Joint Throughput Maximization and Power Control in Poisson CoopMAC Networks

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Abstract

A cooperative medium access control (CoopMAC) network with randomly distributed helpers is considered. We introduce a new helper selection scheme which maximizes the average throughput while maintaining a low power consumption profile in the network. To this end, all transmissions are assumed to be performed using power control. We assume that each node can estimate the channel between itself and a receiving node. Then, it evaluates the minimum transmission power needed to achieve the desired signal to noise ratio (SNR). If the required transmission power is less than the maximum transmission power of the node, the communication is regarded as successful. Otherwise, the transmission is canceled. In order to increase the average throughput, we assume that the cooperative link with the highest transmission rate is chosen from those that can successfully forward the source signal to destination. Also, when there are several links with the same rates, the one with minimum required power is given the highest priority. Assuming that the helpers are distributed as a Poisson point process with fixed intensity, we derive exact expressions for the average throughput and the power consumption of the network. Simulation results show that our scheme is able to significantly increase the throughput in comparison to the conventional CoopMAC network. It is also able to reduce the power consumption compared to a network with no power control approach.

Keywords: Cooperative medium access control (CoopMAC), IEEE 802.11b, Poisson point process, Power control, stochastic geometry.
1. Introduction

In wireless networks with battery powered nodes, the rate versus power consumption has always been a trade-off. The higher the rate, the lower the network lifetime. The power control mechanisms are used to achieve desired rate levels with optimizing the lifetime of the nodes and consequently the network. Power control can also be seen as a tool to provide efficient spectral reuse by alleviating the level of interference in the network. Recently, a noticeable part of studies is dedicated to incorporate power control tools into the IEEE 802.11 standard specifically in the MAC schemes. Two different cases are considered for power control in MAC protocols, namely similar power levels and varying power levels. When the same level of power is assumed for all the links, symmetric links are created in the network [16]. Symmetric links along with the simplicity of the algorithms are the main advantage of this design. However, it is shown that this case is a time-consuming approach since nodes must declare their agreement with sharing the same power level before any transmission. We shall notice that using the same power level while interference is involved, cannot guarantee symmetry [22, 18].

In [18], a power control scheme based on ready-to-send (RTS) and clear-to-receive (CTS) handshaking mode, is presented. In this scheme, the source node specifies its current transmit power level while sending RTS packet and, in turn, recognizes the desired level of transmit power through the received CTS packet from the destination. Therefore, besides maintaining the demanded signal-to-noise ratio (SNR), the data is transmitted at appropriate power level. In power control MAC protocol that has been proposed in [5], the acknowledgment (ACK) and data packets are transmitted in a lower power level than RTS and CTS packets in order to save the energy. It has been shown that the throughput of this protocol degrades since by decreasing the power level of ACK and data packets, their transmission range and carrier sensing zone will be limited [10]. To overcome these deficiencies, a variation of this protocol has been presented in [10] where data packets are transmitted using a maximum power level periodically to be sensible for nodes in carrier sensing zone.

In [1] a new power control MAC protocol has been proposed in which each node saves the required transmit power level of its neighbors after the first RTS / CTS handshake in a table. The maintained table looked up before a communication happens in order to change the transmit power in every node
related to its destination dynamically. The battery power would be saved in this case; however, in mobile scenarios it does not work efficiently He and Li [6]. Transmitting busy tone pulses to control the power has been also investigated in power controlled multiple access (PCMA) protocol Monks et al. [13]. Destination node, while receiving the data packet, sends a set of periodical busy tones through a different channel with the power equal to that of the maximum additional noises that it can tolerate. Other nodes by listening to both channels can bound their transmit power according to the current signal and busy tones’ strength. It has been investigated that this is not a collision-free scheme in time of transmitting the ACK packet Lin et al. [11].

The aforementioned power control MAC protocols are non-cooperative with multi-rate scenarios. Recently, cooperation communications as a promising method have emerged to enhance the performance of IEEE 802.11 based MAC protocols. The benefits of cooperation in MAC layer, mainly in terms of throughput, are presented in [11, 12, 23, 13]. In [12], a cooperative MAC protocol, called CoopMAC, based on RTS-CTS scheme has been proposed to exploit the multi–rate attribute of MAC protocols. Their goal was to provide cooperation communication link for low data rate links such that the throughput increases. A similar scenario has also been investigated in [23] to enhance the throughput performance of ad hoc networks. However, the additional overhead of cooperative control packets has been neglected in [12] and [23]. Handling a busy tone channel in a CoopMAC scheme to avoid collision has been adopted in [20]. An approach to separate the mobile helpers from the static ones in a CoopMAC network has been presented in [9]. Also, in [8], a game theoretic based method has been introduced to examine a CoopMAC protocol with incentive design.

The existing CoopMAC protocols mainly focus on throughput performance improvement through different helper selection scenarios, and power control mechanisms with regard to minimizing the energy consumption and network lifetime have been conducted in a limited number of research efforts in the literature. However, in energy constrained wireless networks, energy conservation is a critical issue that should be taken into account. In [21], a distributed energy-adaptive location-based CoopMAC (DEL-CMAC) protocol with a novel approach to enhance the performance of the mobile ad hoc networks (MANET) from the lifetime and energy perspectives has been investigated. In this scheme, among potential helpers, the one with minimum transmitting power is defined as the best helper. DEL-CMAC is
known to prolong the network lifetime significantly. A total power control CoopMAC (TPC-MAC) protocol has been proposed in [19] to minimize the overall transmit power in wireless sensor networks. In this protocol, an extended CTS packet with a non–cooperative power field is applied. Similarly, the best helper in this case is a potential node that minimizes the transmitting power.

In our previous work [17], in order to improve the throughput performance of the CoopMAC protocols in the presence of shadowing, we proposed a new helper selection approach in which the potential helpers are divided into several tiers based on their distances from the source and destination nodes. From the helper’s tiers with the maximum cooperative transmission rate, the helper that is less affected by shadowing is chosen for cooperation. We derived upper and lower bounds on the average cooperative throughput for the proposed CoopMAC protocol and observed that the performance of our proposed scheme was quite close to the upper bound.

In this paper, we propose a new CoopMAC scheme with a novel helper selection approach and an efficient power control mechanism to simultaneously improve the overall throughput and the energy consumption. In our cooperative protocol, among potential helpers that maximize the overall throughput, the helper with the minimum transmission power is defined as the best helper. We assume that in the network, the helpers are distributed randomly based on a homogeneous two-dimensional Poisson point process (PPP) with a fixed density. We derive an expression for cooperative throughput and the power consumption in our random CoopMAC protocol.

The remainder of this paper is organized as follows. In Section 2.1, the system model is defined. Our helper selection approach is proposed in Section 2.2. Throughput performance analysis and average power consumption of our helper selection algorithm are presented in Section 3 and Section 4, respectively. Simulation results are provided in Section 5 to demonstrate the superiority of our scheme over a conventional CoopMAC protocol. Finally, the paper is concluded in Section 6.

2. Cooperative MAC Model

In this section, we present our CoopMAC system model as well as the method the helpers are chose in the network by the source node.
2.1. System Model

A CoopMAC protocol is considered, where all transmissions are performed according to an IEEE 802.11b Standard. In this standard, the transmission rate of a link depends on the distance between the source and destination nodes. Hence, all point-to-point links of the network can be classified into four groups of rates. Table 1 shows these rates along with the corresponding link distances. Fig. 1 illustrates a typical Cooperative MAC network where a source node, S, intends to communicate with a destination node, D, at the distance of $L_{SD}$. This communication can be performed either through a direct link between S and D or by making use of any available helper node, H, via a dual-hop communication. Helpers are assumed to be distributed over the region $C$, according to a homogeneous two-dimensional Poisson point process (PPP) with fixed density $\lambda$. Also, $L_{SH}$ and $L_{HD}$ represent the source-to-helper and helper-to-destination distances, respectively.

Let $t_{SH}$ and $t_{HD}$ show the transmission time of one bit over S–H and H–D.
Table 1: Classification of the point-to-point links in the IEEE 802.11b Standard (for BER ≥ $10^{-5}$).

| Link Group | distance (m) | Rate (Mbps) |
|------------|--------------|-------------|
| 1          | [0, 48.2)    | 11          |
| 2          | (48.2, 67.1) | 5.5         |
| 3          | (67.1, 74.7) | 2           |
| 4          | (74.7, 100)  | 1           |

links, respectively. Assuming helper has single transceiver and employs a decode-and-forward scheme, the total achievable rate from cooperative link of S–H–D, denoted by $R_{Coop}$, is given by [12]

$$R_{Coop} = \frac{1}{t_{SH} + t_{HD}} = \frac{1}{R_{SH} + R_{HD}} = \frac{R_{SH}}{R_{SH} + R_{HD}}, \quad (1)$$

where $R_{SH}$ and $R_{HD}$ are the rates of S–H and H–D links, respectively. Deducing from Table 1 and eq. (1), it can be seen that different rates are achievable via cooperative links.

According to Table 1, values of $R_{SH}$ and $R_{HD}$ are relative to the distances of helper from the source and destination. For instance, assuming that helper H has a S-H link of group 1 and H-D link of group 2, i.e, $0 \leq L_{SH} < 48.2$ and $48.2 \leq L_{HD} < 67.1$, that results in $R_{SH} = 11$Mbps and $R_{HD} = 5.5$Mbps. In this case $R_{Coop}$ by considering (1) is 3.67Mbps. Table 2 categorizes the helpers into 6 groups, namely $H_1$ through $H_6$, based on the amount of $R_{Coop}$ that they can provide.

Another characteristic that determines the performance of a link is its average channel gain. We consider channels to be modeled by path-loss and fading. Therefore, when a signal is transmitted over a link, the received SNR at the receiver is given by [2, Eq. 1]

$$\Gamma = \frac{P K_0}{N_0 d^\alpha} \Omega, \quad (2)$$

where $P$ is the transmission power, $d$ is the link distance, $\alpha$ is the path-loss exponent of the system and $\Omega$ is the fading power of the channel. Values of $\Omega$ for different channels are identical independent random variables with cumulative distribution function (CDF) of $F_\Omega(.)$ that assumed to be identical.
Table 2: Classification of helpers based on their relative position from source and destination

| Helper’s Group | $L_{SH}$ (m) | $R_{SH}$ (Mbps) | $L_{HD}$ (m) | $R_{HD}$ (Mbps) | $R_{Coop}$ (Mbps) |
|----------------|---------------|-----------------|---------------|-----------------|-------------------|
| $\mathcal{H}_1$ | [0, 48.2) | 11 | [0, 48.2) | 11 | 5.5 |
| $\mathcal{H}_2$ | [0, 48.2) | 11 | [48.2, 67.1) | 5.5 | 3.67 |
| | [48.2, 67.1) | 5.5 | [0, 48.2) | 11 | |
| $\mathcal{H}_3$ | [48.2, 67.1) | 5.5 | [48.2, 67.1) | 5.5 | 2.75 |
| $\mathcal{H}_4$ | [0, 48.2) | 11 | [67.1, 74.7) | 2 | 1.69 |
| | [67.1, 74.7) | 2 | [0, 48.2) | 11 | |
| $\mathcal{H}_5$ | [67.1, 74.7) | 5.5 | [67.1, 74.7) | 2 | 1.47 |
| | [67.1, 74.7) | 2 | [48.2, 67.1) | 5.5 | |
| $\mathcal{H}_6$ | [67.1, 74.7) | 2 | [67.1, 74.7) | 2 | 1 |

for different channels in our network. Also, $K_0$ and $N_0$ are constants that considered to be the same for all links of network; the earlier referring to antennas gain and the latter to the power of the additive Gaussian noise at the receiver of the link. In order to decrease the power consumption, all transmissions are considered to be performed by the minimum required power. A transmission is assumed to be successful, if its corresponding received SNR at the end of the link is greater than a threshold, $\gamma_{th}$. Consequently, from (2), it can be deduced that the minimum power needed for successful transmission over S–D link is

$$P_{SD}^{\min} = \frac{N_0 L_{SD}^\alpha}{K_0 \Omega_{SD}} \gamma_{th},$$  

(3)

where $\Omega_{SD}$ is the fading power over S–D. Similarly, the minimum required power for successful transmission over S–H and H–D links are respectively given by

$$P_{SH}^{\min} = \frac{N_0 L_{SH}^\alpha}{K_0 \Omega_1} \gamma_{th},$$  

(4)

$$P_{HD}^{\min} = \frac{N_0 L_{HD}^\alpha}{K_0 \Omega_2} \gamma_{th},$$  

(5)
where $\Omega_1$ and $\Omega_2$ are fading powers of S–H and H–D links, respectively. Deriving from (4) and (5), the total required power for successful transmission over S–H–D is

$$P_{\text{min}}^H = \frac{N_0 L_{\text{SH}}^\alpha}{K_0 \Omega_1} \gamma_{\text{th}} + \frac{N_0 L_{\text{HD}}^\alpha}{K_0 \Omega_2} \gamma_{\text{th}}.$$  

We note that in our model, a maximum transmission power of $P_{\text{max}}$ has been taken into account for all nodes, including the source, the destination and the helpers. If the required power for successful communication in a link exceeds this value, the transmission would be discarded. As a result, the probability of successful communication over direct link, can be computed as

$$P_{\text{Succ}}(L_{SD}) = \Pr\left\{P_{\text{min}}^{SD} \leq P_{\text{max}}\right\} = \Pr\left\{\frac{N_0 L_{SD}^\alpha}{K_0 \Omega_{SD}} \gamma_{\text{th}} \leq P_{\text{max}}\right\} = \Pr\left\{\Omega_{SD} \geq \frac{N_0 \gamma_{\text{th}}}{K_0 P_{\text{max}}} L_{SD}^\alpha\right\} = 1 - F_{\Omega}(\mathcal{A} L_{SD}^\alpha),$$

where

$$\mathcal{A} = \frac{N_0 \gamma_{\text{th}}}{K_0 P_{\text{max}}}. \quad (7a)$$

Similarly, the probability of successful transmission over S–H–D link is given by

$$P_{\text{H Succ}}(L_{SH}, L_{HD}) = \Pr\{P_{\text{min}}^{SH} \leq P_{\text{max}}\} \Pr\{P_{\text{min}}^{HD} \leq P_{\text{max}}\} = (1 - F_{\Omega}(\mathcal{A} L_{SH}^\alpha)) \times (1 - F_{\Omega}(\mathcal{A} L_{HD}^\alpha)). \quad (8)$$

The performance of a link is evaluated by its throughput which is introduced as the rate of successful transmission and is given by

$$\mathcal{T} = \mathcal{R} \times P_{\text{Succ}}, \quad (9)$$

where $\mathcal{R}$ is the corresponding rate of the link, and $P_{\text{Succ}}$ is its probability of successful transmission.

2.2. Helper Selection Scheme

In case that there are more than one helper that can cooperate in the transmission, the source needs to select the best helper based on an objective.
In this section, we propose a helper selection scheme that can increase the throughput and can decrease power consumption of the network. In this article, helper H and its corresponding cooperative path are called Potential, provided that the transmission over S–H–D is successful, i.e., $P_{SH}^{min} \leq P_{max}$ and $P_{HD}^{min} \leq P_{max}$. To this end, we consider the following essential conditions for the helper, which is being chosen for cooperation:

- The helper must be potential (i.e., $P_{SH}^{min} \leq P_{max}$ and $P_{HD}^{min} \leq P_{max}$).
- The corresponding cooperative link should have an equal or greater transmission rate than the direct link.
- In the cases that the transmission rate of the cooperative link is equal to the direct link, the source plus helper power consumption must be less than the direct link.

Suppose there are more than one helper that can satisfy the above conditions. In such cases, to maximize the throughput, the helper with the maximum $R_{Coop}$ would be chosen for cooperation. In addition, to satisfy the power control purposes, when several helpers can provide the largest $R_{Coop}$, the one that minimizes the power consumption should be selected for cooperation. If no helper could meet the above mentioned conditions, it would be more beneficial to perform the transmission through the direct link.

According to the above mentioned conditions, only those groups of helpers that provide an equal or higher rate than the direct link are asked to participate in cooperation. In Table 3, we define five different communication cases, based on the direct link transmission rate and helper’s group that can assist them. Also, the beneficial helper’s groups for each case are illustrated in Fig. 2 where $S_i$ ($i = 1, ..., 5$) represents a sample source node of the $i$th case. It should be mentioned that for Case 5, in which the distance between the source and destination nodes is more than 96.4 meters, no helper from $H_1$ group exists in the network.

Upon receipt of an RTS from the source, the destination node is able to calculate the transmission power and the rate of the direct link. Then, it attaches them to the CTS packet to inform the source. Each idle helper that overhears the RTS and extended CTS respectively, evaluates the channel condition between itself and the source and destination, and examines the mentioned conditions for the helper. Any helper, that can satisfy those three conditions, is a potential helper and can be used for cooperation. In
Table 3: The link types and their corresponding beneficial helper groups.

| Link Case | \(L_{SD}\) (m) | \(R_{SD}\) (Mbps) | Beneficial Helper(s) |
|-----------|----------------|------------------|----------------------|
| 1         | [0, 48.2]      | 11               | None                 |
| 2         | [48.2, 67.1]   | 5.5              | \(H_1\)              |
| 3         | [67.1, 74.7]   | 2                | \(H_1, H_2, H_3\)    |
| 4         | [74.7, 96.4]   | 1                | \(H_1, H_2, H_3, H_4, H_5, H_6\) |
| 5         | (96.4, 100)    | 1                | \(H_2, H_3, H_4, H_5, H_6\) |

Figure 2: Operating regions of different groups of potential helpers (all distances are in meter).

Figure 2: Operating regions of different groups of potential helpers (all distances are in meter).

For our proposed helper selection algorithm, the helper with the highest rate has priority for cooperation. Then, among the cooperative paths with the same rate, the one with minimum total power consumption is chosen for cooperation. To this end, we employ a timer based approach for finding the suitable helper. Upon hearing the CTS, each helper that could satisfy three above conditions, runs a timer according to some parameters. When its timer is expired, the node transmits the helper-ready-to-send (HTS) packet. If the helper receives HTS from another node before expiry of its own timer, it
cancels its timer. We define timer duration for a helper as

\[ T = \vartheta \left( P_{\min}^H + 2(i - 1) P_{\max} \right), \]  

(10)

where \( \vartheta \) is a normalizing constant, \( P_{\min}^H \) is the required power of source plus helper for successful transmission, and \( i \) represents the group of helper. According to equation (10), we can see that the timer of each helper is definitely greater than the helpers with higher rate, and lower than those with less rates. For example, the timer of the helpers of the first and second group are respectively equal to \( \vartheta P_{\min}^H \) and \( \vartheta P_{\min}^H + 2P_{\max} \). Since the maximum possible value of \( P_{\min}^H \) is \( 2P_{\max} \), we can be sure that the timer of helpers in first group are always smaller than that for helpers of second group, hence, desired order would be established in helper selection. Also, among the helpers with the same rate, the helper with minimum required power has the lowest timer duration, and highest priority for being selected for cooperation. The helper whose timer expires first, sends a helper-ready-to-send (HTS) packet to the source and is chosen for cooperation. Meanwhile, other potential helpers must cancel their timers as soon as they receive an HTS packet. If an HTS packet is received by source, the required power is evaluated from the strength of the HTS packet and data would be transmitted to the selected helper. If the HTS packet is not received after a certain time duration, the data would be transmitted through the direct link, supposing that \( P_{SD}^{\min} < P_{\max} \). Our proposed CoopMAC protocols have been presented for the source, destination and helper nodes, in Algorithms 1, 2 and 3, respectively.

3. Performance Analysis

In this section, we evaluate the average throughput, which is the rate of successful transmission, for the proposed algorithm in different cases. Assume that \( P_{i}^{\text{Loss}} \) denotes the probability that no potential helper of the \( i \)th group exists. Also assume that \( \mathcal{C}_i \) is the region in which the helpers of Group \( \mathcal{H}_i \) are located. Then, the helpers in this region are distributed according to a homogeneous two-dimensional PPP with density \( \lambda \). Suppose that the number and the positions of the helpers in \( \mathcal{C}_i \) are known. Then, \( P_{i}^{\text{Loss}} \) equals the probability that none of Group \( \mathcal{H}_i \) helpers being potential for cooperation.
Algorithm 1 Best helper selection and data transmission protocol for source

1: Initialization:
2: send an RTS packet
3: if CTS packet received then goto Step 7
4: else
5: goto Step 1
6: end if
7: if HTS packet received then
8: Evaluate $P_{\text{SH}}^{\text{min}}$ from HTS
9: send data to the helper with transmission power of $P_{\text{SH}}^{\text{min}}$ goto Step 19
10: else
11: goto Step 13
12: end if
13: Extract $P_{\text{SD}}^{\text{min}}$ from CTS
14: if $P_{\text{SD}}^{\text{min}} < P_{\text{max}}$ then
15: send data to the destination with transmission power $P_{\text{SD}}^{\text{min}}$
16: else
17: goto Step 20
18: end if
19: if an ACK packet is not received then
20: perform a random backoff and goto Step 1
21: end if
22: Transmission Complete

Algorithm 2 Data receiving protocol for destination

1: Silent
2: if an RTS packet received then
3: evaluate $P_{\text{SD}}^{\text{min}}$ and $R_{\text{SD}}$ from RTS
4: attach $P_{\text{SD}}^{\text{min}}$ and $R_{\text{SD}}$ to CTS
5: send CTS packet and goto Step 7
6: end if
7: if data packet received then
8: send ACK packet and goto Step 1
9: else
10: goto Step 1
11: end if
Algorithm 3 Cooperation protocol for helpers

1:  Silent
2:  if an RTS packet received then
3:       evaluate $P_{\text{min}}^\text{SH}$ and $R_{\text{SH}}$ from RTS and goto Step 5
4:  end if
5:  if CTS packet received then
6:       evaluate $P_{\text{min}}^\text{HD}$ and $R_{\text{HD}}$ from the strength of CTS
7:       extract $P_{\text{min}}^\text{SD}$ and $R_{\text{SD}}$ from CTS and goto Step 9
8:  end if
9:  if One of the conditions defined in Steps 10 and 11 holds, then goto Step 13
10:  $P_{\text{min}}^\text{SH} < P_{\text{max}}$, $P_{\text{min}}^\text{HD} < P_{\text{max}}$, $R_{i}^{\text{Coop}} > R_{\text{SD}}$
11:  $P_{\text{min}}^\text{SH} < P_{\text{max}}$, $P_{\text{min}}^\text{HD} < P_{\text{max}}$, $P_{\text{min}}^\text{SH} + P_{\text{min}}^\text{HD} < P_{\text{min}}^\text{SD}$, $R_{i}^{\text{Coop}} = R_{\text{SD}}$
12:  end if
13:  set timer according to eq. (10)
14:  if HTS packet received then
15:       reset timer and goto Step 1
16:  else if timer reaches zero then
17:       send HTS packet and goto Step 19
18:  end if
19:  if data packet received then
20:       send data to the destination with power of $P_{\text{min}}^\text{SH}$ and goto Step 1
21:  else
22:       goto Step 1
23:  end if
By averaging on different realizations of helper’s placements, we have

\[ P^\text{Loss}_i = \mathbb{E}\left\{ \prod_{H_j \in C_i} (1 - P^\text{Succ}(L_{j,1}, L_{j,2})) \right\}, \]

(11)

where \( H_j \) is the \( j \)th helper of the system, located at the distance of \( L_{j,1} \) and \( L_{j,2} \) form the source and destination nodes, respectively and \( P^\text{Succ}(\cdot, \cdot) \) can be obtained from (8). Using \([7, \text{Eq. 3.35}]\), for PPP random variables, (11) can be rewritten as

\[ P^\text{Loss}_i = \exp \left( -\lambda \int_{C_i} P^\text{Succ}(L_{SH}, L_{HD}) \, ds \right). \]

(12)

As proved in appendix \textbf{Appendix A}, (12) can be evaluated for \( i = 1, \ldots, 6 \) as

\begin{align*}
P^\text{Loss}_1 &= \exp \left( -\lambda S(48.2, 48.2, L_{SD}) \right), \\
P^\text{Loss}_2 &= \exp \left( -2\lambda S(67.1, 48.2, L_{SD}) \right) \times (P^\text{Loss}_1)^{-2}, \\
P^\text{Loss}_3 &= \exp \left( -\lambda S(67.1, 67.1, L_{SD}) \right) \times (P^\text{Loss}_1 P^\text{Loss}_2)^{-1}, \\
P^\text{Loss}_4 &= \exp \left( -2\lambda S(74.7, 48.2, L_{SD}) \right) \times (P^\text{Loss}_1)^{-2} \times (P^\text{Loss}_2)^{-1}, \\
P^\text{Loss}_5 &= \exp \left( -2\lambda S(67.1, 74.7, L_{SD}) \right) \times (P^\text{Loss}_1 P^\text{Loss}_2 P^\text{Loss}_3)^{-2} \times (P^\text{Loss}_4)^{-1}, \\
P^\text{Loss}_6 &= \exp \left( -\lambda S(74.7, 74.7, L_{SD}) \right) \times (P^\text{Loss}_1 P^\text{Loss}_2 P^\text{Loss}_3 P^\text{Loss}_4 P^\text{Loss}_5)^{-1},
\end{align*}

(13)

where \( S(\cdot, \cdot, \cdot) \) is given by

\begin{align*}
S(u, v, x) &\triangleq \int_{-\theta(u,v,x)}^{\theta(u,v,x)} \int_{0}^{u} P^\text{Succ}(r, \sqrt{r^2 + x^2 - 2r x \cos \theta}) \, r \, dr \, d\theta_s \\
&\quad + \int_{-\theta(v,u,x)}^{\theta(v,u,x)} \int_{0}^{v} P^\text{Succ}(r, \sqrt{r^2 + x^2 - 2r x \cos \theta}) \, r \, dr \, d\theta_d \\
&\quad + 2x^2 \int_{0}^{\theta(u,v,x)} \min(\theta(v,u,x), \pi - \theta_d) \int_{0}^{\min(\theta(v,u,x), \pi - \theta_d)} P^\text{Succ}_H \left( \frac{x \sin(\theta_d)}{\sin(\theta_s + \theta_d)}, \frac{x \sin(\theta_s)}{\sin(\theta_s + \theta_d)} \right) \, d\theta_s \, d\theta_d \\
&\quad \times \frac{\sin(\theta_s) \sin(\theta_d)}{\sin^3(\theta_s + \theta_d)}
\end{align*}

(13)
and $\theta(\cdot, \cdot, \cdot)$ is

$$
\theta(u, v, x) \triangleq \arccos \left( \frac{v^2 - u^2 - x^2}{2uv} \right).
$$

(13h)

In the following, we use (13a) through (13f) and also (7a) to evaluate the throughput of the links in different cases defined in Table 3.

3.1. Case 1 ($0 \leq L_{SD} < 48.2$)

As discussed earlier, for this type of links, communications are performed only through the direct path with transmission rate of 11 Mbps. As a result, the throughput can be obtained from (9) as

$$
T_1 = \mathcal{P}_{\text{Succ}} \times 11\text{(Mbps)}.
$$

(14)

3.2. Case 2 ($48.2 \leq L_{SD} < 67.1$)

In this case, among cooperative links of $\mathcal{H}_1$ and the direct link, the path with the minimum required power would be selected for cooperation. Recall that $\mathcal{H}_1$ is the first group of helpers where $0 \leq L_{SH} < 48.2$, $0 \leq L_{HD} < 48.2$ and $R_{\text{Coop}} = 5.5\text{Mbps}$. Any selected path of this case has the rate of 5.5 Mbps. Hence, the total achieved throughput would be

$$
T_2 = \mathcal{P}_{\text{Succ}} \times 5.5
= (1 - P_{\text{Loss}}) \times 5.5\text{(Mbps)},
$$

(15)

where $P_{\text{Loss}}$ is the probability of the event in which, no potential path exists among the cooperative paths of the first group and direct link

$$
P_{\text{Loss}} = P_{1\text{Loss}} \times P_{\text{DirLoss}}(L_{SD}),
$$

(16)

where $P_{\text{DirLoss}}(L_{SD})$ is the outage probability of the direct link that can be obtained by

$$
P_{\text{DirLoss}}(L_{SD}) = 1 - P_{\text{Succ}}(L_{SD}).
$$

Substituting (16) in (15), $T_2$ is given by

$$
T_2 = (1 - P_{1\text{Loss}} \times P_{\text{DirLoss}}(L_{SD})) \times 5.5 \text{ (Mbps)}.
$$

(17)

3.3. Case 3 ($67.1 \leq L_{SD} < 74.7$)

As discussed before, transmission path selection for Case 3 links is performed based on an order. First of all, the $\mathcal{H}_1$ group would be searched for a
potential cooperative path with minimum transmission power. If no helper is found, the search is continued among helpers of \( H_2 \) and \( H_3 \), respectively. Finally, when all previous searches failed, the transmission would be performed through the direct link. So, the average throughput in this case is

\[
T_3 = \sum_{i=1}^{3} \left( \prod_{j=1}^{i-1} P_{\text{Loss}}^j \right) P_{\text{Succ}}^i R_{i}^{\text{Coop}} + \left( \prod_{j=1}^{3} P_{\text{Loss}}^j \right) P_{\text{Succ}}^{\text{Dir}}(L_{SD}) \times 2(\text{Mbps}),
\]

where \( R_{i}^{\text{Coop}} \) is the cooperative transmission rate that can be achieved from helpers of \( H_i \) group which is defined in Table 2.

3.4. Case 4 \((74.7 \leq L_{SD} < 96.4)\)

In this case, the search for a potential helper would be done among helpers of \( H_1 \) through \( H_5 \), respectively. If no potential helper found, the path with minimum required power will be selected among cooperative paths of \( H_6 \) and direct link. Hence, the average throughput in this case is

\[
T_4 = \sum_{i=1}^{5} \left( \prod_{j=1}^{i-1} P_{\text{Loss}}^j \right) P_{\text{Succ}}^i R_{i}^{\text{Coop}} + \left( \prod_{j=1}^{5} P_{\text{Loss}}^j \right) \left( 1 - P_{\text{Loss}}^{\text{Dir}}(L_{SD}) P_{\text{Loss}}^6 \right) \times 1(\text{Mbps}).
\]

3.5. Case 5 \((96.4 \leq L_{SD} \geq 100)\)

This case is actually the same as the previous case, except that there is not any helper of \( H_1 \) group for this kind of the links. So, the average throughput is

\[
T_5 = \sum_{i=2}^{5} \left( \prod_{j=2}^{i-1} P_{\text{Loss}}^j \right) P_{\text{Succ}}^i R_{i}^{\text{Coop}} + \left( \prod_{j=2}^{5} P_{\text{Loss}}^j \right) \left( 1 - P_{\text{Loss}}^{\text{Dir}}(L_{SD}) P_{\text{Loss}}^6 \right) \times 1(\text{Mbps}).
\]

4. Average Power Consumption

In this section, we investigate the average of the power consumption for our proposed helper selection scheme. We investigate three scenarios of the proposed scheme, namely direct transmission, cooperative transmission, direct-cooperative transmission.
4.1. Direct Transmission

Depending on the distance of $L_{SD}$, one step of the scheme may include transmission over S–D link. In this scenario, the required power for transmission would be equal to $P_{SD}^{\min}$, defined in (3). As mentioned before, the maximum transmission power of each node of system is equal to $P_{\max}$. Therefore, the transmission power of this scenario, denoted by $P_{SD}$, is given by

$$P_{SD} = \begin{cases} 
P_{SD}^{\min} & P_{SD}^{\min} \leq P_{\max} \\
0 & P_{SD}^{\min} > P_{\max}.
\end{cases}$$ (21)

We denote the complementary cumulative distribution function (CCDF) of $P_{SD}$ by $Y_{SD}(x)$ as

$$Y_{SD}(x) \triangleq \Pr\{P_{SD} > x\}. \quad (22)$$

By substituting (21) in (22), $Y_{SD}(x)$ can be computed as

$$Y_{SD}(x) = \Pr\{x < P_{SD}^{\min} \leq P_{\max}\}$$

$$= \Pr\{P_{SD}^{\min} \leq P_{\max}\} - \Pr\{P_{SD}^{\min} \leq x\} \quad (23a)$$

substituting (3) into (23b)

$$Y_{SD}(x) = \Pr\left\{\frac{N_0 L_{SD}^\alpha}{K_0 \Omega_{SD}} \gamma_{th} \leq P_{\max}\right\} - \Pr\left\{\frac{N_0 L_{SD}^\alpha}{K_0 \Omega_{SD}} \gamma_{th} \leq x\right\}$$

$$= \Pr\{\Omega_{SD} > A L_{SD}^\alpha\SD\} - \Pr\{\Omega_{SD} > A P_{\max} \frac{x L_{SD}^\alpha}{x}\}$$

$$= 1 - F_{\Omega}(A L_{SD}^\alpha) - \left(1 - F_{\Omega}(A P_{\max} \frac{x L_{SD}^\alpha}{x})\right)$$

$$= F_{\Omega}(A P_{\max} \frac{x L_{SD}^\alpha}{x}) - F_{\Omega}(A L_{SD}^\alpha) \quad 0 \leq x \leq P_{\max}. \quad (24)$$

CCDF function $Y_{SD}(x)$ is used in evaluating the CDF of power consumption in the network later.

4.2. Cooperative Transmission

Consider the scenario in which among the potential helpers of group $i$, the one with the minimum required power is selected for cooperation. Let $P_{H,i}$ denote the the total transmission power of the selected path in this scenario and let $Y_{H,i}(x)$ denote the related CCDF. As discussed before, the distribution of the helpers on $C_i$ is a two-dimensional PPP random variable
with density $\lambda$. Let $k$ and $k_1$ denote the total number of helpers in $C_i$ and the number of those helpers which are potential for cooperation, respectively. Since $P_{H,i}$ is the minimum transmission power of the potential cooperative paths in $H_i$, it can be represented as

$$P_{H,i} = \min\{P_{H,i}^j \mid j = 1, \ldots, k_1\}, \quad (25)$$

where $P_{H,i}^j$ is the total power consumption of the $j$th potential cooperative path of group $i$. $Y_{H,i}(x)$ is equal to the probability of the event, in which, the required power of all potential helpers in $C_i$ are greater than $x$. From (6), we can see that the required power of each cooperative path depends on its helper location and fading power of the S–H ($\Omega_1$) and H–D links ($\Omega_2$). The fading power of all the channels are identical independent random variables. Also, from the properties of PPPs, we know that if the number of helpers in region $C_i$ is known, their location would be independent uniform random variables over $C_i$. We deduce that the required power for all the cooperative paths are identical random variables. Hence, $Y_{H,i}(x)$ can be evaluated as

$$Y_{H,i}(x) = \sum_{J=1}^{\infty} \sum_{I=1}^{J} \Pr\{P_{H,i} \geq x \mid k = J, k_1 = I\}$$

$$= \sum_{J=1}^{\infty} \Pr\{k = J\} \sum_{I=1}^{J} \Pr\{P_{H,i} \geq x \mid k = J\} \quad (26a)$$

$$= \sum_{J=1}^{\infty} \frac{e^{-\lambda |C_i|} \lambda |C_i|^J}{J!} \sum_{I=1}^{J} \binom{J}{I} \mu_1^I \mu_2^{J-I}$$

$$= \sum_{J=1}^{\infty} \frac{e^{-\lambda |C_i|} \lambda |C_i|^J}{J!} \left[(\mu_1 + \mu_2)^J - \mu_2^J\right] \quad (26b)$$

$$= e^{-\lambda |C_i| (1-\mu_1-\mu_2)} - e^{-\lambda |C_i| (1-\mu_2)} \quad (26c)$$

$$= e^{-\lambda |C_i| (1-\mu_2)} \left(e^{\lambda |C_i| \mu_1} - 1\right), \quad (26d)$$

where $\mu_1$ is the probability of the event in which, a helper with uniform random position over $C_i$, is potential for cooperation and also, requires a total transmission power greater than $x$. As shown in appendix $B$, $\mu_1$.
\[ \mu_1 = \frac{1}{|C_i|} \int_{\mathcal{C}_i} \mathcal{G}(L_{SH}, L_{HD}, x) \, ds, \quad (27a) \]

where

\[ \mathcal{G}(L_{SH}, L_{HD}, x) = \begin{cases} 
\int_0^x \frac{B L_{SH}^2}{a^2} f_\Omega \left( \frac{B L_{SH}^2}{a^2} \right) \left[ F_\Omega \left( \frac{B L_{SH}^2}{a^2} \right) - F_\Omega \left( \frac{B L_{HD}^2}{a^2} \right) \right] \, da 
& \quad 0 \leq x < P_{\text{max}} \\
\int_{x-P_{\text{max}}}^{P_{\text{max}}} \frac{B L_{SH}^2}{a^2} f_\Omega \left( \frac{B L_{SH}^2}{a^2} \right) \left[ F_\Omega \left( \frac{B L_{HD}^2}{a^2} \right) - F_\Omega \left( \frac{B L_{HD}^2}{a^2} \right) \right] \, da 
& \quad P_{\text{max}} \leq x < 2P_{\text{max}} \\
0 & \quad x \geq 2P_{\text{max}}. 
\end{cases} \quad (27b) \]

where \( \mathcal{B} \triangleq N_0 \gamma_{th}/K_0 \). \( \mu_2 \) can be computed as

\[ \mu_2 = \frac{1}{|C_i|} \int_{\mathcal{C}_i} 1 - \mathcal{P}_{\text{H}}^{\text{Succ}}(L_{SH}, L_{HD}) \, ds. \quad (28) \]

Substituting (27a) and (28) in (26f), we have

\[ \mathbb{V}_{H, i}(x) = \exp \left( -\lambda \int_{\mathcal{C}_i} \mathcal{P}_{\text{H}}^{\text{Succ}}(L_{SH}, L_{HD}) \, ds \right) \left( \exp \left( \lambda \int_{\mathcal{C}_i} \mathcal{G}(L_{SH}, L_{HD}, x) \, ds \right) - 1 \right). \quad (29) \]

Using (12) and (29), we have

\[ \mathbb{V}_{H, i}(x) = \mathcal{P}_{\text{Loss}}^i \times (\mathcal{G}^i(x) - 1), \quad (30a) \]

where

\[ \mathcal{G}^i(x) \triangleq \exp \left( \lambda \int_{\mathcal{C}_i} \mathcal{G}(L_{SH}, L_{HD}, x) \, ds \right). \quad (30b) \]

From Appendix A, \( \mathcal{G}^i(x) \) is obtained for \( i = 1, \ldots, 6 \) as

\[ \mathcal{G}_1(x) = \exp \left( \lambda \mathcal{D}(48.2, 48.2, L_{SD}, x) \right) \quad (31a) \]
\[ \mathcal{G}_2(x) = \exp \left( 2\lambda \mathcal{D}(67.1, 48.2, L_{SD}, x) \right) \left( \mathcal{G}_1(x) \right)^{-2} \quad (31b) \]
\( G_3(x) = \exp (\lambda \mathbb{D}(67.1, 67.1, L_{SD}, x)) \left( G_1(x) G_2(x) \right)^{-1} \) \hfill (31c)

\( G_4(x) = \exp (2\lambda \mathbb{D}(74.7, 48.2, L_{SD}, x)) \left( G_1(x) \sqrt{G_2(x)} \right)^{-2} \) \hfill (31d)

\( G_5(x) = \exp (2\lambda \mathbb{D}(67.1, 74.7, L_{SD}, x)) \left( G_1(x) G_2(x) G_3(x) \sqrt{G_4(x)} \right)^{-2} \) \hfill (31e)

\( G_6(x) = \exp (\lambda \mathbb{D}(74.7, 74.7, L_{SD}, x)) \left( G_1(x) G_2(x) G_3(x) G_4(x) G_5(x) \right)^{-1} \) \hfill (31f)

where \( \mathbb{D}(\cdot, \cdot, \cdot, \cdot) \) is defined by

\[
\mathbb{D}(a, b, c, x) \triangleq \int_{-\theta(a,b,c)}^{\theta(a,b,c)} \int_0^{\phi(a,b,c)} G(r, \sqrt{r^2 + c^2 - 2rc \cos \theta}, x) r \, dr \, d\theta_s \\
+ \int_{-\theta(a,b,c)}^{\theta(a,b,c)} \int_0^{\phi(a,b,c)} G(r, \sqrt{r^2 + c^2 - 2rc \cos \theta}, x) r \, dr \, d\theta_d \\
+ 2c^2 \int_0^{\phi(a,b,c)} \int_0^{\min(\theta(a,b,c), \pi-\theta_d)} G \left( c\frac{\sin(\theta_d)}{\sin(\theta_s + \theta_d)}, c\frac{\sin(\theta_s)}{\sin(\theta_s + \theta_d)}, x \right) \\
\times \frac{\sin(\theta_s) \sin(\theta_d)}{\sin^3(\theta_s + \theta_d)} d\theta_s \, d\theta_d,
\] \hfill (31g)

and \( \theta(\cdot, \cdot, \cdot, \cdot) \) defined in (13h).

4.3. Joint Direct and Cooperative Transmission

Under some circumstances, the last step of the proposed scheme includes selecting a potential link with minimum required power, among cooperative paths of \( H_i \) and the direct link. Let \( P_{SD,H}^i \) denote the power consumption of the selected path in this scenario. Let \( Y_{SD,H}^i(\cdot) \) denote the CCDF of this variable. This scenario is the combination of the two previous scenarios where from the direct link and the selected path of the second scenario, the potential one with minimum required power is selected for transmission. If the direct path is not a potential link for successful transmission, this scenario is similar to the cooperation scenario in Subsection B with power consumption of \( P_{H,i} \). Also, in scenario that no potential helper exists in \( H_i \), this scenario is equivalent to the direct path scenario in Subsection A where power consumption is equal to \( P_{SD} \). Supposing that the direct link is a potential transmission link and at least one potential helper exists in \( H_i \), the transmission power of this scenario would be equal to \( \min\{P_{SD}, P_{H,i}\} \),
where $P_{SD}$ and $P_{H,i}$ are both greater than zero. So, it can be deduced that

$$Y^i_{SD,H}(x) = \Pr\{P_{H,i} > x\} \Pr\{P_{SD} > x\} + \mathcal{P}^i_{Loss} \Pr\{P_{SD} > x\} + \mathcal{P}^i_{Loss}(L_{SD}) \Pr\{P_{H,i} > x\}. \quad (32)$$

Using the definition of CCDF, $Y^i_{SD,H}(x)$ can be obtained as

$$Y^i_{SD,H}(x) = Y^i_{SD}(x)Y^i_{H}(x) + \mathcal{P}^i_{Loss} Y^i_{H}(x) + \mathcal{P}^i_{Loss}(L_{SD}) Y^i_{SD}(x). \quad (33)$$

### 4.4. The CDF of power consumption

We denote the CDF function of the consumed power in the $i$th case (defined in Table 3) by $F^i_{P}(x)$. Based on the path selection scheme proposed for each scenario, and using equations (22) and definition of CDF function, $F^i_{P}(x)$ can be computed for $i = 1, ..., 5$ as

$$F^1_{P}(x) = 1 - Y^1_{SD}(x) \quad (34a)$$

$$F^2_{P}(x) = 1 - Y^2_{SD,H}(x) \quad (34b)$$

$$F^3_{P}(x) = 1 - \sum_{i=1}^{3} Y^i_{H}(x) \prod_{j=1}^{i-1} \mathcal{P}^j_{Loss} - Y^3_{SD}(x) \prod_{j=1}^{3} \mathcal{P}^j_{Loss} \quad (34c)$$

$$F^4_{P}(x) = 1 - \sum_{i=1}^{5} Y^i_{H}(x) \prod_{j=1}^{i-1} \mathcal{P}^j_{Loss} - Y^6_{SD,H}(x) \prod_{j=1}^{5} \mathcal{P}^j_{Loss} \quad (34d)$$

$$F^5_{P}(x) = 1 - \sum_{i=2}^{5} Y^i_{H}(x) \prod_{j=2}^{i-1} \mathcal{P}^j_{Loss} - Y^6_{SD,H}(x) \prod_{j=2}^{5} \mathcal{P}^j_{Loss}. \quad (34e)$$

Using the fact that the average of a positive random variable $x$ is equal to $\int_{0}^{\infty} 1 - F_X(x) \, dx$, the average power consumption of each case would be equal to

$$\bar{P}_i = \int_{0}^{2P_{\text{max}}} 1 - F^i_{P}(x) \, dx. \quad (35)$$

### 5. Numerical Results

In this section, we confirm our analytical derivations and investigate the performance of our scheme via computer simulation. Table 4 shows the parameters settings used for simulations. The results are obtained via 2 millions independent realizations of the system.
Density of helpers ($\lambda$) \times 10^{-3}

0.5 1 1.5 2 2.5 3 3.5 4 4.5 5

Average Throughput

2 3 4 5 6 7 8

Simul. proposed CoopMAC with $L_{SD}=60$ m
Simul. conventional CoopMAC with $L_{SD}=60$ m
Simul. proposed CoopMAC with $L_{SD}=70$ m
Simul. conventional CoopMAC with $L_{SD}=70$ m
Analytical results

Figure 3: The average throughput as a function of $\lambda$ for cases 1 and 2 ($L_{SD}$ = 60 and 70 meters).

Simul. Proposed CoopMAC, $L_{SD}=80$ m
Simul. conventional CoopMAC, $L_{SD}=80$ m
Simul. Proposed CoopMAC, $L_{SD}=98$ m
Simul. conventional CoopMAC, $L_{SD}=98$ m
Analytical results

Figure 4: The average throughput as a function of $\lambda$ for cases 2 and 3 ($L_{SD}$ = 80 and 98 meters).
Table 4: The simulation parameters.

| Parameter | $P_t$  | $P_{th}$ | $\alpha$ | $E(\Omega)$ | $K$  | Fading model |
|-----------|--------|----------|----------|-------------|------|--------------|
| Value     | 1 mW   | −98 dBm  | 3        | 1           | −40 dB| Rayleigh     |

Figs. 3 and 4 illustrate the average throughput performance of the network as a function of $\lambda$, for different values of the distance between source and destination ($L_{SD} = 60, 70, 80$ and $98$ meters), representing cases 2, 3, 4 and 5, respectively. In this part, our proposed protocol has been compared to the conventional CoopMAC scheme, in which, a helper is randomly chosen from the table of helpers, with overall transmission rate greater than the direct link. Since the throughput results of our scheme and conventional CoopMAC are the same for the first case, simulation results of this case has not been illustrated. As can be seen, compared to the conventional CoopMAC, the average throughput of our scheme has been improved significantly for cases 2 to 5. We can see that by increasing the $\lambda$, the performance of our scheme is also getting better. It is because the source node has more opportunity to find a cooperative path with the highest rate to send its packet. Also, we can see that, by increasing the density of the helpers in the network, throughput of the conventional method does not change considerably and has a fixed value. This is because of the fact increasing the number of helpers in the network leads to more successful transmissions and throughput as a result. However, for the networks with enough number of successful transmissions, this increase is not noticeable. Also, due to the uniform distribution of helpers, increasing lambda does not affect the average rate of the randomly selected path.

Fig. 3 depicts the CDF of the power consumption in a network using our proposed CoopMAC scheme, for $L_{SD} = 60, 70, 80$ and $98$ meters. As we can see, the simulation results follow the analytical results for all cases. Also, it has been shown that the statistics of power consumption varies in different cases. As the distance between the source and destination rises, the density of power consumption moves toward higher values and its average value increases as a result.

Fig. 5 illustrates the average power consumption of the network as a function of helpers density, for $L_{SD} = 60, 70, 80$ and $98$ meters. In a network that power control is not being used, the transmission power of each cooperative link would be equal to $2P_{max}$. In this figure, the power efficiency of
Figure 5: The average power consumption as a function of $\lambda$ for $L_{SD} = 60, 70, 80$ and 98.

Figure 6: The CDF of the power consumption of network, for $\lambda = 2.5 \times 10^{-3}$ and $L_{SD} = 70, 80$ and 98
our proposed scheme has been compared with conventional metgo d where no power control is being used. As we see, the average power consumption is significantly lower in all cases. Besides, as expected, by decreasing the distance between the source and destination, the consumed power will be reduced. In our scheme, Increasing density of helpers , leads to a rise in number of successful transmissions and also the chance of finding less power consuming links. So, we can deduce that in networks with low number of successful transmissions (referred to the cases where the number of helpers is low and the distance between source and destination is high), increasing the value of $\lambda$ leads to the rise of successful transmissions, and power consumption as a result. On the other hand, when the number of successful transmissions is high enough, increasing the density of helpers leads to lower power consumption in each transmission and reduction of average consumed power consequently. As we see in Fig. 5 for $L_{SD} = 98$, increasing $\lambda$ leads to power consumption rises at first, and when the number of successful transmissions reaches a high level, it starts to decrease. Also, for $L_{SD} = 70$ and 80, where the distance of the source and destination is shorter, the curve has a descending trend.

6. Conclusion

In this paper, we considered a CoopMAC network in a Poisson field of decode-and-forward helpers and general fading environment. We proposed a new helper selection scheme which aims to improve the throughput and power efficiency of the network. We first classified helpers into six groups, based on their corresponding rates defined in IEEE 802.11b. Also, a power control mechanism was proposed in which all transmissions were performed with the minimum required power. In our scheme, the highest priority is given to the links with the highest cooperate rate and with minimum power consumption. Three different protocols namely, transmission, cooperation and reception were proposed for the source, helper and destination nodes, respectively. Simulations results showed that our scheme can outperform the conventional CoopMAC protocol in having superior average throughput. Also, it was shown that the power consumption in our scheme reduces significantly, compared to the networks with fixed power transmission.
7. References

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Appendix A. Proof Eq. (13a) through (13f), and (31a) through (31g)

We denote $C^{r_1,r_2}$ as a part of system region which is determined by

$$C^{r_1,r_2} = \begin{cases} 0 \leq L_{SH} \leq r_1 \\ 0 \leq L_{HD} \leq r_2, \end{cases}$$

(A.1)

where $L_{SH}$ and $L_{HD}$ are distances of the helper from the source and destination nodes, respectively. As illustrated in Fig. A.7, we see that $C^{r_1,r_2}$ can be represented by the combination of three other areas, as follows:

$$C^{r_1,r_2} = C^{r_1,\theta_1}_{a} + C^{r_2,\theta_2}_{b} - C^{\theta_1,\theta_2}_{c},$$

(A.2)

where $C^{r_1,\theta_1}_{a}$, $C^{r_2,\theta_2}_{b}$ and $C^{\theta_1,\theta_2}_{c}$ are the areas respectively specified in Fig. A.7d through Fig. A.7d. According to the cosines laws, $\theta_1$ and $\theta_2$ are obtained as a function of $r_1$, $r_2$ and $L_{SD}$ as

$$\theta_1 = \arccos\left(\frac{r_2^2 - r_1^2 - L_{SD}^2}{2 r_1 r_2}\right)$$

(A.3)

$$\theta_2 = \arccos\left(\frac{r_1^2 - r_2^2 - L_{SD}^2}{2 r_1 r_2}\right).$$

(A.4)
According to the rules of integral, we can deduce from (A.2) that

\[
\int_{C^{r_1,r_2}} g(L_{SH}, L_{HD}) ds = \int_{C^{r_1,\theta_1}_a} g(L_{SH}, L_{HD}) ds + \int_{C^{r_2,\theta_2}_b} g(L_{SH}, L_{HD}) ds
\]
where \( g(.) \) is an arbitrary function of \( L_{SH} \) and \( L_{HD} \). In order to evaluate (A5), an appropriate coordinate system should be considered for each region. As shown in Fig. A.7b in a polar coordinate system with center of S, each point of the \( C_{a1, \theta_1} \) can be uniquely represented by the pair of \( (L_{SH}, \theta_s) \). Using the law of cosines, \( L_{HD} \) can be obtained as

\[
L_{HD} = \sqrt{L_{SH}^2 + L_{SD}^2 - 2 L_{SH} L_{SD} \cos \theta_s}, \quad (A.6)
\]

also, \( ds \) is given by

\[
ds = L_{SH} dL_{SH} d\theta_s. \quad (A.7)
\]

We can determine \( C_{a1, \theta_1} \) as

\[
C_{a1, \theta_1} = \begin{cases} 
0 \leq L_{SH} \leq r_1 \\
-\theta_1 \leq \theta_s \leq \theta_1,
\end{cases} \quad (A.8)
\]

and by using equations (A.6), (A.7) and (A.8), it can be deduced that

\[
\int_{C_{a1, \theta_1}} g(L_{SH}, L_{HD}) ds = \int_{-\theta_1}^{\theta_1} \int_{0}^{r_1} g(L_{SH}, L_{HD}) L_{SH} dL_{SH} d\theta_s. \quad (A.9)
\]

Similarly, in a polar coordinate system with center of D, each point of \( C_{b2, \theta_2} \) (shown in Fig. A.7c) can be uniquely determined by the pair of \( (L_{HD}, \theta_d) \). Making use of cosines laws, \( L_{SH} \) is

\[
L_{SH} = \sqrt{L_{HD}^2 + L_{SD}^2 - 2 L_{HD} L_{SD} \cos \theta_d}, \quad (A.10)
\]

also, \( ds \) is defined by

\[
ds = L_{HD} dL_{HD} d\theta_d, \quad (A.11)
\]

and \( C_{b2, \theta_2} \) can be specified as

\[
C_{b2, \theta_2} = \begin{cases} 
0 \leq L_{HD} \leq r_2 \\
-\theta_2 \leq \theta_d \leq \theta_2.
\end{cases} \quad (A.12)
\]
Deducing from equations (A.10), (A.11) and (A.12) we have

\[ \int_{\mathcal{C}_{\theta_1,\theta_2}^{\theta_1,\theta_2}} g(L_{SH}, L_{HD}) \, ds = \int_{-\theta_2}^{\theta_2} \int_{0}^{\theta_2} g(L_{SH}, L_{HD}) L_{HD} \, dL_{HD} \, d\theta_d, \quad (A.13) \]

where \( g(,.) \) is an arbitrary function of \( L_{SH} \) and \( L_{HD} \).

In order to evaluate the integral of \( \int g(L_{SH}, L_{HD}) \, ds \) over the surface of \( \mathcal{C}_{\theta_1,\theta_2}^{\theta_1,\theta_2} \), we use a biangular coordinate system \(^3\) given the poles of S and D, where each point is uniquely represented by a pair of \((\theta_s, \theta_d)\) that shown in Fig. \(^3\). Also, due to the symmetry of this model the integral can only be evaluated for the upper half of \( \mathcal{C}_{\theta_1,\theta_2}^{\theta_1,\theta_2} \) plane over S–D line. Using this coordinate system, the upper half of \( \mathcal{C}_{\theta_1,\theta_2}^{\theta_1,\theta_2} \), named \( \mathcal{C}_{\theta_1,\theta_2}^{\theta_1,\theta_2,up} \), is determined by

\[ \mathcal{C}_{\theta_1,\theta_2}^{\theta_1,\theta_2,up} = \begin{cases} 
0 \leq \theta_s \leq \theta_1 \\
0 \leq \theta_d \leq \theta_2 \\
0 \leq \theta_s + \theta_d \leq \pi.
\end{cases} \quad (A.14) \]

According to the law of sines, \( L_{SH} \) and \( L_{HD} \) are given by

\[ L_{SH} = L_{SD} \frac{\sin(\theta_d)}{\sin(\theta_s + \theta_d)}, \quad (A.15) \]
\[ L_{HD} = L_{SD} \frac{\sin(\theta_s)}{\sin(\theta_s + \theta_d)}, \quad (A.16) \]

and directly from \(^4\), Eq. 21, \( ds \) can be obtained as

\[ ds = L_{SD}^2 \frac{\sin(\theta_s) \sin(\theta_d)}{\sin^3(\theta_s + \theta_d)}. \quad (A.17) \]

From equations (A.13) through (A.17), we have

\[ \int_{\mathcal{C}_{\theta_1,\theta_2}^{\theta_1,\theta_2}} g(L_{SH}, L_{HD}) \, ds = 2 L_{SD}^2 \int_{0}^{\theta_2} \int_{0}^{\min(\theta_1, \pi - \theta_d)} g(L_{SH}, L_{HD}) \frac{\sin(\theta_s) \sin(\theta_d)}{\sin^3(\theta_s + \theta_d)} \, d\theta_s \, d\theta_d. \quad (A.18) \]
By Substituting equations (A.9) through (A.18) in (A.5), finally
\[
\int_{C_{r_1,r_2}} g(L_{SH}, L_{HD})\, ds = \mathbb{H}(r_1, r_2, L_{SD}),
\]
where \(\theta_1\) and \(\theta_2\) are obtained from (A.3) and (A.4), and \(\mathbb{H}(\ldots, \ldots)\) is
\[
\mathbb{H}(u, v, x) \triangleq \int_{-\theta(u,v,x)}^{-\theta(u,v,x)} \int_{0}^{u} g(r, \sqrt{r^2 + x^2 - 2r\,x\cos\theta})\, rdr\,d\theta + \int_{-\theta(v,u,x)}^{-\theta(v,u,x)} \int_{0}^{v} g(r, \sqrt{r^2 + x^2 - 2r\,x\cos\theta})\, rdr\,d\theta
\]
\[+ 2x^2 \int_{0}^{\min(\theta(v,u,x),\pi-\theta(u,v,x))} \int_{0}^{\theta(v,u,x)} g\left(\frac{x}{\sin(\theta_d)\sin(\theta_s)}, \frac{x}{\sin(\theta_s + \theta_d)}\right)\, d\theta_s\,d\theta_d,\]
where
\[
\theta(a, b, c) \triangleq \arccos\left(\frac{b^2 - a^2 - c^2}{2\,a\,b}\right).
\]

As illustrated in Fig. 2, we can see that each area of \(C_i (i = 1, \ldots, 6)\) can be written as a combination of \(C_{r_1,r_2}\)s with different values of \(r_1\) and \(r_2\). Therefore, we have
\[
C_1 = C_{48.2,48.2} \quad \text{(A.21a)}
\]
\[
C_2 = C_{67.1,48.2} + C_{48.2,67.1} - 2C_1 \quad \text{(A.21b)}
\]
\[
C_3 = C_{67.1,67.1} - C_1 - C_2 \quad \text{(A.21c)}
\]
\[
C_4 = C_{48.2,74.7} + C_{74.7,48.2} - 2C_1 - C_2 \quad \text{(A.21d)}
\]
\[
C_5 = C_{67.1,74.7} + C_{74.7,67.1} - 2C_1 - 2C_2 - 2C_3 - C_4 \quad \text{(A.21e)}
\]
\[
C_6 = C_{74.7,74.7} - C_1 - C_2 - C_3 - C_4 - C_5. \quad \text{(A.21f)}
\]

We denote \(D\) as
\[
D_i \triangleq \int_{C_i} g(L_{SH}, L_{HD})\, ds \quad i = 1, \ldots, 6 \quad \text{(A.22)}
\]
where \(L_{SH}\) and \(L_{HD}\) are distances from the source and the destination respect-
tively, and \( ds \) is the surface element. Using the equations (A.20a) through (A.21f), and also some mathematical manipulations, it can be summarized as

\[
D_1 = \mathbb{H}(48.2, 48.2, L_{SD}) \tag{A.23a}
\]

\[
D_2 = \mathbb{H}(67.1, 48.2, L_{SD}) + \mathbb{H}(48.2, 67.1, L_{SD}) - 2D_1 \tag{A.23b}
\]

\[
D_3 = \mathbb{H}(67.1, 67.1, L_{SD}) - D_1 - D_2 \tag{A.23c}
\]

\[
D_4 = \mathbb{H}(74.7, 48.2, L_{SD}) + \mathbb{H}(48.2, 74.7, L_{SD}) - 2D_1 - D_2 \tag{A.23d}
\]

\[
D_5 = \mathbb{H}(67.1, 74.7, L_{SD}) + \mathbb{H}(74.7, 67.1, L_{SD}) - 2D_1 - 2D_2 - 2D_3 - D_4 \tag{A.23e}
\]

\[
D_6 = \mathbb{H}(74.7, 74.7, L_{SD}) - D_1 - D_2 - D_3 - D_4 - D_5 \tag{A.23f}
\]

From equation (12), we can deduce that \( P_{\text{Loss}}^i \) would be equal to \( \exp(-\lambda D_i) \) by substituting \( g(L_{SH}, L_{HD}) = P_{\text{Succ}}^H(L_{SH}, L_{HD}) \), which leads to equations (13) to (13f). Also, by replacing \( g(L_{SH}, L_{HD}) = G(L_{SH}, L_{HD}, x) \), \( G_i(x) \) would be equal to \( \exp(\lambda D_i) \), that resulted in equations (31) to (31g).

**Appendix B. Proof of eq. (27a) and (27b)**

Consider a helper, H, at the distances of \( L_{SH} \) and \( L_{SD} \) from the source and the destination respectively. We consider \( G(L_{SH}, L_{HD}, x) \) as the probability of the event in which, S-H-D is a potential cooperative path with the required transmission power greater than \( x \). As discussed earlier, helper H would be potential for cooperation, supposing that the required powers for successful transmission over S–H and H–D are both less than \( P_{\text{max}} \). As a result, \( G(L_{SH}, L_{HD}, x) \) can be represented as

\[
G(L_{SH}, L_{HD}, x) = \Pr\{P_{\text{min}}^{\text{SH}} < P_{\text{max}}, P_{\text{min}}^{\text{HD}} < P_{\text{max}}, P_{\text{min}}^{\text{SH}} + P_{\text{min}}^{\text{HD}} > x\}. \tag{B.1}
\]

We can see that for \( x \geq 2P_{\text{max}} \), equation (B.1) would be equal to zero. In order to evaluate \( G(L_{SH}, L_{HD}, x) \) for \( 0 \leq x < 2P_{\text{max}} \), we first obtain the probability distribution functions (PDF) of \( P_{\text{min}}^{\text{SH}} \) and \( P_{\text{min}}^{\text{HD}} \). We denote \( F_{P,1}(x) \) as the CDF of \( P_{\text{min}}^{\text{SH}} \), which can be evaluated as follows:

\[
F_{P,1}(x) = \Pr\{P_{\text{HD}}^{\text{min}} \leq x\}
\]

\[
= \Pr\left\{\frac{N_0 L_{SH}^{\text{th}}}{K_0 \Omega_1} \leq x\right\}
\]

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\[ = 1 - \Pr \left\{ \Omega_1 < \frac{N_0 L_{\text{SH}}^\alpha \gamma_{\text{th}}}{K_0 x} \right\} \]
\[ = 1 - F_{\Omega}(\frac{B L_{\text{SH}}^\alpha}{x}), \quad (B.2a) \]

where
\[ B \triangleq \frac{N_0 \gamma_{\text{th}} K_0}{L_{\text{SH}}^\alpha}. \quad (B.2b) \]

The PDF function of \( P_{\text{SH}}^{\min} \), can be obtained by differentiating from equation (B.2a) as
\[ f_{P,1}(x) = \frac{B L_{\text{SH}}^\alpha}{x^2} f_{\Omega}(\frac{B L_{\text{SH}}^\alpha}{x}). \quad (B.3) \]

With the same trend, CDF and PDF functions of \( P_{\text{HD}}^{\min} \), can be obtained respectively as
\[ F_{P,2}(x) = 1 - F_{\Omega}(\frac{B L_{\text{HD}}^\alpha}{x}) \]
\[ f_{P,2}(x) = \frac{B L_{\text{HD}}^\alpha}{x^2} f_{\Omega}(\frac{B L_{\text{HD}}^\alpha}{x}). \quad (B.5) \]

Using equations (B.3) and (B.4), \( G(L_{\text{SH}}, L_{\text{HD}}, x) \) can be evaluated for \( x \in [P_{\text{max}}, 2P_{\text{max}}] \) as follows:
\[ G(L_{\text{SH}}, L_{\text{HD}}, x) = \int_0^{P_{\text{max}}} f_{P,1}(a) \Pr\{P_{\text{SH}}^{\min} < P_{\text{max}}, P_{\text{HD}}^{\min} < P_{\text{max}}, P_{\text{SH}}^{\min} + P_{\text{HD}}^{\min} > x \mid P_{\text{SD}}^{\min} = a\} da \]
\[ = \int_0^{P_{\text{max}}} f_{P,1}(a) \Pr\{x - a < P_{\text{HD}}^{\min} < P_{\text{max}}\} da \quad (B.6) \]

Supposing that \( 0 \leq x < P_{\text{max}} \), it can be deduced that \( x - a \) is always less than \( < P_{\text{max}} \). Also, due to the fact that \( P_{\text{HD}}^{\min} \) has a positive value, for \( a > x \), the value of \( \Pr\{x - a < P_{\text{HD}}^{\min} < P_{\text{max}}\} \) would be equal to \( \Pr\{P_{\text{HD}}^{\min} < P_{\text{max}}\} \). Hence, for \( 0 \leq x < P_{\text{max}} \) one can obtain (B.6) as
\[ G(L_{\text{SH}}, L_{\text{HD}}, x) = \int_0^x f_{P,1}(a) \Pr\{< x P_{\text{HD}}^{\min} < P_{\text{max}}\} da \]
\[ + \int_x^{P_{\text{max}}} f_{P,1}(a) \Pr\{P_{\text{HD}}^{\min} < P_{\text{max}}\} \]
\[
\int_0^x f_{P,1}(a) \left( F_{P,2}(P_{\text{max}}) - F_{P,2}(x - s) \right) \, da \\
+ \int_{x}^{P_{\text{max}}} f_{P,1}(a) F_{P,2}(P_{\text{max}}) \, da
\]  

(B.7)

Substituting (B.3), (B.4) in (B.7), one can obtain the \( G(L_{\text{SH}}, L_{\text{HD}}, x) \) for \( 0 \leq x < P_{\text{max}} \)

\[
G(L_{\text{SH}}, L_{\text{HD}}, x) = \int_0^x \frac{BL_{\text{SH}}^\alpha}{a^2} f_{\Omega}(\frac{BL_{\text{SH}}^\alpha}{a}) \left[ F_{\Omega}(\frac{BL_{\text{HD}}^\alpha}{x - a}) - F_{\Omega}(\frac{BL_{\text{HD}}^\alpha}{P_{\text{max}}}) \right] \, da \\
+ \int_{x}^{P_{\text{max}}} \frac{BL_{\text{SH}}^\alpha}{a^2} f_{\Omega}(\frac{BL_{\text{SH}}^\alpha}{a}) \left[ 1 - F_{\Omega}(\frac{BL_{\text{HD}}^\alpha}{P_{\text{max}}}) \right] \, da
\]

(B.8)

Supposing that \( P_{\text{max}} \leq x < 2P_{\text{max}} \), it would be clear that \( x - a > 0 \) for \( a < P_{\text{max}} \). Also if \( x - a > P_{\text{max}} \), the equation (B.6) would be equal to zero. As a result, for \( P_{\text{max}} \leq x < 2P_{\text{max}} \), one can obtain (B.6) as

\[
G(L_{\text{SH}}, L_{\text{HD}}, x) = \int_{x-P_{\text{max}}}^{P_{\text{max}}} f_{P,1}(a) \, \text{Pr}\{x - a < P_{\text{min}}^{\text{HD}} < P_{\text{max}}\} \, da
\]

(B.9)

To summarize, \( G(L_{\text{SH}}, L_{\text{HD}}, x) \) can be presented as

\[
G(L_{\text{SH}}, L_{\text{HD}}, x) = \\
\begin{cases} 
\int_0^x \frac{BL_{\text{SH}}^\alpha}{a^2} f_{\Omega}(\frac{BL_{\text{SH}}^\alpha}{a}) \left[ F_{\Omega}(\frac{BL_{\text{HD}}^\alpha}{x - a}) - F_{\Omega}(\frac{BL_{\text{HD}}^\alpha}{P_{\text{max}}}) \right] \, da \quad \text{for} \quad 0 \leq x < P_{\text{max}} \\
+ \int_{x}^{P_{\text{max}}} \frac{BL_{\text{SH}}^\alpha}{a^2} f_{\Omega}(\frac{BL_{\text{SH}}^\alpha}{a}) \left[ 1 - F_{\Omega}(\frac{BL_{\text{HD}}^\alpha}{P_{\text{max}}}) \right] \, da \\
+ \int_{x-P_{\text{max}}}^{P_{\text{max}}} \frac{BL_{\text{SH}}^\alpha}{a^2} f_{\Omega}(\frac{BL_{\text{SH}}^\alpha}{a}) \left[ F_{\Omega}(\frac{BL_{\text{HD}}^\alpha}{x - a}) - F_{\Omega}(\frac{BL_{\text{HD}}^\alpha}{P_{\text{max}}}) \right] \, da \\
0 \quad \text{for} \quad P_{\text{max}} \leq x < 2P_{\text{max}} \\
\end{cases}
\]

(B.10)

(B.11)
In equation (26f), $\mu_1$ can be evaluated by integrating from $G(L_{SH}, L_{HD}, x)$ over the surface of $C_i$, which leads to (27a) and (27b).