication, while in spoofing, the attacker impersonates a legitimate node for malicious purposes [3]. The latter two, though more serious in impact, are often preceded by the former. Presently, there are two well-established approaches for securing wireless networks, i.e., cryptography and physical layer security (PLS). Cryptography secures the message or content of communication using keys for both encryption and decryption of the messages. However, this requires the exchange of keys (in symmetric encryption), their management, and computational capabilities at the terminals. PLS provides a complementary solution for securing communication by protecting the wireless link (and the physical signal traversing it) between legitimate nodes using the properties of the channel and transceivers [4].

In the context of this work, we focus on the development of a coordinated multipoint (CoMP)-assisted PLS solution, that leverages channel shortening to protect communication against eavesdropping attacks. While the CoMP concept has been around for over a decade, only a handful of works have considered its application for securing wireless communication [5]–[9]. CoMP has been leveraged in [5] to address the limitation of directional modulation as it fails to secure the communication if the eavesdropper is in the same direction as the legitimate receiver. The coordinating transmission points (TPs) transmit copies of the same signal using directional modulation, such that these are correctly received only at the legitimate receiver’s location, providing location-based security. Building on top of that, CoMP is proposed to be used for sparse radio environments such that data is only decodable at the intersection of information beams while a distorted constellation is observed at other locations [6]. CoMP-based transmissions from distributed antenna elements in an underwater scenario are proposed in [7], where the power and schedule of transmissions are manipulated such that the messages are non-overlapping at the legitimate receiver while being overlapped (and interfering) at the eavesdropper. A dynamic CoMP scheme is proposed in [8] to enhance secured coverage. The proposed scheme is based on the received signal power for the legitimate users where TPs far from the legitimate user are blocked for security and energy consumption concerns. The CoMP scheme is also being used in unmanned aerial vehicle (UAV) systems to achieve secrecy. CoMP reception-enabled secrecy UAV communication system is proposed in [9], in which multiple ground nodes cooperatively detect the legitimate information sent from the UAV to enhance the legitimate communication performance in eavesdropper’s presence.

Channel shortening, on the other hand, has been utilized to improve security against eavesdropping in [10], where the channel shortening equalizer is designed considering the
channel between legitimate transmitter (Alice) and legitimate receiver (Bob). The security is provided by shortening the effective channel impulse response (CIR) at Bob and designing/selecting the cyclic prefix (CP) accordingly. Since the CIR experienced by the illegitimate eavesdropper (Eve) is longer, the signal it receives is prone to inter-symbol interference (ISI), deteriorating its reception. However, the shortening approach fails when Eve experiences a better channel (shorter CIR) as compared to Bob. This shortcoming is addressed in the current work, which contributes the following:

- This work proposes a CoMP-assisted solution against eavesdropping which, in conjunction with channel shortening, addresses the limitation of multiple PLS mechanisms that fail when the attacker experiences a better channel compared to the legitimate receiver.
- The effect of correlated channel between the eavesdropper and legitimate receiver on the proposed technique is also studied.
- The limitations and future directions for this work are provided.

The rest of this article is organized as follows. Section II describes the preliminary system model and its associated assumption. The proposed method is given in Section III. Section IV provides the simulation results. Section V concludes the paper by highlighting the limitations and future directions associated with this work.

II. SYSTEM MODEL AND ASSUMPTIONS

In this work, downlink communication using orthogonal frequency-division multiplexing (OFDM) is considered. There are $K$ coordinating TPs present, that use joint transmission (JT) to serve the user in an urban environment. For simplicity, a single legitimate receiver, referred to as Bob, and a single eavesdropper called Eve are considered. Both Bob and Eve are located randomly within the coverage area of the cooperating TPs and are assumed to experience independent and uncorrelated frequency-selective Rayleigh fading (Section IV, however, looks at the effect of correlated channels), albeit with the same exponentially decaying power delay profile. In general, the received signal at either Bob or Eve from the multiple cooperating TPs can be expressed as

$$Y_j(i) = \sum_{k=1}^{K} \sqrt{P_k} H_{j,k}(i) X_k(i) + W(i),$$

where $j \in \{b, e\}$, depending on whether the receiver is Bob or Eve, $X_k(i)$ is the $i$-th transmitted symbol from $k$-th TP, $H_{j,k}(i)$ represents the $N$-point fast Fourier transform (FFT) of the $k$-th TP’s CIR, $W(i) \sim \mathcal{N}(0, \sigma)$ represents the additive white Gaussian noise (AWGN), where $\sigma$ is the noise power spectral density (PSD), $B_T$ is the system bandwidth and $P_k$ is the signal power received from $k$-th TP. This power is calculated considering the pathloss described for urban macrocell environment given in [11] using the following equation:

$$P_k = P_k^{Tx} - (22 \log_{10}(d) + 20 \log_{10}(f_c) + 28 + \sigma),$$

where $P_k^{Tx}$ is the power transmitted from the $k$-th TP, $d$ is the 3-D distance between the TP and the user equipment (UE) in meters, $f_c$ is the carrier frequency in GHz, and $\sigma$ represents the shadow fading modeled as a zero-mean log-normal distribution. Since the goal of this work is to highlight the potential of the proposed method (described in Section III) for securing the communication, we assume perfect channel estimation and ideal synchronization/backhaul [12] in the JT-CoMP.

III. PROPOSED APPROACH

In this work, we aim to tackle the issue arising in conventional channel-adaptation based PLS mechanisms when the channel of the eavesdropper is better as compared to the legitimate node. This is achieved by leveraging the geographically distributed TPs offered by CoMP networks to provide security against eavesdropping attackers in a wireless communication system. The main stages of the proposed technique are listed below:

- **Selection of the coordinating TPs:** Different criteria may be considered for the selection of coordinating TPs, such as the received signal strength indicator (RSSI), received power relative to the serving TP, or a combination of both [13], [14]. It is also possible to have different sets of cooperating TPs for each user, or the same set for a group of users. The selection of coordination set can also be done for different objectives/constraints such as capacity maximization, spectral efficiency, energy efficiency, etc. [15]. For the sake of this work, we have considered an interference-free scenario, where only two TPs are present and coordinating. Hence, there is no need of selecting any TPs.

- **Splitting of the data:** The data that is to be sent to the aforementioned user in split into $K$ parts, where $K$ is the number of TPs used. For the sake of this work, we
restrict ourselves to a very simple approach, i.e., into real and imaginary parts where TP 1 transmits the former, while TP 2 sends the latter. Here it should be pointed out that further analysis is required to determine the optimum splitting mechanism, especially in the case of \( K \neq 2 \). However, it is beyond the scope of the present work.

- **Channel-based manipulation**: This step covers the design of a channel-based manipulation mechanism for the transmitted signal to ensure the signal received at the legitimate node has delay spread, \( \tau_{\text{max}} \) less than the guard duration, i.e., \( \tau_{\text{max}} < T_g \). In other words, CIR length, \( L \) (assuming sample spaced taps) is less than CP length. However, the goal is to ensure that the same is NOT true for the illegitimate node, i.e., Eve. In our particular case, we consider the usage of a CSF. A CSF is typically used at the receiver to shorten the CIR observed by it, allowing it to use smaller CP/guard, thereby improving the spectral efficiency of the system [16]. However, it has been used for PLS in [10] as described in Section I but is only applicable in the case where Eve is farther from the TP compared to Bob. Since we use distributed TPs in this work, it ensures that Eve experiences longer \( \tau_{\text{max}} \) over at least one of the links which will lead to intersymbol interference (ISI) and degrade its interception capability.

Figure 2 illustrates the block diagram for the proposed method. It can be seen that the data splitting and CSF blocks set the transmitter apart from a conventional OFDM one. On the other hand, receiver side is typical of what we expect in an OFDM transceiver. The received signal can be mathematically represented by expanding (1) as

\[
Y_j(i) = \sqrt{P_1} H_{j,1}^{c}f(i) X_1(i) + \sqrt{P_2} H_{j,2}^{c}f(i) X_2(i) + W(i),
\]

(3)

where \( X_1(i) \) and \( X_2(i) \) represent the real and imaginary parts of the transmitted symbol, \( X(i) \), i.e.,

\[
X_1(i) = 9\Re\{X(i)\},
\]

(4)

\[
X_2(i) = 3\Im\{X(i)\},
\]

(5)

and

\[
H_{j,k}^{c}f(i) = H_{j,k}(i) H_{b,k}^{c}f(i).
\]

(6)

Here, \( H_{b,k}^{c}f \) refers to the maximum shortening signal-to-noise ratio (MSSNR) CSF [16] designed specifically for the link between the \( k \)-th TP and Bob. It should be noted that the CSF block is part of the transmitter, therefore, received signals at both Bob and Eve pass through the same shortening filter. However, since its design is done to increase the shortening signal-to-noise ratio (SNR) for Bob only, the effective channel for both differ significantly, as shown in Fig. 3. Original CIR for both, Bob and Eve is assumed to have length, \( L = 8 \) while the desired CIR length is set as 4. The length of the MSSNR shortening filter is four times the original CIR length. It can be seen that the CIR for Bob after shortening is indeed limited to 4 taps (near zero values after that). On the other hand, for Eve a significant amount of energy lies outside the original CIR length which is exploited in the form of ISI to degrade its decoding capability. This is also shown in Fig. 2 where the CIR experienced by Eve from the far TP exceeds the CP duration. For Bob, however, both links experience a CIR which lies within the CP.
The simulations carried out in this works assume a macro urban environment, with two TPs at a distance of 500m. Carrier frequency, $f_c$ is assumed to be 2 GHz, and shadow fading standard deviation, $\sigma$ is 4 dB. Total transmit power of the each TP is 40dBm and noise PSD, $N_0$, is $-174$dBm/Hz. The original CIR length, $L$ for both Bob and Eve is 8. However, desired CIR for the CSF is 4, which is also used as the CP duration. The reported results are obtained over 2500 iterations, where each iteration sends 64 OFDM symbols with Quadrature Phase Shift Keying (QPSK) modulation. The receiver employs maximum likelihood detection to detect the real and imaginary parts of the symbols accurately. These and other simulation parameters are summarized in Table I.

As mentioned earlier, the goal of Eve is to intercept and interpret the ongoing legitimate communication. Consequently, the target of any PLS mechanism is to ensure that Eve is unable to capture the least possible information. A practical metric used to evaluate the performance of the security mechanisms, therefore, is the gap in error rates (bit, symbol, packet, etc.) experienced by Bob and Eve, which is also referred to as the security gap. Ideally, this should be increased without compromising Bob’s (baseline) performance. Accordingly, in this work we evaluate the performance of the proposed approach by comparing the bit error rates (BERs) experienced by both Bob and Eve when i) only channel shortening is used, ii) only data splitting is used, iii) both shortening and splitting are used, as shown in Fig. 4. The BER performance of a conventional OFDM system is also presented to serve as a baseline.

It can be seen that data splitting itself provides no advantage in terms of security as both Bob and Eve experience similar BERs as the baseline. This is expected since they are like the baseline case themselves when looked at in isolation. As in the case of [10], channel shortening provides a significant gain in terms of the security gap while providing a degraded BER performance for Bob as compared to the baseline case. The proposed approach improves on the shortening, by further exacerbating Eve’s performance without any degradation in Bob’s reception quality. Quantitatively speaking, there is an approximately threefold worsening of Eve’s BER at 29 dBm transmit power, as shown in Fig. 5. This specific value is chosen since it represents the transmit power for one resource block (RB) when the maximum transmit power is equally distributed amongst all RBs. Since CSF performance is closely related to the original and desired CIR lengths, we have evaluated the system for various symbol ($N$) and CP ($N_{CP}$) durations where the CP length is always chosen as equal to the desired CIR length, which is in turn, half the original CIR. Table I summarizes these results. It can be seen that as the CP (and desired CIR) ratio increases, the gap in BER performance of Bob and Eve reduces significantly. This indicates the importance of selecting the most appropriate CP/desired CIR length during the shortening process.

Here, it should be noted that we have assumed the channels between the TPs and Bob and Eve to be uncorrelated and independent. In fact, most channel-based PLS mechanisms rely on this assumption to provide the required security gap. Accordingly, we look at the performance of the proposed approach by comparing the BERs as the baseline. This is expected since they are like the baseline case themselves when looked at in isolation. As in the case of [10], channel shortening provides a significant

### Table I

| Parameter                      | Value |
|-------------------------------|-------|
| Simulation environment        | Urban macro |
| Carrier frequency ($f_c$)     | 2 GHz |
| Number of RBs/TP              | 50    |
| System bandwidth ($B_T$)      | 10 MHz |
| Shadow fading standard deviation ($\sigma$) | 4 dB |
| Noise power density ($N_0$)   | $-174$ dBm/Hz |
| Inter-site distance           | 500 m |
| CIR length ($L$)              | 8     |
| Desired CIR ($= N_{CP}$)      | 4     |

![Fig. 4. Performance comparison of the proposed approach with channel shortening, data splitting, and baseline OFDM in terms of BER at Bob and Eve.](image1)

![Fig. 5. Performance comparison of the proposed approach with channel shortening [10] in the presence of channel correlation between Bob and Eve, where $\rho$ represents the correlation coefficient.](image2)
V. CONCLUSION AND FUTURE WORK

Enhancing the privacy and security of user data is increasingly becoming a major concern for wireless networks. Conventional methods such as cryptography are prone to computationally advanced attackers, while also suffering from key management issues, especially in ultra-dense heterogeneous networks. PLS provides a complementary solution to these security concerns, however, the majority of these methods also struggle when the eavesdropper boasts a better (stronger) channel as compared to the legitimate receiver. In this work, the distributed TPs offered by CoMP are leveraged to address this problem. Specifically, the user data is split into multiple parts, where each part is sent using a different TP. This ensures that at least one of the illegitimate links has a worse channel as compared to the legitimate one. Additionally, a channel shortening filter is applied w.r.t legitimate links, which results in ISI being introduced at the receiver. Simulation results verify that the proposed method is more advantageous as compared to the existing shortening-based PLS mechanism.

It should be noted that this work provides a rudimentary method (and analysis) of leveraging CoMP with channel shortening for security. Further studies are required to fully explore the potential of these two mechanisms in securing communication. In this context, one of the future studies that we believe is highly merited is the analysis of the effect of data splitting mechanisms and its dependence on the number of cooperating TPs in improving security. Furthermore, it might also be worthwhile to look at the performance of the proposed method (and any other mechanisms arriving from it) under different propagation environments, line-of-sight (LoS) assumptions, channel estimation errors, and scattering levels, etc.

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