Efficient Concurrent Transmission Scheduling for Cooperative Millimeter Wave Systems*

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***Abstract*—Millimeter-wave (mmWave) communications is a promising technology to provide high data rates (multiGigabit) for indoor multimedia applications. However, indoor mmWave links are highly susceptible to blockage because of the limited ability to diffract around obstacles such as the human body and furniture. In order to realize high-rate reliable transmission, cooperative communication is utilized to tackle with the scenarios where LOS link of source node and destination node is blocked. Specifically, with directional antenna, we first select the node in the feasible region with best achievable rate of cooperative communication as the cooperative relay. Then, cooperative concurrent transmission scheduling is formulated as an optimization problem to maximize the transmission efficiency. A flip-based heuristic scheduling algorithm is proposed to obtain the real-time solution. Extensive simulations demonstrate that the proposed cooperative concurrent transmission scheduling (CCTS) scheme can significantly increase the transmission throughput and utilize network resource efficiently while maintaining network connectivity.**

I. INTRODUCTION

Millimeter-wave (mmWave) communications attracts more and more attention for short-range indoor applications of wireless personal area networks (WPANs) [1], [2] and wireless local area networks (WLANs) [3], [4]. The large available bandwidth at mmWave bands (7 GHz spectrum between 57 GHz and 64 GHz approved by the Federal Communications Commission (FCC)), coupled with the recent progress in inexpensive and low power 60 GHz transceiver components design [5], enables wireless connections to support high-speed wireless multimedia services such as uncompressed high-definition TV (HDTV) and high speed downloading service, requiring multiple Gbps transmission rate. The ultimate purpose of indoor mmWave system is to deliver reliable medium access control (MAC) throughput in the order of multi-Gbps per flow over a reasonable range. To accomplish this, cooperative relays play a significant role in keeping network connectivity and improving flow throughput.

One fundamental distinguishing feature of mmWave communications is the large propagation loss resulting from the high frequency, since free space propagation loss is proportional to the square of carrier frequency. Additionally, oxygen absorption peaks at 60 GHz, which makes the propagation loss more severe. In order to compensate for the high propagation loss in mmWave channels, high-gain directional antennas are deployed at both transmitter and receiver to achieve larger range and higher transmission rate. The short wavelengths in mmWave bands impose challenges such as greater signal diffusion and difficulty in diffracting around obstacles. Non-line-of-sight (NLOS) transmissions suffer from significant attenuation and a shortage of multipaths [8]. Therefore, mmWave systems rely on line-of-sight (LOS) transmissions to achieve the high data rate. The obstacles and moving people can easily block the LOS transmission in indoor environments, and greatly reduce the transmission data rate. To tackle the link blockage problem in mmWave systems, an alternative relaying path is required to keep the network connectivity and provide the required data rate for bandwidth-intensive multimedia applications.

Since the destination can receive signals from the source and relaying nodes and then combine and decode the received signals to achieve the diversity gain, the use of cooperative relaying is able to increase the capacity of wireless networks [9], [13], [15]. In mmWave systems, if the LOS link is blocked, the received signal strength at the destination from the source is considerably weakened, which leads to lower transmission rate. In case of LOS link blockage, the transmission rate can be greatly improved by selecting an appropriate cooperative relay to provide an additional path. Meanwhile, cooperative communication causes redundancy on the transmitted data, i.e., the total achievable rate of the two paths is higher than the achievable rate of cooperative communications. Due to the utilization of directional antennas and high propagation loss, spatial reuse can be exploited to enable multiple nodes to transmit concurrently. As shown in [3], [11], [12], [14], multi-user interference (MUI) resulting from concurrent transmissions has great impact on achievable rates of the direct path, relaying path and cooperative communication. To reduce the transmission redundancy and improve the network capacity, the efficient concurrent transmission scheduling algorithm is required while considering MUI.

The problem of blockage and concurrent transmission scheduling in mmWave systems has been investigated in the literature [1], [3], [10], [11]. Cross-layer modeling and design approaches are presented in [10] to account for the problems of directionality and blockage. It uses a minimum number of hops for data transmission. Specifically, if the LOS link

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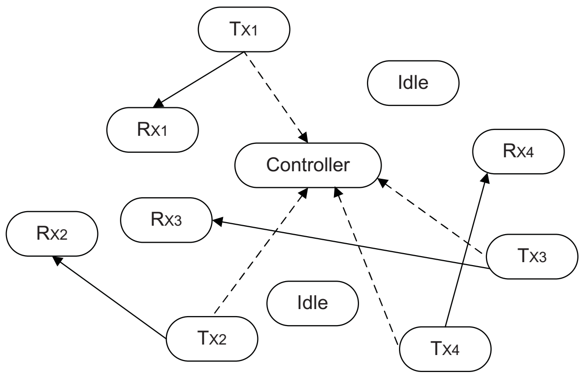

Fig. 1. Indoor mmWave Network Architecture

is available between the source and destination nodes, single hop transmission is employed; otherwise, an intermediate node is selected as the relay. Multi-hop concurrent transmissions are enabled in [1] to maintain network connectivity and to further improve flow throughput. In [3], [11], taking the unique features of mmWave systems into account, multiple communication links are scheduled to be active simultaneously to exploit the spatial reuse and increase network throughput. In this paper, we introduce cooperative communication to deal with link blockage and achieve higher flow throughput compared with multi-hop transmissions. In addition, a concurrent transmission scheduling algorithm is proposed to reduce the transmission redundancy resulting from multi-path diversity of cooperative communications and achieve efficient resource utilization.

The main contributions of this paper are three-fold. First, a novel metric is designed to select proper cooperative relay and obtain an alternative path, in order to increase the achievable rate. Second, we propose a concurrent transmission scheduling algorithm to exploit the spatial reuse and improve the transmission efficiency, considering the unique features of mmWave communications. Finally, extensive simulations are conducted to demonstrate the effectiveness and efficiency of the proposed scheme.

The remainder of the paper is organized as follows. The system model is described in Section II. The cooperative concurrent transmission scheduling (CCTS) scheme including cooperative relay selection and concurrent transmission scheduling is proposed in Section III. The performance of the proposed scheme is evaluated by extensive simulations in Section IV, followed by concluding remarks in Section V.

II. System Model

Since mmWave indoor systems (e.g., WPANs/WLANs) are centralized in nature [4], [10], we consider a network composed of multiple wireless nodes (WNs) and a single network controller with the system architecture shown in Fig. 1. All nodes are equipped with an electronically steerable directional antenna and are able to direct their beams towards each other for transmission and reception. With the accurate localization service provided by the mmWave indoor system [6], [7], the network controller has the valid network topology information to select the cooperative relay and make the scheduling decision. As shown in [13], the diversity gain achieved by exploiting multiple relays is marginally higher than the diversity gain that can be obtained by selecting the best relay. In addition, the communication range for indoor mmWave systems is relatively short (in the order of 10 meters). As a result, we consider one cooperative relay between source node and destination node if the LOS transmission is blocked. Due to the large available bandwidth at mmWave bands, the LOS transmission can achieve the required data rate to support the multimedia applications. Therefore, we do not consider cooperative relay to obtain an alternative path if LOS is available, with the fact that cooperative communication results in transmission redundancy and utilize more network resources.

A. Directional MAC Structure

A hybrid multiple access of carrier sensing multiple access/collision avoidance(CSMA/CA) and time division multiple access (TDMA) is applied. The superframe structure is shown in Fig. 2. A superframe is composed of three phases: the Beacon period (BP) for network synchronization and control messages broadcasting from the network controller, the contention access period (CAP) for devices sending transmission requests to the network controller using the carrier sensing multiple access/collision avoidance (CSMA/CA) technology, and the channel time allocation period (CTAP) for data transmissions among devices in a peer-to-peer fashion, respectively. There are at most M channel time slots in CTAP of each superframe. The network controller can adjust the length of CTAP adaptively according to the total occupied number of time slots if it does not exceed M. In IEEE 802.15.3c draft standardization, TDMA is used to allocate each time slot to a specific flow, i.e., each time slot is occupied by one flow exclusively. Due to the utilization of directional antenna and the high propagation loss in mmWave bands, we allow concurrent transmissions to exploit spatial reuse. In other words, each time slot in CTAP can be allocated to multiple flows. With directional transmission and reception, there is a so-called deafness problem when a directional receiver does not point its beamwidth towards the direction of the transmitter and thus fails to receive a message from the transmitter. To avoid the deafness problem, which involves very complicated MAC design, the network controller operates in the omni-directional mode by switching all its beams on during the random access period to hear the transmission requests from all directions.

B. Achievable Rates in Cooperative Communications

Fig. 3 shows the three-node model for cooperative communication, where node S is source node, node D is destination node, and node R is relay node. Since the achievable rates have considerable impact on concurrent transmission scheduling, we describe the achievable rates for direct path, the relaying path, and cooperative communication.

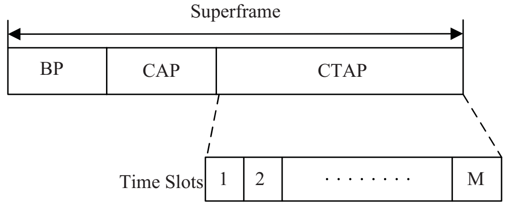

Fig. 2. IEEE 802.15.3 MAC structure

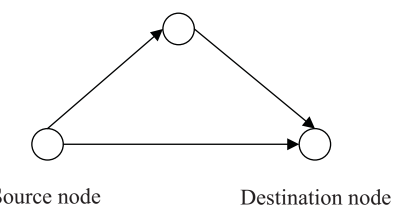

Fig. 3. Three-Node Model for Cooperative Communication

Due to LOS transmission for indoor mmWave systems, the received signal power can be estimated by the Friis transmission equation and is given by

$$P_r(d) = P_t G_r G_t \frac{\lambda^2}{16\pi^2 d^\gamma} = P_t K d^{-\gamma} \quad (1)$$

where $K = G_r G_t \lambda^2/16\pi^2$ is a constant, P_t is the transmission power, G_t and G_r are respectively the antenna gains of the transmitter and receiver. λ is the wavelength, d is the transmission distance between the transmitter and the receiver, and γ is the path loss exponent, which is usually determined using a measurement approach (usually in the range of 2 to 6 for indoor environment [8]).

The received $SINR$ is determined by not only the received signal power but also the noise and the received interference. Due to the utilization of directional antenna, the MUI at the receiver comes from the active transmitters which are within beamwidth of the receiver and direct their beams towards the receiver.

The received power from transmitter T_i to receiver R_j is $P_R^{i,j} = f_{i,j} k P_t d_{i,j}^{-\gamma}$, $f_{i,j} = 1$ if the transmitter T_i and the receiver R_j direct their beams towards each other; otherwise, $f_{i,j} = 0$. For the additive white Gaussian noise (AWGN) channel and wideband interference, the received $SINR$ at receiver R_i is given by

$$SINR_i = \frac{K u_{k,i} P_t d_{i,i}^{-\gamma}}{N_0 W + b \sum_{l \neq i} f_{l,i} u_{k,l} K P_t d_{l,i}^{-\gamma}} \quad (2)$$

where b denotes the MUI factor and it is related to the cross correlation of signals from different users, and N_0 is one-side power spectral density of white Gaussian noise. $u_{k,i}$ indicates whether flow i is active in the k^{th} time slot of CTAP period.

Direct Transmission When cooperative communication is applied, on the assumption that the interference is broadband and approximately Gaussian distribution, the achievable rate from source node S_i to destination node D_i (forming link L_i) can be estimated according to Shannon channel capacity as

$$R_i = W \cdot log_2(1 + \frac{K u_{k,i} P_t d_{i,i}^{-\gamma}}{N_0 W + b \sum_{l \neq i} f_{l,i} u_{k,l} K P_t d_{l,i}^{-\gamma}}) \quad (3)$$

where W is the system bandwidth.

Cooperative Communications When applying cooperative communication, the LOS link from source S_i to destination D_i is blocked. NLOS components exist, mostly in the form of reflection. mmWave bands measurements show that in general [8] the strongest reflected components are at least 10 dB below the LOS component. Thus, the received signal power at the destination from the source node is estimated as 10 dB below the received power calculated in Eq. (1) when LOS is blocked. Similarly, the achievable rate from source node to destination node with the blockage of LOS also approaches the Shannon channel capacity.

For full-duplex case, the flow throughput of the path with cooperative relay is given by

$$R_R = \min\{R_{SR}, R_{RD}\} \quad (4)$$

where R_{SR} is the achievable rate for link $S \rightarrow R$ and R_{RD} is the achievable rate for link $R \rightarrow D$. Since link $S \rightarrow R$ and link $R \rightarrow D$ rely on LOS for transmission, similarly, R_{SR} and R_{RD} can be also obtained according to Eq. (3).

For the cooperative communications with decode-and-forward (DF) scheme, the relay node R first decodes and estimates the received signal from source node S, and then transmits the estimated data to destination node D [16]. For AWGN channel, the achievable rate under DF mode for cooperative communication is

$$\begin{aligned} R_C = \min\{&W log_2(1 + SINR_{SR}), \\ &W log_2(1 + SINR_{SD} + SINR_{RD})\} \end{aligned} \quad (5)$$

where $SINR_{SR}$, $SINR_{SD}$, and $SINR_{RD}$ are the $SINR$ from node S to node R, from node S to node D, and from node R to node D, respectively. $SINR_{SR}$ and $SINR_{RD}$ can be obtained according to Eq. (2). $SINR_{SD}$ can be calculated based on Eq. (2) with the received signal power 10 dB below the received power calculated in Eq. (1). Note that in cooperative communications with DF, the received signal power at destination node D from the source node S and that from the relay node R do not interfere with each other. With combining techniques, diversity gain can be achieved to increase the network capacity.

III. Multi-hop Concurrent Transmission with Cooperative Relay

In this section, we describe the CCTS scheme including a cooperative relay selection metric and a concurrent transmission scheduling algorithm. First, we select a cooperative relay for a pair of source and destination nodes if LOS link between them is blocked, aiming to achieve the maximum capacity for

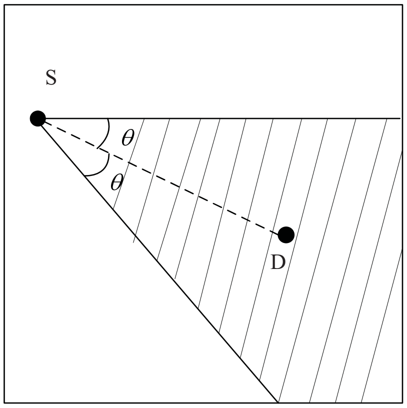

Fig. 4. Feasible Region for Cooperative Relay Selection

cooperative communication. Then a concurrent transmission scheduling algorithm for cooperative communication is presented to improve the transmission efficiency.

A. Cooperative Relay Selection

Due to LOS transmission in mmWave systems, the received signal power is mainly affected by link distance. Thus, the location of relay node has considerable impact on the achievable rate of cooperative communication. It is important to select the best relay in order to attain the achievable rate as per Eq. (5).

In cooperative communication, the source node broadcasts data to the destination and relay nodes; then the relay node decodes the received signal, encodes and forwards it to the destination node. With directional antennas, simultaneous transmissions to the destination and relay nodes, require both destination and relay nodes to be within the beamwidth of source node. Given the location of source and destination nodes, there exists a feasible region, for nodes to be considered as candidates for cooperative relay. The feasible region for source node S and destination node D is shown in Fig. 4, where θ is the beamwidth of directional antenna.

When the network controller receives the transmission request for a pair of source and destination nodes, it checks whether LOS link exists. If positive, direct transmission without cooperative communication is adopted. Otherwise, the network controller starts to select the cooperative relay from all the nodes within the feasible region. The network controller has topology information and generates a set which includes nodes located in the feasible region for a specific pair of source and destination. For each candidate relay $R_{i,j}$ (j^{th} relay candidate for source node S_i and destination node D_i), the network controller calculates the corresponding achievable rate $R_C^{i,j}$ for cooperative communication based on Eq. (5). The node with largest $R_C^{i,j}$ is selected as cooperative relay for source node S_i and destination node D_i.

B. Concurrent Transmission Scheduling

To exploit spatial reuse and increase network capacity, concurrent transmissions are utilized in mmWave systems. To provide the required data rate for bandwidth intensive applications, cooperative relaying is utilized to increase the transmission throughput if LOS link between source and destination nodes is blocked. Cooperative communication uses two paths to achieve the diversity gain at the destination node, which also results in transmission redundancy. As shown in Eq. (5), the achievable rate of cooperative communication is a function of the received $SINR$ at both relay and destination nodes. MUI can be adjusted by allowing different sets of active links in each time slot, and so is $SINR$. Therefore, concurrent transmission scheduling makes scheduling decisions for each time slot of CTAP period to achieve the maximum transmission efficiency, which is defined as the total data transmitted by cooperative communication divided by total data transmitted by direct path with LOS blockage and the alternative path with cooperative relaying.

There are N transmission requests obtained by the network controller during CAP period in a superframe. Each of them specifies a required throughput Thr_{min}^i. The CTAP of each superframe contains M time slots. For the k^{th} time slot, the scheduling decision can be represented by a vector $U_k = [u_{k,1}, u_{k,2}, ...u_{k,N}]$, where $u_{k,i} = 1$ indicates whether flow i is scheduled in the k^{th} time slot, otherwise $u_{k,i} = 0$. Note that if flow i with cooperative communication is active in the k^{th} time slot, three links (i.e., $S(i) \to D(i)$, $S(i) \to R(i)$, and $R(i) \to D(i)$) are active. To maximize the transmission efficiency, we formulate the concurrent scheduling problem with cooperative communication as the following optimization model (P1):

$$\max_{u_{k,i}\in\{0,1\}} \frac{\sum_{k=1}^{M}\sum_{i=1}^{N} R_C(k,i)}{\sum_{k=1}^{M}\sum_{i=1}^{N}[R_D(k,i)+R_R(k,i)]} \tag{6}$$

where $R_C(k,i)$, $R_D(k,i)$, and $R_R(k,i)$ can be obtained from Section II-B. Since each flow has a minimum required throughput Thr_{min}^i, we have

$$F_i \geq Thr_{min}^i \tag{7}$$

where F_i denotes the throughput of flow i according to the scheduling results and is defined as

$$F_i = \frac{\sum_{k=1}^{M}[(1-C(i))R(k,i)+C(i)R_C(k,i)]\Delta T}{T_{BP}+T_{CAP}+M\Delta T} \tag{8}$$

where T_{BP} and T_{CAP} are the time duration for beacon period and contention access period, respectively, and ΔT is the time duration of each time slot in CTAP period. $R(k,i)$ is the data rate of flow i without cooperative communication in slot k. $C(i)$ indicates whether cooperative communication is deployed in flow i and is defined as

$$C_i = \begin{cases} 1, & \text{cooperative communication adopted in flow i;} \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

Optimization problem (P1) is a nonlinear integer programming problem and is NP-hard. The transmission data rate

Algorithm 1 Concurrent Transmission Scheduling Algorithm

```
BEGIN:
1:  The network controller gets transmission request r_i (i = 1, 2...N)
    with minimum throughput Thr^i_min
2:  Set the initial scheduling basis vector H_1 = \vec{0}
3:  for non-scheduled slot k (1 ≤ k ≤ M) do
4:      if H_k = H_{k-1} then
5:          U_k = U_{k-1}
6:          go to line 18
7:      else
8:          repeat
9:              for flow i=1 to N do
10:                 if h_{k,i} = 1 or h_{k,i} is marked as unchanged then
11:                     Keep the corresponding h_{k,i} the same
12:                 else
13:                     set h_{k,i} = u_{k,i} according to
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$$\arg\max_{u_{k,i}\in\{0,1\}} \left\{\frac{\sum_{i=1}^{N} R_C(k,i)}{\sum_{i=1}^{N}[R_D(k,i)+R_R(k,i)]}\right\}$$

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14:                 end if
15:             end for
16:         until H_k = [h_{k,1}, h_{k,2}, ...h_{k,N}] converges
17:         update U_k = H_k
18:         update F_i = \sum_{n=1}^{k}[(1-C(i))R(n,i)+C(i)R_C(n,i)]ΔT / (T_BP + T_CAP + MΔT)
19:         if any F_i ≥ Thr^i_min then
20:             change h_{k,i} from 1 to 0, and mark it as unchanged
21:         end if
22:         update H_{k+1} = H_k
23:         update k=k+1
24:         if k > M then
25:             go to END
26:         end if
27:     end if
28: end for
END;
```

of each flow in a time slot can not be determined until scheduling decision for this slot is made because of the MUI. The size of search space is $2^{N\cdot M}$ if exhaustive search is implemented. With the fact that the network controller needs real-time solution to make the scheduling decision, we propose a heuristic scheduling algorithm to solve the optimization problem (P1). Since the scheduling problem has a slotted structure in the time domain, we decompose the scheduling problem and make the scheduling decision slot by slot.

During the CAP period of the m^{th} superframe, the network controller receives many transmission requests, each of which specifies the source and destination nodes. The network controller makes the scheduling decision for the $(m+1)^{th}$ CTAP before the $(m+1)^{th}$ beacon period, during which the network controller sends the scheduling information to corresponding nodes. The nodes start data transmission according to the scheduling information in the $(m+1)^{th}$ CTAP period. After the network controller receives the transmission requests, it checks whether LOS link exists. If positive, direct transmission without cooperative communication is utilized. Otherwise, it selects the cooperative relay for the source and destination nodes as presented in Section III-A. We propose a flip-based algorithm to obtain the set of active flows in each slot. Initially, we set $U_k = \overrightarrow{0}$. For each flow i $(i = 1, 2...N)$, $u_{k,i}$ is set to 1 if adding it to the active flow set can increase the transmission efficiency in slot k. Otherwise, we set $u_{k,i} = 0$. Note that for an active flow with cooperative communication, there are three active links which affect the MUI and so do the transmission efficiency. All the flows are traversed to obtain the decision vector. The above process is repeated until U_k converges. For the first slot of the CTAP, we use the flip-based algorithm to obtain the set of active flows. We keep this set of flows active for a number of following time slots until one flow's minimum throughput requirement is satisfied. These time slots have the same active flow set since there are the same flows available to be scheduled. In the next time slot, the set of active flows is re-determined. Then, the same schedule is used for the following time slots until the throughput requirement of at least one flow is satisfied. The above procedure is repeated until all time slots have been scheduled. The pseudo code for the concurrent transmission scheduling algorithm with cooperative relay is shown in Algorithm 1.

TABLE I
SIMULATION PARAMETERS

Parameters	Symbol	Value
System bandwidth	W	1200 MHz
Transmission power	P_t	0.1mW
Background noise	N_0	-134dBm/MHz
Path loss exponent	γ	2
Reference distance	d_{ref}	1.5m
Path loss at d_{ref}	PL_0	71.5 dB
Slot time	ΔT	18μs
Beacon period	T_{bea}	50 μs
Random access period	T_{ran}	800 μs
Number of slots in transmission period	$\overline{N}$	1000

IV. Performance Evaluation

In this section, we present simulation results to evaluate the performance of the proposed CCTS scheme. We consider a typical mmWave indoor environment (i.e., large office space) with the area of 10×10 m^2. The network controller is placed in the center with 40 WNs randomly distributed in the area. The source and destination nodes of each flow are randomly selected. The required throughput of each flow is uniformly distributed between 1.5 Gbps and 2.5 Gbps. All transmitters equipped with directional antennas with beamwidth of $60°$, use the same transmission power. A typical physical layer parameter setting of mmWave systems is shown in Table I.

For the flows with cooperative communication, Fig. 5 shows the average transmission throughput of direct path, alternative relaying path, and cooperative communication, respectively. The average transmission throughput decreases if more flows in the network are competing for the network resource. The flow throughput can be improved significantly with cooperative communication compared with that of direct and alternative paths. As shown in Fig. 5, the throughput of cooperative communication approximates the total throughput of direct

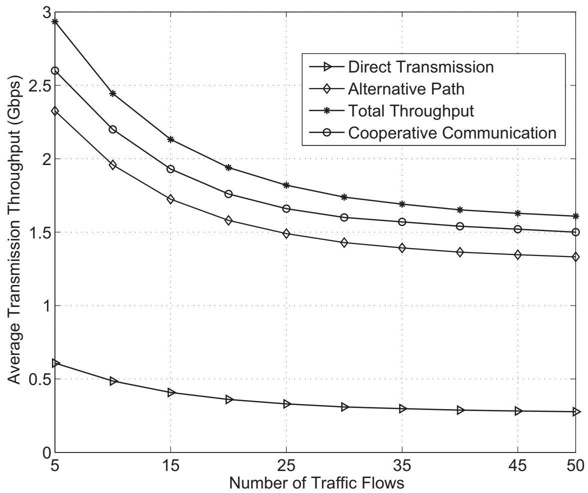

Fig. 5. Average Transmission Throughput in Cooperative Communication

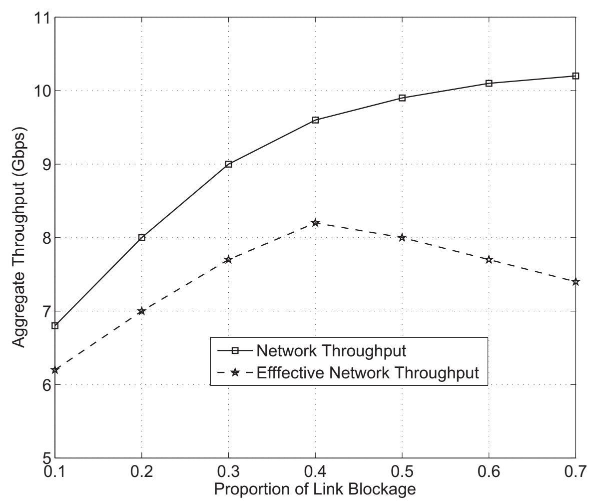

Fig. 6. Network Throughput and Effective Network Throughput

and alternative paths, demonstrating that the proposed concurrent transmission scheduling algorithm utilizes the network resource efficiently.

Fig. 6 shows the network throughput and effective network throughput with different proportions of link blockage. There are a total of 35 flows in the network. Effective network throughput considers the throughput of cooperative communication if LOS is blocked while network throughput is the throughput of all the active links in the network. The effective network throughput increases with the proportion of cooperative communication first because cooperative communication can improve the transmission throughput. Then the effective network throughput decreases since more flows use cooperative communication, resulting in more transmission redundancy, which occupies the network resource. Thus, fewer flows can be scheduled in the network.

V. Conclusion

In this paper, we have proposed a cooperative concurrent transmission scheduling scheme for indoor mmWave systems, considering the unique characteristics of mmWave communication. The proposed CCTS scheme enables cooperative communication in mmWave systems with directional antennas and makes concurrent transmission scheduling decisions to reduce the transmission redundancy due to multi-path diversity. The proposed CCTS scheme can increase the transmission throughput and improve network resource utilization efficiency. The mmWave systems with CCTS scheme can maintain network connectivity and support numerous multimedia applications requiring large data rate.

References

[1] J. Qiao, L. X. Cai, X. Shen, and J. W. Mark, "Enabling Multi-hop Concurrent Transmissions in 60 GHz Wireless Personal Area Networks", *IEEE Trans. on Wireless Commun.,* vol. 10, no. 11, pp. 3824-3833, Nov. 2011.

[2] L. X. Cai, L. Cai, X. Shen, and J. W. Mark, "REX: a Randomized EXclusive Region based Scheduling Scheme for mmWave WPANs with Directional Antenna," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, pp. 113-121, Jan. 2010.

[3] J. Qiao, L. X. Cai, X. Shen, and J. W. Mark, "STDMA-based Scheduling Algorithm for Concurrent Transmissions in Directional Millimeter Wave Networks," *Proc. IEEE ICC 2012,* May 2012.

[4] A. Maltsev, R. Maslennidov, A. Sevastyanov, A. Khoryaey, and A. Lomayev, "Experimental Investigations of 60 GHz WLAN Systems in Office environment," *IEEE J. Sel. Areas Commun.,* vol. 27, no. 8, pp. 1488-1499, Oct. 2009.

[5] F. Gutierrez, S. Agarwal, K. Parrish, and T. S. Rappaport, "On-Chip Integrated Antenna Structures in CMOS for 60 GHz WPAN Systems," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, pp. 1367-1378, Oct. 2009.

[6] N. Deparis, C. Loyez, N. Rolland, and P. A. Rolland, "UWB in Millimeter Wave Band With Pulsed ILO," *IEEE Tran. Circuits and Systems*, vol. 55, no. 4, pp. 339-343, Apr. 2008

[7] F. Winkler, E. Fischer, E. Grass, and P. Langendörfer, "An Indoor Localization System Based on DTDOA for Different Wireless LAN Systems," *Proc. WPNC*, pp. 117-122, Hannover, Mar. 2006

[8] S. Y. Geng, J. Kivinen, X. W. Zhao, and P. Vainikainen, "Millimeter-Wave Propagation Channel Characterization for Short-Range Wireless Communications," *IEEE Trans. Veh. Technol.*, vol. 58, no.1, pp. 3-13, Jan. 2009

[9] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative Strategies and Capacity Theorems for Relay Networks," *IEEE Trans. Inf. Theory*, vol. 51, no. 9, pp. 3037-3063, Sept. 2005

[10] S. Singh, F. Ziliotto, U. Madhow, E. M. Belding, and M. J. W. Rodwell, "Millimeter Wave WPAN: Cross-Layer Modeling and Multihop Architecture," *Proc. IEEE INFOCOM*, pp. 2336-2240, Alaska, May 2007.

[11] C. Sum, Z. Lan, R. Funada, J. Wang, T. Baykas, M.A. Rahman, and H. Harada, "Virtual Time-Slot Allocation Scheme for Throughput Enhancement in a Millimeter-Wave Multi-Gbps WPAN System," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 8, pp. 1379-1389, Oct. 2009

[12] K. H. Liu, L. Cai, and X. Shen, "Multiclass Utility-Based Scheduling for UWB Networks," *IEEE Trans. on Vehicular Technology*, vol. 57, no. 2, pp. 1178-1187, March 2008.

[13] Y. Zhao, R. Adve, and T. J. Lim, "Improving Amplify-and-Forward Relay Networks: Optimal Power Allocation Versus Selection," *Proc. IEEE ISIT*, pp. 12341238, Seattle, Jul. 2006.

[14] Z. Yang, L. Cai and W. Lu, "Practical Concurrent Transmission Scheduling Algorithms for Rate-adaptive Wireless Networks," *Proc. IEEE INFOCOM*, San Diego, Mar. 2010.

[15] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[16] T. Cover, and A. E. Gamal, "Capacity Theorems for the Relay Channel," *IEEE Trans. Inf. Theory*, vol. 25, no. 5, pp. 572-584, Sept. 1979.