Physical Layer Security for NOMA: Requirements, Merits, Challenges, and Recommendations

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Abstract—Non-Orthogonal Multiple Access (NOMA) has been recognized as one of the most significant enabling technologies for future wireless systems due to its eminent spectral efficiency, ability to provide an additional degree of freedom for Ultra Reliable Low Latency Communications (URLLC) and grant free random access. Meanwhile, Physical Layer Security (PLS) has got much attention for future wireless communication systems due to its capability to provide security without relying on traditional cryptography based algorithms. In this article, security design requirements for NOMA and solutions provided by PLS to fulfill these requirements are discussed. The merits and challenges arising from employing PLS to NOMA are identified. Finally, future recommendations and prospective solutions are also presented.

I. INTRODUCTION

On-Orthogonal Multiple Access (NOMA) has received significant attention for 5G and beyond wireless systems due to its unique properties such as high spectral efficiency, low latency, improved coverage, massive connectivity, fairness and so on [1]. However, there are some critical security risks in NOMA, for example, due to the broadcast of messages from multiple users at the same time over the same resources, there is a risk that an eavesdropper can overhear the information of multiple users if NOMA transmission is successfully intercepted. Moreover, in NOMA, there is a need of securing confidential messages from each other in case of untrusted users.

The conventional solutions to provide secure communication in NOMA and other wireless technologies are based on cryptography, but they are not enough for future communication [2] due to the following reasons: Firstly, future networks consist of decentralized and heterogeneous wireless networks in which key management processes are quite challenging. Secondly, future networks need to support new wireless technologies such as Internet of Things (IoT) including both massive Machine-Type Communications (mMTC) and Ultra-Reliable Low-Latency Communications (URLLC). The transceiver devices in these wireless technologies are naturally power-limited, processing-restricted and delay-sensitive which make cryptography-based techniques infeasible for such type of technologies. Thirdly, future networks are expected to support diverse services and scenarios that have different levels of security requirements. However, the encryption-based methods can only provide binary level of security [2]. To cope up with these problems, Physical Layer Security (PLS) techniques have emerged as a promising solution that can complement and may even replace the cryptography based approaches [3]. PLS exploits the dynamic features of wireless communications, for example, random channel, fading, interference and noise, etc., to prevent the eavesdropper from decoding data while ensuring that the legitimate user can decode it successfully [2]. PLS has the following advantages with respect to future networks as compared to cryptography. Firstly, PLS approaches can be exploited to extract keys from the channel that is common between legitimate transmitter and receiver, thus avoiding key management issues. Secondly, some of the PLS approaches can be implemented by relatively simple signal processing techniques which make it suitable for processing-restricted and delay-sensitive services. Thirdly, in PLS, channel-dependent resource allocation and link adaptation can be designed to provide flexible and scenario-specific security schemes [3].

On the basis of the potential of PLS for future networks and security concerns in NOMA, designing PLS techniques for NOMA seems more promising than cryptography-based approaches. However, there is still a paucity of research works in this direction [4]. In this article, we first provide a quick overview of NOMA flavors and basic principles to explain security concerns more clearly. This is followed by security design objectives and solutions provided by PLS. Then, we present the merits of PLS in NOMA as compared to Orthogonal Multiple Access (OMA). Challenges of PLS in NOMA, possible solutions, and future directions are addressed in the following section. The final section concludes the article.

II. DOMINANT FLAVORS AND SYSTEM MODEL FOR NOMA

In this section, different types of NOMA, basic system model and NOMA principles are presented to explain the security designs more clearly in subsequent sections.

A. NOMA Dominant Flavors

NOMA supports massive connectivity and enhanced spectral efficiency by allowing resource allocation in non-orthogonal manner. There are two basic types of NOMA schemes: Power-Domain (PD) NOMA and Code-Domain (CD) NOMA [1]. In PD-NOMA, different users’ signals are directly superimposed by assigning channel quality-based power allocation to them, while sharing the same frequency-time resources. CD-NOMA, on the other hand, is similar to Code Division Multiple Access (CDMA), where different
users are allowed to share same frequency-time resources by using unique orthogonal spreading code in CDMA. However, CD-NOMA uses non-orthogonal codes with lower cross correlation or sparse sequences. Generally speaking, there is more attention to downlink PD-NOMA, especially in the standardization bodies such as the Third Generation Partnership Project (3GPP) and IEEE. For example, a downlink version of PD-NOMA has been proposed for 3GPP-LTE-Advanced [5]. Moreover, we do not need to do major changes in the physical layer procedures at the transmitter in case of downlink PD-NOMA compared to conventional technologies. Also, from the PLS point of view for NOMA, most of the work in the literature is focused on downlink PD-NOMA. The reason is that downlink PD-NOMA has novel challenges in terms of security due to its unique implementation. Firstly, due to the broadcast of superimposed messages of multiple users at the same time, there is a risk of information leakage of the superimposed users. Secondly, near user has to decode the signal of the far user, which causes a serious security risk for the far user in the case of an untrusted near user. Furthermore, the channel availability of users and other resources can be exploited at the base station (BS) to tackle security challenges of downlink NOMA. Hence, this paper will mainly focus on PLS techniques applied to downlink PD-NOMA to elaborate the novel challenges and future recommendations for it.

Fig. 1. Downlink NOMA detailed model which consists of a single Base Station (BS) with one Near User (NU) and one Far User (FU) in the presence of an external eavesdropper (cloned at different possible positions)

B. System Model and Principles of NOMA

Consider a simple two-user downlink NOMA scenario that consists of a single Base Station (BS) with one Near User (NU) and one Far User (FU) in the presence of an external eavesdropper (cloned at different possible positions) as presented in Fig. 1. The BS first superimposes the users’ signals by allocating them different power levels and broadcasts the mixture to all users using the same time-frequency resources. The power allocation in NOMA is done in such a way that the FU (user with lower channel gain) is allocated more power and NU (user with higher channel gain) is given low power. The receivers of NOMA employ different strategies for different users in accordance with their channel characteristics. More specifically, the NU has to decode the signal intended for FU first, afterwards it subtracts the detected signal from the received signal and then decodes its intended data. This process is known as Successive Interference Cancellation (SIC). On the other hand, the FU directly decodes its own information while considering the information of its partner as noise [6]. It should be noted that for the sake of explanation two users case is considered here; however, the discussion is also applicable to multiple users (more than two) case.

The above mentioned case is for single-input-single-output (SISO)-NOMA, where channels are represented by scalars. However, matrices are used to represent the channels of multi-input-multi-output (MIMO)-NOMA. In the case of matrices, ordering of users based on power is quite challenging [1]. In the literature, two main designs are proposed for MIMO-NOMA case: 1) Beamformer based MIMO-NOMA, where different beams are allocated to different users and SIC is employed at users sharing the same resource block [1], 2) Cluster based MIMO-NOMA, where users are divided into clusters and a single beam can serve all the users in the cluster. In this approach, SIC is adopted among users sharing the same cluster [1].

III. SECURITY DESIGNS OBJECTIVES

In this section, different security design objectives for NOMA are presented and explained. In general, different users in NOMA can have different Quality-of-Service (QoS) requirements, which implies that the design of PLS techniques should consider these requirements. Moreover, there are two types of eavesdroppers: 1) External, and 2) Internal. Internal eavesdropper is from the set of legitimate users of the network, while the external one is not from that set. The eavesdropper can be considered 1) active, which is the case when its channel state information is available at transmitter, or 2) passive, which is the case when its CSI is not available at the

1Note that we will use the term NOMA in the remaining part of the paper to represent PD-NOMA.
transmitter. Usually, internal eavesdroppers are active while the external eavesdroppers are passive.

This work is focused on both active internal eavesdropping as well as passive external eavesdropping. The objectives of security design for NOMA can be divided into three major categories based on its requirements as follows:

- Security designs against external eavesdroppers.
- Security designs against internal eavesdroppers.
- Security designs against both internal and external eavesdroppers.

The details of security designs and solutions provided by PLS are presented in subsequent part.

A. Security Designs against External Eavesdroppers

In this scenario, NU and FU are trusted. So, the design goal here is to secure the messages of NU and FU from an external eavesdropper. Based on the basic model presented in Fig. 1, there are five possibilities for Eves location: 1) Eve can be closer to BS than NU, which means its channel is better than both users, 2) Eve can be at the same distance from BS as NU, 3) Eve can be somewhere between NU and FU, which means that its channel is better than FU but worse than NU, 4) Eve can be at the same distance from BS just like FU, 5) Eve can be at the farthest location from BS as compared to NU and FU, which means its channel condition is worst as compared to them. On the basis of these possibilities, it should be noted that the location of Eve can affect the security performance of NOMA system and should be considered while designing security algorithms.

The necessary conditions that need to be taken into consideration while designing algorithms for this scenario are as follows: Firstly, the basic SIC should be normally operated with the security algorithm, which means that the proposed algorithm should not affect the basic SIC process and the performance of normal NOMA. Secondly, the algorithm should also work even in the case of having strong spatial similarity between channels of legitimate parties and illegitimate parties.

It should be pointed out that in the case of NOMA, different users are allocated with different power levels due to which they are protected in an unequal manner and thus experiencing asymmetric security performance. More specifically, users with weak channel conditions are allocated more power. Hence, they are less secure because the probability of their detection at Eve is more as compared to NU signal with less allocated power. Therefore, advanced algorithms are needed to ensure that different security targets of different users can be met.

The popular PLS techniques for external eavesdropping in the literature include channel based optimization of the power allocation for each user, subcarrier assignment to users, channel ordering of NOMA users along with the decoding order, optimization of beamforming policies, adding interference signal, Transmit Antenna Selection (TAS) approaches and inter-user interference exploitation, etc. [3][7].

B. Security Designs against Internal Eavesdroppers

In this scenario, no external eavesdropper is assumed; however, the users are untrusted. The design goal here is to secure information of users from each other, while making sure that the SIC operation works normally. Moreover, in this case, the channel is known at the BS, which makes the design process different than the previous case. Internal eavesdropping can be divided into two types:

- Eavesdropping of FU by NU
- Eavesdropping of NU by FU

The details of these two types are as follows:

1) Eavesdropping of FU by NU: In basic NOMA principle, the main security risk for FU is that the NU has to decode (or demodulate) the signal of FU in order to apply SIC. Another important thing is that the FU’s signal is allocated more power, which makes its detection easier for the NU. The design goal here is to avoid leakage of information of FU to NU, while making sure that SIC works normally. To further elaborate on this issue, it should be pointed out that there are two types of SIC receiver. The first one is symbol-level SIC receiver, in which FUs signal is demodulated but not decoded in order to apply SIC, while the other one is codeword-level SIC receiver, where FU’s signal is demodulated and decoded in order to apply SIC [8]. In codeword-level-SIC case, the data can only be secured by cryptography-based techniques. However, for the case of symbol-level-SIC, PLS techniques can be applied. In symbol-level based SIC, security can be provided to FUs data by transforming its data into another domain by using a special sequence such that NU can apply SIC normally but cannot decode the information of FU [8].

Note that there is no significant work in the literature in this direction.

2) Eavesdropping of NU by FU: In basic NOMA principle, the FU has been allocated more power and it can decode its signal directly considering the information of near as noise. However, after obtaining its own signal it may detect the signal of NU. The design goal here is to secure the data of NU from FU while making sure that SIC work normally. In this case, designing security methods is easier as compared to the security problem of FUs data. The BS can employ PLS techniques based on power allocation, beamforming or any other adaptation-based algorithm to satisfy the security requirement of NU while making sure that the basic data rate requirement of FU is fulfilled [3].

C. Security Designs against both Internal and External Eavesdroppers

In this scenario, there is an external eavesdropper as well as an internal eavesdropper where the users in the network are not trustable. The design goals here include: security of signals intended for NU and FU from external eavesdropper as well from each other. This case is the most challenging one with respect to security design. The design algorithms should make sure that SIC will work normally while fulfilling the above goals. One possible way to provide security in this case can be by the transformation of signal of near and far users into another domain by using some randomization sequences [8]. However, this is still an open research area and a lot of research efforts are needed in this direction.

A summary of the objectives of security designs, complexity and popular solutions for NOMA are presented in Table. I.
TABLE I
SUMMARY OF THE OBJECTIVES OF SECURITY DESIGNS FOR DIFFERENT SCENARIOS IN NOMA FOCUSING ON PASSIVE EXTERNAL EAVESDROPPER AND ACTIVE INTERNAL EAVESDROPPER.

| Scenarios for security | Design objectives | Design Complexity | Candidate solutions |
|------------------------|------------------|------------------|---------------------|
| External Eavesdropper  | Securing NU and FU data against external Eavesdropper while keeping normal SIC | Normal | Beamforming, Power allocation based, interference exploitation based, TAS, relay selection, etc. |
| Internal Eavesdropper  | Securing users information from each other while ensuring normal SIC | Against NU: High, Against FU: Normal | Transformation of FU to other domain, Beamforming Power allocation, TAS etc. |
| External and Internal Eavesdropper | Securing users information from each other as well as from external Eve while having normal SIC | Highest | Transformation of users’ signal into another domain, interference assisted, etc. |

IV. MERITS OF PLS IN NOMA

In this section, we present some of the merits of NOMA over OMA in terms of security under certain conditions.

A. Higher Sum-Secrecy Rate

In NOMA, the signals are not sent separately as compared to OMA, hence, multi-user interference and PLS can be processed collaboratively. Moreover, user selection, number of users in each cluster, number of clusters, intra-cluster and inter-cluster power allocation can be designed to enhance the secrecy capacity of the system. For example, power allocation based on channel conditions of legitimate users can make interception of users signal difficult for eavesdropper under certain settings as presented in Fig. 2 [9]. It should be noted from the figure that the Average Sum Secrecy Rate (ASSR) of NOMA system improves with the increase in the number of users as compared to OMA under specific settings [9]. The reason is that higher diversity gain (multi-user diversity) can be offered in case of NOMA because the whole band can be used by each user simultaneously [9].

![Fig. 2. Average Sum Secrecy Rate (ASSR) versus the transmit power for different number of users (n=2, n=3, n=4).](image)

B. Inter-User Interference Exploitation for Securing Massive MIMO System

In the case of a massive MIMO system, Artificial Noise (AN)-based security techniques face complexity issues. In such cases, NOMA can help us to provide secure communication without using AN [10]. For example, consider a clustering based Massive MIMO NOMA system employing non-orthogonal channel estimation in the presence of multiple active eavesdroppers [10] as presented in Fig. 3. The nodes in this system suffer from intra-cluster and inter-cluster interference; however, this inter-user interference can be exploited intelligently to provide secure communication [10]. More specifically, power allocation coefficients during channel estimation and multiples access stage can be designed in such a way that it will enhance the performance of legitimate users and degrade the performance of active eavesdroppers [10].

![Fig. 3. Secure massive MIMO with NOMA by using inter-user interference, where users are divided into four clusters.](image)

C. Link Adaptation for Secure Communication

Link adaptation using adaptive modulation, adaptive coding and optimal power allocation based on legitimate users channels can provide some level of security [11]. It should be pointed out that NOMA does not require exact channel state information or fine feedback from users [11]. Hence, NOMA
can respond to the changes in channel quickly and is capable of link adaptation more easily, which is an attractive feature, especially, for high speed mobile environment.

D. Securing Uni-Cast Message from Multi-Cast Receivers

An interesting advantage of NOMA is to secure uni-casting message from interception by the untrusted multi-casting receivers while improving spectral efficiency \[12\] as presented in Fig. 4, where uni-casting message is for specific receiver while multi-casting message is for all the receivers in the set of specific receivers. In OMA, uni-casting and multi-casting are transmitted separately and can be intercepted easily by multi-casting receivers as presented in Fig. 4. However, NOMA principle can be used to degrade the intercepting capabilities of the multi-casting receivers similar to the case of securing NU message from untrusted FU receiver \[12\]. More specifically, joint power allocation and beamforming strategies can be used to enhance the secrecy of uni-casting message while preserving the reliability of multi-casting message \[12\]. Moreover, in OMA, two slots are required to send uni-casting and multi-casting information while in NOMA both information types can be transmitted simultaneously by using a single slot \[12\] as presented in Fig. 4.

![Fig. 4. Multi-casting and Uni-casting in NOMA and OMA \[12\].](image)

E. Channel Correlation and Security

Most, if not all, PLS techniques (based on small scale fading) assume that the received signals at Eve and Bob will experience independent fading, if they are roughly half a wavelength apart \[3\]. This assumption is valid only in sufficiently rich scattering environment. In case of poor scattering environment, these algorithms will not ensure secure communication. However, NOMA with large scale fading based security algorithms can provide secure communication under certain circumstances even in a poor scattering environment \[4\] \[10\]. Moreover, in case of rich scattering environment both the small and large scale fading based security algorithms can be applied in NOMA.

F. QoS based Security

NOMA has a great capability to support different QoS requirements of different users, such as data rate and security. More specifically, since users can be categorized based on their QoS requirements, user scheduling, power allocation, SIC decoding order, etc. can be designed to fulfill these requirements. For example, in \[13\], an opportunistic hierarchical security model for a 3D massive MIMO channel based on NOMA is proposed for enhancing both security and spectral efficiency as presented in Fig. 5. Particularly, the proposed model can be used for transmitting multi-cast messages to users with different security levels. The users are divided into a high security group and a low security group \[13\]. The high security group is further divided into NOMA group and non-NOMA group, where the NOMA group signal is superimposed onto the low security group signal \[13\]. The users included in NOMA group have smaller path loss, lower power level allocated to their signal by BS and have higher security level, whereas the low security group has users with characteristics of large path loss, low power allocation to their signal, and lower level of security. In the proposed algorithm, multi-cast beamforming, null space-based interference cancellation and power control are employed for transmission of multi-cast messages to different groups while fulfilling their security requirements \[13\].

![Fig. 5. Opportunistic security model for massive MIMO based on NOMA principle \[13\].](image)

Note that the presented benefits are under certain settings and there are situations where NOMA have marginal benefits over OMA.

V. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

The development of new technologies gives rise to new challenges that lead to interesting and new research areas. This section presents the challenges in securing NOMA using PLS alongside some of the proposed solutions and research directions.
A. Challenges for Security against FU and External Eavesdroppers

There are considerable contributions in the literature regarding the provision of secure communication schemes against untrusted FU and external eavesdroppers (in case of trusted internal users), such as channel dependent power allocation, beamforming, TAS and inter-user interference, etc. [3]. However, the majority of the research works assumes the availability of full, partial or statistical information about the channel state information of Eve, which is difficult to achieve in case of passive eavesdropping. Moreover, some techniques provide security at the cost of performance degradation. Hence, conventional techniques should be intelligently modified, and novel techniques should be proposed to provide security for NOMA. Some of the potentially interesting techniques like multi-dimensional directional modulation scheme, cyclic feature suppression-based techniques and channel based interleaving, etc. have not been explored for such cases, whereas these techniques have the potential to be used in such situations [3] [14].

B. Security Challenges against Untrusted NU and both External and Internal Eavesdroppers

The design of security algorithms against untrusted NU and both internal and external eavesdropper is extremely challenging. The only solutions available in the literature so far are based on transformation of signals into another domain. In these solutions, the signal transformation into another domain is done by using a transformation sequence that needs to be shared between the legitimate parties [8]. The sequence can be shared by PLS approaches, such as full duplex jamming based techniques for sequence sharing [8] which requires complex hardware. In this direction, cross layer security techniques can also be effective. For example, Automatic Repeat Request (ARQ) with AN can be jointly designed to provide security against internal and external eavesdropping in NOMA similar to the work presented in [15]. Moreover, joint composite constellation design and ARQ with adaptive modulation can also be used to provide security against untrusted NU. In case of rich scattering environment, channel-based manipulation security techniques can also be employed in such scenarios. This is still an open area and a lot of research efforts are needed to provide security for such cases, while making sure the SIC operation works normally.

C. Passivity and Limited Observations

A lot of techniques in the literature of secure NOMA consider that the illegitimate user is just spying the information. However, in future networks, there may exist illegitimate nodes that can interfere with the normal operation of NOMA system by active attacks, such as pilot spoofing attack, etc. These attacks are more critical in NOMA because of the broadcast of superimposed messages of multiple users at the same time. Quite a few PLS techniques in the NOMA literature are robust to active eavesdroppers case [10]. Hence, there is a need of designing PLS techniques that are robust to active attacks from eavesdroppers.

Moreover, multiple collaborative eavesdroppers with multiple observations may lead to zero secrecy capacity [14]. Hence, there is a need for understanding the implications of multi-eavesdropper and multi-observation case while developing security techniques for NOMA communication.

D. SIC and Eve Capability

In the literature, it is assumed that the eavesdroppers use the same SIC procedure as the legitimate users. However, eavesdropper can apply alternative strategies for eavesdropping, for example, it may decode a signal in the first step that is decoded in the last stage of SIC at legitimate users, which can affect the overall security performance of the system. Possible alternative approaches by eavesdropper should also be considered while designing security algorithms.

E. SIC Error Propagation and Secrecy

The security algorithms in NOMA mainly rely on the assumptions that perfect channel estimate is available, and the signals are perfectly separated at the receiver side (perfect SIC). However, if there is an error in any of these signals during SIC, then the remaining signals may also have detected erroneously [6]. Hence, the effect of imperfect SIC and imperfect channel estimation should be considered while designing security algorithms for NOMA, so that these drawbacks can be avoided. Therefore, it is also recommended to use an efficient non-linear detection algorithm at each stage of SIC to alleviate the effect of imperfect SIC and practical channel calibration solutions for imperfect channel estimation case. Moreover, new interference cancellation schemes and improvement in signal processing chip technology that can benefit the legitimate receivers are also of special interest [11].

F. Artificial Noise (AN) based Security Schemes

AN based techniques are one of the popular techniques in the literature. In these techniques, an artificial interference signal is added in the null-space of legitimate user channel to degrade the performance of Eve. However, in NOMA, when AN is added based on individual user, it also causes AN leakage in the range space of other NOMA users which degrades their performance. Moreover, AN may increase Peak to Average Power Ratio (PAPR), sacrifices some power and is also sensitive to imperfect channel estimation. Thus, it is recommended to design AN, not only to provide security but also to reduce the amount of Out-Of-Band Emission (OObE), adjacent channel interference and average PAPR, etc. [15].

G. Multi-Cell Case and Other Technologies

In the case of multi-cell NOMA, there are a lot of challenges to provide secure and reliable communication due to inter-channel interference. However, there is no much work in this area. Algorithms for joint processing, coordinated beamforming, and coordinated scheduling need to be proposed to ensure reliable and secure multi-cell NOMA.
Moreover, there is also paucity of PLS research works for NOMA integrated with other technologies such as millimeter wave, full-duplex, visible light communication, cognitive radio, heterogeneous networks, and coordinated multi-point, etc.

**H. Cross-layer, Context Aware and Hybrid Security Techniques for NOMA**

In the literature of PLS techniques in NOMA, transmission parameters of the physical layer are optimized according to legitimate users’ channel characteristics to provide secure communication without considering upper layer parameters. However, to meet the diverse requirements of NOMA users and for joint design of throughput, secrecy, delay, reliability and respective trade-off among them, the concept of cross-layer security design from the perspective of physical layer should also be considered such as: 1) Cross MAC-PHY layer: In this approach, MAC layer features (for example, channel accessing, multiplexing, ARQ and control of resource allocation, etc.) can be optimized jointly with physical layer parameters to provide efficient QoS based security solution [15]. 2) Cross NET-PHY layer security: In this approach, the network layer features such as relaying, routing and path determination, etc. can be optimized jointly with physical layer parameters for enhancing security of the system [14]. 3) Cross APP-PHY layer: In this approach, physical layer parameters of transmission are jointly optimized based on channel characteristics as well as on the basis of applications, services and features of data to provide efficient security solution based on the requirements of users [3].

Finally, designing hybrid techniques by combining signals security approaches (PLS) with data security approaches (cryptographic techniques) can further enhance the security of the NOMA-based systems [5].

**VI. CONCLUSION**

NOMA promises high spectral efficiency, low latency and massive connectivity, while PLS offers simple and effective security solutions. Together, these two technologies are capable of supporting the exceeding efficiency and security requirements of 5G and beyond networks. In this article, the key security design requirements of NOMA and the strength of PLS as a solution to fulfill these requirements are discussed. By employing PLS to NOMA, spectrally efficient, adaptive and secure systems can be realized. However, the challenges and future recommendations explained in this work need to be investigated further to address the open issues. Practical secure NOMA systems can be developed by modification of current PLS techniques and/or proposing new novel techniques that do not require extra processing, extra signalling or major modification in the receiver structure.

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