Secure Communication with a Proactive Eavesdropper Under Perfect CSI and CDI

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Abstract. This paper studies physical layer security of a three node multicarrier network with a source node, a destination node and a full-duplex proactive eavesdropper who sends jamming signals for improving its eavesdropping performance. The problem of transmit power allocation for minimizing the average secrecy outage probability on all subcarriers is investigated under the assumptions that the channel state information (CSI) related to the eavesdropper is perfectly known and only channel distribution information (CDI) is known. Algorithms are proposed for the optimization problem and are shown to greatly outperform the benchmark algorithms.

Keywords: Physical layer security · Proactive eavesdropper · Secrecy outage probability · Channel distribution information

1 Introduction

Physical layer security is a promising technology that can achieve perfect secure communication from the aspect of information theory [1–4]. In physical layer security, the eavesdroppers can be passive or proactive. Specially, passive eavesdroppers only receive legitimate communication signals, while proactive eavesdroppers not only receive legitimate communication signals but also send jamming signals to interfere with the legitimate communication for improving the eavesdropping performance. This paper focuses on proactive eavesdroppers.

Secure communication with proactive eavesdroppers has been researched a lot in literature. The work in [5] modeled the interaction between the proactive eavesdropper and the legitimate user as a Stackelberg game, where the eavesdropper acted as a leader and the legitimate user acted as a follower to minimize power consumption with the minimum secrecy rate constraint. The work in [6] maximized the secrecy rate at the legitimate user's side and the wiretap rate at the eavesdropper's side. The work in [7] proposed to adopt cooperative relays to improve the secrecy rate of the legitimate user with attacks from the proactive eavesdroppers. The work in [8] modeled the interaction between the proactive eavesdropper and the legitimate user as a non-cooperative game. The work in [9] proposed to let the legitimate user send jamming signals to interfere with the proactive eavesdropper and derived the expression for the hybrid outage

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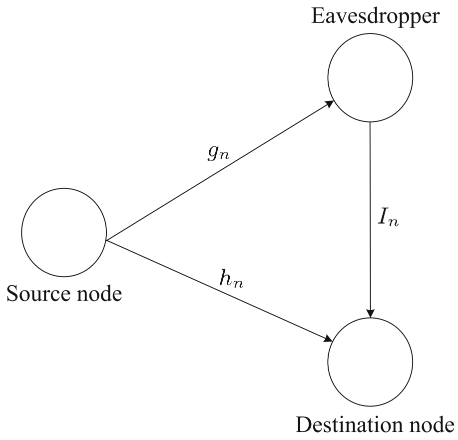

Fig. 1. System model.

probability. The work in [10] proposed to let the legitimate receiver transmit jamming signals using a subset of the antennas and maximized the secrecy rate by optimizing the antenna allocation. Although the work in [5–10] has investigated various problems with proactive eavesdroppers, secrecy outage probability was seldom minimized by optimizing resource allocation with imperfect channel state information (CSI).

This paper investigates secure communication of a three node multicarrier network with a source node, a destination node, and a full-duplex proactive eavesdropper. The eavesdropper keeps sending jamming signals for improving its eavesdropping performance. The source node aims to minimize the average secrecy outage probability on all subcarriers by optimizing the transmit power allocation. Two scenarios are considered. The first scenario assumes perfect CSI and the second scenario assumes only channel distribution information (CDI) on the channels related to the eavesdropper is available. For both scenarios, we propose algorithms to solve the optimization problems. It is shown that the proposed algorithms can achieve much lower average secrecy outage probability than the benchmark algorithms.

The rest of the paper is organized as follows. Section 2 presents the system model and formulates the problem. Section 3 investigates the perfect CSI scenario and Sect. 4 investigates the CDI scenario. Section 5 verifies the proposed algorithm by simulations. Section 6 concludes the paper.

2 System Model

As shown in Fig. 1, a three-node network consisting of a source node, a destination node and an eavesdropper, is considered. Both the source node and the destination node are assumed to be half-duplex, while the eavesdropper is assumed to be full-duplex. The spectrum is assumed to be divided into N subcarriers, and the channel gains on subcarrier n from the source node to the destination node, from the source node to the eavesdropper, and from the eavesdropper to the destination node are denoted as h_n, g_n and I_n, respectively. It is assumed that the source node knows the perfect CSI on h_n. For the CSI on g_n and I_n, two scenarios are considered. The first scenario assumes that g_n and I_n are perfectly known. The second scenario assumes that only CDI on g_n and I_n is available. Specially, the channels from the source node to the eavesdropper and from the eavesdropper to the destination node follow Rayleigh fading with unit mean, i.e., the probability density functions of g_n and I_n are respectively as $f_{g_n}(g_n) = e^{-g_n}$ and $f_{I_n}(I_n) = e^{-I_n}$.

Let p_n denote the transmit power of the source node on subcarrier n and q denote the fixed transmit power of the eavesdropper on all subcarriers. Note that $\{p_n\}$ is restricted by the total transmit constraint, as well as the peak transmit power constraint. Specifically, the total transmit power constraint is written as

$$\sum_{n=1}^{N} p_n \leq P_{max}, \tag{1}$$

where P_{max} is the total transmit power limit. The peak transmit power constraint is written as

$$p_n \leq P_{pk}, n = 1, \ldots, N. \tag{2}$$

The achievable communication rate of the source-destination pair on subcarrier n is written as

$$r_{0,n} = \log_2 \left(1 + \frac{p_n h_n}{\sigma^2 + qI_n}\right), \tag{3}$$

where σ^2 denotes the noise power. The achievable eavesdropping rate of the eavesdropper on subcarrier n is written as

$$r_{1,n} = \log_2 \left(1 + \frac{p_n g_n}{\sigma^2}\right). \tag{4}$$

The secrecy rate of the source-destination pair on subcarrier n is defined as $(r_{0,n} - r_{1,n})^+$ [11], where $(.)^+ = \max(0, .)$. The secrecy outage probability on subcarrier n is then defined as $\Pr\{(r_{0,n} - r_{1,n})^+ < R\}$, where R is the target secrecy rate.

We aim to minimize the average secrecy outage probability of the source-destination pair on all subcarriers by optimizing the transmit power $\{p_n\}$ as given by

$$(\text{P1}) : \min_{\{p_n\}} \frac{1}{N} \sum_{n=1}^{N} \Pr\{(r_{0,n} - r_{1,n})^+ < R\} \tag{5}$$

$$\text{s.t.} \sum_{n=1}^{N} p_n \leq P_{max}, \tag{6}$$

$$0 \leq p_n \leq P_{pk}, n = 1, \ldots, N. \tag{7}$$

3 Perfect CSI Scenario

In this section, we investigate P1 under the scenario of perfect CSI on g_n and I_n. To solve P1, we define

$$X_n = \begin{cases} 1, & r_{0,n} - r_{1,n} < R, \\ 0, & r_{0,n} - r_{1,n} \geq R. \end{cases} \tag{8}$$

Then, P1 is reformulated as

$$\text{(P1.1)}: \min_{\{p_n\}} \frac{1}{N} \sum_{n=1}^{N} \mathbb{E}\{X_n\} \tag{9}$$

$$\text{s.t.} \sum_{n=1}^{N} p_n \leq P_{max}, \tag{10}$$

$$0 \leq p_n \leq P_{pk}, n = 1, \ldots, N, \tag{11}$$

where $\mathbb{E}\{.\}$ denotes the expectation. P1.1 can be decomposed into subproblems, one for each channel fading state as

$$\text{(P1.2)}: \min_{\{p_n\}} \frac{1}{N} \sum_{n=1}^{N} X_n \tag{12}$$

$$\text{s.t.} \sum_{n=1}^{N} p_n \leq P_{max}, \tag{13}$$

$$0 \leq p_n \leq P_{pk}, n = 1, \ldots, N. \tag{14}$$

We solve P1.2 using the Lagrange duality method [12,13]. The Lagrangian of P1.2 is written as

$$L(\lambda, \{p_n\}) = \frac{1}{N} \sum_{n=1}^{N} X_n + \lambda \left(\sum_{n=1}^{N} p_n - P_{max} \right), \tag{15}$$

where λ is the non-negative dual variable associated with the constraint in (13). The Lagrange dual function is then defined as

$$G(\lambda) = \min_{\{p_n\}} L(\lambda, \{p_n\}) \tag{16}$$

$$\text{s.t. } 0 \leq p_n \leq P_{pk}, n = 1, \ldots, N. \tag{17}$$

The problem in (16) can be decomposed into N subproblems, as given by

$$\text{(P1.3)}: \min_{p_n} \frac{1}{N} X_n + \lambda p_n \tag{18}$$

$$\text{s.t. } 0 \leq p_n \leq P_{pk}, \tag{19}$$

for $i = 1, \ldots, N$. Let $f(p_n) = r_{0,n} - r_{1,n}$. Then, the inequality $f(p_n) < R$ is equivalent to $p_n < y_n$, where

$$y_n = \frac{2^R - 1}{\frac{h_n}{\sigma^2 + qI_n} - \frac{2^R g_n}{\sigma^2}}. \tag{20}$$

Theorem 1. The optimal solution of P1.3, p_n^*, is given by

$$p_n^* = \begin{cases} y_n, & 0 \leq y_n \leq P_{pk}, \frac{1}{N} \geq \lambda y_n, \\ 0, & \text{otherwise.} \end{cases} \tag{21}$$

Proof. The value of p_n^* is discussed in the following two cases:

Case 1: $y_n < 0$. In this case, $\frac{1}{N}X_n + \lambda p_n$ is equal to λp_n in the interval $[0, P_{pk}]$. Thus, it is easy to obtain $p_n^* = 0$.

Case 2: $0 \leq y_n \leq P_{pk}$. In this case, $\frac{1}{N}X_n + \lambda p_n$ is equal to $\frac{1}{N} + \lambda p_n$ in the interval $[0, y_n)$ and is equal to λp_n in the interval $[y, P_{pk}]$. Thus, the minimum of $\frac{1}{N}X_n + \lambda p_n$ is achieved at $p_n = 0$ or $p_n = y_n$ depending on the objective function values achieved at $p_n = 0$ and $p_n = y_n$, i.e.

$$p_n^* = \begin{cases} 0, & \frac{1}{N} < \lambda y_n, \\ y_n, & \frac{1}{N} \geq \lambda y_n. \end{cases} \tag{22}$$

Case 3: $y_n > P_{pk}$. In this case, $\frac{1}{N}X_n + \lambda p_n$ is equal to $\frac{1}{N} + \lambda p_n$ in the interval $[0, P_{pk}]$. Thus, it is easy to obtain $p_n^* = 0$.

Based on the above discussions, p_n^* is given by

$$p_n^* = \begin{cases} y_n, & 0 \leq y_n \leq P_{pk}, \frac{1}{N} \geq \lambda y_n, \\ 0, & \text{otherwise.} \end{cases} \tag{23}$$

This completes the proof. ■

Then, the dual problem is defined as

$$\max_{\lambda \geq 0} \; G(\lambda), \tag{24}$$

which can be solved efficiently with the bisection method.

The algorithm to solve P1 with perfect CSI is summarized in Algorithm 1.

4 CDI Scenario

In this section, we investigate P1 under the scenario of CDI on g_n and I_n. By inserting $f_{g_n}(g_n) = e^{-g_n}$ and $f_{I_n}(I_n) = e^{-I_n}$ into $\Pr\{(r_{0,n} - r_{1,n})^+ < R\}$, we have

Algorithm 1. Proposed algorithm to solve P1 with perfect CSI.

Initialize: λ_{min}, λ_{max}.
repeat
  $\lambda = \frac{\lambda_{min}+\lambda_{max}}{2}$.
  $p_n^* = \begin{cases} y_n, & 0 \leq y_n \leq P_{pk}, \frac{1}{N} \geq \lambda y_n, \\ 0, & \text{otherwise.} \end{cases}, n = 1, \ldots, N.$
  if $\sum_{n=1}^{N} p_n^* > P_{max}$ **then**
    $\lambda_{min} = \lambda$.
  else
    $\lambda_{max} = \lambda$.
  end if
until λ converges to a desired accuracy.

$$
\begin{aligned}
&\Pr\{(r_{0,n} - r_{1,n})^+ < R\} \\
=&\Pr\left\{\log_2\left(1 + \frac{p_n h_n}{\sigma^2 + qI_n}\right) - \log_2\left(1 + \frac{p_n g_n}{\sigma^2}\right) < R\right\} \\
=&\Pr\left\{g_n > \frac{\sigma^2}{p_n}\left(\frac{1}{2^R}\left(1 + \frac{p_n h_n}{\sigma^2 + qI_n}\right) - 1\right)\right\}.
\end{aligned} \tag{25}
$$

The Lagrangian of P1 is then written as

$$
\begin{aligned}
&L(\lambda, \{p_n\}) \\
=&\frac{1}{N}\sum_{n=1}^{N}\Pr\left\{g_n > \frac{\sigma^2}{p_n}\left(\frac{1}{2^R}\left(1 + \frac{p_n h_n}{\sigma^2 + qI_n}\right) - 1\right)\right\} \\
&+ \lambda\left(\sum_{n=1}^{N} p_n - P_{max}\right),
\end{aligned} \tag{26}
$$

where λ is the non-negative dual variable associated with the constraint in (13). The Lagrange dual function is defined as

$$G(\lambda) = \min_{\{p_n\}} \; L(\lambda, \{p_n\}) \tag{27}$$

$$\text{s.t. } 0 \leq p_n \leq P_{pk}, n = 1, \ldots, N, \tag{28}$$

which can be decoupled into N subproblems, as given by

$$
\begin{aligned}
(\text{P1.4}): \min_{p_n} \frac{1}{N}\Pr\left\{g_n > \frac{\sigma^2}{p_n}\left(\frac{1}{2^R}\left(1 + \frac{p_n h_n}{\sigma^2 + qI_n}\right) - 1\right)\right\}& \\
+ \lambda p_n&
\end{aligned} \tag{29}
$$

$$\text{s.t. } 0 \leq p_n \leq P_{pk}, \tag{30}$$

for $i = 1, \ldots, N$. P1.4 can be decomposed into two subproblems as given by

$$\begin{aligned}(\text{P1.4.1}) : \min_{p_n} \frac{1}{N} \Pr\left\{g_n > \frac{\sigma^2}{p_n}\left(\frac{1}{2^R}\left(1+\frac{p_n h_n}{\sigma^2+qI_n}\right)-1\right)\right\} \\ + \lambda p_n \quad (31)\end{aligned}$$

$$\text{s.t. } 0 \le p_n \le P_{pk}, \tag{32}$$

$$\frac{p_n h_n}{2^R - 1} \le \sigma^2, \tag{33}$$

and

$$\begin{aligned}(\text{P1.4.2}) : \min_{p_n} \frac{1}{N} \Pr\left\{g_n > \frac{\sigma^2}{p_n}\left(\frac{1}{2^R}\left(1+\frac{p_n h_n}{\sigma^2+qI_n}\right)-1\right)\right\} \\ + \lambda p_n \quad (34)\end{aligned}$$

$$\text{s.t. } 0 \le p_n \le P_{pk}, \tag{35}$$

$$\frac{p_n h_n}{2^R - 1} \ge \sigma^2. \tag{36}$$

The solution of P1.4 is the solution of the problem with lower objective function value. Since $\frac{\sigma^2}{p_n}\left(\frac{1}{2^R}\left(1+\frac{p_n h_n}{\sigma^2+qI_n}\right)-1\right)$ must be small than zero when $\frac{p_n h_n}{2^R-1} \le \sigma^2$, P1.4.1 can be rewritten as

$$\min_{p_n} \frac{1}{N} + \lambda p_n \tag{37}$$

$$\text{s.t. } 0 \le p_n \le P_{pk}, \tag{38}$$

$$\frac{p_n h_n}{2^R - 1} \le \sigma^2. \tag{39}$$

It is easy to verify that the optimal solution of the above problem is $p_n = 0$ and the optimal objective function value is $\frac{1}{N}$. As for P1.4.2, when $\frac{p_n h_n}{2^R-1} \ge \sigma^2$, the probability $\Pr\left\{g_n > \frac{\sigma^2}{p_n}\left(\frac{1}{2^R}\left(1+\frac{p_n h_n}{\sigma^2+qI_n}\right)-1\right)\right\}$ can be rewritten as given by

$$\begin{aligned}
&\Pr\left\{g_n > \frac{\sigma^2}{p_n}\left(\frac{1}{2^R}\left(1+\frac{p_n h_n}{\sigma^2+qI_n}\right)-1\right)\right\} \\
=&\Pr\left\{g_n > \frac{\sigma^2}{p_n}\left(\frac{1}{2^R}\left(1+\frac{p_n h_n}{\sigma^2+qI_n}\right)-1\right)\middle| I_n \le \frac{1}{q}\left(\frac{p_n h_n}{2^R-1}-\sigma^2\right)\right\} \\
&+\Pr\left\{g_n > \frac{\sigma^2}{p_n}\left(\frac{1}{2^R}\left(1+\frac{p_n h_n}{\sigma^2+qI_n}\right)-1\right)\middle| I_n \ge \frac{1}{q}\left(\frac{p_n h_n}{2^R-1}-\sigma^2\right)\right\} \\
=&\int_0^{\frac{1}{q}\left(\frac{p_n h_n}{2^R-1}-\sigma^2\right)} e^{-I_n} dI_n \int_{\frac{\sigma^2}{p_n}\left(\frac{1}{2^R}\left(1+\frac{p_n h_n}{\sigma^2+qI_n}\right)-1\right)}^{\infty} e^{-g_n} dg_n \\
&+\int_{\frac{1}{q}\left(\frac{p_n h_n}{2^R-1}-\sigma^2\right)}^{\infty} e^{-I_n} dI_n \int_0^{\infty} e^{-g_n} dg_n \\
=&e^{\frac{\sigma^2}{p_n}\left(1-\frac{1}{2^R}\right)} \int_0^{\frac{1}{q}\left(\frac{p_n h_n}{2^R-1}-\sigma^2\right)} e^{-I_n - \frac{\sigma^2 h_n}{2^R(\sigma^2+qI_n)}} dI_n + e^{-\frac{1}{q}\left(\frac{p_n h_n}{2^R-1}-\sigma^2\right)}.
\end{aligned} \tag{40}$$

Algorithm 2. Proposed algorithm to solve P1 with CDI.

Initialize: λ_{min}, λ_{max}.
repeat
  $\lambda = \frac{\lambda_{min}+\lambda_{max}}{2}$.
  for $i = 1$ to N **do**
    if $\frac{\sigma^2(2^R-1)}{h_n} > P_{pk}$ **then**
      Set $p_n = 0$.
    else
      Obtain p_n by solving the problem in (41) using a one-dimensional exhaustive search over $\left[\frac{\sigma^2(2^R-1)}{h_n}, P_{pk}\right]$.
      if the optimal objective function value in (41) is larger than $\frac{1}{N}$ **then**
        Set $p_n = 0$.
      end if
    end if
  end for
  if $\sum_{n=1}^{N} p_n^* > P_{max}$ **then**
    $\lambda_{min} = \lambda$.
  else
    $\lambda_{max} = \lambda$.
  end if
until λ converges to a desired accuracy.

Therefore, P1.4.2 can be rewritten as

$$\min_{p_n} \frac{1}{N} e^{\frac{\sigma^2}{p_n}\left(1-\frac{1}{2^R}\right)} \int_0^{\frac{1}{q}\left(\frac{p_n h_n}{2^R-1}-\sigma^2\right)} e^{-I_n-\frac{\sigma^2 h_n}{2^R(\sigma^2+qI_n)}} dI_n + \frac{1}{N} e^{-\frac{1}{q}\left(\frac{p_n h_n}{2^R-1}-\sigma^2\right)} + \lambda p_n \quad (41)$$

$$\text{s.t.} \ \frac{\sigma^2(2^R-1)}{h_n} \le p_n \le P_{pk}. \quad (42)$$

The above problem is infeasible if $\frac{\sigma^2(2^R-1)}{h_n} > P_{pk}$. If the above problem is feasible, the optimal solution can be obtained by a one-dimensional exhaustive search of p_n over the interval $\left[\frac{\sigma^2(2^R-1)}{h_n}, P_{pk}\right]$.

Finally, the value of λ can be obtained by the bisection method. The algorithm to solve P1 with CDI is summarized in Algorithm 2.

5 Simulation Results

The parameters of simulation are set as follows. The channel from the source node to the destination node is assumed to following Rayleigh fading with mean 5. Unless otherwise specified, we set $\sigma^2 = 1$, $N = 8$, $P_{max} = 1.5$ Watt, $P_{pk} = 0.5$ Watt, $q = 0.5$ Watt and $R = 0.3$ bps/Hz. For the purpose of comparison, we propose one benchmark algorithm named as the equal-power allocation algorithm which equally allocates the transmit power, and one benchmark algorithm

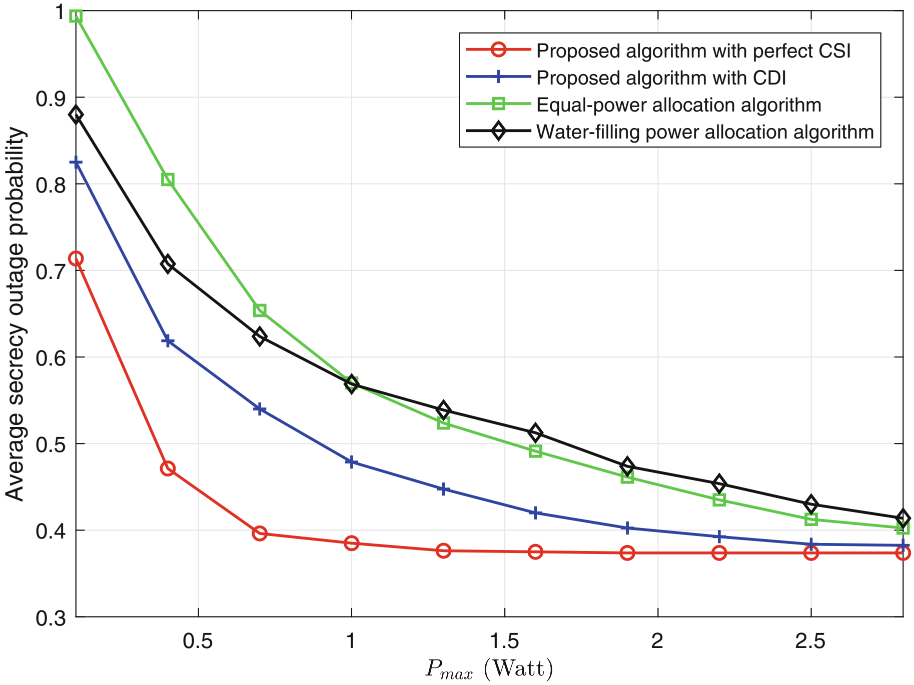

Fig. 2. Average secrecy outage probability achieved by different algorithms versus P_{max}.

named as the water-filling power allocation algorithm which allocates the transmit power following the water-filling style.

Figure 2 plots the average secrecy outage probability achieved by different algorithms versus P_{max}. It is seen that the average secrecy outage probability decreases as P_{max} increases until saturates to a certain level. It is also seen that the average secrecy outage probability achieved by the proposed algorithm with perfect CSI is the lowest, while the average secrecy outage probability achieved by the proposed algorithm with CDI is higher than the proposed algorithm with perfect CSI. This indicates that only knowing CDI degrades the secrecy performance compared to perfect CSI. Besides, it is seen that both the proposed algorithm with perfect CSI and the algorithm with CDI achieve lower average secrecy outage probability than the other two benchmark algorithms. It is also seen that the average secrecy outage probabilities achieved by different algorithms are very close when P_{max} is large.

Figure 3 plots the average secrecy outage probability achieved by different algorithms versus P_{pk}. It is seen that the average secrecy outage probability decreases as P_{pk} increases until saturates to a certain level. It is also seen that the average secrecy outage probability achieved by both the proposed algorithm with perfect CSI and the proposed algorithm with CDI is much lower than

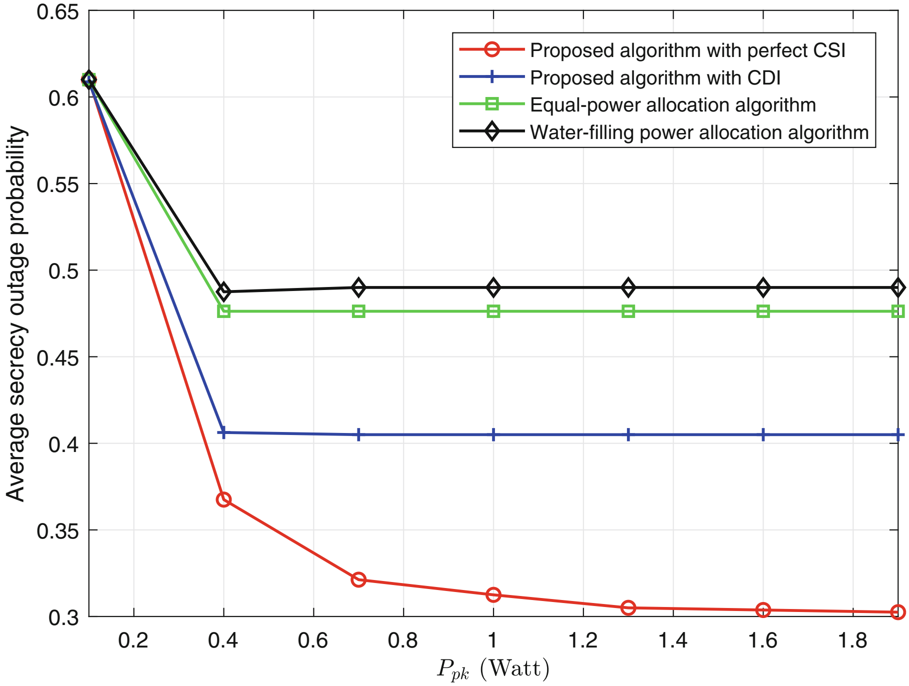

Fig. 3. Average secrecy outage probability achieved by different algorithms versus P_{pk}.

the other two algorithms, especially when P_{pk} is large. Besides, it is seen that the average secrecy outage probability achieved by the proposed algorithm with perfect CSI is much lower than the proposed algorithm with CDI, especially when P_{pk} is large. It is also seen that the average secrecy outage probabilities achieved by different algorithms are very close when P_{pk} is small.

Figure 4 plots the average secrecy outage probability achieved by different algorithms versus q. It is seen that the average secrecy outage probability increases as q increases. This is as expected since lower secrecy rate is achieved with higher interference from the eavesdropper. It is also seen that the average secrecy outage probability achieved by the proposed algorithm with perfect CSI is the lowest while the average secrecy outage probability achieved by the proposed algorithm with CDI is the second lowest among the four algorithms. Besides, it is seen that the performance gap between the proposed algorithm with perfect CSI and the proposed algorithm with CDI is almost independent of q.

Figure 5 plots the average secrecy outage probability achieved by different algorithms versus R. It is seen that the average secrecy outage probability increases as R increases. It is also seen that the proposed algorithms outperform the water-filling power allocation benchmark algorithm, especially when

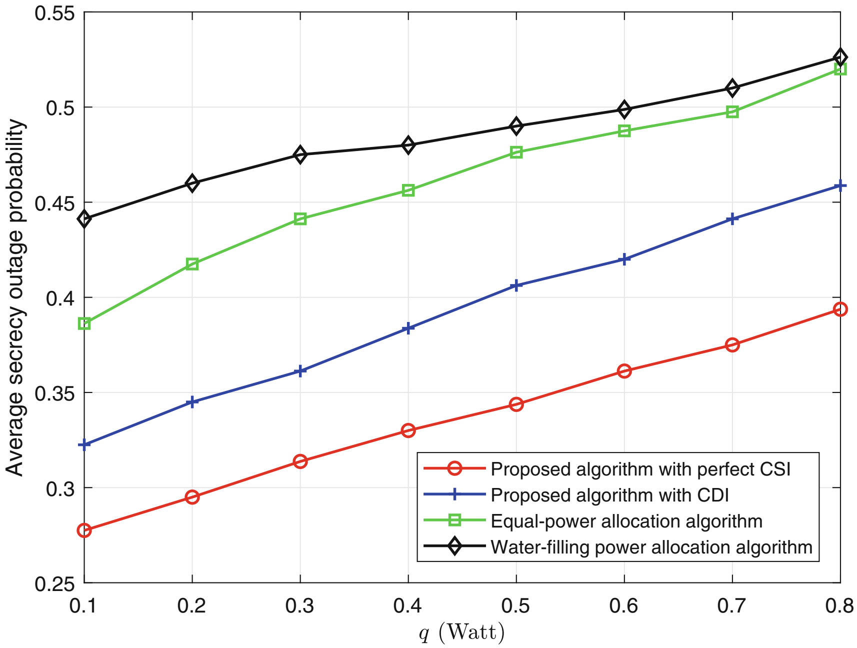

Fig. 4. Average secrecy outage probability achieved by different algorithms versus q.

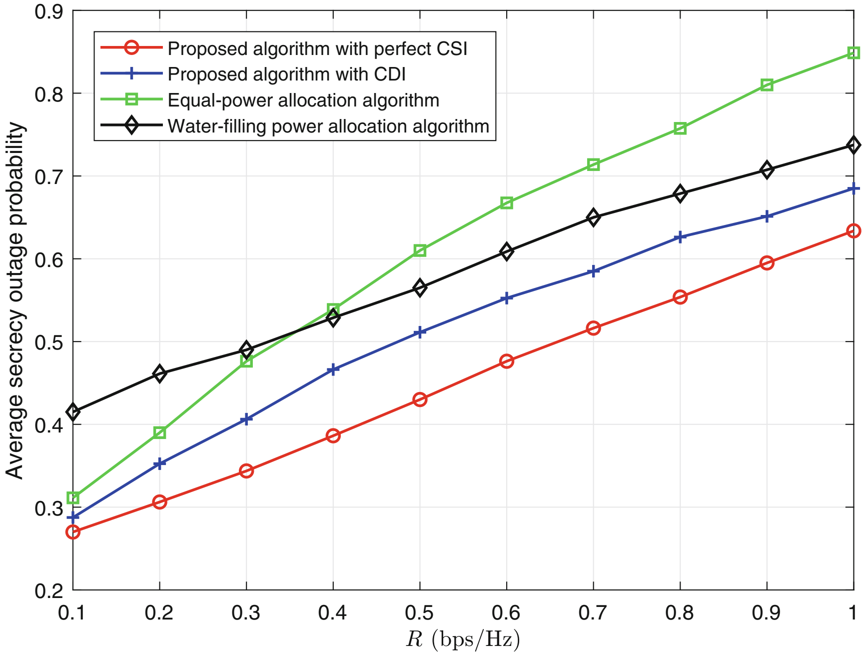

Fig. 5. Average secrecy outage probability achieved by different algorithms versus R.

R is large, and outperform the equal-power allocation benchmark algorithm, especially when R is small.

6 Conclusions

In this paper, the problem for minimizing the average secrecy outage probability of a three node multicarrier network by optimizing the transmit power allocation is investigated. Algorithms to solve the optimization problem with perfect CSI and CDI are proposed. It is shown that the proposed algorithms achieve significantly lower average secrecy outage probability than the benchmark algorithms.

References

1. Xu, D., Li, Q.: Resource allocation for cognitive radio with primary user secrecy outage constraint. IEEE Syst. J. **12**, 893–904 (2018)
2. Liu, Y., Chen, H.H., Wang, L.: Physical layer security for next generation wireless networks: theories, technologies, and challenges. IEEE Commun. Surv. Tutor. **19**(1), 347–376 (2017)
3. Xu, D., Li, Q.: Resource allocation for secure communications in cooperative cognitive wireless powered communication networks. IEEE Syst. J. **13**(3), 2431–2442 (2019)
4. Zhang, H., Xing, H., Cheng, J., Nallanathan, A., Leung, V.C.: Secure resource allocation for ofdma two-way relay wireless sensor networks without and with cooperative jamming. IEEE Trans. Ind. Inf. **12**(5), 1714–1725 (2015)
5. Tang, X., Ren, P., Han, Z.: Power-efficient secure transmission against full-duplex active eavesdropper: a game-theoretic framework. IEEE Access **5**, 24632–24645 (2017)
6. Tang, X., Ren, P., Wang, Y., Han, Z.: Combating full-duplex active eavesdropper: a hierarchical game perspective. IEEE Trans. Commun. **65**(3), 1379–1395 (2017)
7. Fang, H., Xu, L., Zou, Y., Wang, X., Choo, K.K.R.: Three-stage stackelberg game for defending against full-duplex active eavesdropping attacks in cooperative communication. IEEE Trans. Veh. Technol. **67**(11), 10788–10799 (2018)
8. Huang, W., Chen, W., Bai, B., Han, Z.: Wiretap channel with full-duplex proactive eavesdropper: a game theoretic approach. IEEE Trans. Veh. Technol. **67**(8), 7658–7663 (2018)
9. Liu, C., Lee, J., Quek, T.Q.: Secure transmission in the presence of full-duplex active eavesdropper. In: IEEE Global Communications Conference, pp. 1–6. IEEE (2017)
10. Li, L., Petropulu, A.P., Chen, Z.: Mimo secret communications against an active eavesdropper. IEEE Trans. Inf. Forensics Secur. **12**(10), 2387–2401 (2017)
11. Xu, D., Zhu, H.: Secure transmission for SWIPT IoT systems with full-duplex IoT devices. IEEE Internet Things J. **6**(6), 10915–10933 (2019)
12. Boyd, S., Vandenberghe, L.: Convex Optimization. Cambridge University Press, Cambridge (2004)
13. Xu, D., Li, Q.: Improving physical-layer security for primary users in cognitive radio networks. IET Commun. **11**(15), 2303–2310 (2017)