Design and Performance Analysis of Secure Multicasting Cooperative Protocol for Wireless Sensor Network Applications

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Abstract—This letter proposes a new security cooperative protocol, for dual phase amplify-and-forward large wireless sensor networks. In such a network, a portion of the $K$ relays can be potential eavesdroppers. The source agrees to share with the destination a given channel state information (CSI) of a source-trusted relay-destination link to encode the message. Then, in the first hop, the source will use this CSI to map the right message to a certain sector while transmitting fake messages to the other sectors using sectoral transmission. In the second hop, the relays retransmit their received signals to the destination, using the distributed beamforming technique. We derived the secrecy outage probability and demonstrated that the probability of receiving the right encoded information by an untrustworthy relay is inversely proportional to the number of sectors. We also showed that the aggressive behavior of the cooperating untrusted relays is not effective compared to the case where each untrusted relay is trying to intercept the transmitted message individually.

Index Terms—Physical layer security, secrecy outage probability, amplify and forward, secrecy capacity.

I. INTRODUCTION

IN WIRELESS networks, nodes can join and leave frequently, which increases the risk of the malicious nodes that are penetrating the wireless network. Therefore, the demand for security solutions in the physical layer is becoming more and more essential. One of the important metrics that evaluate the security performance in the physical layer is the secrecy rate, which is the difference between the channel capacity of the legitimate links and the channel capacity of the illegitimate ones [1]. Many techniques have been proposed to achieve a positive secrecy rate, such as multi-antenna scenarios, beamforming, game theory, power allocation schemes and cooperative jamming [2], [3], [4] and [5]. A wireless network could benefit from the new joining nodes, by using them as relays, or by treating them as potential eavesdroppers. However, as shown in [4] and [6], taking advantage of these nodes and using them as relays could be more useful to the wireless network, from a security perspective, than treating them as eavesdroppers. The authors in [7] studied the secrecy performance for the case of multiple passive untrusted relays, where each passive untrusted relay is trying to intercept its received message individually. In [8], the authors studied the secrecy capacity scaling with aggressive untrusted relays. We define the aggressive behavior as when the untrusted relays are cooperating between each other by sending their received messages to an external wiretapper. Both [7] and [8] considered two transmission schemes, namely opportunistic relaying (OR) and distributed beamforming (DBF). They also demonstrated that DBF outperforms OR technique from a secrecy perspective. In [9], a new location-based multicasting technique was proposed considering both passive and aggressive untrusted relays behaviors. It was shown that this technique enhances the security compared to [7] and [8].

On the other hand, the randomness of the channel has been exploited for different purposes, whether to enhance the reliability or to secure the communication system as it was used to generate keys in [10]. Therefore, in this letter, we combine the channel randomness with multicasting transmission to propose a new location-based multicasting protocol in two-hops wireless sensor networks (WSN). The goal of this protocol is to increase the security of these networks while taking into account that wireless sensor nodes have limited capabilities. In the proposed protocol, the source and the destination share the channel state information (CSI) to map the source’s transmission by sending the useful encoded message towards a specific sector, while sending other fake messages, similar to the useful one, towards the other sectors to confuse the eavesdroppers. Thus, we propose two strategies: the first one is to prevent the eavesdropper from receiving the transmitted message all the time by multicasting the signal to a different sector in each transmission time. Hence, for an eavesdropper located in a certain sector, the probability that it would be in the right sector is inversely proportional to the number of sectors, $p = 1/N \ll 1$. This eavesdropper can still know when there is a transmission towards it and when there isn’t. Also, it can know to which sector this transmitted signal is multicasted when this eavesdropper cooperates with other eavesdroppers located in other sectors. Therefore, we came up with the second strategy which is based on sending fake messages towards the other sectors to increase the entropy and the confusion, related to being in the right sector, at the eavesdroppers. We provide analytical expressions for the secrecy outage probability (SOP) of both passive and aggressive untrusted relays. Our numerical results show how our technique enhances the security performance and how immune it is against the aggressive behavior of the untrusted relays. Finally, adopting such a security protocol by allowing a part of the nodes to forward fake messages is promising because of the availability of high number of cheap electronic sensors with limited computational capabilities.
II. SYSTEM MODEL AND PROBLEM FORMULATION

Consider a source $s$ equipped with multi-sectoral antennas, $K$ amplify-and-forward (AF) cooperative relay node sensors with limited capabilities, and a destination $d$, provided with sectoral antennas. Out of the $K$ relays, there are $U$ untrustworthy relays that could be potential eavesdroppers. Each relay is equipped with a single antenna and works in a half-duplex mode, as shown in Fig. 1. It is assumed that there is no direct link between $s$ and $d$, i.e., all the transmitted information should be forwarded by the relays. To perform the proposed security method, $s$ and $d$ should share the CSI knowledge of the source-trusted relay-destination link, which is the kernel of our developed security method. This CSI is considered to be the main cause of randomness and it is completely mapped into a vector of digital values. It should be noted that this security algorithm is implemented just before the communication process starts, and it can be renewed at any time $s$ and $d$ agree on to keep refreshing the source of security and to make it as strong as possible. Moreover, since the received signal-to-noise ratio (SNR) in an AF two-hop wireless network over the first hop is higher than the received SNR after two hops. Therefore, considering the case where the eavesdropper is in the first hop, we are studying the worst case security scenario. In the first hop, the source will encode the data prior to the transmission by using the vector $V$. Then, $s$ will use this vector again to map its transmission of the different messages $x_i$’s towards $N$ different sectors, where $1 \leq i \leq N$, $N \in \mathbb{N}^+$. We will denote the desired encoded signal by $x_{i^r}$, whereas the other signals $x_{i \neq i^r}$ are the fake ones that are transmitted over the other sectors. Without the knowledge of $V$, each untrusted relay $e$ will try to randomly guess the useful signal with a probability $1/N$. Even if it succeeds in guessing and receiving the useful message, the untrusted relay would still need the vector $V$ to decode it. In the second phase, all the $K$ relays will resend their received messages towards $d$ using the DBF technique. Since it has the same vector $V$, after removing the interference coming from the fake messages by using self-interference cancellation (SIC), the destination will be able to know from which sector the useful message is coming and decode it using $V$. The received signal, at the $k$th relay, where $1 \leq k \leq K$, is given by

$$y_k = \sqrt{P_k} h_{s,k} x_i + n_k,$$

where $n_k \sim \mathcal{C}(0, N_0)$ is the complex additive white Gaussian noise (AWGN) at the $k$th relay, with mean 0 and variance $N_0$, $P_k$ is the transmitted power from $s$ towards the $k$th sector. We assume that the channels are quasi-static block log-normal channels, i.e., the channel coefficient $h_{s,r} \sim \ln \mathcal{N}(\mu_s, \sigma_s^2)$, where $\{v, r\} \subset \{\{s, k\}, \{k, d\}\}$, is considered constant during the transmission time of one message, but it may change independently thereafter, the CSI is known by the receiving nodes, and the noise variance $N_0$ has the same value in the first and the second phases. It is important to note that adopting such security solution by allowing a part of the nodes to forward fake messages is feasible due to the availability of a high number of electronic sensors with limited capabilities. Consequently, the received SNR, at the $k$th relay, is expressed as

$$\gamma_k = \frac{\rho_s h_{s,k}^2}{\rho_s h_{s,k}^2 + N_0},$$

where $\rho_j = \frac{A}{P_j/N_0}$, $j \in \{s, k, e\}$. In the second hop, the retransmitted message from the $k$th relay will be $x_k = \alpha_k w_k y_k$, where $w_k$ is the beamforming weight, and $\alpha_k$ represents the normalized amplifying coefficient

$$\alpha_k = \frac{1}{\sqrt{\rho_s h_{s,k}^2 + N_0}}.$$ 

The received useful messages at $d$ will be written as

$$y_d = \sum_{m=1}^{M} h_{m,d} \alpha_m w_m y_m + n_d,$$

where $M$ is the number of the relays in the sector that receives the right message. $1 \leq m \leq M$, $n_d \sim \mathcal{N}(0, N_0)$ is the complex AWGN at $d$. After optimizing the beamforming weights from [7] and the references therein, the SNR at the destination is obtained as

$$\gamma_d = \sum_{m=1}^{M} \frac{\rho_s h_{s,m}^2 \rho_m h_{m,d}^2}{\rho_s h_{s,m}^2 + \rho_m h_{m,d}^2 + 1} = \sum_{m=1}^{M} \gamma_m.$$ 

The channel capacity at $d$ will be

$$C_d = \left[\frac{1}{2} \log(1 + \gamma_d)\right]^+,\$$

where $[\xi]^+$ denotes $\max\{\xi, 0\}$.

A. Non Colluding Eavesdropping Relays

In this scenario, there are two different hypotheses $H1$ and $H2$ as follows:

Hypothesis $H1$: the untrusted relay is in the right sector with a probability $p_1 = 1/N$ and it knows how to recover $V$ and decode the message.

Hypothesis $H2$: the untrusted relay is in a wrong sector, with a probability $p_0 = 1 - p_1 = 1 - 1/N$. Then, this relay
will not impact the security and the channel capacity at the eavesdropper $e$ will be equivalent to zero from a security point of view. Considering the aforementioned two hypotheses, the channel capacity at $e$ will be expressed as

$$C_e = \frac{1}{2} \log(1 + \gamma_e) H_1 \quad H_2,$$

where $\gamma_e = \rho_s |h_{s,e}|^2$ is the SNR of the useful message at $e$.

### B. Colluding Eavesdropping Relays

Assuming aggressive untrusted relays, cooperating between each other and sending their messages towards an external wire-tapper $A$, the received useful signal at $A$ will be written as

$$y_A = \sum_{u=1}^{U_1} h_{u,A} \alpha_u w_u y_u + n_A,$$

where $U_1$ is the number of the untrusted relays that are in the right sector and sending the useful messages $x_{tr}$, and $1 \leq u \leq U_1 \leq U$. Moreover, $n_A \sim N_c(0, N_0)$ is the complex AWGN at $A$. Hence, the SNR at $A$ will become

$$\gamma_A = \sum_{u=1}^{U_1} \frac{\rho_s |h_{s,u}|^2 |h_{u,A}|^2}{\rho_s |h_{s,u}|^2 + |h_{u,A}|^2 + 1} = \sum_{u=1}^{U_1} \gamma_u.$$

We will define two hypotheses for $A$:

Hypothesis $H'_1$: $A$ receives the right message with a probability $p_1 = 1/N$ and knows how to recover $V$ and decodes the message.

Hypothesis $H'_2$: the colluding relays are just in the wrong sectors, or $A$ cannot recover $V$, which means that $A$ won’t have any impact on the security. Hence, the channel capacity at $A$ will be equivalent to

$$C_A = \frac{1}{2} \log(1 + \gamma_A) H'_1 \quad H'_2.$$

We will define the worst security case as when $e$, (in the non colluding state), or $A$, (in the colluding state), knows how to recover $V$ and decode the message. Therefore, the channel capacity at $q$, where $q \in \{e, A\}$, is given as

$$C_q = \left[ \frac{1}{N} \frac{1}{2} \log(1 + \gamma_q) \right]^+.$$

From (6) and (11), the general secrecy capacity expression of the worst case is calculated as

$$C_{S,q} = \left[ C_d - C_q \right]^+ = \left[ \frac{1}{2} \log(1 + \gamma_d) - \frac{1}{2N} \log(1 + \gamma_q) \right]^+.$$

### III. Secrecy Outage Probability

**Theorem 1**: The secrecy outage probability expression of our proposed method $C_{S,q}$, for both passive and aggressive untrusted relays scenarios, is expressed as

$$\Pr[C_{S,q} < R] = \frac{2}{3} \Phi \left( \left( \ln \left( \frac{1}{2} \left( 1 + e^{\beta q} \right) \right) - \beta \frac{\mu_d}{\sigma_d} \right) \sigma_d^{-1} \right) + \frac{1}{6} \Phi \left( \ln \left( \frac{1}{2} \left( 1 + e^{\beta q + \sqrt{2} \sigma_d} \right) \right) - \beta \frac{\mu_d}{\sigma_d} \right) \sigma_d^{-1} - \frac{1}{6} \Phi \left( \ln \left( \frac{1}{2} \left( 1 + e^{\beta q - \sqrt{2} \sigma_d} \right) \right) - \beta \frac{\mu_d}{\sigma_d} \right) \sigma_d^{-1}.$$

**Proof**: From (12), and for a threshold $R$, the SOP is defined as [7]

$$\Pr[C_{S,q} < R] = \Pr\left[ \frac{1}{2} \log(1 + \gamma_d) - \frac{1}{2N} \log(1 + \gamma_q) < R \right] = \Pr\left[ \gamma_d < 2^{2R} \left( 1 + \gamma_q \right) \right] = \int_0^\infty \Phi \left( \ln \left( \frac{1}{2} \left( 1 + e^{\beta q} \right) \right) - \beta \frac{\mu_d}{\sigma_d} \right) \sigma_d \ d \gamma_q.$$

Since $\gamma_q$ and $\gamma_d$ are following a log-normal distribution, (please refer to the Appendix for the proof), then their probability density function (PDF) and cumulative distribution function (CDF) are respectively given by

$$f_X(x; \mu, \sigma) = \frac{1}{x \sigma \sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}},

F_X(x; \mu, \sigma) = \Phi \left( \frac{\ln x - \mu}{\sigma} \right),$$

where $\Phi$ is the CDF of the standard normal distribution. Thus, the SOP in (14) is obtained as

$$\Pr[C_{S,q} < R] = \int_0^\infty \Phi \left( \ln \left( \frac{1}{2} \left( 1 + e^{\beta q} \right) \right) - \beta \frac{\mu_d}{\sigma_d} \right) e^{\frac{-\left( \ln \gamma_q - \mu_q \right)^2}{2 \sigma_q^2}} \ d \gamma_q.$$

Let $\beta = \ln(\gamma_q)$, then

$$\gamma_q = e^\beta,$$

and

$$d \gamma_q = e^\beta \ d \beta.$$ 

Thus, $\beta$ is a normally distributed r.v. $\beta \sim N(\mu_q, \sigma_q^2)$. Substituting $\beta$ and (19) in (17), the secrecy outage probability $\Pr[C_{S,q} < R]$ is written as

$$\int_0^\infty \Phi \left( \ln \left( \frac{1}{2} \left( 1 + e^{\beta} \right) \right) - \beta \frac{\mu_d}{\sigma_d} \right) e^{\frac{-\left( \beta - \mu_q \right)^2}{2 \sigma_q^2}} \ d \beta.$$

It is noticed that (20) denotes the expectation of $\psi(\beta)$. We will use Holtzman’s tool [11] to approximate $E[\psi(\beta)]$ in terms
of three points located at \( \mu_q, \mu_q + \sqrt{3}\sigma_q \) and \( \mu_q - \sqrt{3}\sigma_q \) as follows:

\[
\Pr[C_{S,q} < R] = E[\psi(\beta)] = \frac{2}{3} \psi(\mu_q) + \frac{1}{6} \psi(\mu_q + \sqrt{3}\sigma_q) - \frac{1}{6} \psi(\mu_q - \sqrt{3}\sigma_q).
\]

Substituting \( \psi(\beta) \) from (20) to (21) yields (13).

IV. SIMULATION RESULTS

In this section, we demonstrate the validity of our derived results using MATLAB software. Fig. 2 shows the SOP as a function of the SNR. It is noticed that the derived expressions accurately characterize the simulation results. It is assumed that \( R = 3 \) bps/Hz, \( M = 4 \), \( \sigma_s = \sigma_k = 0.95 \) and \( \mu_s = \mu_k = 1 \).

From Fig. 2, we can see how the secrecy performance improves when the number of sectors \( N \) is increased. For example, to keep the SOP level at \( 10^{-6} \), the source has to increase the number of sectors \( N \) from 4 to 8, which also reduces the required SNR from 23 dB to 17 dB. Also, it is shown that our technique outperforms the conventional jamming technique, where the destination jams the nodes while the source is transmitting in the first hop. As we can see from Fig. 2, the margin between the worst and the best case, when \( e \) does not know how to recover \( V \), depends on \( e \)'s capability of recovering \( V \) and decoding the message.

Fig. 3 shows the SOP of our proposed technique for different values of \( N \), when \( R = 2 \) bps/Hz, \( \sigma_s = \sigma_k = 1.1 \), and \( \mu_s = \mu_k = 0.69 \). It can be seen that the greater the number of sectors, the better the secrecy performance. Moreover, we can see from Fig. 3 that there is not that much difference between the case of one and that of three aggressive untrusted relays. For example, for an SNR level of 18 dB, the SOP just goes from \( 1.05 \times 10^{-2} \) to \( 1.85 \times 10^{-2} \) when two extra aggressive untrusted relays are added, which means that our proposed technique is immune towards adding more eavesdropping relays that are cooperating with each other. Also, it is shown that the security performance is improved when our technique is applied compared to the jamming technique. To evaluate the diversity order, we calculated the slope at 20 dB for the following cases: when all the relays are trusted, the brown curve in Fig. 2, and when all the relays are untrusted and aggressive, the blue curve in Fig. 3. For the first case, the slope is 1.1, whereas it becomes 0.7 for the second case.

V. CONCLUSION

In this letter, we proposed a new location-based multicasting protocol that is using the knowledge of the CSI of a trusted link in two-hops WSN to map the transmission. We provided an analytical study for the SOP for both passive and the aggressive behaviors of the untrusted relays. The results showed the immunity of our technique towards the untrusted relays’ aggressive behavior, and an improvement in the security compared to the conventional jamming technique.

APPENDIX

We will prove that \( \gamma_q \) and \( \gamma_d \) are following a log-normal distribution. First, we will define the SNR \( \gamma_{i,j} \) as follows

\[
\gamma_{i,j} = \rho_i |h_{i,j}|^2,
\]

where \( i \in \{s, m\} \) and \( j \in \{m, e, d\} \).

Lemma 1: Let \( X \sim \ln\mathcal{N}(\mu, \sigma^2) \), then \( aX \sim \ln\mathcal{N}(\mu + \ln a, \sigma^2) \), and \( X^a \sim \ln\mathcal{N}(a\mu, a^2\sigma^2) \), \( a \in \mathbb{R} \).

From Lemma 1, where \( a = 2 \), the channel gain \( |h_{i,j}|^2 \sim \ln\mathcal{N}(2\mu_i, 4\sigma_i^2) \). By using the properties in Lemma 1, we find that

\[
\gamma_{i,j} \sim \ln\mathcal{N}(\mu_{i,j}, \sigma^2_{i,j}), \quad \text{where} \quad \mu_{i,j} = 2\mu_i + \ln(\rho_i) \quad \text{and} \quad \sigma^2_{i,j} = 4\sigma_i^2.
\]

Hence, \( \gamma_i \sim \ln\mathcal{N}(\mu_s, \sigma^2_s) \).

Now, we will find the distribution of \( \gamma_m \) (5) with the following approximation for high SNRs,

\[
\gamma_m = \frac{\gamma_s, m \gamma_m, d}{\gamma_s, m + \gamma_m, d + 1} \approx \frac{\gamma_s, m \gamma_m, d}{\gamma_s, m + \gamma_m, d} = \frac{1}{\frac{1}{\gamma_s, m} + \frac{1}{\gamma_m, d}} = \frac{1}{\frac{1}{z_1} + \frac{1}{z_2}},
\]

where \( z = z_1 + z_2 \), \( z_1 = \frac{1}{\gamma_s, m} \) and \( z_2 = \frac{1}{\gamma_m, d} \).
Lemma 2: Let $X_j \sim \ln \mathcal{N}(\mu_j, \sigma_j^2)$ be independent log-normally distributed variables with varying $\sigma$ and $\mu$ parameters, and $Y = \sum_{j=1}^{n} X_j$. Then the distribution of $Y$ has no closed form expression, but can be reasonably approximated by another log-normal distribution $Z$ with parameters [12]

\[
\begin{align*}
\mu_Z &= \ln \left[ \sum e^{\mu_j + \sigma_j^2/2} \right] - \frac{\sigma_Z^2}{2}, \\
\sigma_Z^2 &= \ln \left[ \frac{\sigma_Z^2}{2} \right].
\end{align*}
\]

Form Lemma 1, where $a = -1$, we find that $Z_1 \sim \ln \mathcal{N}(-\mu_{\gamma, m}, \sigma_{\gamma, m}^2)$ and $Z_2 \sim \ln \mathcal{N}(-\mu_{\gamma, d}, \sigma_{\gamma, d}^2)$. Also, from Lemma 2, $Z \sim \ln \mathcal{N}(\mu_z, \sigma_z^2)$, where

\[
\mu_z = \ln(2\exp(\mu_{\gamma, m})) + 0.5\left(\sigma_{\gamma, m}^2 - \sigma_{\gamma, d}^2\right).
\]

Thus, from Lemma 1 and (23), we get $\gamma_m \sim \ln \mathcal{N}(\mu_{\gamma, m}, \sigma_{\gamma, m}^2)$, $\mu_{\gamma, m} = -\mu_z$, and $\sigma_{\gamma, m}^2 = \sigma_{\gamma, d}^2$. From (5), since $\gamma_d$ is a sum of many $\gamma_m$, we will again use Lemma 2 to find that $\gamma_d \sim \ln \mathcal{N}(\mu_{\gamma, d}, \sigma_{\gamma, d}^2)$, where

\[
\begin{align*}
\sigma_{\gamma, d}^2 &= \ln \left( \exp(\sigma_{\gamma, m}^2) - 1 \right)/M + 1, \\
\mu_{\gamma, d} &= \ln(M \exp(\mu_{\gamma, m})) + 0.5\left(\sigma_{\gamma, m}^2 - \sigma_{\gamma, d}^2\right).
\end{align*}
\]

Since the expressions of $\gamma_u$ and $\gamma_A$ in (9) are similar to $\gamma_m$ and $\gamma_d$ respectively, by following the same steps, we show that $\gamma_u \sim \ln \mathcal{N}(\mu_{\gamma, m}, \sigma_{\gamma, m}^2)$ and $\gamma_A \sim \ln \mathcal{N}(\mu_{\gamma, A}, \sigma_{\gamma, A}^2)$ where

\[
\begin{align*}
\sigma_{\gamma, A}^2 &= \ln \left( \exp(\sigma_{\gamma, m}^2) - 1 \right)/U_1 + 1, \\
\mu_{\gamma, A} &= \ln(U_1 \exp(\mu_{\gamma, m})) + 0.5\left(\sigma_{\gamma, m}^2 - \sigma_{\gamma, A}^2\right).
\end{align*}
\]

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