Comparison Between Asymmetric and Symmetric Channel-Based Authentication for MIMO Systems

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Abstract—Authentication is a key element of security, by which a receiver confirms the sender identity of a message. Typical approaches include either key-based authentication at the application layer or physical layer authentication (PLA), where a message is considered authentic if it appears to have gone through the legitimate channel. In both cases a source of randomness is needed, whereas for PLA the random nature of the communication channel is exploited. In this paper we compare the various approaches using in all cases the channel as a source of randomness. We consider a multiple-input multiple-output (MIMO) system with a finite number of antennas. Simple auto-regressive (AR) models for its evolution as well as the relation of the legitimate and attacker channel are considered. In this setting the attacker can either predict the key used for key-based authentication or forge the channel estimated at the legitimate receiver for PLA. The analysis includes both symmetric and asymmetric key-based authentication. We compare the schemes in terms of false alarm and missed detection probability and we outline best attack strategies.

Index Terms—Authentication, Cryptographic Authentication, Physical layer security, Symmetric and Asymmetric Authentication.

I. INTRODUCTION

By authentication the destination establishes if a received message is coming from the claimed source or not. Typically, this procedure is performed at the application layer by means of cryptographic protocols that are either symmetric or asymmetric, i.e., either a key is shared by the source and destination or a couple of private/public keys is generated by the source that uses the private key to encrypt a message, whose authenticity can be confirmed by any destination having the public key [1]. In both cases, a source of randomness must be available to generate the secret (private) key, and the key must be renewed from time to time to cope with the possibility that the key has been disclosed to the attacker, e.g., due to either protocol vulnerabilities or intensive computational effort by the attacker, possibly supported by quantum computing.

An alternative authentication approach is implemented (typically in wireless systems) at the physical layer in the so-called physical layer authentication (PLA). It consists in checking if the channel over which the message arrives to the destination remains unaltered over time: in general, the destination will experience different channels to the attacker and the legitimate transmitter, due to their different position and other wireless phenomena. Further details and possible attacks are described in [2]–[4].

In this paper the unique source of randomness is assumed to be the wireless channel, as estimated by the either or both the transmitter and receiver. Therefore we can compare both PLA and cryptography-based authentication techniques. We consider a finite number of flat antennas for multiple-input multiple-output (MIMO) systems, over which the randomness is obtained to generate the key, therefore we do not apply asymptotic capacity results. The aim is to compare the various authentication schemes in terms of probability of false alarm (FA) and missed detection (MD), i.e. the probability that a packet coming from the legitimate source is not authenticated and a packet coming from the attacker is accepted as legitimate, respectively.

The rest of the paper is organized as follows. Section II introduces the MIMO channel model described by a matrix with N entries and its evolution. The three considered authentication schemes, namely asymmetric-key based authentication (AKBA), symmetric-key based authentication (SKBA) and PLA are described in Section III. Performance of the schemes in terms of FA and MD probabilities is assessed in Section IV. Finally, conclusions are outlined in Section V.

II. SYSTEM MODEL

We consider the usual three users model in security, where Alice aims at authenticating messages coming from Bob, and Eve aims at sending messages to Alice impersonating Bob. In particular, after an initialization stage, upon reception of a packet Alice aims at taking a decision between the two hypothesis \( H_0 \): the packet is coming from Bob or \( H_1 \): the packet is not coming from Bob.

We assume that the only sources of randomness are the time-varying channels among devices, which are estimated and used to provide the desired authentication process. In particular, devices are equipped with \( M \) antennas each, implementing a MIMO system, so that channels are described by \( M \times M \) matrices. We assume that entries of channel matrices are independent and identically distributed (i.i.d.) complex normal (CN), and correlated over time and across devices.

Channel matrices are converted into vectors of size \( N = M^2 \), so that \( h(t) = [h_1(t), \ldots, h_N(t)] \) is the Alice-Bob channel (assumed to be reciprocal) at slot \( t \). We assume an auto-regressive (AR) evolution of the channel, i.e., for \( n = 1, \ldots, N \)

\[
h_n(t) = \alpha h_n(t-1) + \sqrt{1-\alpha^2} z_n(t),
\]  

(1)
where $\alpha$ is the correlation factor and $z_n(t)$ are i.i.d. CN variables.

A similar channel model is available between Eve and both Alice and Bob. In particular the reciprocal Alice-Eve channel is

$$g_{1,n}(t) = \beta_1 h_n(t) + \sqrt{1 - \beta_1^2} z_{1,n}(t),$$

and the Bob-Eve channel is

$$g_{2,n}(t) = \beta_2 h_n(t) + \sqrt{1 - \beta_2^2} z_{2,n}(t),$$

where $\beta$ are correlation factors and $z_{n}(t)$ are CN variables.

In order to exploit the channel as a random source the users must estimate it, and this is obtained by letting one of the two legitimate users to transmit pilot symbols. In particular, the channel estimate obtained by Alice when Bob is transmitting pilots is an additive white Gaussian noise (AWGN)-corrupted version of $h_n(t)$, i.e.,

$$\hat{h}_{A,n}(t) = h_n(t) + \sigma_A w_{A,n}(t),$$

where $w_{A,n}(t)$ are i.i.d. CN variable. Similarly for a pilot transmission by Alice, Bob estimates

$$\hat{h}_{B,n}(t) = h_n(t) + \sigma_B w_{B,n}(t),$$

where $w_{B,n}(t)$ are i.i.d. CN variable. Lastly, when either Alice ($i = 1$) or Bob ($i = 2$) are transmitting, Eve obtains estimates

$$\tilde{g}_{i,n}(t) = g_{i,n}(t) + \sigma_E w_{E,n}(t),$$

where $w_{E,n}(t)$ are i.i.d. CN variable.

**Attacker Model:** Here we consider that Eve will only try to transmit packets impersonating Alice, while not performing attacks aiming at disrupting the authentication process (such as jamming and pilot contamination attacks) that will be considered in future studies. We assume that Eve is able to transmit modifying the transmitted signal so that Alice will estimate any desired channel.

### III. AUTHENTICATION SCHEMES

Three authentication schemes are considered: PLA, AKBA and SKBA.

#### A. Physical Layer Authentication

PLA exploits the coherence time of the channel in order to provide authentication. In synthesis, it provides two steps: a) the initialization step by which the channel to the user to be authenticated is measured, being sure that the legitimate node is transmitting; b) the authentication step, in which upon reception of a packet the channel is estimated again and compared with that estimated in the initialization step.

Let us now consider the detailed implementation of PLA in the considered scenario. We first observe that we can rewrite $\hat{h}_{A,n}(t)$ as

$$\hat{h}_{A,n}(t) = \alpha^{t-1} h_n(1) + \gamma_n(t) \epsilon_n(t),$$

with $\epsilon_n(t)$ i.i.d. CN variables and $\gamma_n(t) = \sigma^2 A + (1 - \alpha^2) \alpha^{t-1}$.

The physical layer authentication as described in [2] includes the following phases:

1. In the first slot Bob transmits pilots to Alice, who estimates the channel $\hat{h}_{A,n}(1)$. This first transmission is assumed to be authenticated with some other means other than PLA.
2. At slot $t > 1$, when Alice receives a packet that contains pilot symbols, she estimates the channel $\hat{h}_{A,n}(t)$ then she computes the distance between it and the channel estimated at the first slot as

$$\psi(t) = \frac{1}{N \gamma_A^2} \sum_{n=1}^{N} |\hat{h}_{A,n}(t) - \alpha^{t-1} \hat{h}_{A,n}(1)|^2,$$

and decides that the packet is authentic if

$$\psi(t) < \theta(t),$$

otherwise she discards it as non-authentic.

3. Eve on her side estimates the channel from Bob in the first slot $g_{2,n}(1)$ and in forthcoming slots she estimates the channel from Alice and Bob whenever they are transmitting. Then she obtain the maximum likelihood (ML) estimate of the Alice-Bob channel at the first slot $\tilde{h}_{E,n}(t)$, which is used to impersonate Bob by forging channel $\alpha^{t-1} \tilde{h}_{E,n}(t)$ at slot $t$.

We now suppose that at odd slots (starting from $t = 1$) Bob is transmitting, and at even slots Alice is transmitting. Then at slot $t = 2 \nu + 1$, with $\nu$ natural number, Eve performs the attack. From (1) and (2) we can write $\tilde{g}_{i,n}(t)$ as a function of $h_n(1)$ as

$$\tilde{g}_{i,n}(t) = \beta_i \alpha^{t-1} h_n(1) + \beta_i \sqrt{1 - \alpha^2} \sum_{k=2}^{t} \alpha^{t-k} z_n(k) +$$

$$+ \sqrt{1 - \beta_i^2} z_{i,n}(t) + \sigma_E w_{E,n}(t),$$

$$= \beta_i \alpha^{t-1} h_n(1) + u_{i,n}(t),$$

with $u_{i,n}(\tau), \tau = 1, \ldots, t$ CN variables. Now, let $w(2\nu)$ be a $2\nu$-size column vector with entries $w_{2j+1} = \beta_{2-j} \alpha^{2j+1-1}$, and $\tilde{g}_n(2\nu)$ be the column vector collecting channel estimates at Eve up to slot $2\nu$ for channel entry $n$, then

$$\tilde{g}_n(2\nu) = w h_n(1) + u,$$

with Gaussian zero-mean random vector $u$ having correlation matrix $K = E[u^t u]$ with entries

$$K_{t1, t2} = (\sigma_E^2 + 1 - \beta^2_{1+t1+t2}) \delta(t1 - t2) +$$

$$+ \beta_{1+t1+t2} \beta_{1+t2} (1 - \alpha^2) \times$$

$$\times E \left[ \sum_{k1=2}^{t1} \alpha^{t1-k1} z_n(k1) \sum_{k2=2}^{t2} \alpha^{t2-k2} z_n(k2) \right],$$

$$= (\sigma_E^2 + 1 - \beta^2_{1+t1+t2}) \delta(t1 - t2) +$$

$$+ \beta_{1+t1+t2} \beta_{1+t2} (1 - \alpha^2) \sum_{k=2}^{\min(t1, t2)} \alpha^{2(t-k)}$$

$$= (\sigma_E^2 + 1 - \beta^2_{1+t1+t2}) \delta(t1 - t2) +$$

$$+ \beta_{1+t1+t2} \beta_{1+t2} (1 - \alpha^2) \sum_{k=2}^{\min(t1, t2) - 1} \alpha^{2(t-k)}.$$
and $t_1$, $t_2$ denotes the remainder of a division of $t$ by 2. The ML estimate of $h_n(1)$ is obtained as

$$\hat{h}_{E,n}(t) = (w^H \mathbf{K}^{-1} w)^{-1} w^H \mathbf{K}^{-1} \hat{g}_n(2\nu). \quad (13)$$

When multiple attacks are possible, an exploration of the channel space $\hat{h}(1)$ can be performed, where the first attempted point is the ML estimate [13] and then the other points correspond to the next most probable channels, given the observations. This approach has been explored in [2],

**B. Asymmetric-key Based Authentication**

With AKBA we exploit the channel as a random number generator and the random number is then used to generate a couple of private and public keys that will be used to sign and check the packets to be authenticated. In particular, the randomness is used by Bob to generate a private/public key couple. The public key is broadcast to all users and when Bob transmits packets he will encrypt a time-varying signature with the private key, and Alice will be able to decrypt it using the public key, thus ensuring that the packet is authentic.

Let us now provide the details of key generation for AKBA in the considered scenario. The AKBA works as follows:

1) At slot 1 Alice transmits pilots and Bob estimates the channel $\hat{h}_{B,n}(1)$.

2) Bob quantizes the real and imaginary parts of the channel estimate with a quantizer of $K_Q$ quantization levels and saturation value $v_{\text{sat}}$, obtaining a bit sequence $b$.

3) Bob applies a known (to all users) hashing and compression function to extract a shorter key from $b$ and then generate a private and public key couple $(S_A, P_A)$. 

4) At slot 2 Bob broadcasts the public key $P_A$. In his transmissions Bob encodes a (time-varying) signature with the private key so that Alice is able to authenticate messages coming from Bob.

5) Eve estimates the channel in the first slot $\hat{g}_{1,n}(1)$ and the channel in the second slot $\hat{g}_{2,n}(2)$.

6) From the two estimates she will obtain a bit sequence $\hat{b}$ as detailed in the following.

7) Eve uses $\hat{b}$ as the key to generate a private and public key couple $(S_E, P_E)$ and performs attacks signing the time-varying signature with the private key $S_E$.

**Optimal Attack:** Let us now derive the optimal choice of $\hat{b}$ by Eve at slot $t = 2\nu + 1$ after she has collected $\nu$ observations of the channels to Alice and Bob. We now have that odd slots (starting from $t = 1$) Bob is transmitting, and at even slots Alice is transmitting. Now, let $w'$ be a $2\nu$-size column vector with entries $[w']_{2j+i} = \beta_i a^{2j+i-1}$, and let $\hat{g}'_{n}(2\nu)$ be the column vector collecting channel estimates at Eve up to slot $2\nu$ for channel entry $n$, then

$$\hat{g}'_{n}(2\nu) = w'^H h_n(1) + u', \quad (14)$$

where Gaussian zero-mean random vector $u'$ has correlation matrix $\mathbf{K}' = \mathbb{E}[u'^H u']$ with entries (obtained analogously as in the previous section)

$$\mathbf{K}'_{t_1,t_2} = (\sigma_{E,1}^2 + 1 - \beta_{2-t_1,t_2}^2)\delta(t_1 - t_2) + \beta_{2-t_1,t_2}^2\beta_{2-t_2,t_1}^2(1 - \alpha^{2(\min(t_1,t_2) - 1)}) \quad (15)$$

Indicating with $(\tau_k, \tau_{k+1})$ the quantization interval for the quantization level $k = 1, \ldots, K_Q$, and $\tau_1 = -\tau_{K_Q+1} = \infty$, the index of the most probable quantized value (for the real part) is

$$k^* = \arg\max_{k} \mathbb{E}[\Re\{h_n(1)\} \in (\tau_k, \tau_{k+1}) | \hat{g}'_{n}(2\nu) \delta(t - t_2)]$$

$$= \max_{k} \int_{\tau_k}^{\tau_{k+1}} \mathbb{E}[\Re\{h_n(1)\} | \hat{g}'_{n}(2\nu)] dh$$

$$= \max_{k} \int_{\tau_k}^{\tau_{k+1}} e^{-\frac{1}{2}(\hat{g}'_{n}(2\nu)-w'h)^H \mathbf{K}^{-1}(\hat{g}'_{n}(2\nu)-w'h)} dh. \quad (16)$$

Now, defining

$$a = w'^H w', \quad (17)$$

$$b = -\hat{g}'_{n}(2\nu) \mathbf{K}' w' - w'^H \mathbf{K}' \hat{g}'_{n}(2\nu), \quad (18)$$

we have

$$k^* = \arg\max_{k} \int_{\tau_k}^{\tau_{k+1}} e^{-(aw'^H b + bh)} dh$$

$$= \arg\max_{k} \left[ \text{erf} \left( \frac{2a\tau_{k+1} + b}{2\sqrt{a}} \right) - \text{erf} \left( \frac{2a\tau_k + b}{2\sqrt{a}} \right) \right], \quad (19)$$

with erf the error function of the normal distribution.

Also in this case if multiple attacks are available, various quantized points can be explored, jointly among all $2N$ quantized value. Therefore, after having considered the key obtained using quantized values (19), we must find the next quantized values in all $N$ observations having the highest probability, thus changing only one quantized value, and so on.

**C. Symmetric-key Based Authentication**

With SKBA the two legitimate devices must agree on a secret key by which authentication is performed. In particular, once Alice and Bob has agreed on a (secret) key, when Bob is transmitting a packet it will encode a time-varying signature with the secret key so that Alice can check that the packet is coming from Bob.

For the establishment of the secret key we resort to the source-based secret key agreement method [5] where the two users extract the quantized randomness from the channel and then go through the steps of advantage distillation, information reconciliation and privacy amplification. In particular, in the step of information reconciliation error correcting codes are used to ensure that the keys between the two users coincide.

We consider the following scheme, in which all users have agreed on a codebook $C$ of codewords of length $N$:
1) At slot 1 Alice transmits a set of pilot symbols and Bob estimates the channel $h_{B,n}(1)$. Eve estimates the channel $\tilde{g}_{1,n}(1)$.

2) At slot 2 Bob transmits a set of pilot symbols and Alice estimates the channel $h_{A,n}(2)$. Alice finds in $C$ the codeword closest to $h_{A}(2)$, vector collecting the channels for all $2N$ observations, i.e.,

$$c_{A}^{\ast} = \arg \min_{c \in C} ||\hat{h}_{A}(2) - c||^{2}. \tag{20}$$

Eve estimates the channel $\tilde{g}_{2,n}(2)$.

3) Alice sends the error of her estimated channel with respect to the selected codeword, i.e.,

$$e = \hat{h}_{A}(2) - c_{A}^{\ast}. \tag{21}$$

4) Bob computes $\hat{h}_{B} = \hat{h}_{B}(1) - e$ and decodes it in the codebook $C$, i.e., computes

$$c_{B}^{\ast} = \arg \min_{c \in C} ||\hat{h}_{B} - c||^{2}. \tag{22}$$

5) Eve obtains from the two estimates at point 1) and 2) the ML estimate of the Alice-Bob channel $\hat{h}_{E}(1)$, adds $e$ and decodes the resulting vector, i.e., she computes

$$c_{E}^{\ast} = \arg \min_{c \in C} ||\hat{h}_{E}(1) - e - c||^{2}. \tag{23}$$

6) The three users will apply a hash function to the index of the decoded sequences to extract $R_{n}$ bits that will be used as key for authentication.

In this case multiple attacks can be performed by considering the next most probable decoded codewords, given the observations.

IV. PERFORMANCE ANALYSIS

We consider now the performance of each authentication scheme separately, in terms of FA and MD probabilities.

A. Physical Layer Authentication

For the PLA scheme FA and MD probabilities have been derived in [2] without considering the channel evolution of $H$.

Conditioned on $H_{0}$ and for any value of $\hat{h}_{A,n}(1)$, $\Psi(t)$, $t > 1$ is a central chi-square distributed random variable with $2n$ degrees of freedom, yielding the FA probability

$$P_{PLA,FA} = P[\Psi(t) > \theta(t)|H_{0}] = 1 - F_{2n,0}(\theta(t)), \tag{24}$$

where

$$F_{2n,0}(x) = 1 - Q_{n}(\sqrt{x}), \tag{25}$$

is the cumulative distribution function (CDF) of a chi-square random variable with $2n$ degrees of freedom and noncentrality parameter $\mu$, $Q_{n}(\sqrt{x})$ is the Marcum Q-function, and $\gamma(a; b)$ is the normalized lower incomplete gamma function.

Conditioned on $H_{1}$, the realization of $\hat{h}_{A,n}(1)$ and the forged channel $\hat{h}_{E,n}(1)$, $\Psi(t)$ is a noncentral chi-square distributed random variable with $2n$ degrees of freedom and noncentrality parameter

$$\beta(t) = \frac{1}{N\gamma^{2}(t)} \sum_{n=1}^{N} |\hat{h}_{E,n}(t) - \alpha^{t-1}\hat{h}_{A,n}(1)|^{2} \tag{26}$$

which provides the MD probability

$$P_{PLA,MD}(\hat{h}(1), \tilde{h}(t)) = \mathbb{P}[\Psi(t) \leq \theta(t)|H_{1}, \hat{h}(1), \tilde{h}(t)] = F_{2n,\beta(t)}(\theta(t)). \tag{27}$$

B. Asymmetric-key Based Authentication

For the SKBA scheme $F_{A}$ and MD probabilities have been derived in [3] without considering the channel evolution of $H$.

1) At slot 1 Alice transmits a set of pilot symbols and Bob transmits a set of pilot symbols and Bob estimates the channel $h_{B}(1)$, vector collecting the channels for all $2N$ observations, i.e.,

$$c_{A}^{\ast} = \arg \min_{c \in C} ||\hat{h}_{A}(2) - c||^{2}. \tag{30}$$

2) The PLA scheme $F_{A}$ and MD probabilities have been derived in [2] without considering the channel evolution of $H$.

3) Eve estimates the channel $\tilde{g}_{2,n}(2)$.

4) Alice sends the error of her estimated channel with respect to the selected codeword, i.e.,

$$e = \hat{h}_{A}(2) - c_{A}^{\ast}. \tag{31}$$

5) Bob computes $\hat{h}_{B} = \hat{h}_{B}(1) - e$ and decodes it in the codebook $C$, i.e., computes

$$c_{B}^{\ast} = \arg \min_{c \in C} ||\hat{h}_{B} - c||^{2}. \tag{32}$$

6) Eve obtains from the two estimates at point 1) and 2) the ML estimate of the Alice-Bob channel $\hat{h}_{E}(1)$, adds $e$ and decodes the resulting vector, i.e., she computes

$$c_{E}^{\ast} = \arg \min_{c \in C} ||\hat{h}_{E}(1) - e - c||^{2}. \tag{33}$$

7) The three users will apply a hash function to the index of the decoded sequences to extract $R_{n}$ bits that will be used as key for authentication.

In this case multiple attacks can be performed by considering the next most probable decoded codewords, given the observations.

C. Symmetric-key Based Authentication

For the SKBA scheme the FA probability is the probability that $c_{A}^{\ast}$ and $c_{B}^{\ast}$ do not coincide. The MD probability is the probability that Eve decodes $c_{A}^{\ast}$ and the MD probability $P_{SKBA,MD}$ is the probability that Eve decodes $c_{A}^{\ast}$.

Conditioning on $H_{0}$ and for any value of $\hat{h}_{A,n}(1)$, $\Psi(t)$, $t > 1$ is a central chi-square distributed random variable with $2n$ degrees of freedom, yielding the FA probability

$$P_{SKBA,FA} = P[\Psi(t) > \theta(t)|H_{0}] = 1 - F_{2n,0}(\theta(t)), \tag{35}$$

where $P[\Psi(t) > \theta(t)|H_{1}], \hat{h}(1), \tilde{h}(t)] = F_{2n,\beta(t)}(\theta(t)). \tag{36}$$

and we have that $P_{SKBA,FA}$ is the missed detection probability of the detection process, i.e.,

$$P_{SKBA,FA} = \pi_{B,MD}(c_{A}^{\ast}, \lambda) = \mathbb{P}[\Lambda_{B}(c_{A}^{\ast}, \tilde{h}_{B}) \leq \lambda], \quad \tilde{h}_{B} \sim p_{h_{B}}(\tilde{h}_{B}), \quad c_{A}^{\ast} \sim p_{c_{A}^{\ast}}(c_{A}^{\ast}). \tag{37}$$

On the other hand, the FA probability of the detection process sets an upper bound on the rate of the secret key $R$, therefore the threshold $\lambda$, in particular

$$R \leq -\frac{1}{N} \log_{2} \pi_{B,FA}(\lambda) \tag{38}$$

where

$$\pi_{B,FA}(\lambda) = \mathbb{P}[\Lambda_{B}(c_{A}^{\ast}, \tilde{h}_{B}) > \lambda], \quad \tilde{h}_{B} \sim p_{h_{B}}. \tag{39}$$
Following similar derivations to those for the FA, it turns out that the MD probability of the authentication process is the complementary of the MD probability of the detection process at Eve, i.e., defining

$$\Lambda_E(c_A^*, \tilde{h}_E) = \frac{1}{N} \ln \frac{p_{\tilde{h}_E | h_A}(\tilde{h}_E | c_A^*)}{p_{\tilde{h}_E}(\tilde{h}_E)},$$  \hspace{1cm} (36)$$

we have

$$P_{SKBA, MD} = 1 - P_{B, MD}(c_A^*, \lambda)$$
$$= 1 - P[\Lambda_E(c_A^*, \tilde{h}_E) > \lambda], \quad \tilde{h}_E \sim p_{\tilde{h}_E | h_A}, \quad \tilde{h}_A = c_A^*.$$  \hspace{1cm} (37)$$

Efficient methods to compute the FA and MD probabilities of the detection process have been derived in [6].

V. CONCLUSIONS

In this paper we have considered a MIMO time-varying channel model among two legitimate users and an eavesdropper. We have compared three authentication methods, all based on the randomness of the MIMO channels: physical layer authentication, asymmetric-key based authentication and symmetric-key based authentication. We have described how to exploit the channel in this scenario, which is the best attack by the eavesdropper and we have obtained the performance in terms of FA and MD probabilities for the authentication process.

REFERENCES

[1] W. Stallings, *Cryptography and Network Security: Principles and Practice*, 5th ed. Upper Saddle River, NJ, USA: Prentice Hall Press, 2010.

[2] P. Baracca, N. Laurenti, and S. Tomasin, “Physical layer authentication over mimo fading wiretap channels,” *IEEE Transactions on Wireless Communications*, vol. 11, no. 7, pp. 2564–2573, July 2012.

[3] A. Ferrante, N. Laurenti, C. Masiero, M. Pavon, and S. Tomasin, “On the error region for channel estimation-based physical layer authentication over Rayleigh fading,” *IEEE Transactions on Information Forensics and Security*, vol. 10, no. 5, pp. 941–952, May 2015.

[4] E. Jorswieck, S. Tomasin, and A. Sezgin, “Broadcasting into the uncertainty: Authentication and confidentiality by physical-layer processing,” *Proceedings of the IEEE*, vol. 103, no. 10, pp. 1702–1724, Oct 2015.

[5] M. Bloch and J. Barros, *Physical-Layer Security. From Information Theory to Security Engineering*. Cambridge: Cambridge University Press, 2011.

[6] T. Erseghe, “Coding in the finite-blocklength regime: Bounds based on Laplace integrals and their asymptotic approximations.” *CoRR*, vol. abs/1511.04629, 2015. [Online]. Available: http://arxiv.org/abs/1511.04629