STDMA-based Scheduling Algorithm for Concurrent Transmissions in Directional Millimeter Wave Networks

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***Abstract*—In this paper, a concurrent transmission scheduling algorithm is proposed to enhance the resource utilization efficiency for multi-Gbps millimeter-wave (mmWave) networks. Specifically, we exploit spatial-time division multiple access (STDMA) to improve the system throughput by allowing both non-interfering and interfering links to transmit concurrently, considering the high propagation loss at mmWave band and the utilization of directional antenna. Concurrent transmission scheduling in mmWave networks is formulated as an optimization model to maximize the number of flows scheduled in the network such that the quality of service (QoS) requirement of each flow is satisfied. We further decompose the optimization problem and propose a flip-based heuristic scheduling algorithm with low computational complexity to solve the problem. Extensive simulations demonstrate that the proposed algorithm can significantly improve the network performance in terms of network throughput and the number of supported flows.**

I. Introduction

The US Federal Communications Commission (FCC) has approved an un-precedented 7 GHz spectrum in the 60 GHz band, which is referred to as mmWave communication. Due to the large available bandwidth, mmWave communication has been considered as one of the most promising candidates to support high-speed wireless multimedia services such as uncompressed high-definition TV (HDTV), instantaneous music, and image data transmissions, requiring multiple Gbps transmission rate [2], [6]. With the recent success in mmWave transceivers design [11], there have been growing interests in standardization efforts for mmWave systems, including IEEE 802.15.3c, IEEE 802.11 VHT and ECMA international TC48.

High propagation loss is one of the unique characteristics of mmWave communications since the free space propagation loss is proportional to the square of carrier frequency, e.g., 28 dB higher at mmWave band than at 2.4 GHz band. High-gain directional antenna is utilized to combat the severe propagation loss and achieve high data rate. The high propagation loss and the utilization of directional antenna result in relatively low multi-user interference (MUI), so that more concurrent transmissions can be supported to further improve the spatial reuse. In other words, appropriate concurrent transmissions are desirable in mmWave networks where nodes can communicate with each other in a peer-to-peer fashion, such as mmWave WPAN [1], [6] and outdoor mesh networks [2]. Therefore, in a spatial time-division multiple-access (STDMA) system [5], a time slot can be allocated to multiple communication links to improve the spatial reuse, thus significantly increase the system throughput. On the other hand, allowing multiple communication links to transmit in the same time slot leads to a higher MUI, which can decrease the system throughput. How to schedule appropriate concurrent transmissions in mmWave networks to improve system performance, e.g., network throughput and flow throughput, is an important and challenging issue.

The problem of concurrent transmission scheduling has been investigated extensively in the literature [3], [4], [6]–[8], [10], [14]–[16]. Multiple links are scheduled to transmit concurrently to improve the system throughput, based on the derived exclusive region or a link selection metric in [7], [8]. A concurrent transmission scheduling algorithm is proposed in [10] in wireless networks with rate adaptation, but it does not consider the unique features of mmWave systems, e.g., high propagation loss and the use of directional antenna. In [6], [15], multiple communication links are scheduled in the same time slot if the accumulated interference in this slot is below a specific threshold. The optimal concurrent transmission scheduling problem can be converted to a Knapsack problem which is known to be NP-complete [13]. With the knowledge of the hardness of concurrent transmission scheduling and the fact that the real time scheduling decision should be made within a few milliseconds, we propose an efficient heuristic scheduling algorithm with reasonable computational complexity.

The main contributions of this paper are three-fold. First, we formulate the concurrent transmission scheduling problem into an optimization one, i.e., to maximize the number of flows that can be scheduled successfully in the network while satisfying the throughput requirement of each flow. Second, we apply a dynamic programming approach to decompose the problem and propose a heuristic scheduling algorithm to move towards the sub-optimal solution in each time slot with significantly reduced complexity. Finally, extensive simulations are conducted to demonstrate that the proposed scheme is effective

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and efficient.

The remainder of the paper is organized as follows. The system model is described in Section II. The concurrent transmission scheduling is formulated as an optimization problem in Section III. A heuristic scheduling algorithm is proposed in Section IV. The performance of the proposed algorithm is evaluated by extensive simulations in Section V followed by concluding remarks in Section VI.

II. SYSTEM MODEL

We consider an indoor IEEE 802.15.3c WPAN composed of several wireless nodes (WNs) and a single piconet controller (PNC). Each WN in the network is equipped with an electronically steerable directional antenna and both transmitters and receivers can direct their beams towards each other for data transmission.

A. Transmission Data Rate

According to Shannon theory, the achievable data rate of flow i is determined by the received $SINR$. The received signal power is dependent of the path loss, shadowing, multipath fading, and other wireless channel impairments. As it is difficult to obtain the instantaneous channel conditions of all flows, we consider the average link throughput which is mainly affected by the path loss. It is assumed that the network topology and channel conditions remain unchanged during the period of each superframe. This assumption holds well for mmWave WPANs with low user mobility and line-of-sight (LOS) transmission. The path loss at distance d in dB can be estimated using the following model

$$PL(d)[dB] = PL(d_0)[dB] + 10\gamma log_{10}(\frac{d}{d_0}) \quad (1)$$

where γ is the path loss exponent which can be determined experimentally and is usually in the range of 2 to 6 for indoor environment [12]. $PL(d_0)$ is the path loss at the reference distance d_0, and can be calculated by the Friis free-space equation

$$PL(d_0)[dB] = 10 \cdot log_{10}(g_t g_r \frac{\lambda^2}{16\pi^2 d^2 L}) \quad (2)$$

where λ is the wavelength, L denotes the system loss factor, g_t and g_r are the antenna gains of the transmitter and receiver, respectively.

The received $SINR$ is determined by not only the received signal power but also the noise and the interference level. In mmWave WPANs, due to the high propagation loss and the use of directional antenna, concurrent transmissions can be supported with a relatively low MUI.

The received power from sender s_i to receiver r_j is $P_r^{i,j} = f_{i,j} k P_t d_{i,j}^{-\gamma}$, where $k = 10^{PL(d_0)/10}$ is the constant scaling factor corresponding to the reference path loss. $f_{i,j} = 1$ if the sender s_i and receiver r_j direct their beams towards each other; otherwise, $f_{i,j} = 0$. The received $SINR$ at receiver r_i is then given by

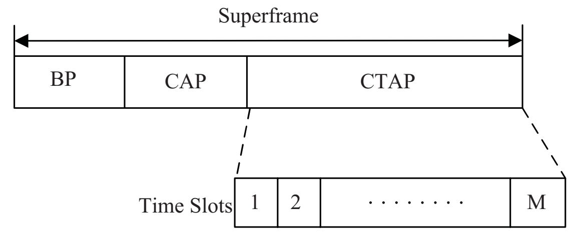

Fig. 1. IEEE 802.15.3 MAC structure

$$SINR_i = \frac{P_r^{i,i}}{WN_0 + b\sum_{l\neq i} P_r^{l,i}} = \frac{kP_t d_{i,i}^{-\gamma}}{WN_0 + b\sum_{l\neq i} f_{l,i} kP_t d_{l,i}^{-\gamma}} \quad (3)$$

where b denotes the MUI factor and it is related to the cross correlation of signals from different users, and W is the system bandwidth. For an AWGN channel, the achievable data rate of flow i (s_i and r_i) can be estimated according to Shannon's channel capacity as

$$R_i \leq \eta W \cdot log_2(1 + \frac{kP_t d_{i,i}^{-\gamma}}{WN_0 + b\sum_{l\neq i} f_{l,i} kP_t d_{l,i}^{-\gamma}}) \quad (4)$$

where $\eta \in (0, 1)$ is the coefficient describing the efficiency of the transceiver design.

B. Directional MAC Structure

A hybrid multiple access of CSMA/CA and TDMA is applied. The superframe structure is shown in Fig. 1. A superframe consists of three phases: the Beacon period (BP) for network synchronization and control messages broadcasting from the PNC, the contention access period (CAP) for devices sending transmission requests to the PNC 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. There are at most M channel time slots in CTAP of each superframe. The PNC can adjust the length of CTAP adaptively according to the total occupied number of time slots if it does not exceed M. Currently, 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 use of directional antenna and the high propagation loss of mmWave band, we allow concurrent transmissions to exploit the spatial reuse. In other words, each time slot in CTAP can be allocated to multiple flows.

III. OPTIMAL SCHEDULING PROBLEM FORMULATION

There are N transmission requests submitted to the PNC and each of them specifies a required minimal throughput R_{min}^i. The CTAP of each superframe contains M time slots. For the k^{th} time slot of the CTAP in a superframe, the scheduling decision can be represented by a control vector $U_k = [u_{k,1}, u_{k,2}, ...u_{k,N}]$, where $u_{k,i} = 1$ if flow i is scheduled in the k^{th} time slot, otherwise $u_{k,i} = 0$. To maximize the total throughput, we first formulate the concurrent scheduling problem as an optimization problem (P1):

$$\max_{u_{k,i}\in\{0,1\}} \sum_{k=1}^{M}\sum_{i=1}^{N} R_{k,i} \tag{5}$$

where

$$R_{k,i} = \eta W \cdot log_2(1 + \frac{k u_{k,i} P_t d_{i,i}^{-\gamma}}{W N_0 + b\sum_{l\neq i} f_{l,i} u_{k,l} k P_t d_{l,i}^{-\gamma}}) \tag{6}$$

The optimization problem is a non-linear integer programming problem. The transmission data rate of each flow in a time slot can not been determined until scheduling decision for this slot is made because of the MUI. The concurrent transmission scheduling problem is similar to $0-1$ Knapsack problem [13] in the case that items (flows) can be added into the knapsack (allocated to the slot). The objective is to maximize the total profit (total throughput) with the weight (interference) constraints. It is well-known that the Knapsack problem is NP-complete [13]. The concurrent transmission scheduling problem here is even more difficult than the Knapsack problem, since the profits of items (flow throughput) would change with the selected subsets of flows. Therefore, the existing approximation algorithms for Knapsack problems cannot be applied directly. In addition, the optimal solution may be unfair because the time slots are more likely to be allocated to those flows with a higher throughput while some unlucky flows will be starved. In other words, the throughput requirements of the starved flows can not be satisfied.

The bandwidth-intensive applications supported by mmWave networks require multi-Gbps throughput, e.g., the mandatory data rate for uncompressed video streaming is 1.78 or 3.56 Gbps. The transmission demands need to be satisfied to provide the required quality of service (QoS) for the applications. With TDMA scheme, to achieve the high flow throughput, each flow will be allocated a greater number of time slots. Thus, we formulate an optimal scheduling problem to find maximum number of flows scheduled in the network, subject to the minimum throughput requirement R_{min}^i of each flow. The optimal scheduling problem with the constraints is formulated as (P2):

$$\max_{u_{k,i}\in\{0,1\}} \sum_{i=1}^{N} I_i \tag{7}$$

where

$$I_i = \begin{cases} 1, & F_i \geq R_{min}^i; \\ 0, & \text{otherwise}; \end{cases} \tag{8}$$

I_i indicates whether the transmission demand of flow i is satisfied. A flow is scheduled successfully if and only if its minimum throughput requirement is ensured. By allowing a number of flows to transmit concurrently in each time slot, we try to maximize the number of flows in the network aiming to utilize the resource efficiently. F_i denotes the throughput of flow i according to the scheduling results and is defined as

$$F_i = \frac{\sum_{k=1}^{M} R_{k,i}\Delta T}{T_{BP} + T_{CAP} + M\Delta T} \tag{9}$$

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 given in (6). Maximizing the number of flows successfully scheduled in the network (P2) has advantages on fairness and resource utilization efficiency, compared with maximizing the network throughput with constraints that $F_i \geq R_{min}^i$ $(i = 1, 2, 3...N)$ (P1 with constraints). First, P1 with constraints is for the case that the network resources are sufficient to meet the transmission demands of all flows in the network, which holds well only for the scenario that a small number of flows need to be scheduled in the networks. In this case, the transmission demands can be satisfied even without efficient scheduling. Thus, it is more interesting in considering a more challenging case where the network resources are limited compared with the intensive traffic demands of users. Second, to maximize the network throughput, network resources (time slots) would be allocated to the flows with a higher transmission data rate while satisfying the throughput requirement of each flow. The extra throughput of a flow makes little contributions on improving the network performance. To utilize the resource efficiently, we allocate the resources which are assigned to flows to obtain extra flow throughput, to other flows. Therefore, the network can support more users with limited amount of resources.

The problem of P2 is a non-convex integer programming problem and is NP-hard. The searching space is $2^{N\cdot M}$ if exhaustive searching approach is implemented. Given the hardness of solving the optimization problem of P2 in polynomial time, we propose a practical heuristic scheduling algorithm to obtain the scheduling decision with full consideration of the unique features of mmWave networks.

IV. Scheduling Algorithm Design

In this section, we present a heuristic scheduling algorithm for optimization problem (P2), considering the unique characteristics of mmWave networks.

Since the scheduling problem has a slotted structure in the time domain, we make the scheduling decision slot by slot instead of optimizing all the N flows in M time slots simultaneously. The decomposed method can solve the problem in an iterative manner by reducing the searching space of the states from $2^{N\cdot M}$ to 2^N. The problem of maximizing network throughput based on the slotted structure has been studied in [10]. In this paper, we propose a slot-based concurrent transmission scheduling algorithm to allow as many flows scheduled in the network as possible, considering the minimum throughput requirement for each flow. For the k^{th} time slot, the scheduling algorithm generates the decision vector U_k that indicates which flows are scheduled in the k^{th} slot. The schedule for the data transmission period is $\widetilde{U}_{N\times M} = [U_1, U_2...U_k...U_M]$.

To schedule as many flows as possible within the data transmission period while satisfying the minimum throughput requirement of each flow, we have the following requirements on algorithm design: 1) transmitting as much data as possible in each slot; and 2) reducing the number of *fractional flows*, where *fractional flow* is defined as a flow which is scheduled in the network, but its transmission throughput requirement is not satisfied. The fractional flow results in inefficient resource utilization since the resources (time slots) are allocated to it but the fractional flow can not support the specific applications.

Algorithm 1 Concurrent Transmission Scheduling Algorithm

BEGIN:

PNC receives transmission request $r_i (i = 1, 2...N)$ requiring minimum throughput R^i_{min}

Initialize the scheduling basis vector $\mathbf{B}_1 = \overrightarrow{0}$

for non-scheduled slot $k (1 \le k \le M)$ **do**

  if $B_k = B_{k-1}$ **then**

    $U_k = U_{k-1}$

    go to line 20

  else

    repeat

      for flow i=1 to N **do**

        if $b_{k,i} = 1$ or $b_{k,i}$ is marked as unchanged **then**

          Keep the corresponding $b_{k,i}$ the same

        else

          if flow i does not have shared nodes with other links scheduled in slot k **then**

            set $b_{k,i} = u_{k,i}$ according to

$$\arg\max_{u_{k,i} \in \{0,1\}} \{R_{k,i} + \sum_{l=1, l \neq i}^{N} R_{k,l}\}$$

          end if

        end if

      end for

    until $B_k = [b_{k,1}, b_{k,2}, ...b_{k,N}]$ converges

    update $U_k = B_k$

    update $F_i = \frac{\sum_{n=1}^{k} R_{n,i} \Delta T}{T_{BP} + T_{CAP} + M \Delta T}$

    if any $F_i \ge R^i_{min}$ **then**

      change $b_{k,i}$ from 1 to 0, and mark it as unchanged

    end if

    update $B_{k+1} = B_k$

    update k=k+1

    if $k > M$ **then**

      go to END

    end if

  end if

end for

END;

During the CAP period of the m^{th} superframe, the PNC receives a number of transmission requests, each of which needs a specific required minimum flow throughput. The PNC makes the scheduling decision for the $(m+1)^{th}$ CTAP before the $(m+1)^{th}$ beacon period, during which the PNC distributes the scheduling information to all the nodes in the network. The nodes start data transmission according to the scheduling information in the $(m+1)^{th}$ CTAP period. To transmit as much data as possible in each time slot, let flow i be active in slot k if the profit of adding flow i is greater than the degradation of throughput it causes to other pre-selected flows. Based on this approach, we propose a flip-based algorithm to obtain the set of flows active 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 set can increase the throughput in slot k. Otherwise, we set $u_{k,i} = 0$. The above process is repeated until U_k converges. Therefore, the searching complexity for each slot changes from 2^N to $O(T_1 N)$, where T_1 is the number of iterations for U_k to converge. 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. We do not flip $u_{k,i}$ if flow i's minimum throughput requirement is satisfied and set $u_{k,i} = 0$ for all the following time slots. Also, to minimize the number of fractional flows, $u_{k,i}$ is set to 1 if flow i is scheduled in the previous time slot but its transmission requirement is not satisfied. We only flip the variables of $u_{k,i}$ if the corresponding flow i is not scheduled in the previous slots, to obtain better throughput performance in slot k. Then, the same schedule is used for the following time slots until the throughput requirement of one flow is satisfied. The above procedure is repeated until all the time slots have been scheduled. The pseudo code for the concurrent transmission scheduling algorithm is shown in Algorithm 1.

V. PERFORMANCE EVALUATION

In this section, we describe the performance evaluation procedure and present the simulation results for the proposed scheme compared with other concurrent transmission scheduling schemes. We evaluate the performance of the proposed scheme in terms of the number of scheduled flows and the network throughput in a 10×10 m^2 area. The PNC is placed in the center and WNs are randomly distributed in the area. Each node is equipped with a steerable directional antenna with a beamwidth of $60°$. There are sufficient number of flows with constant bit rates, and we schedule them in the network. The source and destination of each flow are randomly selected. The required throughput of each flow is uniformly distributed between 1.5 Gbps and 3.5 Gbps. All senders use the same transmission power level for transmission. A typical physical layer parameter setting of mmWave systems is shown in Table I.

We compare the proposed concurrent transmission scheduling scheme with three other transmission schemes, namely, the exhaustive search, exclusive region based scheduling scheme [7], and TDMA scheme. Exhaustive search takes long time to achieve the optimal solution, exclusive region based scheduling only allows non-interfering links to transmit concurrently, and TDMA scheme supports only one active link in each time slot.

Fig. 2 shows the number of flows scheduled successfully in the network. The total number of flows is $N = 50$. It is shown that the proposed scheme can utilize the resource more

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	n	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

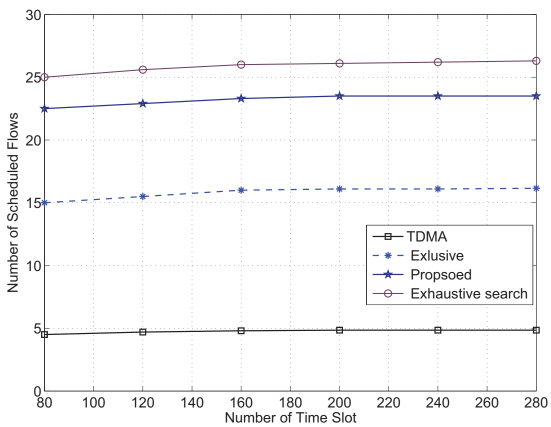

Fig. 2. Number of Scheduled Flows

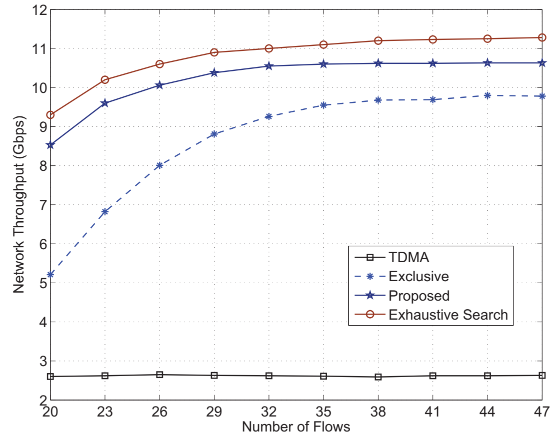

Fig. 3. Network Throughput in mmWave WPAN

efficiently than exclusive region based scheduling and TDMA scheme since it can schedule more flows in the network, each of which needs a minimum throughput requirement.

The network throughput is shown in Fig. 3. For TDMA scheme, there is at most one transmission at any time slot in the network. Concurrent transmissions can enhance the spatial reuse and significantly increase the network throughput. Our proposed scheme can further improve the network throughput by allowing both interfering links and non-interfering links to transmit simultaneously, compared with exclusive region based scheduling [7].

VI. Conclusion

In this paper, we have proposed a heuristic algorithm for appropriate concurrent transmissions scheduling in mmWave networks, considering the unique characteristics of mmWave networks, i.e., high path loss, directional antenna, and large required flow throughput. The proposed algorithm can greatly reduce the computational complexity and achieve the sub-optimal solution quickly. The simulation results demonstrate that the proposed algorithm significantly improves the resource utilization efficiency in mmWave networks. The mmWave networks with our proposed concurrent transmission scheduling algorithm can support more number of users.

References

[1] K.H. Liu, X. Ling, X. Shen, and J.W. Mark, “Performance Analysis of Prioritized MAC in UWB-WPAN with Bursty Multimedia Traffic,” *IEEE Trans. Vehicular Technology,*, vol. 57, no. 4, pp. 2462-2473, July 2008.

[2] S. Singh, R. Mudumbai, and Upamanyu Madhow, “Distributed Coordination with Deaf Neighbors: Efficient Medium Access for 60 GHz Mesh Networks,” *Proc. IEEE INFOCOM*, May 2010.

[3] H. Jiang, and W. Zhuang, “Effective Packet Scheduling with Fairness Adaptation in Ultra-wideband Wireless Networks,” *IEEE Trans. Wireless Commun.,* vol. 6, no. 2, pp. 680-690, Feb. 2007.

[4] 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.

[5] R. Nelson and L. Kleinrock, “Spatial-TDMA: A collision-free multihop channel access protocol,” *IEEE Trans. Commun.,* vol. 33, no. 9, pp. 934-944, Sept. 1985.

[6] 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

[7] J. Qiao, L. X. Cai, and X. Shen, “Multi-Hop Concurrent Transmission in Millimeter Wave WPANs with Directional Antenna,” *Proc. IEEE ICC*, 23-27 May 2010.

[8] 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.

[9] L. X. Cai, L. Cai, X. Shen, and J. W. Mark, “Spatial Multiplexing Capacity Analysis of mmWave WPANs with Directional Antennae,” *Proc. IEEE GLOBECOM*, Nov. 2007.

[10] Z. Yang, L. Cai and W. Lu, “Practical Concurrent Transmission Scheduling Algorithms for Rate-adaptive Wireless Networks,” *Proc. IEEE INFOCOM*, March 2010.

[11] RF and mmWave Design at Berkeley Wireless Reaearch Center. [Online].Avaiable:http://bwrc.eecs.berkeley.edu/Research/rf_and_mmwave.htm

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

[13] D. Pisinger, “Where are the hard knapsack problems?” *Computers and Operations Research*, pp. 2271–2284, 2005.

[14] P. Dutta, V. Mhatre, D. Panigrahi, and R. Rastogi, “Joint Routing and Scheduling in Multi-hop Wireless Networks with Directional Antennas,” *Proc. IEEE INFOCOM*, March 2010.

[15] C. S. Sum, Z. Lan, M. A. Rahman, et. al., “A Multi-Gbps Millimeter-wave WPAN System based on STDMA with Heuristic Scheduling,” *Proc. IEEE GLOBECOM*, June 2009.

[16] K. H. Liu, L. Cai, and X. Shen. “Exclusive-region based scheduling algorithms for UWB WPAN,” *IEEE Trans. Wireless Commun.*, vol. 7, no. 3, pp. 933-942, Jan. 2008.