Secure Routing in OFDM based Multi-Hop Underwater Acoustic Sensor Networks

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Abstract—Consider an OFDM based, multi-hop underwater acoustic sensor network with \( M + 1 \) underwater sensing nodes that report their sensed data to a sink node (on water surface). A malicious node Eve attempts to eavesdrop the ongoing communication between a sensor node and the sink node. To this end, this work performs joint optimal node selection for data forwarding and sub-carrier power allocation (across OFDM sub-carriers) to maximize the secrecy capacity on each hop. Specifically, the optimization problem formulated is a mixed binary-integer program, which is solved via dual decomposition method. Since this is the first work on secure routing, we compare the performance of the proposed scheme with the classical depth-based routing (DBR) scheme in simulations. The simulation results show that: i) the proposed scheme outperforms the DBR scheme (i.e., the performance gap between the two schemes increases) with increase in the transmit power budget of the sensor nodes, ii) the proposed scheme benefits from the increase in the density of sensor nodes (while the DBR scheme fails in such situation).

I. INTRODUCTION

Communication between underwater acoustic sensor networks (UWASN) nodes is susceptible to various attacks—including passive attacks (such as eavesdropping) as well as active attacks (such as impersonation)—due to the broadcast nature of the acoustic medium [1]. Traditionally, communication systems have been secured via cryptographic measures (e.g., RSA, AES) which provide security at the higher layers of the protocol stack. But such measures are fallible as demonstrated by researchers in recent times who have managed to break into the crypto-based security measures employed by the IEEE 802.11/Wi-Fi systems [2].

The limitations of the cryptography based security measures have motivated the researchers to focus on the alternate approach of physical layer security (PLS)—an information-theoretic approach whose foundations were laid down by Shannon in his landmark paper [3]. Later, in an influential work [4], Wyner introduced the wiretap-channel, and defined secrecy capacity as the maximum achievable secure rate (secret bits/sec) between two legal nodes, in the presence of an eavesdropper. Since then, secrecy capacity maximization has become a de-facto metric to evaluate the performance of communication systems facing an eavesdropping attack.

This work considers the problem of data forwarding/routing from a sensor node to the sink node when a (passive) malicious node Eve is present in the close vicinity. Eve listens to ongoing communication between a sensor node and the sink node, thereby potentially decoding confidential information fully or partially. The shortest data forwarding path from a sensor node to the sink node may still consist of multiple hops; therefore, the communication on each hop needs to be protected from passive attack by Eve.

This work does joint optimal node selection for data forwarding/routing and power allocation across the orthogonal frequency division multiplexing (OFDM) sub-carriers at each hop such that the secrecy capacity at each hop is maximized. The optimization problem at hand turns out to be a mixed binary integer programming problem, which is known to be non-convex and NP-hard. Therefore, we resort to a sub-optimal dual decomposition method based approach. However, we note that the duality gap of the proposed dual decomposition based solution approaches zero as the number of OFDM sub-carriers grows large [5].

A. Related work

The recent surge of interest in multi-hop UWASNs has led the researchers to design a plethora of routing/data forwarding protocols, each with a different design objective, to address the unique set of challenges that UWASNs pose (see the survey article [6] and the references therein for more details). There are few works on secure routing in UWASNs though [7], [8], which design routing protocols to detect a wormhole link in an UWASN. Zhang et. al. [7] detect a wormhole link through a set of neighbor discovery protocols based on the direction of arrival (DoA) of the acoustic wave. A secure, anonymous routing protocol is presented in [8] which does two-way signature-based authentication under some assumptions (e.g., attack node has no information about the location, ID etc. of the legitimate nodes). However, while the works [7], [8] deal with wormhole attack through crypto-based measures, this work counters a passive eavesdropping attack through PLS.

From a different perspective, there are few more works that deal with the passive eavesdropping attacks in single-hop UWASNs [9], [10]. The work [9] considers a 2-D region (a disk) comprising multiple UWASN nodes (and one Eve node) distributed according to a Poisson point process. The authors then consider a critical region around Eve to compute the probability that the eavesdropper is able to intercept the communication ongoing within the network. Huang et. al. [10] consider a situation where a node (Alice) transmits to another node (Bob) in the presence of an eavesdropper node (Eve); authors propose that the Bob node exploits the block transmissions nature and large propagation delays of the

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![Fig. 1: The system model.](image)

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all other candidate helper nodes. The SC of $A_i$ (summed over all the $N$ OFDM sub-carriers) is defined as follows:

$$SC^{(i)} = \frac{1}{N} \sum_{j=1}^{N} \log_2(1 + \text{SNR}_{j}^{(E)}) - \log_2(1 + \text{SNR}_{j}^{(E)})$$

where $(x)^+ = \max(x, 0)$; $\text{SNR}_{j}^{(i)}$ ($\text{SNR}_{j}^{(E)}$) is the signal to noise ratio (SNR) on $j$-th sub-carrier at $A_i$ (Eve). In plain words, $SC^{(i)}$ is the channel capacity of $A_i$ less the channel capacity of Eve.

The SNR on the $j$-th sub-carrier at $A_i$ is:

$$\text{SNR}_{j}^{(i)} = \frac{P_j}{\left(\int_{B_j(f)} PL^{(i)}(d, f)df\right) \left(\int_{B_j(f)} N(f)df\right)}$$

Similarly, the SNR on the $j$-th sub-carrier at Eve is:

$$\text{SNR}_{j}^{(E)} = \frac{P_j}{\left(\int_{B_j(f)} PL^{(E)}(d, f)df\right) \left(\int_{B_j(f)} N(f)df\right)}$$

where $p_j$ is the transmit power over $j$-th sub-carrier; $B_j(f)$ is the bandwidth of the $j$-th sub-carrier. $PL(d, f)$ is the frequency-dependent path-loss between a transmit and receive pair with separation $d$, given (in dB scale) as $[11]$:

$$PL(d, f)_{AB} = \nu 10 \log d + d\alpha(f)_{AB}$$

where $\nu$ is the so-called spreading factor, while $\alpha(f)$ is the coefficient of absorption, given as $[11]$:

$$\alpha(f)_{AB} = \frac{0.11f^2}{1 + f^2} + \frac{44f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.003$$

$N(f)$ is the frequency-dependent power spectral density (PSD) of the ambient noise (comprising of noise contributions from turbulence, shipping, waves, and thermal noise) $[11]$:

$$N(f)_{AB} \approx N_1 - \tau 10 \log f$$

where $N_1$ and $\tau$ are the experimental constants. Note that the above approximation of the PSD $N(f)$ of ambient noise holds for frequency range $1 - 100$ kHz only $[11]$. To select one such node for data forwarding whose secrecy capacity is maximum among all other candidate helper nodes, $A_0$ formulates the following optimization problem:

$$\max_{\{(n_i)_{i \in C}, \{p_j\}_{j=1}^{N}\}} \sum_{i \in C} \eta_i SC^{(i)}(\{p_j\}_{j=1}^{N})$$

s.t. $\sum_{i \in C} \eta_i \sum_{j=1}^{N} p_j \leq P_T$

$$\sum_{i \in C} \eta_i = 1$$

where $\eta_i \in \{0, 1\}$ $\forall i \in C$; $\eta_i = 1$ ($\eta_i = 0$) implies that the helper node $A_i$ is selected (not selected). The first constraint of the optimization problem in Eq. (7) ensures that for any candidate helper node $A_i$, the total power allocated over the $N$ sub-carriers should not exceed the total power budget $P_T$ of the sensor node $A_0$. The second constraint ensures that only one node is selected for data forwarding at each hop.

$^1$This assumption is needed for the proposed secure routing algorithm (to be described in the next section) to terminate. This assumption is reasonable because the sink node is typically a very powerful node equipped with proximity sensors (and thus, is capable of detecting a malicious node nearby).
The optimization program in Eq. (7) is a mixed binary-integer program; we use dual decomposition approach to solve it. Regardless of convexity of the original problem, the duality gap between primal solution and dual solution is nearly zero provided that the number of OFDM sub-carriers is sufficiently large [5]. The dual problem is formulated as:

$$\min_{\lambda} D(\lambda)$$ \quad (8)

where $D(\lambda)$ is the dual function, and $\lambda > 0$ is the dual variable/Lagrangean multiplier. The dual function is given as:

$$D(\lambda) = \max_{(\{p_i\}_{i=1}^N, \{\eta_i\}_{i\in C})} L\{\eta_i\}_{i\in C}, \{p_j\}_{j=1}^N, \lambda\} \quad (9)$$

s.t. $\sum_{i\in C} \eta_i = 1$

where $L(.)$ is the Lagrangian function, given as:

$$L = \sum_{i\in C} \sum_{j=1}^N \eta_i \left( \log_2 \left( \frac{\Omega_j^{(i)} \Omega_j^{(E)} + p_j \Omega_j^{(E)}}{\Omega_j^{(i)} \Omega_j^{(E)} + p_j \Omega_j^{(i)}} \right) + \lambda P_T - \lambda p_j \right)$$

where $\Omega_j^{(i)} = \int_{B_{j}(f)} P_{L}^{(i)}(d,f) df, \int_{B_{j}(f)} N(f) df, \quad \Omega_j^{(E)} = \int_{B_{j}(f)} P_{L}^{(E)}(d,f) df, \int_{B_{j}(f)} N(f) df$.

Now, for any selected helper node $A_i$, Eq. (9) becomes:

$$\max_{(p_j)_{j=1}^N} \sum_{j=1}^N \left( \log_2 \left( \frac{\Omega_j^{(i)} \Omega_j^{(E)} + p_j \Omega_j^{(E)}}{\Omega_j^{(i)} \Omega_j^{(E)} + p_j \Omega_j^{(i)}} \right) + \lambda P_T - \lambda p_j \right)$$ \quad (10)

Eq. (10) is a standard convex optimization program. Let $\{p_j^*\}_{j=1}^N$ (derived in the Appendix) be the solution of Eq. (10).

By putting $\{p_j^*\}_{j=1}^N$ back into Eq. (9), we are left with the following problem:

$$D(\lambda) = \max_{(\{\eta_i\}_{i\in C})} L\{\eta_i\}_{i\in C}, \{p_j^*\}_{j=1}^N, \lambda\} \quad \text{subject to} \quad \sum_{i\in C} \eta_i = 1$$ \quad (11)

Let $i^* = \arg \max_{i \in C} L\{\eta_i\}_{i\in C} \quad \forall i \in C$, then the optimal solution to Eq. (11) is:

$$\eta_i^* = \begin{cases} 1, & i^* = i \quad \& \quad D_i < D_0 \\ 0, & \text{else} \end{cases}$$ \quad (12)

where $D_i$ is the depth of node $A_i$. By plugging $\{\eta_i^*\}_{i\in C}, \{p_j^*\}_{j=1}^N$ back into Eq. (9), we are left with the problem in Eq. (8). To this end, we use the sub-gradient method, which iteratively solves Eq. (8) according to the following control law:

$$\lambda(m+1) = \lambda(m) + \delta(P_{\text{alloc}}(m) - P_T)$$ \quad (13)

where $\delta$ is the step size, and $P_{\text{alloc}}(m) = \sum_{i\in C} \sum_{j=1}^N \eta_i(m)p_j(m)$. The algorithm converges when $P_{\text{alloc}}(m) = P_T$.

The proposed method (when run on the first hop) is fully summarized in Algorithm 1. The Algorithm 1 is repeatedly invoked at each helper node to select the node for the next hop until the data reaches the sink node.

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### Algorithm 1: The proposed method for secure routing

**Input:** $d_i, D_i \forall i, d_E$

**Output:** $p_j^* \forall j, \eta_i^* \forall i$

**Parameters:** $\lambda(0), \delta, P_T, M, N$

1. Optimization:
2. while ($\ell$) do
3. repeat
4. implement Eq. (14) \forall j;
5. implement Eq. (13) \forall i;
6. until $P_{\text{alloc}} = P_T \forall i$;
7. return $p_j^*, \forall j$;
8. implement Eq. (12) to return $\eta_i^*$;

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### IV. Simulation Results

#### A. Simulation Setup

The simulations were performed in MATLAB. We used the specification of a commercial OFDM modem (AM-D2000) by Aquasent [12] for simulation. Specifically, we assume an OFDM system with $N = 1024$ sub-carriers which span a bandwidth of 6 KHz (from 9-15 kHz). We deploy $M + 1$ number of legal nodes, and an Eve node according to a uniform distribution in a (vertical) square region of area 5000 ± 5000 m$^2$ under the water. We set $\nu = 1.5$, $N_1 = 50$ dB, $\tau = 18$ dB in Eqs. (12), (6) [11]. We assume that each sensor node knows the distance of Eve from itself. The secrecy capacity SC plotted in each of the following figures is the minimum secrecy capacity among all the hops (after a routing path has been computed by the Algorithm 1). In other words, SC = $\min\{SC_1, ..., SC_k, ..., SC_K\}$ where $SC_k$ is the secrecy capacity obtained by solving the optimization program in Eq. (7) at $k$-th hop (assuming that there are $K$ hops in total).

#### B. Simulation Results

Fig. [2] studies the impact of transmit power budget on secrecy capacity achieved for the proposed secure routing scheme and the benchmark under the scenarios of equal and optimal sub-carrier power allocation. For Fig. [2] we set $M + 1 = 10$. We make the following observations: i) the secrecy capacity is a piece-wise linear monotonic-increasing function of the total power budget $P_T$; ii) the proposed method achieves the minimum secrecy capacity among all the hops (after a routing path has been computed by the Algorithm 1).

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2This assumption is inline with the previous works which perform secrecy capacity analysis of the underwater/terrestrial communication systems [13].

10. One example scenario where such assumption holds is the case where we have our network as well as an outsider node (potentially from some other nearby UWASN). Such situations frequently arise in shared regions, e.g., in international waters. In such situation, the system administrator could manually feed this info to the sensor nodes.
secure routing scheme (no matter the sub-carriers are loaded with equal powers, or, with optimal powers) outperforms the classical DBR scheme (for $P_T > 120$ dB$m\mu$ Pascals), with a margin that grows with increase in the transmit power budget; iii) the performance loss of the strategy of equal power allocation across the sub-carriers in comparison to the optimal power allocation strategy is very minimal (for both schemes, the proposed scheme and the DBR scheme).

Fig. 3 investigates how secrecy capacity behaves as the density of legitimate UWASN nodes is increased. For Fig. 3 we set $P_T = 110$ dB$m\mu$ Pascals. We learn that an increase in the density of legitimate nodes results in an increase in the secrecy capacity for our proposed scheme, and zero secrecy capacity for the DBR scheme. The reason for zero secrecy capacity for the DBR scheme is as follows: as the node density increases, it becomes very likely that the DBR scheme selects a node very close to Eve (at some hop) along the routing path which culminates in zero secrecy capacity.

V. CONCLUSION

This work studied (for the first time) the eavesdropping attack on an OFDM-based, multi-hop UWASN. We performed joint optimal node selection for data forwarding and power allocation (across the OFDM sub-carriers) to maximize the secrecy capacity at each hop. The proposed scheme outperforms the DBR scheme as the transmit power budget of the sensor nodes is increased beyond 120 dB$m\mu$ Pa. Finally, the proposed scheme benefits from the increase in the density of sensor nodes (while the DBR scheme fails in such situation).

VI. APPENDIX

The Lagrangian associated with Eq. (7) is:

$$\Delta = \sum_{j=1}^{N} \left( \log_2 \left( \frac{\Omega_j^{(1)} \Omega_j^{(E)}}{\Omega_j^{(2)} \Omega_j^{(E)}} + p_j \Omega_j^{(1)} \Omega_j^{(E)} + \mu_j p_j \right) \right) + \lambda P_T - \lambda p_j + \mu_j p_j$$

where $\mu_j$ is the Lagrangian multiplier associated with $p_j$. Now, applying Karush-Kuhn-Tucker (KKT) stationary conditions, i.e., $\frac{\partial \Delta}{\partial p_j} = 0$, we obtain:

$$\mu_j = \lambda \left( \frac{\left( \Omega_j^{(1)} \Omega_j^{(E)} - \Omega_j^{(2)} \Omega_j^{(E)} \right)}{\left( \Omega_j^{(1)} \Omega_j^{(E)} + \Omega_j^{(1)} \Omega_j^{(2)} p_j + \Omega_j^{(1)} \Omega_j^{(2)} \Omega_j^{(E)} p_j \right)^2} \right) / \ln(2)$$

Next, we apply KKT complementary slackness condition, i.e., $\mu_j p_j = 0$. Then, for any $p_j > 0$ we have:

$$\lambda = \left( \frac{\left( \Omega_j^{(1)} \Omega_j^{(E)} - \Omega_j^{(2)} \Omega_j^{(E)} \right)}{\left( \Omega_j^{(1)} \Omega_j^{(E)} + \Omega_j^{(1)} \Omega_j^{(2)} p_j + \Omega_j^{(1)} \Omega_j^{(2)} \Omega_j^{(E)} p_j \right)^2} \right) / \ln(2)$$

This leads to the following solution:

$$p_j^* = \frac{-b_j + \sqrt{b_j^2 - 4a_j c_j}}{2a_j}$$

where $a_j = \Omega_j^{(1)} \Omega_j^{(E)}$, $b_j = \Omega_j^{(1)} \Omega_j^{(E)} + \Omega_j^{(1)} \Omega_j^{(2)}$, and $c_j = \Omega_j^{(1)} \Omega_j^{(E)}^2 / \ln(2)$ + $\frac{\Omega_j^{(1)} \Omega_j^{(2)} \Omega_j^{(E)} p_j}{\lambda \ln(2)}$.

REFERENCES

[1] G. Han, J. Jiang, N. Sun, and L. Shu, “Secure communication for underwater acoustic sensor networks,” IEEE communications magazine, vol. 53, no. 8, pp. 54–60, 2015.

[2] W. A. Arbaugh, N. Shankar, Y. C. J. Wan, and K. Zhang, “Your 802.11 wireless network has no clothes,” IEEE Wireless Communications, vol. 9, no. 6, pp. 44–51, Dec 2002.

[3] C. E. Shannon, “Communication theory of secrecy systems,” Bell Labs Technical Journal, vol. 28, no. 4, pp. 656–715, 1949.

[4] A. D. Wyner, “The wire-tap channel,” The Bell System Technical Journal, vol. 54, no. 8, pp. 1355–1367, Oct 1975.

[5] W. Yu and R. Lui, “Dual methods for nonconvex spectrum optimization of multichannel systems,” IEEE Transactions on Communications, vol. 54, no. 7, pp. 1310–1322, July 2006.

[6] N. Li, J.-F. Martinez, J. M. Meneses Chaus, and M. Eckert, “A survey on underwater acoustic sensor network routing protocols,” Sensors, vol. 16, no. 3, 2016.

[7] R. Zhang and Y. Zhang, “Wormhole-resilient secure neighbor discovery in underwater acoustic networks,” in 2010 Proceedings IEEE INFOCOM, March 2010, pp. 1–9.

[8] X. Du, C. Peng, and K. Li, “A secure routing scheme for underwater acoustic networks,” International Journal of Distributed Sensor Networks, vol. 13, no. 6, p. 155047717713643, 2017.

[9] Q. Wang, H.-N. Dai, X. Li, H. Wang, and H. Xiao, “On modeling eavesdropping attacks in underwater acoustic sensor networks,” Sensors, vol. 16, no. 5, 2016.

[10] Y. Huang, P. Xiao, S. Zhou, and Z. Shi, “A half-duplex self-protection jamming approach for improving secrecy of block transmissions in underwater acoustic channels,” IEEE Sensors Journal, vol. 16, no. 11, pp. 4100–4109, June 2016.

[11] M. Stojanovic, “On the relationship between capacity and distance in an underwater acoustic communication channel,” in Proceedings of the 1st ACM International Workshop on Underwater Networks, ser. WUWNet ’06. New York, NY, USA: ACM, 2006, pp. 41–47.

[12] http://www.aquasent.com/acoustic-modems/

[13] Y. Liu, H. H. Chen, and L. Wang, “Physical layer security for next generation wireless networks: Theories, technologies, and challenges,” IEEE Communications Surveys Tutorials, vol. 19, no. 1, pp. 347–376, Firstquarter 2017.
[14] H. Yan, Z. J. Shi, and J.-H. Cui, “DBR: depth-based routing for underwater sensor networks,” in *International conference on research in networking*. Springer, 2008, pp. 72–86.