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Abstract

With the increasing quality of service (QoS) demands for indoor multimedia applications, millimeter wave (mmWave) communications are emerging as a promising candidate for the wireless personal area networks (WPANs). On the one hand, it has the advantage of providing several-Gbps transmission rate. However, due to the unique characteristics in 60-GHz frequency band, such as high propagation loss, beamforming is fully exploited for mmWave links to achieve directional transmission and reception. In this paper, we propose a novel QoS aware scheduling algorithm for concurrent transmission in mmWave WPANs based on coalition game. First, we formulate the problem of concurrent transmission scheduling into a non-convex integer programming problem. Then, we propose a coalition game based algorithm to maximize the number of flows satisfying the corresponding QoS requirements, while improving the network resource utilization effectively. Besides, our proposed algorithm converges to a Nash-stable equilibrium with greatly reduced complexity. Through extensive simulations under various system parameters, we demonstrate our scheme achieves better network performance in terms of the throughput and the number of flows scheduled successfully, compared with existed protocols.

Using Coalition Games for QoS Aware Scheduling in mmWave WPANs

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***Abstract*—With the increasing quality of service (QoS) demands for indoor multimedia applications, millimeter wave (mmWave) communications are emerging as a promising candidate for the wireless personal area networks (WPANs). On the one hand, it has the advantage of providing several-Gbps transmission rate. However, due to the unique characteristics in 60-GHz frequency band, such as high propagation loss, beamforming is fully exploited for mmWave links to achieve directional transmission and reception. In this paper, we propose a novel QoS aware scheduling algorithm for concurrent transmission in mmWave WPANs based on coalition game. First, we formulate the problem of concurrent transmission scheduling into a non-convex integer programming problem. Then, we propose a coalition game based algorithm to maximize the number of flows satisfying the corresponding QoS requirements, while improving the network resource utilization effectively. Besides, our proposed algorithm converges to a Nash-stable equilibrium with greatly reduced complexity. Through extensive simulations under various system parameters, we demonstrate our scheme achieves better network performance in terms of the throughput and the number of flows scheduled successfully, compared with existed protocols.**

I. Introduction

With the increasing bandwidth-intensive multimedia applications, such as uncompressed high definition TV, bulk file transfer, and so on, millimeter wave (mmWave) communications have attracted considerable attention from both academia and industry. On the one hand, it can provide data rate in multi-gigabit-per-second based on large available bandwidth. There are already several standards defined for indoor wireless personal area networks (WPANs) or wireless local area networks (WLANs) in the mmWave band, such as ECMA-387 [1], IEEE 802.15.3c [2], and IEEE 802.11ad [3]. On the other hand, given the fact that propagation loss in the free space is proportional to the square of carrier frequency, the attenuation of mmWave links is more severe, especially in the case of non-line-of-sight (NLOS) transmission. Hence, mmWave communications require line-of-sight (LOS) transmission [4]. In order to compensate for the path loss, mmWave links are equipped with directional high-gain antennas at both the transmitter and the receiver. At the same time, beamforming technique is also utilized [5]. Additionally, the mmWave network is suitable for indoor scenarios, and the range of the WPANs is generally within 10 meters. On account of the short distance of mmWave links, the density of nodes in WPANs will be quite high, which results in complicated interference [6]. Thus, it is necessary to maximize transmission efficiency and utilize network resource effectively. In the traditional serial time division multiple access (TDMA), it should be note that if a single flow is arranged to one time slot without interference, network resources can be greatly wasted. To make efficient use of the mmWave spectrum resource, we have the motivation to exploit spatial reuse and enable multiple flows to be scheduled for concurrent transmission. Fortunately, the directional transmission has a great potential for spatial reuse.

Concurrent transmission scheduling can improve the network performance in terms of total network throughput and spectrum efficiency. Meanwhile, there has been several related works investigating the problem of concurrent transmission scheduling in mmWave networks. Qiao *et al.* [7] proposed cooperative concurrent transmission scheduling to tackle the problem of LOS link blockage in order to realize high-rate reliable transmission. Cheng *et al.* [8] proposed a rate-adaptive concurrent transmission scheduling algorithm to maximize throughput with fairness considered. Xu *et al.* [9] proposed a novel link scheduling strategy. Specifically, it calculated the signal to interference plus noise ratio (SINR) based on the beamforming feedback information, and then scheduled for concurrent transmission according to the proposed SINR-based link coexistence criterion. In [10], the authors exploit spatial-time division multiple access (STDMA) and propose a heuristic scheduling algorithm to improve the resource utilization efficiency. Niu *et al.* [4] proposed a multi-path multi-hop (MPMH) scheduling scheme.

Coalition game, which is widely used in resource allocation, interference management and power control for device-to-device (D2D) communications underlaying cellular networks in previous work. In [11], a new stackelberg game based scheme is proposed to allow both interfering and non-interfering D2D links to transmit concurrently. Motivated by this, we try to tackle with the scheduling problem from the perspective of game theory. In this paper, we consider a QoS aware scheduling algorithm for concurrent transmission in mmWave WPANs on the basis of coalition game.

The main contributions of this paper are three-fold. First, we formulate the optimization problem of concurrent transmission scheduling into a non-convex integer programming problem, which aims to maximize the number of flows satisfied the corresponding QoS demand. Second, a coalition game based QoS aware scheduling algorithm with decent performance is proposed to exploit the spatial reuse and improve the transmission efficiency. Finally, extensive simulations under different parameters are conducted to demonstrate the superior performance of our proposed scheme.

The rest of the paper is organized as follows. In Section II, we describe the system model and explain the formulated optimization problem in detail. The coalition game based scheduling algorithm is presented in Section III. Section IV shows the simulation results and evaluates the performance compared with existing schemes. Finally, we make an conclusion about this paper in Section V.

II. System Model and Problem Formulation

A. System Model

We consider a scenario of the indoor IEEE 802.15.3c W-PAN, which is composed of a single piconet controller (PNC) distributed in the center and multiple wireless nodes (WNs) under PNC's coverage. Two nodes form a communication flow. In addition to provide basic network synchronization, the PNC also performs functions, such as admission control and network resource allocation, based on pre-defined minimum traffic demands of all flows. Network controller and wireless nodes are equipped with electronically steerable directional antennas, which can achieve directional transmission and reception between nodes in mmWave band. In our investigated system, the total channel time is divided into periodic superframes. As shown in Fig. 1, each superframe is composed of three phases [12]. They are the beacon period (BP), the contention access period (CAP) and the channel time allocation period (CTAP), respectively. In BP phase, the PNC broadcasts management information and the slot allocation scheme to the entire mmWave network. During the CAP period, the wireless nodes will proceed the association process with PNC, at the same time, the nodes transmitting data signals will send a channel time allocation (CTA) request command to the PNC using the carrier sensing multiple access with collision avoidance (CSMA/CA) technology. Besides, the CTAP is consisted of M non-overlapping time slots of equal length, which is called CTA and used for data interaction between nodes. Unlike traditional time division multiple access (TDMA), we allow concurrent transmissions in each time slot in CTAP, which can increase the transmission throughput and utilize network resource efficiently.

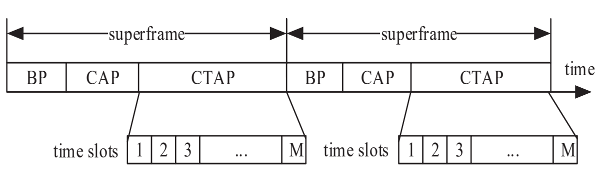

Fig. 1. MAC and superframe structures of IEEE 802.15.3c.

B. Problem Formulation

Due to the high carrier frequency, mmWave links suffer from large propagation loss. Thus, it is reasonable to consider the directional LOS transmission in order to achieve higher transmission rate and support the multimedia applications.

In our investigated system, we assume there are N flows that need to be transmitted in the superframe. Besides, we suppose the considered flows don't share the transceiver, that is to say, they have distinct transmitters and receivers. For each flow i, we denote its required minimum QoS demand as q_i. After the transmission requests from flows are obtained by PNC, the flows for concurrent transmission can be arranged to one CTA. Obviously, there exists multi-user interference. The CTAP of each superframe is composed of M CTAs. For the $k^{th}(1 \leq k \leq M)$ time slot of the CTAP, we define a binary variable a_i^k for flow i to represent whether the flow i is scheduled for concurrent transmission in the k^{th} time slot of CTAP period. If it is, $a_i^k = 1$; otherwise, $a_i^k = 0$. In view of the fact that each flow can be scheduled for no more than M time slots, thus, we have the constraint $\sum\limits_{k=1}^{M} a_i^k \leq M, \forall i$. On the other hand, for flow i, we denote its transmitter and receiver by s_i and r_i, respectively. According to the Friis free-space transmission equation, we can obtain the expression of the received power at r_i from s_i in the k^{th} time slot as

$$P_r^k(i,i) = a_i^k k_0 G_t(i,i) G_r(i,i) l_{ii}^{-n} P_t, \tag{1}$$

where k_0 is a constant coefficient and proportional to $\left(\frac{\lambda}{4\pi}\right)^2$ (λ is the wavelength), l_{ii} is the transmission distance between s_i and r_i, n is the path-loss exponent and it usually takes value from 2 to 6 for indoor environment, and P_t is the transmitted power of flows [13]. For analytical tractability, we assume the mmWave transmission power P_t of each flow is a constant during the superframe. Besides, we denote the transmitter antenna gain of s_i as $G_t(i,i)$ and the receiver antenna gain of r_i is denoted by $G_r(i,i)$.

In mmWave networks, there must exist interference between two mutually independent flows i and j [16], the received interference at r_i from s_j in the k^{th} time slot can be expressed as

$$P_r^k(j,i) = a_j^k \rho k_0 G_t(j,i) G_r(j,i) l_{ji}^{-n} P_t, \tag{2}$$

where ρ denotes the multi-user interference (MUI) factor related to the cross correlation of signals from different flows.

According to Shannon's channel capacity, the channel rate of the flow i is determined by its signal to interference and noise ratio (SINR). The MUI at the receiver of flow i is from other active transmitters in the same time slot, which can be calculated as

$$P_{int,i}^k = \rho \sum_{j \neq i} a_j^k k_0 G_t(j,i) G_r(j,i) l_{ji}^{-n} P_t. \tag{3}$$

In each time slot, different sets of active flows can generate different MUI.

Thus, combining the received signal power, noise and interference, the received SINR at r_i in the k^{th} time slot can be expressed as

$$SINR_i^k = \frac{P_r^k(i,i)}{P_{int,i}^k + N_0 W}, \tag{4}$$

where N_0 is the one-sided power spectral density of white Gaussian noise, and W is the system bandwidth.

Therefore, the achievable data rate for the flow i in the k^{th} time slot, denoted by R_i^k, can be calculated as

$$R_i^k = (1 - P_{out:i,i}) W \log_2(1 + SINR_i^k), \tag{5}$$

where $P_{out:i,i}$ denotes the outage probability in the LOS path between the transmitter and the receiver of flow i. At the same time, the expression of the outage probability is $P_{out:i,i} = 1 - e^{-\beta l_{ii}}$, where l_{ii} is the distance between two terminal nodes of the flow i, and β is the system parameter, which is used to indicate the density and size of obstacles [14].

In order to exploit spatial reuse and maximize the resource utilization efficiency, we focus on the number of flows satisfied the corresponding QoS demand in the mmWave network. Then, we formulate the optimization problem of concurrent transmission scheduling underlaying WPAN as follows.

$$\max \sum_{i=1}^{N} I_i$$
$$s.t. \begin{cases} a_i^k \in \{0,1\}, \ \forall i,k; \\ \sum_{k=1}^{M} a_i^k \le M, \ \forall i; \\ I_i = \begin{cases} 1, & \sum_{k=1}^{M} \frac{R_i^k \Delta}{T_{BP} + T_{CAP} + M\Delta} \ge q_i \\ 0, & \text{otherwise} \end{cases}, \ \forall i, \end{cases} \tag{6}$$

where T_{BP}, T_{CAP} and Δ are the time duration for beacon period, contention access period and one time slot in the CTAP period, respectively. A flow is considered to be scheduled successfully means that its minimum QoS requirement is satisfied. When the constraint is established, $I_i = 1$, otherwise, it is equal to zero.

Obviously, the optimization problem is a non-convex integer programming problem. The constraints involve a series of binary variables $a_i^k, \forall i, k$. When the network topology is determined, other variables are fixed. Removing the flows that can't satisfy the minimum QoS requirements within a superframe, we can calculate the transmission rates of the remaining active flows in current time slot with the MUI considered. On the other hand, the formulated optimization problem of concurrent transmission scheduling is NP-hard and it is complex. In the first time slot of the CTAP period, we tend to schedule the flows which make greater contributions to the system utility. To improve the fairness and the resource utilization efficiency of the system, we involve some flows with relatively lower transmission rates in the following time slots in order to satisfy their required QoS demand as much as possible. However, we still require the total utility of the active flows set to be in a relatively high state. In general, our optimization problem aims to maximize the total throughput and the number of flows scheduled successfully.

III. Coalitional Game Algorithm

In this section, we devise a coalition game algorithm from the view point of game theory to solve the formulated concurrent transmission scheduling problem.

In the coalition game, one key point is choosing which coalition to join for all flows. Thus, we need to carefully define the preference relation. Based on it, the flow can compare and order its potential coalition. For any flow i, the preference relation or order $\succ_i$ is defined as a complete, reflexive, and transitive binary relation over the set of all coalitions that flow i can possibly form. In other words, $F_c \succ_i F_{c'}$ represents the flow i prefers to be a member of the coalition F_c with $i \in F_c$ than $F_{c'}$ with $i \in F_{c'}$. In this paper, we define the preference inequality for all flows as follows [15].

$$F_c \succ_i F_{c'} \Longleftrightarrow R(F_c) > R(F_{c'}), \tag{7}$$

where $R(F_c)$ and $R(F_{c'})$ represent the utility of coalition F_c and $F_{c'}$, respectively. From the inequality, we can see the flow tends to join a coalition with higher utility.

The concurrent transmission scheduling using coalition game is summarized in Algorithm 1, where the flows make switch operation until the final Nash-stable partition is achieved. Additionally, based on the partition obtained by the coalition game, we can get the active flows in the first time slot of the CTAP period. In the algorithm, we first initialize the required minimum QoS q_i for each flow i. Then, we randomly divide all the flows into two coalitions. Initially, the system will choose one flow i. In addition to the current coalition F_c, another coalition $F_{c'}$ is still possible for the flow i to join. The network controller PNC has complete network topology information. Based on these information, it calculates the total transmission rate of both coalitions F_c and $F_{c'} \bigcup \{i\}$. In step 8, if the switch conditions are satisfied according to the preference relation defined in (7), the system will perform a switch operation. Obviously, our goal is to increase the maximum utility of the two coalitions. It is important to note that this is different from maximizing the utility of one of the coalitions. In order to achieve a better convergence and reduce the complexity of the algorithm, we involve the number of consecutive unsuccessful switch operations n. If the switch operation is completed, $n = 0$; otherwise, $n = n + 1$. The final Nash-stable point is reached until n is equal to the number of flows. In this case, the maximum utility of the two coalitions can not be substantially increased. Next, we define the coalition with higher total transmission rate as active and schedule it for concurrent transmission. Another coalition is non-active. From step 19 to step 23, we determine whether the remaining CTAs can satisfy the QoS demand of the flow. In the judgment process, we assume there is no interference from the other flows in the following time slots for flow i, and we denote the corresponding transmission rate as R_i. Then, if the traffic demand can't be satisfied during the superframe, we

Algorithm 1 Concurrent Transmission Scheduling for Flows using Coalition Game Algorithm

1: Given the required minimum QoS q_i of flow $i(i = 1, 2, ...N)$;
2: Given the partition of N flows as $F_{ini} = \{F_{c_1}, F_{c_2}\}$;
3: Set the current partition as $F_{ini} \longrightarrow F_{cur}$, $max = 0$, $sumthroughput = 0$, $number = 0$, $n = 0$;
4: **repeat**
5: Choose one flow i, and denote its current coalition as F_c and another coalition as $F_{c'}$;
6: $F_{c'} \bigcup \{i\} \longrightarrow F_{c''}$;
7: Calculate $R(F_c)$ and $R(F_{c''})$;
8: **if** The switch operation from F_c to $F_{c'}$ satisfying $\arg\max_F \{R(F_c), R(F_{c''})\} \succ_i F_c$ & $R(F) > max$ **then**
9: $max = R(F)$;
10: Update $(F_{cur} \backslash \{F_c, F_{c'}\}) \bigcup \{F_c \backslash \{i\}, F_{c'} \bigcup \{i\}\} \longrightarrow F_{cur}$;
11: $n = 0$;
12: **else**
13: $n = n + 1$;
14: **end if**
15: **until** The partition converges to the final Nash-stable partition F_{fin}.
16: Denote the coalition achieved the larger sum rate as F_c and another coalition as $F_{c'}$;
17: $k = 1$;
18: **while** $k \leq M$ **do**
19: **for** $i(i \in F_c)$ **do**
20: **if** $\frac{R_i^k \Delta + R_i(M-k)\Delta + \sum_{j=1}^{k-1} R_i^j \Delta}{T_{BP} + T_{CAP} + M\Delta} < q_i$ **then**
21: $F_c \backslash \{i\} \longrightarrow F_c$;
22: **end if**
23: **end for**
24: **for** $i(i \in F_c)$ **do**
25: Obtain the minimum required number of CTAs of flow i as $\theta_i = ceil\{\frac{q_i(T_{BP}+T_{CAP}+M\Delta) - \sum_{j=1}^{k-1} R_i^j \Delta}{R_i^k \Delta}\}$;
26: **end for**
27: Obtain $num = \min_{i \in F_c} \{\theta_i\}$;
28: **for** $i(i \in F_c)$ **do**
29: $sumthroughput = sumthroughput + \frac{R_i^k num \Delta}{T_{BP}+T_{CAP}+M\Delta}$;
30: **if** $\theta_i = num$ **then**
31: $F_c \backslash \{i\} \longrightarrow F_c$;
32: $number = number + 1$;
33: **end if**
34: **end for**
35: **for** $j(j \in F_{c'})$ **do**
36: **if** $R(F_c \bigcup j) > R(F_c)$ **then**
37: Update $(F_{fin} \backslash \{F_c, F_{c'}\}) \bigcup \{F_c \bigcup \{j\}, F_{c'} \backslash \{j\}\} \longrightarrow F_{fin}$;
38: **end if**
39: **end for**
40: $k = k + num$;
41: **end while**
42: Return $sumthroughput$ and $number$;

remove the flow. From step 24 to 27, we obtain the minimum number of CTAs needed to satisfy one flow's QoS demand. From step 28 to 34, we calculate the total throughput, while removing the flows satisfying the QoS demand. At the end of this iteration, we make the non-active flow in another coalition scheduled, based on it can increase the total transmission rate of the coalition for concurrent transmission. The algorithm continues to repeat the iterative process until all CTAs have been scheduled.

In this section, we also theoretically analyze the stability of the proposed coalition game based algorithm and further prove the Nash equilibrium reached is stable. First, we give an detailed definition of what is Nash-stable structure.

Definition 1: Nash-stable Structure: A coalitional partition $F = \{F_1, F_2, ..., F_c\}$ is considered to be Nash-stable, if $\forall i(1 \leq i \leq N), i \in F_c \subset F, F_c \succ_i F_{c'} \bigcup \{i\}$ for all $F_{c'} \subset F, F_{c'} \neq F_c$.

Then, we give a proof about the stability of the partition F_{fin} generated before the first round of QoS aware scheduling for concurrent transmission.

Proof: In our algorithm, the coalition game has the Nash-stable coalitional structure means that any flow can not make the utility of the coalition already obtained maximum total rate increased, no matter what strategy it adopts. We prove the stability by contradiction. On assumption of the final generated coalition partition F_{fin} is not Nash-stable. That is to say, there exists a flow $i(1 \leq i \leq N)$, and its current located coalition and another coalition are denoted by F_c and $F_{c'}$, respectively. Both coalitions meet the preference relation $F_{c'} \bigcup \{i\} \succ_i F_c$. Meanwhile, $R(F_{c'} \bigcup i) > max$. Consequently, the flow will perform the switch operation from coalition F_c to the new coalition $F_{c'}$, which leads to the update of F_{fin} and it is not the final partition. Thus, we complete the proof that the final partition F_{fin} of our proposed coalition game based scheduling algorithm is Nash-stable. ■

IV. Performance Evaluation

A. Simulation Setup

In the simulation, we consider a $10m \times 10m$ area in WPAN, where WNs are uniform randomly deployed in the square region with the PNC in the center. For analytical tractability, we set the source and destination of all flows before making a simulation, and all of them don't share common vertices. Besides, the minimum throughput requirement for each flow is uniformly distributed between a predetermined throughput interval from 0.5 to 1.5 Gbps. On the other hand, the widely used realistic directional antenna model is adopted in mmWave WPAN network, which is a main lobe of Gaussian form in linear scale and constant level of side lobes [16]. Based on this model, the gain of a directional antenna in units of decibel (dB), denoted by $G(\theta)$, can be expressed as

$$G(\theta) = \begin{cases} G_0 - 3.01 \cdot \left(\frac{2\theta}{\theta_{-3dB}}\right)^2, & 0^\circ \leq \theta \leq \theta_{ml}/2; \\ G_{sl}, & \theta_{ml}/2 \leq \theta \leq 180^\circ; \end{cases} \tag{8}$$

TABLE 1
SIMULATION PARAMETERS

Parameter	Symbol	Value
System bandwidth	W	2160 MHz
Noise spectral density	N_0	-134 dBm/MHz
Transmission power	P_t	20 dBm
Path loss exponent	n	2
MUI factor	ρ	1
Half-power beamwidth	θ_{-3dB}	30°
Blockage parameter	β	0.01
CTA duration	Δ	18 us
BP duration	T_{BP}	50 us
CAP duration	T_{CAP}	800 us

where θ denotes an arbitrary angle within the range $[0°, 180°]$, θ_{-3dB} denotes the angle of the half-power beam width, and θ_{ml} denotes the main lobe width in units of degrees. The relationship between θ_{ml} and θ_{-3dB} is $\theta_{ml} = 2.6 \cdot \theta_{-3dB}$. G_0 is the maximum antenna gain, and can be expressed as

$$G_0 = 10\log\left(\frac{1.6162}{\sin(\theta_{-3dB}/2)}\right)^2. \quad (9)$$

G_{sl} denotes the side lobe gain, which can be obtained by

$$G_{sl} = -0.4111 \cdot \ln(\theta_{-3dB}) - 10.579. \quad (10)$$

We show the simulation parameters in Table 1. In order to evaluate the performance of our proposed scheduling algorithm in term of throughout and the number of flows satisfied the corresponding QoS, we compare our scheme, labeled as Coalition Game (CG), with STDMA and TDMA. For STDMA, it allows interference and non-interference flows to transmit concurrently, and which is distinguished with the proposed CG algorithm is that, it doesn't attempt to select a coalition with higher utility before the first round of concurrent transmission. For the serial TDMA, it only assigns one flow for transmission in each slot.

B. Performance Evaluation

In Fig. 2, we set the number of flows to be 50. Then, we plot the network throughput comparison of three scheduling algorithms varying the number of time slots from 100 to 200. From the figure, we can see the proposed scheme can significantly increase the transmission throughput. The reason is that CG schedules flows with higher transmission rate as much as possible with fairness considered. When the number of time slots takes the value of 160, the network throughput of CG is larger than that of STDMA and TDMA about 5.9% and 46.8%, respectively. For CG and STDMA, the initial selection of flows for concurrent transmission is stochastic in each simulation, which results in irregular curve changes. For TDMA, more active flows are involved when the number of time slots is increased. Meanwhile, network throughput refers to the throughput of all active flows during the superframe, so it's increased.

In Fig. 3, we set the number of flows to be 50. Then, we plot the number of scheduled flows comparison of three scheduling algorithms varying the number of time slots from 100 to 200. From the figure, the CG achieves significantly

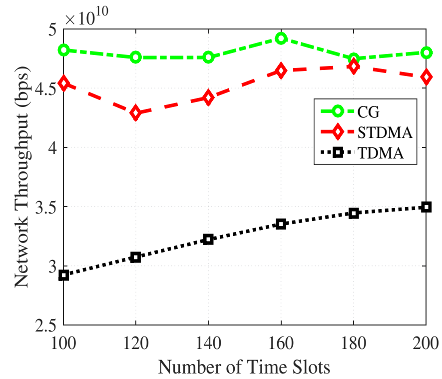

Fig. 2. Network throughput comparison of three scheduling algorithms with different number of time slots.

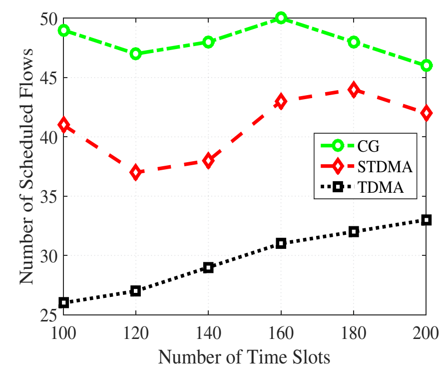

Fig. 3. Number of scheduled flows comparison of three scheduling algorithms with different number of time slots.

better performance than other schemes. The reason is that it schedules many flows with higher transmission rate, and it's generally less time-consuming to reach the minimum QoS demand for these flows. Thus, more flows will be involved with some flows removed. When the number of time slots takes the value of 160, the number of scheduled flows of CG is larger than that of STDMA and TDMA about 16.3% and 61.3%, respectively. The changes of CG and STDMA are still caused by the randomness of the algorithms. For TDMA, the flows have more network resource to utilize to satisfy the traffic demand with more time slots.

In Fig. 4, we set the number of time slots to be 200. Then, we plot the network throughput comparison of three scheduling algorithms varying the number of flows from 50 to 100. It is clear to see that the proposed CG scheme is superior to the other schemes. For the network throughput, the gap at the number of flows of 80 is only about 4% of the STDMA and about 113.8% of the TDMA, respectively. The increase in the number of flows makes the network topology, location information of WNs and minimum QoS requirements of all flows randomly generated changed.

In Fig. 5, we set the number of time slots to be 200. Then, we plot the number of scheduled flows comparison of three

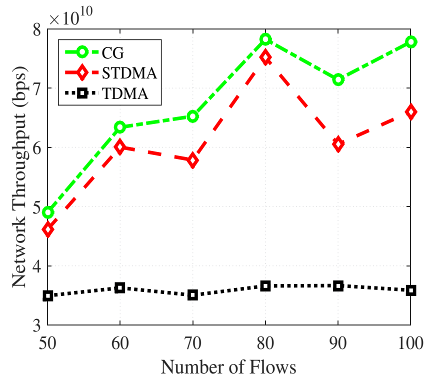

Fig. 4. Network throughput comparison of three scheduling algorithms with different number of flows.

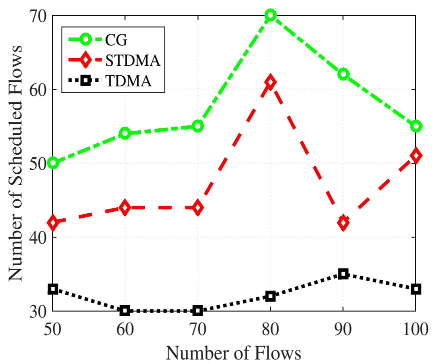

Fig. 5. Number of scheduled flows comparison of three scheduling algorithms with different number of flows.

scheduling algorithms varying the number of flows from 50 to 100. From the figure, we can observe CG outperforms STDMA and TDMA. For the number of scheduled flows, the gap at the number of flows of 80 is about 14.8% of the STDMA and about 118.8% of the TDMA, respectively.

V. Conclusion

In this paper, we investigate the problem of concurrent transmission scheduling in a directional multi-Gbps mmWave WPAN system. With the unique characteristics of mmWave communications considered, we propose a coalition game based QoS aware scheduling algorithm to accomplish the problem. Numerical results have shown that the proposed scheme performs better than STDMA and TDMA in terms of network throughput and the number of flows scheduled successfully. In general, the proposed scheme can increase network throughput and improve resource utilization efficiency, which can further maintain the QoS demand of numerous multimedia applications.

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References

[1] *High Rate 60 GHz PHY, MAC and HDMI PAL*, ECMC TC48, ECMA Std. 387, Dec. 2008.

[2] *IEEE 802.15 WPAN Millimeter Wave Alternative PHY Task Group 3c (TG3c)*. [Online]. Available: http://www.ieee802.org/15/pub/TG3c.html

[3] *Draft Standard for Information Technology—Telecommunications and Information Exchange Between Systems—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications— Amendment 4: Enhancements for Very High Throughput in the 60 GHz Band*, IEEE Std. P802.11ad/D9.0, Oct. 2012.

[4] Y. Niu, C. H. Gao, Y. Li, D. P. Jin, L. Su, and D. P. Wu, "Boosting Spatial Reuse via Multiple-Path Multihop Scheduling for Directional mmWave WPANs," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 8, pp. 6614–6627, Aug. 2016.

[5] B. Ai, K. Guan, R. S. He, J. Z. Li, G. K. Li, D. P. He, Z. D. Zhong, and K. M. S. Huq, "On indoor millimeter wave massive mimo channels: Measurement and simulation," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 7, pp. 1678–1690, Jul. 2017.

[6] W. U. Rehman, T. Salam, and X. F. Tao, "Vertex multi-coloring scheduling algorithm for concurrent transmission in 60-GHz networks," in *IEEE Global Communications Conference (GLOBECOM)*, Austin, TX, Dec. 8–12, 2014, pp. 4751–4757.

[7] J. Qiao, B. Cao, X. X. Zhang, X. M. Shen, and J. W. Mark, "Efficient concurrent transmission scheduling for cooperative millimeter wave systems," in *IEEE Global Communications Conference (GLOBECOM)*, Anaheim, CA, Dec. 3–7, 2012, pp. 4187–4192.

[8] M. X. Cheng, Q. M. Ye, and L. Cai, "Rate-Adaptive Concurrent Transmission Scheduling Schemes for WPANs With Directional Antennas," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 9, pp. 4113–4123, Sep. 2015.

[9] P. P. Xu, and H. Y. Chu, "A novel link scheduling strategy for concurrent transmission in mmWave WPANs based on beamforming information," in *IEEE Wireless Communications and Networking Conference (WCNC)*, Istanbul, Turkey, Apr. 6–9, 2014, pp. 1709–1714.

[10] J. Qiao, L. X. Cai, X. M. Shen, and J. W. Mark, "STDMA-based scheduling algorithm for concurrent transmissions in directional millimeter wave networks," in *IEEE International Conference on Communications (ICC)*, Ottawa, ON, Canada, Jun. 10–15, 2012, pp. 5221–5225.

[11] Y. Li, Z. F. Zhang, W. Wang, and H. G. Wang, "Concurrent transmission based stackelberg game for D2D communications in mmWave networks," in *IEEE International Conference on Communications (ICC)*, Paris, France, May. 21–25, 2017, pp. 1–6.

[12] Z. J. Yan, B. Li, X. Y. Zuo, and M. Yang, "A heuristic clique based STDMA scheduling algorithm for spatial concurrent transmission in mmWave networks," in *IEEE Wireless Communications and Networking Conference (WCNC)*, New Orleans, LA, Mar. 9–12, 2015, pp. 1036–1041.

[13] L. X. Cai, L. Cai, X. Shen, and J. W. Mark, "Rex: a randomized exclusive region based scheduling scheme for mmwave wpans withdirectional antenna," *IEEE Transactions on Wireless Communications*, vol. 9, no. 1, pp. 113–121, Jan. 2010.

[14] I. H. Lee and H. Jung, "Connectivity analysis of millimeter-wave device-to-device networks with blockage," *International Journal of Antennas and Propagation*, Oct. 2016.

[15] W. Saad, Z. Han, and A. Hjorungnes, *Coalitional Games for Cooperative Cellular Wireless Networks*. Cambridge, U.K.: Cambridge Univ. Press, 2011.

[16] Y. Niu, C. Gao, Y. Li, L. Su, D. Jin, Y. Zhu, and D. O. Wu, "Energy-efficient scheduling for mmwave backhauling of small cells in heterogeneous cellular networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 3, pp. 2674–2687, Mar. 2017.