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Throughput maximization for cooperative 60 GHz wireless personal area networks[☆]

Yu Wang[a], Mehul Motani[a], Hari Krishna Garg[a], Xin Kang[b,*], Qian Chen[c]

[a] Department of Electrical and Computer Engineering, National University of Singapore, 119077, Singapore
[b] University of Electronic Science and Technology of China, Cheng Du, 611731, China
[c] Institute for Infocomm Research, 1 Fusionopolis Way, #21-01 Connexis, 138632, Singapore

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ABSTRACT

Transmission in the 60 GHz frequency band performs poorly in long-distance direct links due to the large path loss. The received signal strength can be relatively weak if the line-of-sight path is blocked by obstacles. A device cooperation approach, which effectively combats the severe path loss thereby improving the overall throughput for wireless personal area networks (WPANs), is proposed in this paper. Throughput maximization is formulated as a linear programming problem and the optimal solutions are provided in each case. Comprehensive simulations are performed to quantify the performance of the cooperative approach with different antenna models and spatial reuse strategies. The effect of minor-lobe, imperfect information and other factors are investigated under different network settings. The performance analysis presented here can provide guidelines for the design of cooperative 60 GHz WPANs.

1. Introduction

60 GHz directional communication technology offers various advantages over the conventional omni-directional communication systems, such as higher spatial reuse and large unlicensed bandwidth. It is believed to be one of the most promising technologies to provide gigabit wireless indoor communication. Currently, the most popular usage of 60 GHz technology is to build wireless personal area networks (**WPAN**s). These small networks provide wireless indoor services, such as wireless display, distribution of HDTV and rapid upload/download [2]. Before reaping benefits from 60 GHz transmission, the following issues have to be handled. First, 60 GHz band suffers from significant free space propagation loss, generally 20 dB more than that in 5 GHz band [3]. Second, the strongest component of 60 GHz transmission tends to be line-of-sight (**LOS**). Thus, 60 GHz transmission is vulnerable to long distance and obstacles between transceivers. It is worth mentioning that the deafness problem is also an important issue in 60 GHz WPAN networks, and there are a lot of research papers working on the deafness problem. Many of them [11,34] can solve this deafness problem well. Two simple but effective methods are given here as examples. For instance, all the nodes can be equipped with electronically adjustable antennas and a central controller can coordinate the nodes and adjust the direction of the antennas. Thus, the deafness problem can be solved. Another instance is to use an omni-directional antenna to receive signal but employ a directional antenna to transmit. It is also worth pointing out that the deafness problem is not necessarily coupled with the scheduling problem. In most cases, they can be decoupled. For example, the two methods mentioned above can be directly applied on top of different scheduling methods. Thus, for better exposition, this paper focuses on scheduling part of the 60 GHz networks.

Currently, most 60 GHz WPANs adopt single-hop transmission between the access point and the user. Thus, the users cannot benefit from the directional antenna with potentially higher multiplex ratio. A cooperation strategy is proposed in this work. The potential necessity for this cooperation and the aforementioned issues are illustrated in Fig. 1. In Fig. 1(a), there are 11 devices (**DEV**s) in the WPANs. One DEV is selected as the piconet coordinator (**PNC**) and performs link scheduling for each WPAN. Wireless links are represented by arrows with index on them. $Flow_{(i,\,j)}$ is an end-to-end data flow with the source destination pair DEV_i-DEV_j. $L_{(1,\,5)}$ is a feasible direct route for $flow_{(1,\,5)}$, but $L_{(1,\,5)}$ may not be the best choice for $flow_{(1,\,5)}$ due to the long distance between DEV_1 and DEV_5. In Fig. 1(b), $L_{(9,\,11)}$ is a feasible direct route for $flow_{(9,\,11)}$,

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* Corresponding author.
E-mail addresses: wangyu86@u.nus.edu (Y. Wang), elemm@nus.edu.sg (M. Motani), eleghk@nus.edu.sg (H.K. Garg), kangxin83@gmail.com (X. Kang), qchen@i2r.a-star.edu.sg (Q. Chen).

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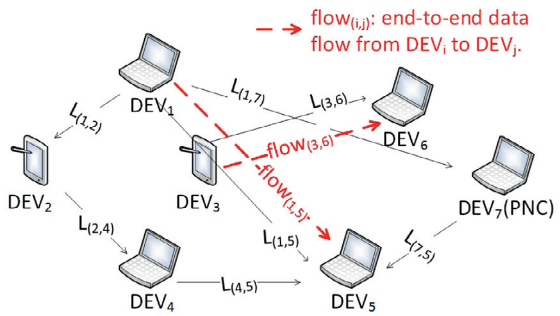
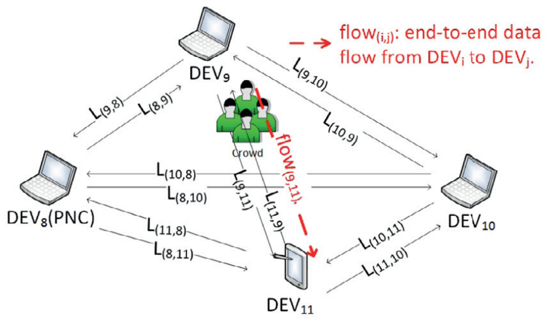


(a) A WPAN with long-distance direct links. Not all links are drawn in this subfigure for simplicity.



(b) A WPAN with direct links being blocked.

Fig. 1. WPAN models. Piconet coordinator (**PNC**) is the scheduler. Devices (**DEV**s) are denoted by DEV_1 to DEV_{11}. $L_{(i,j)}$ is a wireless link from DEV_i to DEV_j.

but a crowd of people standing between the transceivers block the LOS direction of $L_{(9, 11)}$. Cooperative transmission means DEVs may relay data frames for neighbors, which is a promising approach to tackle the aforementioned problems. In the first example, if $flow_{(1, 5)}$ goes through the multi-hop route $L_{(1, 2)}/L_{(2, 4)}/L_{(4, 5)}$, higher throughput may be achieved with shorter distance of each hop. In the second case, if $flow_{(9, 11)}$ uses route $L_{(9, 8)}/L_{(8, 11)}$, it may avoid being blocked and have a higher throughput.

In this work, a cooperation strategy for link scheduling is proposed for 60 GHz WPANs. Cooperation strategy is defined as the scheme to arrange relays and schedule transmission for WPANs. The network can provide better user experience if the transmission time for given amount of data is reduced and the network has shorter latency. We study two scenarios: (i) achievable data demand; and (ii) bursty data demand. Given that each frame has a maximum length, achievable data demand means that all demand for data communication can be completed within the current frame, while bursty demand means that some devices' demand may not be met in the current frame. For (i), if the network does not do scheduling properly, the transmission might not be able to finish in current frame. A better scheduling method can lead to shorter transmission time and shorter latency. For (ii), the network transmits the largest possible amount of data per frame, thus it takes shorter time for transmitting a given amount of data. Both scenarios may be observed in real applications. For instance, demand is achievable when people watch some real time online video, since data is generated sequentially; demand may be bursty, when people do some best-effort downloading task, since data is already there.

Numerous simulations are performed to provide guidelines for real protocol design. The effects of beam-widths, flow rates and other factors are examined under both ideal and practical antenna models. Comprehensive performance analysis is provided for different spatial reuse strategies. The minor-lobe effect of practical antenna model is incorporated and the proposed optimal solutions are compared with existing benchmarks.

The main contributions of this paper are as follows:

1. We propose a cooperative transmission scheme for 60 GHz WPANs and maximize the overall network throughput by optimizing the relay assignment and link scheduling jointly.
2. The optimal relay assignment and link scheduling schemes are derived for two scenarios based on whether all devices' traffic demands can be completed in the current frame or some devices' traffic demands may not be completed in the current frame.
3. We compare the obtained optimal solution with existing benchmark schemes. It is shown that the proposed scheme has excellent performance.
4. We have also performed simulations with different spatial reuse strategies and present comprehensive performance analysis for effects of beamwidth, minor-lobe and other factors.

The rest of the paper is organized as follows. In Section 2, the related works are described and compared. In Section 3, the system model is provided. In Section 4, the problem formulation is presented. In Section 5, the solution of the problem is described. In Section 6, the numerical results and performance analysis are given. The last section concludes the work.

2. Related work

A brief literature review on cooperative link scheduling in 60 GHz networks is provided in this section.

A general review of current achievement and challenges in 60 GHz communication is provided in [7]. Compared with microwave band communication, spectrum at 60 GHz is plentiful and most suitable for providing gigabit wireless data transfer. Moreover, the authors show that the design of efficient 60 GHz medium access control (**MAC**) protocols and scheduling algorithms remains an important research topic. Due to the highly directional property, the interference issue in 60 GHz transmission is different from that in omni-directional transmission. Researchers in [8,9] focused on analyzing interference issues and the related effects in MAC protocol design. In [11], the deafness problem is studied and the method for coordinating different users is proposed. In [34], deafness problem is studied for WPAN and method DA-MAC is proposed for solving it. This kind of methods can be applied on top of different scheduling methods. Considering the special properties, MAC protocols for 60 GHz distributed mesh networks are proposed in [10].

The research on centralized link scheduling in 60 GHz networks starts with no cooperation or relay service being considered. The optimal scheduling problem under fairness constraints in 60 GHz network is solved in [14]. Then, a few heuristic suboptimal scheduling algorithms are provided. In [15], an exclusive region based scheduling algorithm is proposed based on perfect channel information. In [6], the authors propose a spatial reuse strategy which can schedule multiple transmissions appropriately based on beamforming information. In [12], a graph coloring-based heuristic scheduling algorithm is proposed to reduce overall transmission time. Besides aforementioned algorithms, a protocol is designed for 802.15.3c based WPANs to exploit spatial reuse in [13].

However, researchers recognize that direct links may not possess strong signal quality in 60 GHz networks due to the large path loss and possible blockages [22]. Cooperative transmission is proposed to solve this problem, which means the neighboring devices may relay data frame for each other. The idea of using relays is not new in the field of omni-directional networks. In [16,18–21], different cooperative transmission schemes are proposed for the omni-directional cooperative ad hoc, cellular and mesh networks.

The framework of using column generation in capacity maximization is described for omni-directional networks in [17].

Then, study on cooperative transmission is extended to directional networks, but data frames are assumed to be relayed for at most one time. This means no multihop (more than two hop) transmission is allowed. Cooperative transmission with dedicated relays for each source device is studied in [23–26], and demonstrates better throughput performance than non-cooperative transmission. Moreover, a cooperative medium access control protocol is proposed for 60 GHz WPAN based on optimal beamforming information in [29]. However, we know that one-hop relay generally may not provide best relay service.

Therefore, cooperative transmission with multihop relay service is studied. In [30], joint routing and scheduling problem is investigated in multi-hop directional wireless mesh networks, but relay is only used if the destination cannot be reached by direct links. Since WPANs are small networks, devices can reach each other while some long-distance links possess poor rates. If the method in [30] is used, no cooperative transmission will appear in WPANs. However, the overall throughput may be poor, if the low-rate links are scheduled. In [31], the authors examine joint link scheduling and routing for 60 GHz wireless mesh networks. They propose heuristic algorithms for this problem and perform extensive simulations. Again, direct links are used by default as long as they exist.

Observing above issues, the researchers raise that PNC should decide whether to use cooperative or direct transmission based on current channel status in 60 GHz WPANs. In [4,27,28], heuristic algorithms are proposed for scheduling cooperative transmission in 60 GHz WPANs. However, link scheduling is performed only after relay assignment being done ahead. It is known that separate consideration of relay assignment and link scheduling may not provide the optimal end-to-end solution. In our previous work [1], we consider the multi-hop cooperative transmission in 60 GHz WPANs and assume all demand can be completed in current frame. The throughput maximization problem is formulated as linear programming problems and the optimal solution is provided.

From above literature review, we find that cooperative transmission in 60 GHz WPANs has not been studied thoroughly with considering relay assignment and link scheduling jointly. Meanwhile, we have shown in Fig. 1 that cooperative transmission is an excellent approach to overcome blockage of LOS links and severe free space propagation loss in 60 GHz WPANs. Thus, a comprehensive study on cooperative transmission in 60 GHz WPANs is needed. Our paper [1] is limited by the assumption that data demand can be completed in current frame. Observing that the demand may not be completed in current frame due to network capacity, this work extends the throughput maximization problem studied in [1] by taking bursty demand into consideration. Optimal method of joint link scheduling and relay assignment is investigated and proposed. Furthermore, direct observation is provided by the performance analysis and comparison towards existing benchmarks in this work.

3. System model

In this section, information about system model, antenna model and channel model is provided.

3.1. Network model

A centralized 60 GHz WPAN consisting of a PNC and multiple peer DEVs is considered as illustrated in Fig. 1(a). Each DEV is assumed to be equipped with one single electronically steerable directional antenna, i.e., the antenna that is able to direct its beam towards other DEVs for transmission or reception. As WPAN is a small network, all DEVs are assumed to be within other DEVs' transmission range. In addition, we assume slotted transmission, i.e., one slot for one frame. Since we focus on scheduling algorithms, a general frame structure as [12] is used as shown in Fig. 2. One device is selected as the PNC. The PNC polls transmission requests and pushes the schedules to the DEVs during the control period. It then performs scheduling for the conflict-free data transmission during data transmission period (**DTP**). The length of DTP is assumed to be adaptive with a maximum value T. Next frame may start right after the current one ends.

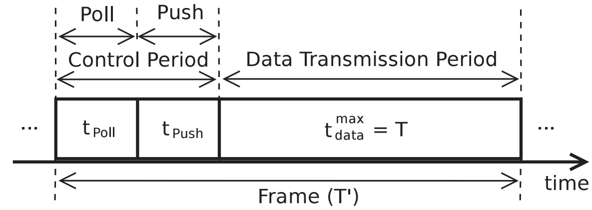


Fig. 2. Frame structure.

Based on traffic demands, we examine two scenarios. First, if all DEVs' data traffic demand can be finished in the current frame, we say that it is achievable data demand. In this case, PNC tries to minimize the transmission time. An instance of such a scenario occurs when DEVs are using online video streaming service and communication with achievable data rates appears in WPANs. Second, if some DEVs' data traffic demand may not be fulfilled within current frame, we say that there is bursty data demand. In this case, PNC tries to maximize amount of received data within current frame. An instance of such a scenario occurs when DEVs in WPANs conduct best effort downloading service and a bunch of data is to be delivered from server side. Adaptive rates are used for the data transmissions in the 802.11ad 60 GHz WPANs standard [33]. Channel status of links are assumed to be the same during one frame and PNC can obtain this information as assumed in [4,18,19].

3.2. Antenna and channel model

To be consistent with the most popular standard in 60 GHz WPAN and make it easier for other researchers to compare, The antenna model in [33] is adopted to approximate a practical antenna, which is

$$\begin{cases} \text{main-lobe gain: } G_m = 10log_{10}(\frac{1.6162}{sin(\alpha/2)})^2; \\ \text{side-lobe gain: } G_s = -0.4111 \cdot ln(\alpha) - 10.579, \end{cases} \quad (1)$$

where α is beamwidth. G_s is set to zero for ideal antenna model. The Friis equation (in dB) as in [33] is used as propagation model and power is in the log sense:

$$P_R(\alpha, f, d, \sigma) = P_T + G_T(\alpha) + G_R(\alpha) - L(f, d, \sigma), \quad (2)$$

where f is frequency and d is distance. P_T and P_R denote the transmission and reception power, respectively. G_T and G_R denote the transmitter's and receiver's antenna gains, respectively. $L(f, d, \sigma)$ represents pathloss. σ is shadow fading factor normally distributed with standard deviation 1.5 dB.

$$L(f, d, \sigma) = 32.5 + 20lg(f) + 20lg(d) + \sigma. \quad (3)$$

3.3. Spatial reuse strategy

Three spatial reuse strategies are (i) conservative strategy for ideal antenna model: two links can coexist when devices from one link are not in the main-lobe sectors of the devices from the other link; (ii) aggressive strategy for ideal antenna model: two links can

Table 1
Defined and used variables.

Variable	Description
K	Number of devices in the studied WPAN
ψ_i	Concurrent links pattern (CLP) with index of i
Ψ	Set of all feasible CLPs
i, j, u, w	Indexes of DEVs
(i, j)	Link from DEV_i to DEV_j
$\upsilon^m_{i,j}$	Status of (i, j) in ψ_m
$r_{i,j}$	Transmission rate of (i, j)
$r^m_{i,j}$	Transmission rate of (i, j) in ψ_m
d_n	data demand of flow n
$x^n_{i,j}$	Amount of data of flow n through (i, j)
τ_m	Active time for ψ_m
f_n	Amount of data received for flow n

coexist when devices from different links do not direct their main-lobe sectors towards each other at the same time; and (iii) impartial strategy for practical antenna model: whether two links may coexist or not is determined by capture effect based on signal-to-noise ratios (SNR) under physical interference model.

The reason we study these strategies is as follows. First, perfect SNR information is difficult to collect in real environment so spatial reuse strategy is usually based on relative location information. Performance gap between (i) and (iii) is largely due to imperfect information. Second, minor-lobe is ignored in ideal antenna model. Thus, the performance gap between (ii) and (iii) shows the minor-lobe effect.

4. Problem formulation

In this section, the problem formulation is presented. The purpose of this paper is to propose a scheduling method which can improve the throughput performance of the 60 GHz WPAN. The advantage of the cooperation is illustrated in Section 1. The scheduling problem is formulated as a optimization problem and solved as follows. The variables are described in Table 1. We assume that there are K nodes in the network, and the entire set of links is L. To focus on the scheduling part, we do not consider the handshakes in any specific protocols. For convenience, we define a term referred to as concurrent links pattern (**CLP**), and represent the i_{th} CLP by ψ_i. A CLP is used to show a group of links which can be activated simultaneously, and can be mathematically expressed as a binary vector where each item corresponds to the working state (active/idle) of a link. For example in Fig. 1(b), $L_{(8,9)}$ and $L_{(11,10)}$ form a CLP ψ_g. If we denote the link sequence in the CLP as $\{L_{(9,8)}, L_{(8,9)}, L_{(11,8)}, L_{(8,11)}, L_{(10,11)}, L_{(11,10)}, L_{(10,9)}, L_{(9,10)}, L_{(9,11)}, L_{(11,9)}, L_{(10,8)}, L_{(8,10)}\}$, ψ_g equals $\{0, 1, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0\}$. Denote Ψ as the set of all feasible CLPs with cardinality $M = |\Psi|$. (i, j) represents a link from DEV_i to DEV_j. Link (i, i) does not exist, thus it is not considered in $\forall(i, j) \in L$. Let $C[(i, j), (u, w)]$ be an indicator function that represents whether two links (i, j) and (u, w) can coexist, and this information is assumed to be available based on either conservative or aggressive spatial reuse strategy during the beamforming process. Thus:

$$C[(i,j),(u,w)] = \begin{cases} 1, & (i,j) \text{ and } (u,w) \text{ can coexist;} \\ 0, & \text{they cannot coexist.} \end{cases} \tag{4}$$

Let m be an index of a generic CLP ψ_m. Binary $\upsilon^m_{i,j}$ represents whether (i, j) is active (1) or idle (0) in ψ_m. Thus, ψ_m is a vector combined by $\upsilon^m_{i,j}$ for all (i, j), $\psi_m = \{\upsilon^m_{i,j}, \ \forall(i, j)\}$. Since each device is equipped with a single half-duplex radio, it should not be scheduled more than once in ψ_m. Due to the half-duplex requirement of single-radio DEV_i, we have:

$$\sum_{j=1\&j\neq i}^{K} \upsilon^m_{i,j} + \sum_{j=1\&j\neq i}^{K} \upsilon^m_{j,i} \leq 1, \ \forall i, \ \forall m. \tag{5}$$

The links' coexistence constraints in ψ_m are given as in (6), which are determined by $C[(i, j), (u, w)]$ as follows:

$$\upsilon^m_{i,j} + \upsilon^m_{u,w} \leq 1 + C[(i,j),(u,w)] \ , \forall(i,j), \ \forall(u,w). \tag{6}$$

$r_{i,j}$ is used to represent the current transmission rate of (i, j). The rate of (i, j) in ψ_m can be calculated as:

$$r^m_{i,j} = \upsilon^m_{i,j} \cdot r_{i,j} \ . \tag{7}$$

We assume that there are N flows, and a flow n is characterized by source device, destination device, and data demand, or $(S(n), D(n), d_n)$.

Our objective is to maximize the throughput of this WPAN. Throughput equals the sum of received data divided by overall transmission time. That is:

$$\text{Throughput} = \frac{\text{Received Data}}{\text{Transmission Time}}. \tag{8}$$

4.1. Scenario I: achievable data demand

There are N flows in the studied WPAN. n is the index for a flow and $n \in \{1, 2, \cdots, N\}$. In Scenario I, all data demands can be fulfilled within the current frame. Since all data are successfully delivered, the numerator in (8) is determined by source devices' demands and fixed. Therefore, maximizing the throughput is equivalent to minimizing the transmission time. At any moment of the transmission period, there is a group of active links, or in other words, a CLP working for the data transmission. Therefore, minimizing the overall transmission time is equivalent to minimizing the sum of the scheduled periods of all the CLPs as shown in (9). τ_m is the active time for CLP ψ_m, and the **objective** of minimizing the transmission time can be represented as $\min_{\tau_1,\tau_2,\ldots,\tau_M} \sum_{m=1}^{M} \tau_m$.

Cooperative transmission: The problem of time minimization with cooperative transmission is formulated as

$$\text{Problem } P_{1,M}: \ \min_{\tau_1,\tau_2,\ldots,\tau_M} \sum_{m=1}^{M} \tau_m \ , \tag{9}$$

subject to

$$\sum_{j=1\&j\neq i}^{K} (x^n_{i,j} - x^n_{j,i}) = \begin{cases} d_n, & i = S(n), \ \forall n; \\ -d_n, & i = D(n), \ \forall n; \\ 0, & i \neq S(n) \text{ or } D(n), \ \forall n; \end{cases} \tag{10}$$

$$\sum_{m=1}^{M} \tau_m \cdot r^m_{i,j} \geq \sum_{n=1}^{N} x^n_{i,j}, \ \forall(i,j); \tag{11}$$

$$\sum_{j=1\&j\neq i}^{K} \upsilon^m_{i,j} + \sum_{j=1\&j\neq i}^{K} \upsilon^m_{j,i} \leq 1, \ \forall i, \ \forall m; \tag{12}$$

$$\tau_m \geq 0, \quad m = 1, 2, \ldots, M; \tag{13}$$

$$\upsilon^m_{i,j} + \upsilon^m_{u,w} \leq 1 + C[(i,j),(u,w)] \ , \forall(i,j), \ \forall(u,w). \tag{14}$$

Eq. (10) provides the flow conservation constraint. For source, destination and relay devices, differences between the outgoing and incoming amounts of data are d_n, $-d_n$ and 0, respectively. $x^n_{i,j}$ denotes the amount of data for flow n through (i, j). Eq. (11) provides the link capacity constraints, which means that the link capacity should be larger than the sum of amount of data through this link.

Eqs. (12) and (14) are explained in (5) and (6) respectively. Eq. (13) means τ_m should be non-negative value, since it represents active transmission time.

Non-cooperative transmission: The problem of time minimization without cooperative transmission is formulated as

$$\text{Problem } P_{2,M}: \min_{\tau_1,\tau_2,\ldots,\tau_M} \sum_{m=1}^{M} \tau_m , \tag{15}$$

subject to

$$\sum_{m=1}^{M} \tau_m \cdot r_{i,j}^m \geq \begin{cases} d_n, & i = S(n) \ \& \ j = D(n); \\ 0, & \text{any other } (i,j); \end{cases} \tag{16}$$

$$\sum_{j=1\&j\neq i}^{K} v_{i,j}^m + \sum_{j=1\&j\neq i}^{K} v_{j,i}^m \leq 1, \ \forall i, \ \forall m; \tag{17}$$

$$\tau_m \geq 0, \quad m = 1, 2, \ldots, M; \tag{18}$$

$$v_{i,j}^m + v_{u,w}^m \leq 1 + C[(i,j),(u,w)] \ , \forall (i,j), \ \forall (u,w). \tag{19}$$

Since only the source and destination DEVs are engaged in the non-cooperative scenario, the flow conservation and link capacity constraint can be merged into (16).

4.2. Scenario II: bursty data demand

In this scenario, there are bursty data demands and not all data demands can be fulfilled in the current frame. The objective is to maximize the throughput of studied WPAN. When there are bursty data demands, the WPAN may not be capable to transmit them completely within the current frame. Since the maximum duration of DTP is fixed and the throughput equals the amount of data received divided by DTP, the objective of maximizing throughput is equivalent to maximizing the amount of data received as shown in (20). We use f_n to represent amount of data received for flow n, thus $f_n \geq 0$. The objective of maximizing amount of data received can be represented as $\max_{f_1,f_2,\ldots,f_N} \sum_{n=1}^{N} f_n$.

Cooperative transmission: Maximization of amount of data received with cooperative transmission can be formulated as

$$\text{Problem } P_{3,M}: \max_{f_1,f_2,\ldots,f_N} \sum_{n=1}^{N} f_n = -\min_{f_1,f_2,\ldots,f_N} \sum_{n=1}^{N} -f_n , \tag{20}$$

subject to

$$f_n \leq d_n, \forall n; \tag{21}$$

$$\sum_{j=1\&j\neq i}^{K} (x_{i,j}^n - x_{j,i}^n) = \begin{cases} f_n, & i = S(n), \ \forall n; \\ -f_n, & i = D(n), \ \forall n; \\ 0, & i \neq S(n) \text{ or } D(n), \ \forall n; \end{cases} \tag{22}$$

$$\sum_{m=1}^{M} \tau_m \cdot r_{i,j}^m \geq \sum_{n=1}^{N} x_{i,j}^n, \ \forall (i,j); \tag{23}$$

$$\sum_{j=1\&j\neq i}^{K} v_{i,j}^m + \sum_{j=1\&j\neq i}^{K} v_{j,i}^m \leq 1, \ \forall i, \ \forall m; \tag{24}$$

$$\sum_{m=1}^{M} \tau_m \leq T; \tag{25}$$

$$\tau_m \geq 0, \quad m = 1, 2, \ldots, M; \tag{26}$$

$$v_{i,j}^m + v_{u,w}^m \leq 1 + C[(i,j),(u,w)] \ , \ \forall (i,j), \ \forall (u,w). \tag{27}$$

The constraint (21) ensures that the amount of data received does not exceed the demand for data. The flow conservation constraints are shown in (22). For source, destination and relay DEVs, differences between the outgoing and incoming amounts of data are f_n, $-f_n$ and 0, respectively. $x_{i,j}^n$ is defined as the amount of data for flow n through link (i, j). The link capacity constraints are shown in (23). The constraint (25) guarantees that the transmission time will not exceed the DTP.

Non-cooperative transmission: Maximization of amount of data received without cooperative transmission can be formulated as

$$\text{Problem } P_{4,M}: -\min_{f_1,f_2,\ldots,f_N} \sum_{n=1}^{N} -f_n , \tag{28}$$

subject to

$$f_n \leq d_n, \forall n; \tag{29}$$

$$\sum_{m=1}^{M} \tau_m \cdot r_{i,j}^m \geq \begin{cases} f_n, & \text{if } i = S(n) \ \& \ j = D(n); \\ 0, & \text{any other } (i,j); \end{cases} \tag{30}$$

$$\sum_{m=1}^{M} \tau_m \leq T; \tag{31}$$

$$\tau_m \geq 0, \quad m = 1, 2, \ldots, M; \tag{32}$$

$$\sum_{j=1\&j\neq i}^{K} v_{i,j}^m + \sum_{j=1\&j\neq i}^{K} v_{j,i}^m \leq 1, \ \forall i, \ \forall m; \tag{33}$$

$$v_{i,j}^m + v_{u,w}^m \leq 1 + C[(i,j),(u,w)] \ , \forall (i,j), \ \forall (u,w). \tag{34}$$

Since only the source and destination DEVs are engaged in the non-cooperative scenario, the flow conservation and link capacity constraint can be merged into (30).

5. Solution via column generation

To solve the problems formulated in the previous section directly, we have to enumerate all the CLPs. However, the number of the entire set of CLPs for a network with N nodes is $M = \sum_{i=1}^{N(N-1)} C_{N(N-1)}^{i}$, which is an extremely large number even for a moderate N. Common desktop computers may run out of memory with using this method, while only a small number of the CLPs will be scheduled in the final result. Therefore, we use the column generation method [32] to decompose the original problem into a master problem and a pricing problem. With column generation method, we do not need to consider all CLPs at the same time but only check potential ones sequentially. Thus, it saves memory and computation time.

5.1. Solution for Scenario I

We use the column generation method to solve our problems. The **master problem** of $P_{1,M}$ is formulated as:

$$\text{Problem } P_{1,M'}: \min_{\tau_1,\tau_2,\ldots,\tau_{M'}} \sum_{m=1}^{M'} \tau_m , \tag{35}$$

subject to:

$$\sum_{j=1\&j\neq i}^{K}(x_{i,j}^{n}-x_{j,i}^{n})=\begin{cases}d_n, & i=S(n),\ \forall n;\\ -d_n, & i=D(n),\ \forall n;\\ 0, & i\neq S(n)\text{ or }D(n),\ \forall n;\end{cases} \tag{36}$$

$$\tau_m\geq 0,\quad m=1,2,\ldots,M'; \tag{37}$$

$$\sum_{m=1}^{M'}\tau_m\cdot r_{i,j}^{m}\geq\sum_{n=1}^{N}x_{i,j}^{n},\ \forall(i,j). \tag{38}$$

There are many methods for solving the linear optimization problem and they are generally based on Simplex algorithm. In this work, CPLEX [5] is used as a built solver to solve the master problem. The CPLEX only needs the user to input the objective and the constraints. It is noticed that M in the original problem (9) becomes M' in the master problem (35). There is $M'\leq M$, which means the master problem only depends on part of the CLPs. To solve the master problem, a group of feasible CLPs should be given. For the problem considered in this work, the initial CLPs contain only the direct links corresponding to source-destination pairs of the flows. After solving the master problem, the optimal values of dual variables are obtained for the link demand constraints in (38) as $\overline{\pi}_{i,j}$. Therefore, the reduced cost for a new column (CLP) with the specific index m' is:

$$\overline{\xi}_{m'}=1-\sum_{(i,j)\in L}\overline{\pi}_{i,j}\cdot r_{i,j}^{m'}\ . \tag{39}$$

The reduced cost in the linear optimization program indicates how much the objective function value can be reduced with the new basis. Here, the value of the objective function $P_{1,(M'+1)}$ of the new master problem including CLP m' is equal to:

$$P_{1,(M'+1)}=P_{1,M'}+\overline{\xi}_{m'}. \tag{40}$$

If the reduced cost $\overline{\xi}_{m'}$ is negative, it means the new CLP m' can reduce the current objective function value $P_{1,M'}$. To minimize $P_{1,(M'+1)}$, the minimum $\overline{\xi}_{m'}$ is needed. That is, the maximum $\sum_{(i,j)\in L}\overline{\pi}_{i,j}\cdot r_{i,j}^{m'}$ is needed in (39). With (7), minimizing (39) can be re-formulated as the **pricing problem**:

$$\max_{v_{i,j}^{m'},\forall(i,j)}\sum_{(i,j)\in L}\overline{\pi}_{i,j}\cdot r_{i,j}\cdot v_{i,j}^{m'}\ , \tag{41}$$

subject to:

$$\sum_{j=1\&j\neq i}^{K}v_{i,j}^{m'}+\sum_{j=1\&j\neq i}^{K}v_{j,i}^{m'}\leq 1,\ \forall i; \tag{42}$$

$$v_{i,j}^{m'}+v_{u,w}^{m'}\leq 1+C[(i,j),(u,w)],\ \forall(i,j),\ \forall(u,w). \tag{43}$$

The solution of the pricing problem is a new CLP $\psi_{m'}$. If the reduced cost $\overline{\xi}_{m'}$ for $\psi_{m'}$ is negative, the new $\psi_{m'}$ is added to the bases of the previous master problem and re-solve it. After several iterations, the reduced cost becomes positive, which means no CLP can reduce the objective function value of the current master problem. Then, the objective function value of master problem in current iteration is optimal for the original $P_{1,\,M}$. $P_{2,\,M}$ can also be solved by a similar method.

5.2. Solution for Scenario II

The solution for $P_{3,\,M}$ comes as follows. The master problem is formulated as

$$\text{Problem } P_{3,M''}:\ \min_{f_1,f_2,\ldots,f_N}\sum_{n=1}^{N}-f_n\ , \tag{44}$$

subject to

$$f_n\leq d_n,\forall n; \tag{45}$$

$$\sum_{j=1\&j\neq i}^{K}(x_{i,j}^{n}-x_{j,i}^{n})=\begin{cases}f_n, & i=S(n),\ \forall n;\\ -f_n, & i=D(n),\ \forall n;\\ 0, & i\neq S(n)\text{ or }D(n),\ \forall n;\end{cases} \tag{46}$$

$$\sum_{m=1}^{M''}\tau_m\cdot r_{i,j}^{m}\geq\sum_{n=1}^{N}x_{i,j}^{n},\ \forall(i,j); \tag{47}$$

$$\tau_m\geq 0,\quad m=1,2,\ldots,M''; \tag{48}$$

$$\sum_{m=1}^{M'}\tau_m\leq T. \tag{49}$$

Again, M in the original problem (20) becomes M'' in the master problem (44), $M''\leq M$. This means the master problem only depends on part of the CLPs. After solving the master problem, we can get the optimal dual variables for (47) and (49) as $\overline{\alpha}_{i,j}$ and $\overline{\beta}$, respectively. Therefore, we can write the reduced cost for a new column (CLP) with the specific index m'' as

$$\overline{\xi}_{m''}=0-\sum_{(i,j)\in L}\overline{\alpha}_{i,j}\cdot r_{i,j}^{m''}-\overline{\beta}\ . \tag{50}$$

The reduced cost in the linear optimization program indicates the amount of objective function value which can be reduced with the new basis. Here, the objective function value $P_{3,(M''+1)}$ of the new master problem including CLP m'' can be expressed as

$$P_{3,(M''+1)}=P_{3,M''}+\overline{\xi}_{m''}. \tag{51}$$

If the reduced cost is negative, the new CLP m'' can reduce the current objective value $P_{3,M''}$. To minimize $P_{3,(M''+1)}$ in (51), minimum $\overline{\xi}_{m''}$ is needed. That is, the maximum $\sum_{(i,j)\in L}\overline{\alpha}_{i,j}\cdot r_{i,j}\cdot v_{i,j}^{m''}+\overline{\beta}$ is needed. With (7), minimizing the reduced cost can be re-formulated as the **pricing problem**

$$\max_{v_{i,j}^{m''},\forall(i,j)}\sum_{(i,j)\in L}\overline{\alpha}_{i,j}\cdot r_{i,j}\cdot v_{i,j}^{m''}+\overline{\beta}\ , \tag{52}$$

subject to

$$\sum_{j=1\&j\neq i}^{K}v_{i,j}^{m''}+\sum_{j=1\&j\neq i}^{K}v_{j,i}^{m''}\leq 1,\ \forall i. \tag{53}$$

$$v_{i,j}^{m''}+v_{u,w}^{m''}\leq 1+C[(i,j),(u,w)],\ \forall(i,j),\ \forall(u,w). \tag{54}$$

The solution of the pricing problem is a new CLP $\psi_{m''}$. If the reduced cost for $\psi_{m''}$ is negative, we add the new $\psi_{m''}$ to the bases of the previous master problem and then re-solve it. After several iterations, the master problem may reach the optimal solution, which is also optimal for the original problem $P_{3,\,M}$. We can solve $P_{4,\,M}$ by a similar approach.

6. Performance evaluation

In this section, we first describe the simulation setup and simulation parameters. After that, the numerical results for both Scenarios I and II are shown and investigated. Following acronyms are used in the figures: impartial strategy for practical antenna model with cooperation (**PAC**), impartial strategy for practical antenna model without cooperation (**PANC**), conservative strategy for ideal

Table 2
Modulation and coding scheme for single carrier.

MCS	Modulation	Repitition	Code rate	Data rate (Mbps)
0	DBPSK	1	1/2	27.5
1	$\pi/2$-BPSK	2	1/2	385
2	$\pi/2$-BPSK	1	1/2	770
3	$\pi/2$-BPSK	1	5/8	962.5
4	$\pi/2$-BPSK	1	3/4	1155
5	$\pi/2$-BPSK	1	13/16	1251.25
6	$\pi/2$-QPSK	1	1/2	1540
7	$\pi/2$-QPSK	1	5/8	1925
8	$\pi/2$-QPSK	1	3/4	2310
9	$\pi/2$-QPSK	1	13/16	2502.5
10	$\pi/2$-16QAM	1	1/2	3080
11	$\pi/2$-16QAM	1	5/8	3850
12	$\pi/2$-16QAM	1	3/4	4620

antenna model with cooperation (**CSC**), conservative strategy for ideal antenna model without cooperation (**CSNC**), and aggressive strategy for ideal antenna model with cooperation (**ASC**), aggressive strategy for ideal antenna model without cooperation (**ASNC**).

First, the effect of cooperation is shown by comparing cooperative and non-cooperative cases. Second, the effect of minor-lobe is shown by comparing PAC and ASC. Third, the effect of perfect information is shown by comparing PAC and CSC. Fourth, the proposed cooperative scheme is compared to its counterpart in [4]. The cooperative scheme in [4] is designed for 60 GHz WPAN and considers multi-hop relay service. This is the reason that the scheme in [4] is chosen as benchmark.

6.1. Simulation settings

C++ and CPLEX [5] are used for simulations. Network topologies are generated in C++. Then, the constraints of linear programming problem will be generated according the studied topology. After that, CPLEX is used solve the linear programming problem. Throughput gain is defined as the ratio between throughput under different schemes or antenna models. The simulation configuration is as follows. The DEVs are randomly deployed in a square area of side 15 m. As shown in Table 2, we use the modulation and coding schemes (**MCS**) in [33]. Transmission power is fixed at 10 dBm. Noise factor and implementation loss are set as 10 and 5 dB, respectively. 50 networking topologies are randomly generated. The simulation results are then averaged and shown.

6.2. Performance analysis of Scenario I

In Scenario I, we assume that transmission time does not reach the maximum DTP length in Fig. 2. Thus, we maximize throughput of WPANs via minimizing transmission time. Four aspects are discussed, namely, antenna beamwidth, number of DEVs, number of flows and data demand per flow. The proposed scheduling scheme is also compared to that used in [4].

In Fig. 3, the effect of antenna beamwidth on transmission time is shown. 20 DEVs are randomly deployed. 4 flows are initialized and amount of data per flow is set as 0.5 Mbits. Transmission time increases with wider beamwidth for all cases. For CSC, the throughput gain between using 15° and 90° antenna is about 100 times. This is due to the fact that wider beamwidths provide smaller spatial reuse ratios, and the consequential fewer concurrent links lead to smaller capability for data transmission. The need for cooperative transmission is low with 15° antenna, since the direct links possess good qualities. Cooperative transmission also does not help much with 90° antenna, because the cooperative scheme needs more concurrent active links. Larger throughput gains between cooperative and non-cooperative transmission

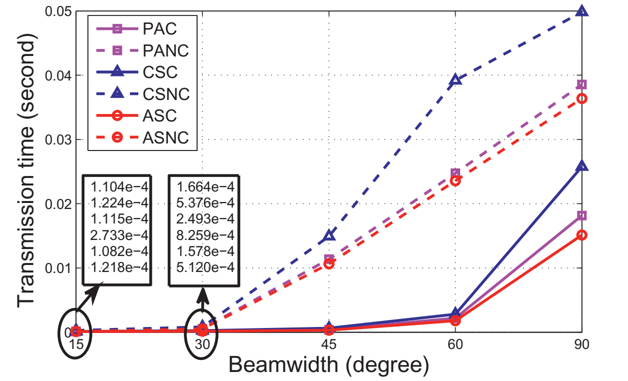


Fig. 3. Transmission time with different antenna beamwidths in Scenario I. (The sequence of the numbers in the text boxes is consistent with that in the legend.).

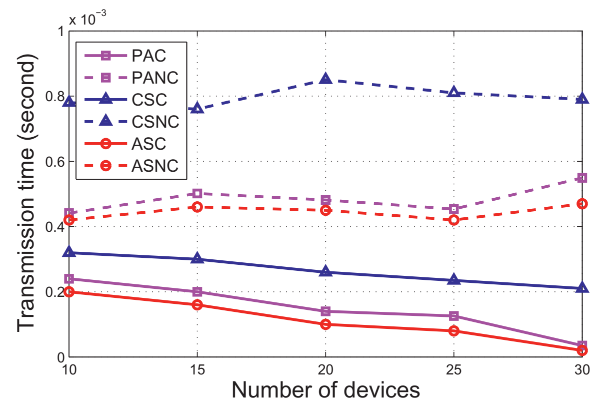


Fig. 4. Transmission time with different numbers of DEVs in Scenario I.

schemes are attained at moderate beamwidths. For example, cooperative transmission scheme is 10 times better with 45° beam as compared to non-cooperative scheme.

In Fig. 4, the effect of different numbers of DEVs on transmission time is shown. The antenna beamwidth is set as 30°. 4 flows are initialized and amount of data per flow is set as 0.5 Mbits. Generally, cooperative schemes provide shorter transmission time as compared to the corresponding non-cooperative schemes. For CSC, ASC and PAC, the transmission time decreases with number of DEVs. This result is as expected because WPANs have better cooperation choices with more relay DEVs. Moreover, we observe that the transmission time fluctuates for the non-cooperative schemes. This demonstrates that number of DEVs does not have an obvious effect on throughput for non-cooperative transmission. The reason is that additional idle DEVs do not bring benefit to the direct transmissions.

In Fig. 5, the effect of different numbers of flows on transmission time is shown. 20 DEVs are randomly deployed. The antenna beamwidth is set as 30° and amount of data per flow is set as 0.5 Mbits. Our first observation is that transmission time increases for larger number of flows for all cases. Then, we see that cooperative transmission schemes provides shorter transmission time as compared to their counterparts. The figure also shows that the difference of transmission time between cooperative and non-cooperative schemes becomes larger as the number of flows increases. That indicates that the network capacity is improved by using cooperative transmission schemes.

In Fig. 6, the effect of different amounts of data per flow is shown. 20 DEVs are randomly deployed. The antenna beamwidth is set as 30°. 4 flows are initialized in the studied WPAN. It is observed that the transmission time for each line increases almost

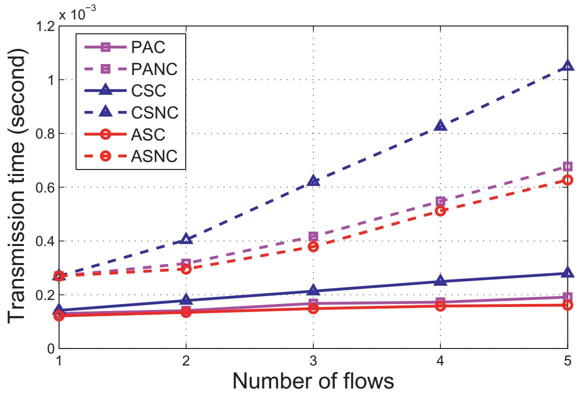


Fig. 5. Transmission time with different numbers of flows in Scenario I.

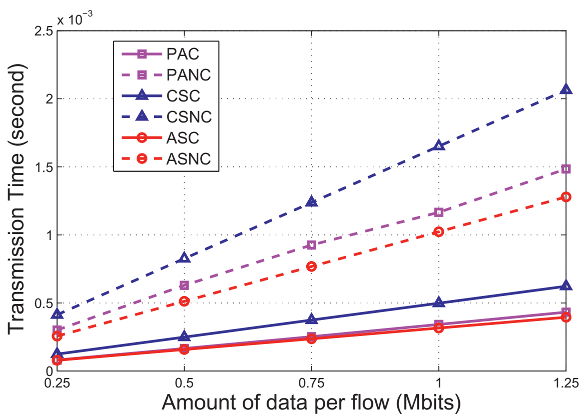


Fig. 6. Transmission time with different amounts of data per flow in Scenario I.

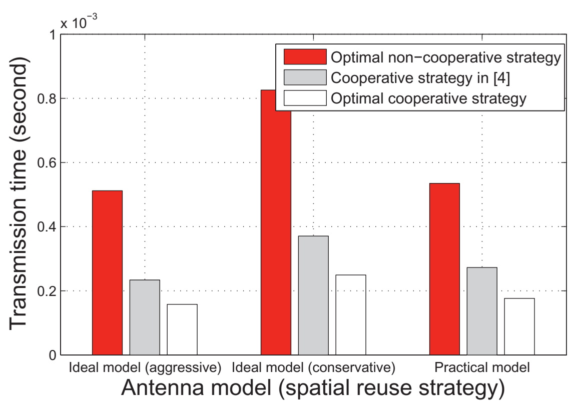


Fig. 7. Comparison among non-cooperative algorithm, cooperative algorithm in [4], and optimal cooperative algorithm in Scenario I.

linearly with amount of data per flow. Since the best routes for given flows are fixed in the corresponding WPAN, the end-to-end data rates for these flows are also fixed. Thus, transmission time increases linearly with amount of data per flow. For transmitting the same amount of data, ASC needs the shortest time. PAC can achieve almost the same performance as ASC, which means minor-lobe of the used antenna model is not strong.

In Fig. 7, we compare different cooperative schemes with different antenna models. 20 DEVs are randomly deployed and antenna beamwidth is set as 30°. 4 flows are initialized and amount of data per flow is set as 0.5 Mbits. The throughput under the practical antenna model is close to the throughput under the ideal antenna model with aggressive strategy. The reason is that the

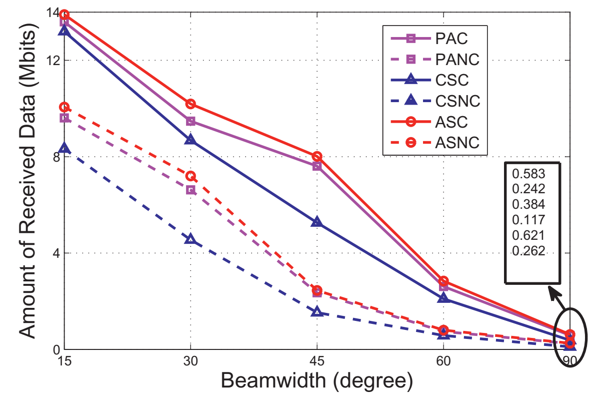


Fig. 8. Amount of received data with different antenna beamwidths in Scenario II. (The sequence of the numbers in the text boxes is consistent with that in the legend.).

side-lobe gain of the realistic antenna model used in this work is low as shown in (1). If an antenna with larger side-lobe gain is used, throughput will be closer to that using conservative strategy with ideal antenna. Moreover, the cooperative strategy in [4] requires more time to transmit the same amount of data as compared to the method described in this work. This is due to the reason that the scheme used in [4] is limited to two-hop device cooperation, and furthermore, the link scheduling and relay assignment are treated as independent problems.

6.3. Performance analysis of Scenario II

In Scenario II, the length of DTP is fixed at 1 micro-second in the simulations. We maximize the throughput of WPAN via maximizing the amount of received data for given demands. Effects from four aspects are discussed, namely, antenna beamwidth, number of DEVs, number of flows and data demand per flow. Again, the scheduling schemes in this work are compared with [4].

In Fig. 8, the effect of different beamwidths is shown. 20 DEVs are randomly deployed. 4 flows are transmitted and amount of data per flow is set as 4 Mbits. It is observed that the amount of data received is larger when cooperative transmission is used as compared to the case when non-cooperative transmission is used. The throughput gain between the cooperative and non-cooperative scheme is in the range 1.5 to 3. The largest gain is attained when the antenna beamwidth is 45°. For narrow beams, the need for node cooperation is low due to the good quality of direct links. For wide beams, cooperative transmission is less effective due to low spatial reuse ability.

In Fig. 9, the effect of different number of DEVs is shown. The antenna beamwidth is set as 30°. 4 flows are initialized and amount of data per flow is set as 4 Mbits. For cooperative scheme, the amount of data received increases with the number of DEVs. The throughput gain between 30 and 10 DEVs is about 1.2 in CSC. Moreover, we observe that number of DEVs has a limited effect on the amount of data received in WPAN with non-cooperative transmission.

In Fig. 10, the effect of different numbers of flows is shown. 20 DEVs are randomly deployed. The antenna beamwidth is set as 30°. Amount of data per flow is set as 4 Mbits. It is clear that the amount of received data increases with number of flows. It is also observed that the gradients for all the lines decrease with number of flows. This is because that the WPAN is saturate. Moreover, it is observed that the cooperative transmission generally provides 50% larger throughput than the non-cooperative transmission.

In Fig. 11, the effect of different amounts of data per flow is shown. 20 DEVs are randomly deployed and the antenna

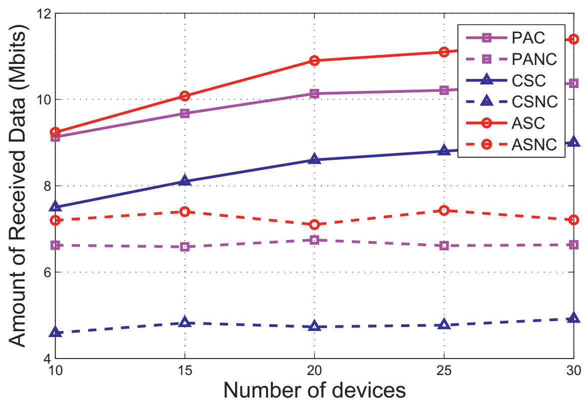


Fig. 9. Amount of received data with different numbers of DEVs in Scenario II.

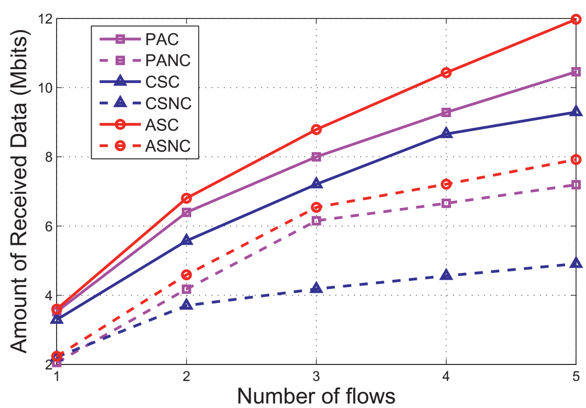


Fig. 10. Amount of received data with different numbers of flows in Scenario II.

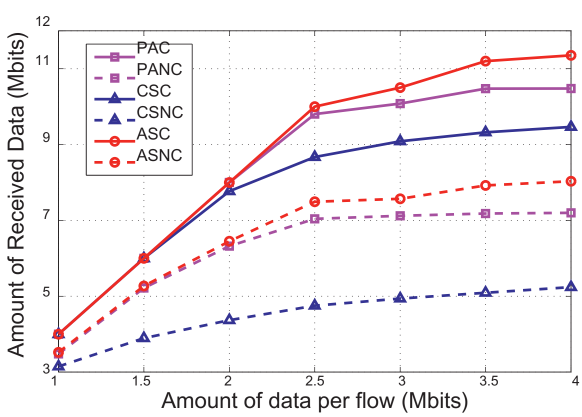


Fig. 11. Amount of received data with different data demand per flow in Scenario II.

beamwidth is set as 30°. 4 flows are initialized. The overall amount of received data increase with demand, and the gradients of the lines decrease during this process. For all cases, the throughput gain is around 1.5 or 2 times between cooperative and non-cooperative schemes. When the amount of data per flow equals 4 Mbits, PAC, CSC and ASC received about 40% to 80% more data as compared to the non-cooperative schemes.

In Fig. 12, we compare various cooperative schemes with different antenna models. 20 DEVs are randomly deployed and the antenna beamwidth is set as 30°. 4 flows are initialized and amount of data per flow is set as 4 Mbits. Since there is no other work discussing bursty data demand, the scheme in [4] is simply extended

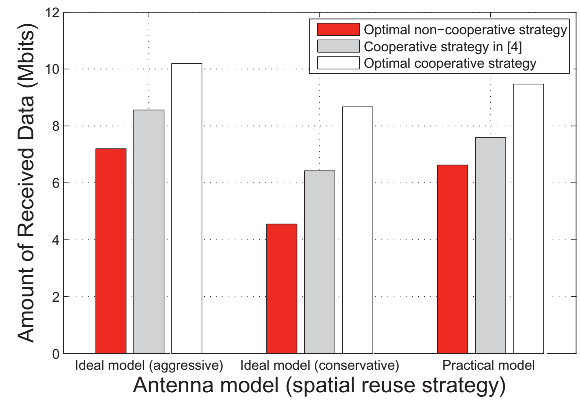


Fig. 12. Comparison among non-cooperative algorithm, cooperative algorithm in [4], and optimal cooperative algorithm in Scenario II.

to comprise bursty demand and used as a benchmark. As in [4], a relay is selected within feasible region for a direct link, when LOS path is blocked. The throughput of the benchmark is in the middle of the throughput with non-cooperative and cooperative schemes proposed in this work. For the three spatial reuse strategies in the figure, the cooperative scheme in this work transmits 21%, 34% and 27% more data than the benchmark. This shows that the scheme proposed in this work provides better cooperative service.

6.4. Observations

First, cooperative schemes generally outperform the non-cooperative ones. We observe that the throughput gain between the cooperative scheme and the non-cooperative scheme in Scenario I is larger than that in Scenario II. The reason is as follows. In Scenario I, all data has to be received, thus the transmission time is mainly determined by the worst flow. It is clear that cooperative transmission may be more helpful for the worst flow. In Scenario II, not all data needs to be received. To maximize the amount of received data, both cooperative and non-cooperative schemes schedule the best flow first. For the flows with best throughput, the difference in end-to-end data rates between cooperative and non-cooperative schemes may not be that large. This is the reason why the throughput gain is around 10 in Scenario I, while it is usually less than 2 in Scenario II. Second, we observe that the performance of PAC is within 10% lower than ASC, which means that the minor-lobe effect is not very strong. Third, we observe that the performance of PAC can be 20% better than that of CSC, which shows the tradeoff between perfect and imperfect information. Fourth, column generation method can reduce computation time from hour to minute level, but it is still too long to implement in real system. Therefore, heuristic algorithms with cooperation which can provide real-time scheduling are needed, and the optimal methods proposed here can provide the guideline to the design of heuristic algorithms.

7. Conclusion

In this work, we propose the use of cooperative transmission to improve the throughput of directional 60 GHz WPANs. Both achievable and bursty data demand scenarios are studied. Throughput maximization is formulated as linear programming problem and solved by the column generation method. Performance analysis is performed based on simulations considering different antenna models and spatial reuse strategies. The minor-lobe effect and performance gap due to imperfect information are investigated under different network settings. We also compare the proposed optimal cooperative scheme with an extension of the protocol used in [4], which presents around 20% to 45% higher throughput. In summary, the proposed cooperative transmission scheme can significantly improve the throughput of 60 GHz WPANs.

References

[1] Y. Wang, X. Kang, H.K. Garg, M. Motani, Q. Chen, Throughput maximization for 60 GHz WPANs via device cooperation, IEEE Commun. Lett. 18 (5) (2014) 785–788.

[2] Agilent Technologies, Wireless LAN at 60 GHz - IEEE 802.11ad explained, Available: http://cp.literature.agilent.com/litweb/pdf/5990-9697EN.pdf.

[3] L. Yang, 60 GHZ: opportunity for gigabit WPAN and WLAN convergence, Proc. ACM SIGCOMM Comput. Commun. Rev. 39 (1) (2009) 56–61.

[4] J. Qiao, B. Cao, X. Zhang, X. Shen, J.W. Mark, Efficient concurrent transmission scheduling for cooperative millimeter wave systems, in: Proc. IEEE Global Telecomm. Conf. (GLOBECOM), Anaheim, USA, 2012, pp. 4187–4192.

[5] IBM, IBM ILOG CPLEX optimizer. Available: http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer

[6] Q. Chen, X. Peng, J. Yang, F. Chin, Spatial reuse strategy in mmwave WPANs with directional antenna, in: Proc. IEEE Global Telecomm. Conf. (GLOBECOM), Anaheim, USA, 2012, pp. 5392–5397.

[7] R.C. Daniels, J.N. Murdock, T.S. Rappaport, R.W. Heath, 60 GHZ wireless: up close and personal, IEEE Microw. Mag. 11 (7) (2010) 44–50.

[8] M. Park, P. Gopalakrishnan, R. Roberts, Interference mitigation techniques in 60 GHz wireless networks, IEEE Commun. Mag. 47 (12) (2009) 34–40.

[9] S. Singh, R. Mudumbai, U. Madhow, Interference analysis for highly directional 60-GHz mesh networks: the case for rethinking medium access control, IEEE/ACM Trans. Netw. 19 (5) (2011) 1513–1527.

[10] R. Mudumbai, S. Singh, U. Madhow, Medium access control for 60 GHz outdoor mesh networks with highly directional links, in: Proc. IEEE INFOCOM 2009 Mini Conf., Rio de Janeiro, Brazil, 2009.

[11] S. Singh, R. Mudumbai, U. Madhow, Distributed coordination with deaf neighbors: efficient medium access for 60 GHz mesh networks, in: Proc. IEEE Int. Conf. Computer Commun. (INFOCOM), San Diego, USA, 2010, pp. 1–9.

[12] I. Son, S. Mao, M. Gong, Y. Li, On frame-based scheduling for directional mmwave WPANs, in: Proc. IEEE Int. Conf. Computer Commun. (INFOCOM), Orlando, USA, 2012, pp. 2149–2157.

[13] S. Jin, M. Choi, K. Kim, S. Choi, Opportunistic spatial reuse in IEEE 802.15.3c wireless personal area networks, IEEE Trans. Veh. Technol. 62 (2) (2013) 824–834.

[14] Z. Yang, L. Cai, W. Lu, Practical scheduling algorithms for concurrent transmissions in rate-adaptive wireless networks, in: Proc. IEEE Int. Conf. Computer Commun. (INFOCOM), San Diego, USA, 2010, pp. 1–9.

[15] L.X. Cai, L. Cai, X. Shen, J. Mark, REX: a random exclusive region based scheduling scheme for mmwave WPANs with directional antenna, IEEE Trans. Wireless Commun. 9 (1) (2010) 113–121.

[16] J. Zhang, H. Wu, Q. Zhang, B. Li, Joint routing and scheduling in multi-radio multi-channel multi-hop wireless networks, in: Proc. IEEE Int. Conf. Broadband Netw. (BROADNETS), Boston, USA, 2005, pp. 631–640.

[17] C. Yu, X. Cao, X. Shen, D. Shila, H. Li, A systematic study of the delayed column generation method for optimizing wireless networks, in: Proc. ACM Int. Symp. Mobile Ad Hoc Networking and Computing (MOBIHOC), Philadelphia, USA, 2014, pp. 23–32.

[18] A. Capone, I. Filippini, F. Martignon, Joint routing and scheduling optimization in wireless mesh networks with directional antennas, in: Proc. IEEE Int. Conf. Commun. (ICC), Beijing, China, 2008, pp. 2951–2957.

[19] A. Capone, G. Carello, I. Filippini, S. Gualandi, F. Malucelli, Routing, scheduling and channel assignment in wireless mesh networks: optimization models and algorithms, Elsevier Ad Hoc Networks 8 (6) (2010) 545–563.

[20] C. Hong, A. Pang, 3-Approximation algorithm for joint routing and link scheduling in wireless relay networks, IEEE Trans. Wireless Commun. 8 (2) (2009) 856–861.

[21] Z. Yang, Q. Zhang, Z. Niu, Throughput improvement by joint relay selection and link scheduling in relay-assisted cellular networks, IEEE Trans. Veh. Technol. 61 (6) (2012) 2824–2835.

[22] S. Singh, F. Ziliotto, U. Madhow, E.M. Belding, M. Rodwell, Blockage and directivity in 60 GHz wireless personal area networks: from cross-layer model to multihop MAC design, IEEE J. Sel. Areas Commun. 27 (8) (2009) 1400–1413.

[23] Z. Genc, G. Olcer, E. Onur, I. Niemegeers, Improving 60 GHz indoor connectivity with relaying, in: Proc. IEEE Int. Conf. Commun. (ICC), Cape Town, South Africa, 2010, pp. 1–6.

[24] Z. Lan, C. Sum, J. Wang, T. Baykas, F. Kojima, H. Nakase, H. Harada, Relay with deflection routing for effective throughput improvement in gbps millimeter-wave WPAN systems, IEEE J. Sel. Areas Commun. 27 (8) (2009) 1453–1465.

[25] Z. Lan, J. Wang, J. Gao, C. Sum, F. Kojima, T. Baykas, H. Harada, S. Kato, Directional relay with spatial time slot scheduling for mmwave WPAN systems, in: Proc. IEEE Veh. Technol. Conf. (VTC), Taipei, China, 2010, pp. 1–5.

[26] Z. Lan, L. Lu, X. Zhang, C. Pyo, H. Harada, A space-time scheduling assisted cooperative relay for mmwave WLAN/WPAN systems with directional antenna, in: Proc. IEEE Global Telecomm. Conf. (GLOBECOM), Houston, USA, 2011, pp. 1–6.

[27] J. Qiao, L. Cai, X. Shen, J. Mark, Enabling multi-hop concurrent transmissions in 60 GHz wireless personal area networks, IEEE Trans. Wireless Commun. 10 (11) (2011) 3824–3833.

[28] J. Qiao, L. Cai, X. Shen, J. Mark, STDMA-based scheduling algorithm for concurrent transmissions in directional millimeter wave networks, in: Proc. IEEE Int. Conf. Commun. (ICC), Ottawa, Canada, 2012, pp. 5221–5225.

[29] Q. Chen, J. Tang, D. Wong, X. Peng, Y. Zhang, Directional cooperative MAC protocol design and performance analysis for IEEE 802.11ad WLANs, IEEE Trans. Veh. Technol. 62 (6) (2013) 2667–2677.

[30] P. Dutta, V. Mhatre, D. Panigrahi, R. Rastogi, Joint routing and scheduling in multi-hop wireless networks with directional antennas, in: Proc. IEEE Int. Conf. Computer Commun. (INFOCOM), San Diego, USA, 2010, pp. 1–5.

[31] H. Su, X. Zhang, Joint link scheduling and routing for directional-antenna based 60 GHz wireless mesh networks, in: Proc. IEEE Global Telecomm. Conf. (GLOBECOM), Honolulu, USA, 2009, pp. 1–6.

[32] G. Desaulniers, J. Desrosiers, M. Soloman, Column generation, Springer, New York, 2005.

[33] Enhancements for Very High Throughput in the 60 GHz Band, 2012. IEEE Std 802.11ad-2012.

[34] N. Woongsoo, P. Laihyuk, C. Sungrae, Deafness-aware MAC protocol for directional antennas in wireless ad hoc networks, Elsevier J. Ad hoc Networks 24 (2015) 121–134.

Yu Wang got the Ph.D. degree in electrical and computer engineering in National University of Singapore. His research interests are link scheduling in the cellular networks and medium access control protocol design for ad hoc networks.

Mehul Motani received the BE degree from Cooper Union, New York, the MS degree from Syracuse University, New York, and the Ph.D. degree from Cornell University, Ithaca, New York, all in electrical and computer engineering. He is currently an associate professor in the Electrical and Computer Engineering Department at the National University of Singapore.

Hari Krishna Garg received the B.Tech. degree from the Indian Institute of Technology (IIT), Delhi, M.Eng. and Ph.D. degrees from Concordia University, Montreal, PQ, Canada, and the MBA degree from Syracuse University, Syracuse, NY, USA. He has been a faculty member of the Electrical and Computer Engineering Department at Syracuse University. Currently, he is with the Electrical and Computer Engineering Department at the National University of Singapore.

Xin Kang received his B.Eng. degree in Electrical Engineering from Xi'an Jiaotong University, China, in 2005. He received his Ph.D. degree in the Electrical and Computer Engineering from National University of Singapore, Singapore, in 2011. He was a research scientist at Institute for Infocomm Research (I2R), A∗STAR, Singapore, from 2011 to 2014. At the end of 2014, he joined Shield Lab, Huawei Singapore as a senior researcher. From July 2016, he has joined University of Electronic Science and Technology of China as a Full Professor. His research interests include physical layer security, network security, heterogeneous network, energy harvesting, cognitive radio, network optimization, game theory, information theory, and 5G communication and security issues.

Qian Chen received the B.Eng. and M.Eng. degrees in computer science and engineering from Xi'an Jiao Tong University, Xi'an, China, in 2003 and 2006, respectively, and the Ph.D. degree from the National University of Singapore, Singapore, in 2011. He is a Scientist with the Institute for Infocomm Research, ASTAR, Singapore.