Intelligent Interference Engineering for Secure Non-Orthogonal Multiple Access

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Abstract

Non-orthogonal multiple access (NOMA) is an effective approach to improving spectrum utilization and supporting massive connectivity for next-generation wireless networks. However, over a wireless channel, the superimposed NOMA signals are highly susceptible to eavesdropping, potentially leading to the severe leakage of confidential information. In this article, we unleash the potential of network interference and exploit it constructively to enhance secrecy in NOMA networks. Particularly, three different types of network interference, including artificial noise, a specifically-designed jamming signal, and inter-user interference, are well engineered to intentionally reduce information leakage while mitigating the effects on signal reception quality of the legitimate users, thus significantly enhancing the transmission security of NOMA. Furthermore, we propose potential interference engineering strategies in more advanced full-duplex NOMA, cognitive NOMA, and multi-cell NOMA networks, and discuss various open research problems and challenges, which could inspire innovative designs of interference engineering for secure NOMA communications.

Index Terms

Non-orthogonal multiple access, wireless security and privacy, physical-layer security, interference engineering, interference cancellation.

I. INTRODUCTION

With the ever-increasing Internet of Things (IoT) applications, it is challenging for current wireless networks to support them over the scarce spectrum by using orthogonal resource allocation. Non-orthogonal multiple access (NOMA) emerges as a promising solution to break the orthogonality constraint for resource allocation [1]. With the joint design of superposition...
coding (SC) and successive interference cancellation (SIC), multiple users can be served by utilizing a same time-frequency resource, thus improving spectral efficiency and achieving massive connectivity. Compared to the conventional orthogonal multiple access (OMA) approaches, NOMA has the advantages of better fairness and lower latency, making it a highly appealing multiple access technique for next-generation wireless networks.

However, the broadcast nature of wireless channels poses secrecy threats to NOMA since: 1) An external eavesdropper can overhear the multiuser superposition transmission and may decode multiple users’ signals for a malicious purpose, and 2) a legitimate user (referred to as an internal eavesdropper) with a strong channel gain can easily recover and intercept other legitimate users’ signals using SIC, leading to a more severe information leakage problem than that in OMA. This calls for physical-layer security, which exploits the intrinsic properties of the wireless medium to increase the rate of the legitimate channel (from a transmitter to its receiver) and/or decrease the rate of the wiretap channel (from the transmitter to the eavesdropper), to improve the secrecy rate (the difference between the rate of the legitimate channel and that of the wiretap channel) [2]. Among different kinds of physical-layer security solutions, the use of network interference is an efficient means to degrade the capability of the eavesdropper and enhance the transmission security of NOMA. This idea is motivated by the following two facts:

- Intentionally generated interference, such as artificial noise (AN) and specifically-designed jamming signal (SJS), can make the wiretap channel a degraded version of the legitimate channel, thus achieving perfect secrecy (which implies a positive secrecy rate).
- Inter-user interference (IUI), that is inherent in NOMA due to the multiuser superposition transmission, is traditionally regarded as a deleterious factor which brings adverse effects to the legitimate users. However, the IUI also affects the eavesdropper and can be engineered towards a security advantage. By striking a balance between the minimization of the IUI at the legitimate users and the maximization of the IUI at the eavesdropper, the secrecy performance can be enhanced significantly.

In this article, we unveil the beneficial role of network interference for physical-layer security and investigate interference engineering for secure NOMA communications. First, both internal and external eavesdropping attacks in NOMA networks are illustrated. Then, we introduce three novel approaches that intelligently engineer the AN, SJS, and IUI to improve the transmission security of NOMA. Furthermore, by integrating NOMA with advanced wireless communication
concepts, we propose several potential interference engineering strategies to exploit more network interference resources that already exist in full-duplex NOMA, cognitive NOMA, and multi-cell NOMA networks for secrecy enhancement, along with open problems and challenges.

II. EAVESDROPPING ATTACKS IN NOMA

We consider three typical NOMA scenarios and discuss the eavesdropping attacks. A base-station (BS) uses the NOMA principle to transmit secret signals to user-1 (who is assumed to have a strong channel gain and be served by the BS directly) and user-2 (who is assumed to have a weak channel gain and be served by the BS directly or through the relay). User-1 performs SIC, i.e., it first decodes user-2’s signal by treating user-1’s signal as noise and removes the decoded signal from its observation, and then decodes its own signal. User-2 decodes its signal by treating user-1’s signal as noise. Due to the broadcast nature of wireless channels, the signals are prone to eavesdropping attacks from both internal and external entities, as shown in Fig. 1 and described below.

- **Case I:** An external eavesdropper located next to the users can receive all the signals and try to decode them using SIC [3].
- **Case II:** Not every user in NOMA networks has the same security level and one may be untrusted to the other, i.e., probably serving as an internal eavesdropper [4]. For instance, if user-1 is untrusted, it can get user-2’s signal easily, as user-1 is designed to decode user-2’s signal first in SIC. If user-2 is untrusted, after decoding its own signal, it is capable of decoding user-1’s signal through SIC.

![Fig. 1. Eavesdropping in NOMA.](image-url)
Case III: In heterogeneous networks, the untrusted relay follows the designated amplify-and-forward protocol to assist the BS transmission, while at the same time serving as an internal eavesdropper to decode the confidential information of user-1 and user-2.

The above scenarios pose serious threats to secure NOMA communications. In the sequel, we leverage physical-layer security techniques in NOMA, where the network interference (i.e., the AN, SJS, and IUI) is judiciously engineered to combat external and internal eavesdropping attacks.

III. AN EXPLOITATION FOR NOMA SECRECY

In some cases, the distance from the eavesdropper to the BS may be shorter than those from the users to the BS. Due to the strong channel gain of the eavesdropper, any signal decoded by the users can be also decoded by the eavesdropper, referred to as the near-far effect.

To avoid information leakage under the near-far effect, it is necessary to create interference intentionally at the eavesdropper to degrade its signal reception quality. To achieve this goal, AN-aided beamforming is an appealing solution. The basic idea behind AN-aided beamforming is to simultaneously transmit the NOMA signals and the AN by using multi-antenna techniques. Unlike OMA where only a single user is considered, NOMA introduces additional constraints to the AN-aided beamforming, including: 1) Each user should still maintain a sufficient power level difference for the received signals to facilitate its SIC decoding, which implies that the
conventional maximum-ratio transmission (MRT) principle is not suitable for designing the signal beams in NOMA networks [5]; and 2) the AN should lie in the null space of the multiuser legitimate channels. Figure 2 gives an example of the AN-aided beamforming, where the signals intended for user-1 and user-2 are denoted by $x_1$ and $x_2$, respectively. For reliable and secure NOMA communications, the signal beams $v_1$ (for transmitting $x_1$) and $v_2$ (for transmitting $x_2$) are jointly designed, such that: 1) At user-1, the power levels of $x_1$ and $x_2$ are boosted in parallel to facilitate user-1’s SIC and signal decoding; and 2) at user-2, the power level of $x_2$ is enhanced while the interference level of $x_1$ is reduced to benefit user-2’s signal decoding. The AN beam $V_0$ is designed following the zero-forcing (ZF) principle to perfectly null out the AN in legitimate channels of both users. Hence, by increasing the transmit power or number of antennas at the BS, the rates of the users increase while the rate of the eavesdropper saturates, such that a positive secrecy sum rate for NOMA is achieved [6]. Furthermore, in AN-aided beamforming, power allocation between the signals and the AN plays a crucial role in the overall secrecy performance [4], and directly maximizing the NOMA secrecy sum rate is in general challenging due to its non-convex form. To improve tractability, a promising approach is to transform this maximization problem to another problem that maximizes the AN power received at the eavesdropper subject to the targeted reliability guarantee of each user [4]. The rationale is that the AN is zero-forced at the users without degrading their signal reception performance, and maximizing the resultant AN power can maximally degrade the capability of the eavesdropper, which benefits secrecy in the considered NOMA networks.

AN-aided jamming is another case of exploiting the AN, also shown in Fig. 2 where the single-antenna BS cannot perform beamforming to ensure that the AN interferes only with the untrusted relay but not the users. In this case, secure communications can be achieved by asking the users to transmit the AN, as described next [7]. During the first phase, the BS sends its NOMA signals and both users send the AN simultaneously to the untrusted relay. During the second phase, the untrusted relay forwards its received signals to the users. To enable the AN cancellation, each user needs to know the AN from itself and from the other user a priori. With the AN information sharing between both users, they can eliminate the negative effect of the AN on their signal reception, while the untrusted relay cannot cancel the AN and hence it is confused by the AN. However, the AN information sharing between the users requires a sophisticated physical-layer key distribution procedure [2], which inevitably yields a very high computational complexity. To realize simple AN cancellation, an effective approach is to let user-
1 transmit the AN and user-2 receive and cache the AN in the first phase [8]. Upon receiving their signals in the second phase, both users can cancel the AN since the AN is a copy which is transmitted by user-1 and cached by user-2 in the first phase. In this way, secrecy against the untrusted relay is efficiently guaranteed without any physical-layer key distribution.

IV. SJS ENGINEERING FOR NOMA SECRECY

Recently, there has been increasing interest in carefully engineering the SJS for enhancing the transmission security of NOMA [9]. Unlike the AN which is generated by the Gaussian pseudo-random sequence, the SJS has a known structure similar to that of the information signals. The design of the SJS assumes that the legitimate users should be able to remove the SJS by using SIC before decoding the NOMA signals (i.e., SJS does not affect the signal reception of legitimate users). This approach can be considered as a complement to the AN-based approaches, for scenarios where the AN is leaked to the legitimate channels.

The SJS engineering concept can be demonstrated by a cooperative NOMA example, shown in Fig. 3, which considers both downlink and uplink transmissions [9]. The downlink signaling works as follows (in the left side of Fig. 3).

- During the first phase, the BS sends the NOMA signals to both users, and user-2 sends the SJS to protect the BS transmission. The SJS is transmitted isotropically, and both the relay and user-1 can receive it, which could be harmful to user-1’s signal decoding. To this end, user-2 selects the SJS rate to guarantee that user-1 can first decode and remove the SJS in SIC, and then decode the NOMA signals. As the SJS rate is chosen based on the channel
gain of the user-2↔user-1↔BS link, which is independent of that of the user-2↔relay↔BS link, the relay may not be able to decode the SJS and is likely to treat the SJS as extra interference, which degrades the signal reception quality.

- During the second phase, the relay forwards its amplified signals and the BS sends a new signal. Since the SJS is transmitted by user-2, it can first remove the SJS and then decode its own signal. With the decoding results of the first phase, user-1 decodes the new signal after removing the previous NOMA signals. Due to the half-duplex operation, the relay cannot receive the new signal from the BS when it is transmitting, meaning that the new signal is securely received by user-1.

The uplink signaling is as follows (in the right side of Fig. 3).

- During the first phase, user-2 sends its signal while user-1 simultaneously sends its signal and the SJS. Specifically, the SJS rate is designed using the channel gain information between user-1 and the BS, such that before decoding user-1’s signal, the BS can decode the SJS by treating user-1’s signal as interference and then subtract the SJS in SIC. When the relay tries to decode the SJS, the signals from both users will serve as interference. Thus, it is very unlikely for the relay to recover the SJS, and thus, the relay’s eavesdropping capability will be degraded by the SJS.

- During the second phase, the relay retransmits its received signals and user-1 sends a new signal. Using the prior knowledge of the SJS and user-1’s signal of the first phase, the BS can remove them and sequentially decode user-2’ signal and user-1’s new signal. Similar to the downlink signaling, this new signal cannot be eavesdropped by the relay due to its half-duplex feature.

Clearly, by increasing the system transmit power, the eavesdropping capability of the relay is bounded since the SJS serves as extra interference to its information decoding, while the performance of the legitimate receivers improves due to its perfect SJS cancellation. In Fig. 4, the ergodic secrecy sum rate (ESSR) of the SJS engineering scheme is compared to that of the AN-based scheme (in which user-2 and user-1 send the AN in downlink and uplink, respectively). It can be observed that the SJS engineering scheme achieves a much higher ESSR than the AN-based scheme for both downlink and uplink transmissions, and the performance gap between the two schemes increases as the system transmit power increases. This reveals that when the AN interferes with the legitimate users in NOMA, exploiting the SJS is an efficient way to enhance
Fig. 4. The ergodic secrecy sum rate vs. the system transmit power for cooperative NOMA. Rayleigh block fading channels are assumed (the average channel gains from the BS to relay, from the relay to user-2, from the BS to user-1, from user-1 to user-2, and from the relay to user-1 are set to 0.9, 0.9, 0.8, 1, and 0.5, respectively).

V. IUI MANAGEMENT FOR NOMA SECRECY

It is true that the IUI simultaneously affects the users and the eavesdropper. If appropriately managed, the IUI can be beneficial to improve secrecy by serving as jamming signals to the eavesdropper. This approach is cost-effective, in the sense that the secrecy is guaranteed not by constructing artificial interference (i.e., AN and SJS) that consumes extra communication resources, but rather by reusing the IUI inherent in NOMA networks.

Hindering SIC at Eavesdropper: Indeed, secrecy can be enhanced by carefully harnessing the IUI to disable SIC at the eavesdropper. We explore this concept by considering a NOMA network comprised of a $K$-antenna BS, $M$ users, and an eavesdropper, where $M > K$. Channel reciprocity is assumed.

- When all $M$ users request secure transmission (in this case, the number of antennas at the BS is inadequate for ZF beamforming with respect to all the users), the SIC can be disabled at the eavesdropper if it has uncertainty about the IUI. To achieve this, for each transmission, all the users transmit their pilots and the BS can acquire the channel gains accordingly. Based on the channel knowledge, the BS designs its signal beams to ensure that the users can successfully carry out SIC to decode the signals. Being unaware of the users’
channels and the BS’s signal beams, the eavesdropper fails to perform SIC and is likely to treat the IUI as noise when it tries to decode the signal of one specific user. This implies that the IUI now becomes useful jamming signals that can help degrade the capability of the eavesdropper [10].

• When only $M_0$ ($< K$) users require secure transmission (for this, the number of antennas at the BS is sufficient for ZF beamforming with respect to these users), we can exploit the IUI more efficiently to impede the eavesdropper’s SIC by joint ZF beamforming, user clustering and scheduling. For brevity, the users that require secure transmission are called secure users (SUs) and the other users are called regular users (RUs). Specifically, the BS groups all the users into $M_0$ clusters with one SU and one or more RUs in each cluster. After user clustering, the IUI exists in two forms: inter- and intra-cluster interference. Then, the BS designs its beams for each SU following the ZF principle, and schedules the RUs in each cluster to guarantee that the SU has the largest effective channel gain. In this way, each SU receives no inter-cluster interference and can subtract the intra-cluster interference by SIC. However, the eavesdropper lacks the information of either the ZF beams or the decoding order and cannot perform SIC, hence its signal reception is severely jammed by both inter- and intra-cluster interference [11].

*Impeding Coherent Detection at Eavesdropper:* It is implied in [12] that if the number of antennas of the eavesdropper is nearly double the number of the BS, AN-aided beamforming
cannot work since the eavesdropper would be able to fully eliminate the AN by using, for example, null-space receive beamforming technique. In this situation, the system can rely on the IUI and artificially create randomness to the IUI for impairing the eavesdropper’s detection performance. An example of this IUI engineering concept is schematically shown in Fig. 5 where a $K$-antenna BS transmits to two single-antenna users in the presence of an $N$-antenna eavesdropper ($K \ll N$). A quasi-static block fading channel is assumed, and the duration of one fading block is $T$. For each time slot $t (< T)$, the BS splits message $W_k$ (intended for user-$k$), $k \in \{1, 2\}$ into two parts $W_{k,1}$ and $W_{k,2}$ and encodes them independently into signals $s_{k,1}(t)$ and $s_{k,2}(t)$. Through NOMA signaling, $s_{1,1}(t)$ and $s_{2,1}(t)$ are superimposed into $s_1(t)$, and $s_{1,2}(t)$ and $s_{2,2}(t)$ are superimposed into $s_2(t)$. After that, the BS linearly precodes $s_1(t)$ and $s_2(t)$ based on MRT and random beamforming (RB), respectively. Here, the RB vector is specifically designed to ensure that both users still experience the block fading channel while the eavesdropper undergoes an equivalent fast fading channel [12]. As a consequence, each user can do coherent detection to retrieve its signal successively. Due to the inserted RB vector, the IUI $s_2(t)$ received at the eavesdropper resembles the random noise that varies across different $t$. Thus, the eavesdropper can only detect $s_1(t)$ and $s_2(t)$ non-coherently without SIC, which greatly degrades its bit-error-rate performance.

**Creating Strong IUI at Untrusted Users:** As discussed previously, when only one specific user requests a secret signal (this user is called private user), other users in the NOMA network may serve as potential eavesdroppers (these users are called untrusted users). To protect the secret signal transmission, a promising solution is to change the SIC decoding order at all the users and create strong IUI at the untrusted users. More specifically, the signal beams for each user are appropriately designed, such that the received power level of the secret signal is the largest at the private user but the smallest at the other untrusted users. Therefore, when the private user decodes the secret signal, it can achieve a high data rate since it receives the secret signal with the largest power. Nevertheless, the secret signal can only be retrieved in the last SIC stage at the eavesdropper. Recall that each untrusted user can partially subtract the signals of other untrusted users whose channel gains are stronger, and should leave the remaining signals as the IUI when it decodes the secret signal. Having the extremely low secret signal power but the strong IUI power, the eavesdropping rates at the untrusted users are thus reduced. As a result, a sufficiently large NOMA secrecy sum rate can be achieved [4].
VI. POTENTIAL INTERFERENCE ENGINEERING STRATEGIES IN ADVANCED NOMA NETWORKS

Preliminary works have revealed that big secrecy benefits for NOMA can be drawn from judiciously engineering the network interference. When we integrate NOMA with other advanced wireless communication concepts, more network interference resources can be engineered for physical-layer security. In the sequel, we propose several potential interference engineering strategies in these advanced NOMA networks, and shed light on open research problems and challenges.

A. Inter-Link Interference and Inter-Relay Interference Engineering in Full-Duplex NOMA

Full-duplex is another cutting-edge technology to improve spectral efficiency by allowing simultaneous information transmission and reception in the same resource block. Thus, the integration of full-duplex techniques into NOMA can bring further performance gains [13]. As shown in the full-duplex BS case of Fig. 6, the BS can have uplink and downlink NOMA transmissions simultaneously, while the untrusted relay intercepts signals of both the uplink and downlink. Here, the uplink signals can serve as beneficial interference, i.e., inter-link interference (ILI), to confuse the untrusted relay. On the other hand, the uplink signals are received by the
downlink users a priori and can be used for subsequent self-interference cancellation at the
downlink users. To make such cancellation possible, joint rate adaptation and power allocation
is needed to guarantee that the downlink users correctly decode the uplink signals with SIC.

Another full-duplex NOMA is illustrated in the virtual full-duplex relay case of Fig. 6 where
two untrusted relays listen and forward signals successively and the inter-relay interference (IRI)
between them can be engineered to prevent eavesdropping. In this situation, relay selection and
user scheduling are meaningful to maximize the IRI at the untrusted relays while minimizing
the IUI at the users, which deserves further investigation.

B. Inter-Network Interference and AN Engineering in Cognitive NOMA

Cognitive radio can be integrated with NOMA in a constructive way to realize better spectrum
usage [14]. In the underlay mode of Fig. 6, the inter-network interference (INI) from the
simultaneous primary and cognitive transmission can be exploited as a source of jamming to the
eavesdropper. The primary BS transmits combined $s_p$ and $w_p s_c$ and the cognitive BS transmits
$w_c s_c$, where $s_p$ denotes the primary user signal, $s_c$ denotes the superimposed NOMA signal for
the cognitive users, and $w_p$ and $w_c$ denote the weighting coefficients. The designs of $w_p$ and
$w_c$ are based on the channel gains of the primary and cognitive nodes, and they facilitate linear
INI cancellation of $s_c$ at the primary user. The cognitive user combines the signals from both
BSs for its information decoding. However, the eavesdropper does not know $w_p$, $w_c$ and cannot
do SIC to eliminate the INI, such that its capability is degraded. Precise channel knowledge is
required in the above design, and efficient channel estimation methods should be devised. In
the overlay mode of Fig. 6, the cognitive users cooperatively transmit the AN when the primary
BS is transmitting $s_p$ in the first phase. Then, the cognitive BS forwards $s_p$ and $s_c$ via NOMA
to all the users, and at the same time the primary BS injects the AN in the second phase. The
AN in both phases is used to intentionally confuse the eavesdropper. The secrecy rate tradeoff
between the primary and cognitive network necessitates the study of a multi-objective power
optimization, to which efficient but low-complexity resource allocation algorithms need to be
developed.

C. Inter-Cell Interference Engineering in Multi-Cell NOMA

With the emergence of massive numbers of IoT devices, transceivers are densely deployed
and multi-cell NOMA is becoming an attractive candidate for future wireless networks [15].
Contrary to popular belief, the inter-cell interference (ICI) in multi-cell NOMA networks is not detrimental but useful to jam the eavesdropper and improve the secrecy performance. An example of ICI engineering is presented in the multi-cell network case of Fig. 6, where two BSs in different cells jointly optimize their beams to simultaneously guarantee the reliability of the cell-edge users and the security of the overall network. Advanced interference alignment aided coordinated beamforming can be applied to achieve zero ICI at the cell-edge users. Since the beams are designed according to the channels between the BS and its serving users, it is not possible for the eavesdropper to cancel the ICI. In this way, the eavesdropper has to treat the ICI as additional noise to decode the signals, which decreases the eavesdropping rates. For scenarios with multiple users, power allocation and user pairing are crucial to minimize the effect of the IUI to improve the secrecy sum rate. Therefore, future works should consider a joint design of optimal beamforming, power allocation, and user pairing for maximally enhancing the network security.

VII. CONCLUDING REMARKS

In this article, we presented a new view on the benefits of network interference and investigated intelligent interference engineering strategies for secure NOMA communications. Specifically, the exploitation of the AN, SJS, and IUI against the eavesdropper and the untrusted relay/user was reviewed. Moreover, various potential interference engineering strategies in more advanced full-duplex NOMA, cognitive NOMA, and multi-cell NOMA networks were proposed, and several open research problems and challenges were also outlined.

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