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Multi-hop Concurrent Transmission in Millimeter Wave WPANs with Directional Antenna

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***Abstract*—Millimeter-wave (mmWave) communications is a promising enabling technology for high rate (Giga-bit) multimedia applications. However, because oxygen absorption peaks at 60 GHz, mmWave signal power degrades significantly over distance. Therefore, a traffic flow transmitting over multiple short hops is preferred to improve flow throughput. In this paper, we first design a hop selection metric for the piconet controller (PNC) to select appropriate relay hops for a traffic flow, aiming to improve the flow throughput and balance the traffic load across the network. We then propose a multi-hop concurrent transmission (MHCT) scheme to exploit the spatial capacity of the mmWave WPAN. Extensive simulations show that the proposed MHCT scheme can significantly improve the traffic flow throughput and network throughput.**

I. INTRODUCTION

Communications at 60 GHz band is referred to as millimeter -wave (mmWave) communications because the wavelength at this band is in the order of millimeters. The FCC has approved an un-precedented 7 GHz spectrum between 57 and 64 GHz for general use, which enables multi-gigabit wireless connections for bandwidth-intensive multimedia applications. With the recent advances of Radio Frequency Integrated Circuits (RFIC) design in mmWave band [1], [2], there have been growing interests in standardization and realizing specifications for mmWave systems, including the IEEE 802.15.3c [3] and IEEE 802.11 VHT [4] task groups.

One fundamental distinguishing feature of mmWave communications is the high propagation loss. As the free space propagation loss increases proportionally with the square of the carrier frequency, the propagation loss at mmWave band is much higher compared with other lower frequency bands, e.g. 28 dB higher than at 2.4 GHz. The path loss becomes more serious since oxygen absorption peaks at 60 GHz. Directional antenna with high directivity gain is utilized to combat the severe path loss and achieve high data rate in mmWave channels. On the other hand, the high path loss and the utilization of directional antenna allow more efficient space reuse. In addition, in high frequency bands, reflection is more dominant than diffraction in received power, which usually requires line-of-sight (LOS) link to achieve high data rate. A relay is needed for data transmission if moving obstacles are located within the LOS link between source and destination.

Recognizing these unique features of mmWave communications, directional medium access control (MAC) in mmWave wireless personal area networks (WPANs) has been appeared in the literature [5], [6], [7], [8]. An architecture is proposed for mmWave WPAN in [5], where an intermediate node is selected as the relay when the LOS link between source and destination is blocked by moving obstacles. The proposed architecture is shown to be effective to keep the network connectivity when serious link outage happens due to moving obstacles. In [6], an exclusive region (ER) based resource management scheme is proposed to explore the spatial multiplexing gain of mmWave WPANs with directional antenna and the optimal ER sizes are analytically derived in [7]. To improve the network capacity, multiple traffic flows that do not cause harmful interference to each other are scheduled for concurrent transmissions. To the best of our knowledge, the previous works in mmWave MAC design use single hop or minimum hop-count for data transmission. However, as mmWave signals attenuate significantly over distance, a traffic flow transmitting over multiple short hops can achieve much higher flow throughput than that over a single long hop in a mmWave network. To leverage the transmission data rate over distance, appropriate multi-hop relaying plays a critical role. In this paper, we study how to select relay nodes to improve the flow throughput and network throughput. In specific, we design a novel hop selection metric for the piconet controller (PNC) to choose proper relay nodes to forward data, aiming to improve the flow throughput and distribute the traffic load across the network. To further improve the network performance, we propose a multi-hop concurrent transmission (MHCT) scheme to allow non-interfering flows to concurrently transmit over a mmWave channel. By properly breaking one long-hop (i.e., low rate) transmission into multiple short-hop (i.e., high rate) transmissions and allowing some non-interfering hops (including inner-flow hops and inter-flow hops) to concurrently transmit, the network capacity can be efficiently improved in terms of flow throughput and network throughput.

The main contribution of the paper is two-fold. First, we design a novel metric to select relay nodes to forward data along a multi-hop path. Second, we efficiently schedule concurrent multi-hop transmissions in a mmWave WPAN, considering the unique features of mmWave communications, e.g., the link outage in mmWave channel and the use of directional antenna. Extensive simulations are also conducted to demonstrate the efficiency of the proposed scheme.

The remainder of the paper is organized as follows. We describe our system model in Section II. A multi-hop concurrent transmission scheme with a hop selection metric is proposed in Section III. In section IV, the performance of the proposed scheme is evaluated by intensive simulations, followed by concluding remarks in section V.

II. System model

We consider an indoor WPAN composed of several wireless terminals (WTs) and a single piconet controller (PNC). Each node in the network is equipped with an electronically steerable directional antenna. Both transmitters and receivers direct their beams towards each other for data transmission. Because of the accurate localization service provided by the Ultra-wideband system, we assume the PNC has the topology information of the network. Moving obstacles greatly degrade the transmission data rate especially if they are located in the LOS link between two nodes. Therefore, the multi-hop concurrent transmission scheme is based on LOS link of each hop.

A. mmWave Communication

According to Shannon theory, the achievable data rate in an additive white Gaussian noise (AWGN) channel is:

$$R = W \log_2[1 + \frac{P_R}{(N_0 + I)W}] \tag{1}$$

where P_R is the received signal power, W is the system bandwidth, N_0 and I are the one-side power spectral density of white Gaussian noise and interference respectively.

We apply the Friis transmission equation to calculate the received power in a free space, which is a function of transmission range r,

$$P_R(r) = P_T G_R G_T (\frac{\lambda}{4\pi r})^2 \tag{2}$$

where P_T is the transmission power, G_T and G_R are the antenna gains of the transmitter and receiver respectively, λ is the wavelength and r is the transmission distance between the transmitter and the receiver. Considering multipath fading and signal dispersion, the received signal power is

$$P_R(r) = P_T G_R G_T (\frac{\lambda}{4\pi})^2 (\frac{1}{r})^n \tag{3}$$

where n is the path loss exponent which can be determined experimentally and is usually in the range of 2 to 6 for indoor environment [9]. Combining (1) and (3), the data rate is obtained as

$$R = W \log_2[1 + \frac{P_T G_R G_T \lambda^2}{16\pi^2 (N_0 + I) W r^n}] \tag{4}$$

In (4), it can be seen that the minimum hop-count metric usually favors the hop with long distance, which significantly reduces the received signal strength and degrades the achieved traffic flow throughput. According to (4), the flow throughput deduction over distance is more serious in mmWave system due to its large bandwidth and small wavelength. Thus it is likely to improve the flow throughput by replacing single long hop by multiple short hops.

B. Antenna Model

We apply an ideal "flat-top" model for directional antenna [10]. Every node employs an antenna with N beams, each of which spans an angle of $2\pi/N$ radians. Each beam has a fixed beamwidth with none overlapping beam radians so that N beams can collectively maintain the seamless coverage for the entire plane. Directional antennas are characterized by their pattern functions that measure the power gain $G(\phi)$ over the angle ϕ. The normalized pattern function is defined as

$$g(\phi) = \frac{G(\phi)}{G_{max}}, \tag{5}$$

where

$$G_{max} = max_{\phi} G(\phi). \tag{6}$$

In an ideal case, the antenna gain is constant, i.e., unit gain, within the beamwidth and zero outside,

$$g(\phi) = \begin{cases} 1, & |\phi| \le \frac{\Delta\phi}{2} \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

where $\Delta\phi = 2\pi/N$ is the antenna beanwidth. In our system, both the transmitters and receivers use directional antenna for data transmissions, thus the antenna gains of transmitters and receivers, $G_T = G_R = 1$ within the antenna beamwidth and $G_T = G_R = 0$ outside.

C. Directional MAC Structure

The MAC protocol is based on IEEE 802.15.3 superframe structure, as shown in Fig. 1. A superframe consists of three periods, beacon period, random access period and data transmission period. During the beacon period, the PNC activates all its beams and sends out beacon frames in all directions to other nodes for synchronization, scheduling information and other management information distribution. The scheduling information includes the transmission start time, a maximum allowed transmission (TXOP) duration and antenna beam direction. The beacon period is followed by a random access period during which the nodes send transmission requests, topology information and load information to the PNC, based on which the PNC schedules contention-free peer-to-peer transmissions in the following data transmission period. To avoid deafness problem caused by directional antenna which invokes very complicated MAC design, the PNC still operates in the omni-directional mode by switching all its beams on in the random access period while it can use one beam for data transmission in the following data transmission period. To fully exploit the mmWave channel capacity, we improve the IEEE 802.15.3 MAC by allowing multiple nodes to concurrently transmit. Two transmissions can operate simultaneously if and only if one receiver is outside the beamwidth of the other transmitter, given that the transmitter and receiver always steer beams to each other [6], [11].

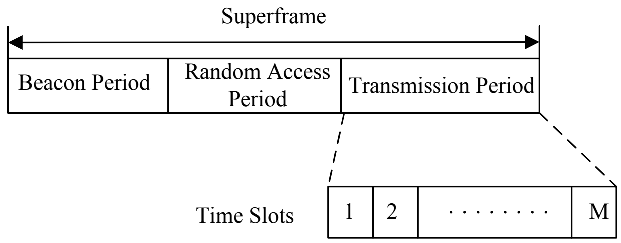

Fig. 1. IEEE 802.15.3 MAC structure

III. Multi-hop concurrent transmission scheme

In this section, we first propose a hop selection metric to determine a multi-hop path for a traffic flow to increase the flow throughput and achieve load-balancing. Based on the metric, we then present a multi-hop concurrent transmission scheme to improve the spatial capacity of mmWave WPAN. The basic idea is that PNC collects the global user information to select an appropriate multi-hop path for each traffic flow and allow non-conflict hops either in one flow or cross flows to transmit concurrently.

A. Hop Selection Metric

To achieve high transmission data rate for each traffic flow, short links are usually preferred in hop selection. Therefore, more hops may be involved in each flow, which results in heavy traffic loads in the network. In addition, when traffic aggregates at some of the nodes, congestion may occur and these nodes become bottleneck for the network. Therefore, we need to select appropriate relay hops to improve the network throughput, considering both the link length and the traffic loads at the node.

When the PNC receives a request, it determines appropriate relaying hops based on the global network information, including the distance from one node to all its neighbors, antenna directions steering to their neighbors, and the traffic load of each node. The traffic load of each node is defined as the traffic at each node before the scheduled transmission over this hop starts. More concurrent transmissions can be supported by well balancing the traffic loads among multiple nodes in the network. To determine the relaying hops for a pair of transmitter and receiver, a weighted graph is generated by the PNC based on the topology information and traffic loads of each node. The weight associated with link $(i \rightarrow j)$ between nodes i and j is given as

$$w(i,j) = \frac{d^2(i,j)}{\overline{D^2}} + \frac{F(j)}{\overline{F}} \tag{8}$$

where $d(i,j)$ is the link length of link $(i \rightarrow j)$; $F(j)$ is the traffic load of node j. $\overline{D^2}$and $\overline{F}$ are the average link length square and average traffic loads of each node, respectively. We use normalized traffic load and link length square for hop selection to smooth the large difference between the node's loads and link lengths. To achieve load balancing and improve flow throughput, link length square and node's load should equally contribute to the hop selection. We use link length square rather than link length to favor multiple hops with shorter links. In other words, the first item in the metric provides high data rate while the second item reduces the traffic loads aggregation. For example, as shown in Fig. 2, there are three options from source to destination, $S \rightarrow A \rightarrow D$, $S \rightarrow A \rightarrow C \rightarrow D$ and $S \rightarrow B \rightarrow C \rightarrow D$. According to above hop selection metric, given link lengths and node loads, the weights of the three options are in the following sequence $W_{S\rightarrow A\rightarrow D} > W_{S\rightarrow A\rightarrow C\rightarrow D} > W_{S\rightarrow B\rightarrow C\rightarrow D}$ while $W_{S\rightarrow A\rightarrow C\rightarrow D} > W_{S\rightarrow B\rightarrow C\rightarrow D} > W_{S\rightarrow A\rightarrow D}$ if the link square item in (8) is replaced by link length. Our analysis in the section of mmWave communication shows that the option $S \rightarrow B \rightarrow C \rightarrow D$ is more likely to achieve higher flow throughput in comparison with the others and the traffic load has large impact on hop selection if there are more traffic flows in the network.

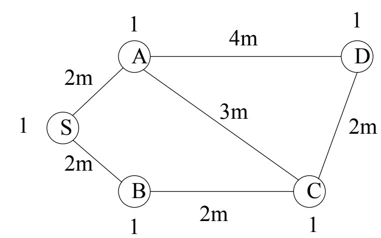

Fig. 2. Illustration for hop selection.

B. The Proposed Concurrent Transmission Scheme

The proposed multi-hop concurrent transmission scheme is based on the hop selection metric designed above. The details on the proposed scheme are given as follows: during the random access period, the PNC activates all the beams to collect global user information, e.g., topology information and traffic loads. When a transmission request is received, the PNC calculates $\overline{D^2}$ and $\overline{F}$ based on the traffic load and topology information received in random access period, and then generates a weighted graph where each link has a weight $w(i,j) = \frac{d^2(i,j)}{\overline{D^2}} + \frac{F(j)}{\overline{F}}$. The PNC calculates accumulated weights for each flow by summing up the weights of each hop along the path from source to destination together. The hops with the lowest accumulated weights are chosen. The PNC then checks if these hops can transmit concurrently with the hops which has been scheduled. During the beacon period, the PNC distributes the scheduling information to all the nodes with data ready to transmit. It is possible that a WT sends a transmission request to PNC but does not receive the scheduling information within a certain time interval (e.g., a random access period plus a beacon period) because moving obstacles in the room may block the LOS link. This WT needs to send another transmission request in the next random access period accordingly. During transmission period, PNC switches to directional mode and acts as pseudo WT for data transmission. The nodes begin to transmit data according to the scheduling information. If the data transmission is not successful due to blocked LOS by moving obstacles, the failures should be reported to the PNC during next random access period so that the PNC can re-schedule the transmission in the next transmission period.

Next, we develop the scheduling algorithm for concurrent transmissions during the transmission period. In some case, due to the network topology, some hops in a dense area have lower probability to transmit concurrently with other hops. Therefore, we need to give the hop, which has less transmission opportunity but higher traffic loads, a higher priority to be scheduled. To achieve this, we sort hops in the descending sequence based on the number of transmission loads to guarantee that the hops with highest loads will be scheduled first. Detail algorithm is described as follows. Initially, there are N slots in a transmission period. A transmission request $r_{I,J}$ (Jth hop in Ith path) needs $n(I,J)$ slots. The PNC sequentially checks the hops to be scheduled in the descending order of their traffic loads, thus gives highly loaded link a higher priority for data transmission. The PNC checks the concurrent transmission condition by comparing the radiation angles of all the transceivers in this group. The PNC also needs to check whether in this group there are adjacent hops which share one common node as a receiver or transmitter. This check is necessary because a wireless node operating in a half-duplex mode can not receive and transmit simultaneously. If the link does not conflict with all existing hops in the group, this link can be added in the group for concurrent transmission. The PNC updates the reserved slots based on the maximum number of required slots in this group. If a hop conflicts with all existing groups, the PNC needs to create a new group for this hop when the number of available slots is sufficient. Otherwise, the PNC rejects the request due to limited network resources. In this case, the PNC will remove all hops involved in the flow where the rejected hop belongs to. The pseudo code for the concurrent transmission scheduling algorithm is shown in Algorithm 1.

Algorithm 1 Concurrent Transmission Scheduling Scheme

BEGIN:
1: PNC receives a request $r_{I,J}$ for $n(I,J)$ time slots
2: **for** all non-empty group($T_b! =$ Null) **do**
3:   **if** $r_{I,J}$'s beams does not conflict with those of all existing hops in T_b **then**
4:     **if** $r_{I,J}$ does not have shared nodes with other hops in T_b **then**
5:       **if** $r_{I,J}$ requires extra slots, $n(I,J) - n(b) > 0$ **then**
6:         **if** Available slots $N \geq n(I,J) - n(b)$ **then**
7:           Schedule $r_{I,J}$ in group T_b;
8:           Update $T_b = T_b \bigcup \{r_{I,J}\}$;
9:           Update the available slots $N = N - [n(I,J) - n(b)]$;
10:           Update $n(b) = n(I,J)$;
11:           Update the allocated slots for $r_{I,J}$;
12:           Sort all hops in the descreasing order of allocated slots.
13:           go to END;
14:         **else**
15:           go to line 26;
16:         **end if**
17:       **else**
18:         Schedule $r_{I,J}$ in T_b;
19:         Update $T_b = T_b \bigcup \{r_{I,J}\}$;
20:         Update the allocated slots for $r_{I,J}$;
21:         Sort all hops in the decreasing order of allocated slots.
22:         Go to END;
23:       **end if**
24:     **end if**
25:   **end if**
26:   Next Group;
27: **end for**
28: **if** Available slots $N \geq n(I,J)$ **then**
29:   Start a new group $T(k) = \{r_{I,J}\}$;
30: **else**
31:   Reject request $r_{I,J}$ and release resources of all hops in $r_{I,J}$;
32: **end if**
END;

IV. PERFORMANCE EVALUATION

In this section, we describe the evaluation methodology and present performance results for our proposed multi-hop concurrent transmission scheme compared with the traditional single hop transmission scheme. We evaluate the performance of the proposed scheme in a typical indoor environment where 60 GHz WPANs are expected to deploy in, e.g. a large office space. The room is of 16×16 square meters. The PNC is placed in the center of the room and total 30 WTs are randomly distributed in the room. Each node is equipped with an directional antenna with beamwidth of 60 degrees, which corresponding to six beams at each node. A node can communicate with all other nodes within its transmission range if the LOS link is available. The moving obstacles located within the LOS link cause data rate great deduction in that hop. Therefore, we assume that for each link, the obstacles located in LOS link is with probability p and the time interval for obstacles to stay in LOS link is T_{NLOS}. According to (3), the received power increases with the decrease of link length r. The maximum data rate is achieved at the reference distance d_{ref}. The corresponding path loss at d_{ref} is PL_0. The parameters used in our simulations are listed in Table I. We simulate for various numbers of traffic flows in the WPAN and each traffic flow is transmitted between a pair of nodes which are randomly chosen. The traffic flow at the source node

Parameters	Symbol	Value
System bandwidth	W	1200 MHz
Transmission power	P_T	0.1mW
Background noise	N_0	-134dBm/MHz
Path loss exponent	n	2
Reference distance	d_{ref}	1.5m
Path loss at d_{ref}	PL_0	71.5 dB
Slot time	Δt	$18\mu s$
Number of slots in transmission period	N	1000
Probability of NLOS link	p	0.1
NLOS period for each link	T_{NLOS}	0.2ms

TABLE I
PARAMETERS

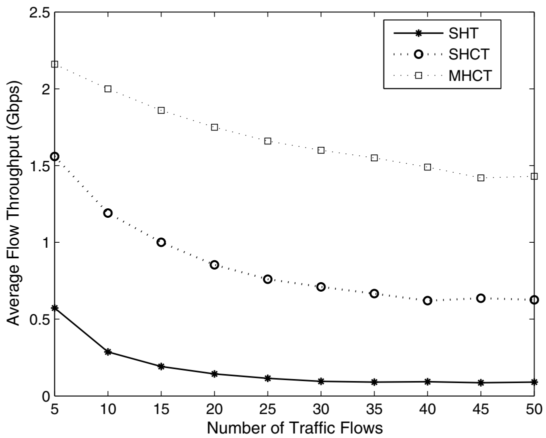

Fig. 3. Average flow throughput versus various number of traffic flows

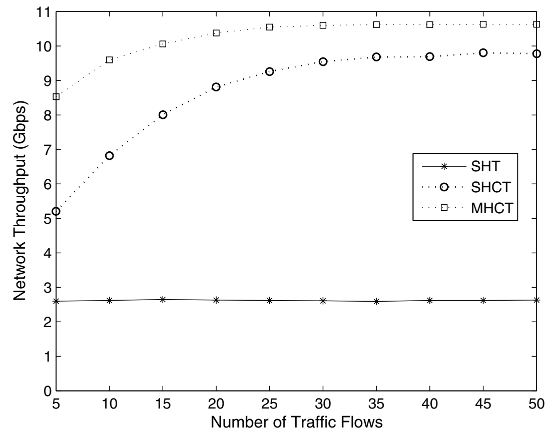

Fig. 4. Network throughput versus various number of traffic flows

is CBR flow with holding time uniformly distributed between 0.5 minute and 2 minutes.

We study the throughput when using the three transmission schemes, multi-hop concurrent transmission (MHCT), single hop concurrent transmission (SHCT) [6] and single hop transmission (SHT) to support P2P transmission in mmWave WPANs. In the single hop concurrent transmission scheme, if LOS link is unavailable, a neighboring WT is randomly chosen to relay the traffic. We use the single hop transmission scheme operating in a TDMA mode as a baseline for comparison.

Fig. 3 shows the average flow throughput for each traffic flow versus various numbers of flows in the network. It can be seen that the MHCT scheme can provide much higher flow throughput on average, which is essential for WPANs to support bandwidth-intensive applications, e.g. uncompressed HDTV. In our scheme, multiple hops of a traffic flow can concurrently transmit if they do not conflict with each other, which significantly increases the flow throughput. The average flow throughput decreases with the increase of the number of flows because more traffic flows share the network resources. From Fig. 3, we find that the concurrent transmissions can improve flow throughput. The proposed multi-hop concurrent transmission scheme outperforms both SHCT and SHT on flow throughput.

The network throughput is shown in Fig. 4. The SHT scheme is a TDMA transmission scheme and there is at most one transmission in the network at any given time. So the network throughput does not vary much for various numbers of flows in the network. The concurrent transmission can significantly increase the network throughput. Our MHCT scheme can support more concurrent transmissions and achieve higher gain on network throughput compared with SHCT scheme. In summary, our proposed scheme can achieve higher flow throughput and network throughput in comparison with SHCT scheme and SHT scheme.

V. Conclusion

In this paper, we have proposed a multi-hop concurrent transmission scheme for mmWave WPANs. Our scheme takes the unique characteristics of mmWave WPANs into consideration, high propagation loss, LOS link and directional antenna. The simulation results demonstrate that the proposed scheme significantly improves the traffic flow throughput and network throughput in comparison with single hop concurrent transmission scheme and single hop transmission scheme. The mmWave WPANs with our proposed multi-hop concurrent transmission scheme can provide higher data rate to enable the numerous multimedia applications requiring large bandwidth.

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