MAC-Layer Integration of Multiple Radio Bands in Indoor Millimeter Wave Networks

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***Abstract*—The abundant bandwidth at 60 GHz band (around 7 GHz) offers the potential for multi-Gbps indoor wireless connections for bandwidth-intensive applications. However, 60 GHz millimeter wave (mmWave) links are highly susceptible to blockage since it is difficult to diffract around obstacles. In this paper, we propose multi-radio band integration framework to have 2.4/5 GHz band assist mmWave band to prevent drastic data rate reduction. Specifically, the problem of multi-radio band integration with TDMA-based MAC is formulated as an optimization problem. We decompose the problem into two sub-problems: radio band selection and space-time scheduling. Firstly, considering network load and mmWave channel status, we define start-integration threshold and stop-integration threshold to select an active radio band for data transmission. Secondly, a space-time scheduling scheme is proposed to allow multiple flows over different radio bands operate concurrently to exploit the spatial reuse. Simulation results of the proposed multi-radio band integration mechanism demonstrate significant improvements of network connectivity and the number of supported traffic flows.**

I. Introduction

Communications at 60 GHz millimeter wave (mmWave) band has been of intensive interest for indoor applications across wireless personal area networks (WPANs) and wireless local area networks (WLANs) [1], [3]–[5]. The abundant bandwidth in the unlicensed 60 GHz band (around 7 GHz), with the recent successes in mmWave transceivers design [6], enables high-rate (multi-Gbps) wireless connections to support short-range multimedia services such as uncompressed high-definition TV (HDTV) and high speed downloading service [7], [8].

The unique propagation features of 60 GHz band make mmWave networks distinguishing from the networks in lower radio bands. mmWave signals suffer from high attenuation as free space propagation loss is proportional to the square of carrier frequency, e.g., 28 dB higher than that at 2.4 GHz. A directional antenna with high directivity gain is used to combat the severe propagation loss and achieve high data rate. The high propagation loss and the utilization of directional antenna result in relatively lower multiuser interference (MUI), which enables more efficient spatial reuse by allowing concurrent transmissions [1], [3], [4]. Since non-line-of-sight (NLOS) transmissions at mmWave band suffer from severe attenuation and a shortage of multipath [10], mmWave communications depends on line-of-sight (LOS) transmissions to achieve high transmission rate. The obstacles and moving people in indoor environments can easily block the LOS transmissions and result in significant reduction on received signal power (20-30 dB) and link outage.

To support the multimedia applications with stringent QoS requirements, we need to improve performances of mmWave networks on transmission range and throughput reliability. Current WLAN technology (based on IEEE 802.11 family) operates on 2.4/5 GHz band with a successful market presence. It can keep network connectivity well within feasible range while it can not achieve high data rate (below 1 Gbps) [11]. The complementary nature of 60 GHz band and the lower 2.4/5 GHz band makes the integration of multi-radio bands a very appealing approach to provide reliable multi-Gbps throughput. In this paper, we first formulate the problem of multi-radio band integration of TDMA mode into an optimization model. Then, the problem is decomposed into two sub-problems of radio band selection and space-time scheduling. Considering mmWave channel and network load status, the start-integration threshold and stop-integration threshold are determined to switch the transmission between mmWave band and 2.4/5 GHz band. Space-time scheduling scheme is proposed to allow multiple communication links free of interference, either in mmWave band or lower radio band, to operate concurrently to improve spatial reuse.

The remainder of the paper is organized as follows. Related work is reviewed in Section II. The system model is described in Section III. The multi-radio band integration problem is formulated as an optimization model in Section IV. A two-component integration mechanism is proposed in Section V. Simulations for the proposed mechanism is conducted in Section VI, followed by concluding remarks in Section VII.

II. Related Work

A wide range of MAC protocols and algorithms for mmWave networks have been proposed to extend the network coverage and improve the throughput of flows with LOS link blockage [1], [3], [4], [12]–[15]. Since mmWave signal power degrades significantly over distance, it can achieve higher flow throughput with proper selection of the relay nodes [1], [12], [13]. Meanwhile, multi-hop transmission also keeps network connectivity by replacing the blocked link with a multi-hop alternative path [12]. Cooperative communication is another

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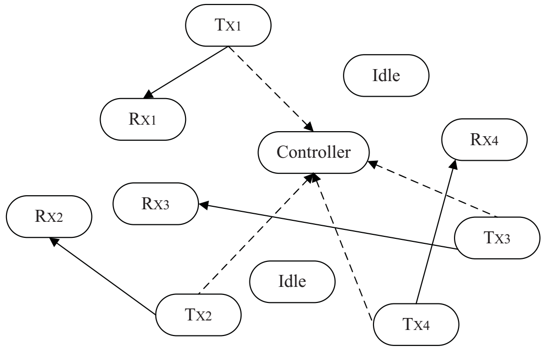

Fig. 1. Indoor mmWave Network Architecture

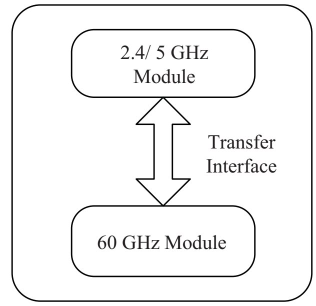

Fig. 2. Wireless Operation Mode of Each Node

strategy to deal with mmWave channel susceptibility to human body or furniture [14], [15]. In [15], a scheduling algorithm is proposed for cooperative relay and maximize the system throughput by scheduling a transmission from the relay to the destination coexisting with a transmission from the source to the relay of another link in the same time slot. To further improve the transmission efficiency [14], concurrent transmission scheduling algorithm is proposed to allow simultaneous transmissions among all the links, while mitigating the transmission redundancy resulting from cooperative communication.

Both non-cooperative [1], [12], [13] and cooperative [14], [15] multi-hop transmission strategies involve more nodes for data transmission. Both strategies would make the network overloaded, and introduce more communication and computation overheads (especially centralized scenarios). They can keep network connectivity well for load-light networks. Moreover, it is possible that a node becomes a network bottleneck if it is preferred to work as a relay by many flows. In this paper, we consider the scenario that many active users contend for network resources which are not sufficient enough to satisfy the transmission demands of all the users. To reduce transmission redundancy caused by relaying, the integration of mmWave band and 2.4/5 GHz frequency bands is proposed to address the problem of transient link blockage and extend the network coverage.

Most of previous work [16]–[19] on integrating heterogeneous wireless networks concentrates on network layer quality of service (QoS), such as blocking probability. Integration at MAC layer is addressed by few work since different networks utilize their own MAC protocol. Moreover, most existing work focuses on network integration for traditional internet applications and voice service [16]–[19], which do not require high transmission rate. In this paper, we propose integration mechanism for multi-radio bands, aiming to provide high data rate for multimedia applications requiring guaranteed performance.

III. System Model

We consider indoor wireless access networks in a single spacious room such as a large office, conference room, and airport, in which many active users contend for network resources and consequently, the MAC mechanism would be designed for the challenging case that the network resources are not sufficient to satisfy the traffic demands of all the users.

A. System Architecture

Wireless indoor mmWave networks (e.g., WPANs/WLANs) have centralized network structure. As shown in Fig. 1, the network is composed of several wireless devices and one network controller. Each pair of nodes (either wireless device or network controller) can communicate to or relay for each other in a peer-to-peer fashion. As shown in Fig. 2, each node in the network has the communication modes of 2.4/5 GHz operation and 60 GHz operation. The system can support fast communication mode transfer between 2.4/5 GHz operation and 60 GHz operation.

All wireless nodes are equipped with electronically steerable directional antennas for mmWave communication and omni-directional antenna for 2.4/5 GHz communication. With beamforming technologies [9] of directional antenna, the wireless nodes can determine the best transmission/reception beam pattern and direct the beams towards each other for transmission and reception at mmWave band.

B. MAC Structure

As indicated in the standards [7], [8] for indoor mmWave networks (either WLANs or WPANs), the networks are based on hybrid multiple access of CSMA/CA and TDMA. Future mmWave indoor networks are expected to support a wide range of applications from HDTV to web browsing, with various QoS requirements. CSMA/CA is used for a burst-type of applications with lower required transmission data rate while TDMA is used to provide guaranteed performance for applications with stringent QoS requirements. As shown in Fig. 3, there are three phases included in each superframe: channel time allocation period (CTAP) composed of M channel time slots for bandwidth-intensive and delay-sensitive applications, contention access period (CAP) based on CSMA/CA for non-delay sensitive applications and the reception of transmission requests, and the Beacon period (BP) for control messages and synchronization among wireless nodes, respectively.

During each period, there are two non-interfering radio bands (2.4/5 GHz and 60 GHz) available for data transmission. Taking into account the characteristics of each radio band

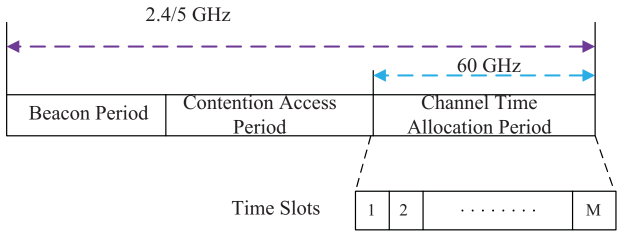

Fig. 3. MAC structure

and the QoS requirements of the transmitted data during each period, the assignment of radio bands is as follows: during BP period, we use 2.4/5 GHz band to achieve reliable transmission for network management information; 2.4/5 GHz band is active in CAP period for data transmission since the applications during CAP do not need very high throughput; mmWave radio band becomes the main transmission medium to support bandwidth-intensive applications during CTAP period while 2.4/5 GHz band assists mmWave operation if the LOS link is blocked. In this paper, we focus on the integration of multi-radio bands in CTAP period. With recent advances of the standards in IEEE 802.11 family [11], WLANs operating in 2.4/5 GHz band are expected to provide larger data rate than before, which can assist the mmWave band to provide required QoS for bandwidth-intensive applications with proper scheduling algorithm in TDMA mode.

C. Transmission Rates of LOS and NLOS

The integration mechanism of multi-radio bands determines the active frequency bands in each time slots of CTAP period. Transmission data rate is essential for bandwidth-intensive applications and it is involved in the integration mechanism as the criteria for radio band selection.

With additive white Gaussian noise (AWGN) and broadband interference assumed as Gaussian distribution, the channel capacity is given by:

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

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

According to Friis transmission equation, the received signal power P_R is a function of the transmitted power P_T and the transmission distance d. In free space, it is

$$P_R(d) = P_T G_R G_T (\frac{\lambda}{4\pi})^2 (\frac{1}{d})^\gamma \tag{2}$$

where G_T and G_R are the antenna gains of the transmitter and the receiver, λ is the wavelength, and γ is the path loss exponent. For LOS scenario, the transmission data rate can be obtained by combining (1) and (2) as

$$R \leq C = W\log_2[1 + \frac{P_T G_R G_T \lambda^2}{16\pi^2 (N_0 + I) W d^\gamma}] \tag{3}$$

For NLOS communication at 60 GHz band in indoor environment, the received signal power greatly depends on the communication scenarios and it is difficult to derive the general channel modeling. It is reported that the shadowing effect of human blockage can add up serious attenuation, up to 40 dB. Since the channel status has significant impact on radio band selection mechanism, we use the feedback (from wireless devices to network controller) to obtain the accurate NLOS channel status, rather than using a general model to estimate it.

IV. Problem Formulation for Integration of Multi-radio Bands

As discussed in Section III-B, $\mathcal{N}$ transmission requests are sent from wireless devices to the network controller, and each of them requires a minimum throughput of R^j_{min} (j =1,2...$\mathcal{N}$). During each superframe, the CTAP period includes M time slots. For the i^{th} time slot, the multi-radio band integration mechanism indicates which radio band is active for each traffic flow. Therefore, the integration mechanism can be determined by a vector $V_i = [v_{i,1}, u_{i,2}, ...u_{i,\mathcal{N}}]^T$, where $v_{i,j} = [v_{i,j,1}, ...v_{i,j,\mathcal{K}}]$ with $\mathcal{K}$ as the total number of available radio bands. $v_{i,j,k} = 1$ if flow j is active in the i^{th} time slot and transmitted over k^{th} radio band; otherwise $v_{i,j,k} = 0$.

As we discussed in [4], it is better to maximize the total number of supporting flows than the total network throughput for mmWave networks with limited resources to support flows with mandatory throughput requirements. We first formulate the problem of multi-radio band integration in TDMA mode as an optimization problem:

$$\max_{v_{i,j,k}\in\{0,1\}} \sum_{j=1}^{\mathcal{N}} I_j \tag{4}$$

where

$$I_j = \begin{cases} 1, & F_j \geq R^j_{min}; \\ 0, & \text{otherwise;} \end{cases} \tag{5}$$

$$F_j = \frac{\sum_{i=1}^{\mathcal{N}} \sum_{k=1}^{\mathcal{K}} R_{i,j,k} \Delta T}{T_{BP} + T_{CAP} + M\Delta T} \tag{6}$$

$$R_{i,j,k} = \eta W \cdot log_2(1 + \frac{v_{i,j,k} P_T d_j^{-\gamma}}{W N_0 + \sum_{l\neq j} v_{i,l,k} P_I(i,l,k)}) \tag{7}$$

F_j is the average throughput of flow j in each superframe, I_j indicates whether j^{th} flow's throughput satisfies the minimum transmission requirement R^j_{min}, and $P_I(i,l,k)$ is the interference power from flow l to flow j at k^{th} radio band in the i^{th} time slot. ΔT, T_{BP}, and T_{CAP} are the duration of each time slot in CTAP, duration of BP, and duration of CAP, respectively.

This optimization problem is non-convex $0-1$ integer programming problem and is NP-hard. With exhaustive searching approach, the searching space is $2^{\mathcal{N}\cdot M\cdot\mathcal{K}}$. To reduce the computation time and obtain the real-time solution, in the following, we propose integration mechanism for multi-radio bands with full consideration of the unique characteristics of the radio bands and the transmission requirements.

V. MAC Design for Multi-radio Band Integration

With the co-existence of both mmWave band and 2.4/5 GHz band, radio band selection is one of the major issues to coordinate multiple radio bands for the wireless devices in the network. Many existing centralized and distributed selection algorithms considering user mobility are proposed to select the best available network or handover in heterogeneous network environment [16], [17].

Contention-based MAC for WLAN operating 2.4/5 GHz band can not provide performance guarantee. The multimedia applications (e.g., HDTV and video streaming) for mmWave indoor networks have stringent QoS requirements and need guaranteed performance. Therefore, both mmWave band and 2.4/5 GHz band are expected to make use of contention-free TDMA mode. Due to the high propagation loss and utilization of directional antenna, concurrent transmissions can be enabled in mmWave band without interference [1], [2]. Meanwhile, with multiuser multiple-input and multiple-output (MU-MIMO) technology and preprocessing of data flows, IEEE 802.11ac WLAN technology [11] can also support concurrent transmissions free of interference in 2.4/5 GHz band. Therefore, how to schedule concurrent transmissions at different radio bands is another significant issue to be addressed.

A. Radio Band Selection

The key idea behind our MAC-layer multi-radio band integration framework is to utilize a mix of peer-to-peer transmission at mmWave band for primary connectivity and resort to 2.4/5 GHz band to prevent drastic reduction of data rates or link outage when the LOS component between two wireless devices at mmWave band is obstructed. We define start-integration threshold ($R_{S,j}$) to initiate the assist of 2.4/5 GHz band, and stop-integration threshold ($R_{T,j}$) to return to the mmWave transmission. If the instantaneous data rate of mmWave communication of the j^{th} flow goes down to $R_{S,j}$, the link blockage would occur and we start to use 2.4/5 GHz band for data transmission. On the other hand, the instantaneous data rate of mmWave communication for the j^{th} flow reaches $R_{T,j}$, then the transmission at 2.4/5 GHz would be switched to mmWave band. The start-integration threshold $R_{S,j}$ is given as

$$R_{S,j} = (1 + \frac{N_{mm}}{\widetilde{N}})\eta_j W \log_2[1 + \frac{P_T G_R G_T \lambda^2}{16\pi^2 (N_0 + I) W d_j^{\gamma}}] \quad (8)$$

where N_{mm} is the number of flows operating in mmWave band, $\widetilde{N}$ is the total number of flows scheduled in the network in both mmWave band and 2.4/5 GHz band, d_j is the transmission distance of flow j, and η_j is a coefficient corresponding to additional 20 dB attenuation of LOS communication. All the other parameters in (8) are corresponding to mmWave system. If there are large number of flows transmitting over 2.4/5 GHz band, the start-integration threshold $R_{S,j}$ is decreased (e.g., $(1 + \frac{N_{mm}}{\widetilde{N}})$ decreases) to let less flows (i.e., flows with very deep attenuation) be transmitted over 2.4/5 GHz band, in order to reduce the congestion at 2.4/5 GHz band. The stop-integration threshold $R_{S,j}$ is given as

$$R_{T,j} = (2 - \frac{N_L}{\widetilde{N}})\delta_j W \log_2[1 + \frac{P_T G_R G_T \lambda^2}{16\pi^2 (N_0 + I) W d_j^{\gamma}}] \quad (9)$$

where N_L is the number of flows operating in lower radio band (i.e., 2.4/5 GHz band), and δ_j is a coefficient. All the other parameters in (9) are corresponding to 2.4/5 GHz system. Similarly, if there are large number of flows operating over 2.4/5 GHz band, to utilize the resource efficiently, we decrease the stop-integration threshold $R_{T,j}$, to let more flows operating at 2.4/5 GHz band switch to mmWave band.

B. Space-Time Scheduling

During the BP period of the m^{th} superframe, the network controller collects the mmWave channel status information and compares them with the start-integration threshold and stop-integration threshold. Then, it determines which radio band is used for data transmission. 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 with minimum flow throughput requirement. Based on the information received during BP and CAP period, network controller makes space-time scheduling decision before $(m+1)^{th}$ BP period. The scheduling information indicates which links are active during each time slot of the $(m+1)^{th}$ CTAP period and the corresponding beams directing to each other if mmWave band is active. During $(m+1)^{th}$ BP period, network controller distributes the scheduling information to all the nodes. The nodes start data transmission accordingly in the $(m+1)^{th}$ CTAP period.

A transmission request r_j for flow j comes with minimum throughput requirement R^j_{min}. If r_j is in mmWave band, then network controller can obtain the number of time slots for flow j. Then, it checks the concurrent transmission condition and schedules flow j in this group if flow j does not conflict with all the existing flows in the current group. Meanwhile, network controller updates the reserved slots for this group based on the maximum number of required time slots of all the flows in this group. If flow j conflicts with at least one flow in the current group, network controller will check the following groups sequentially for concurrent transmissions. If a flow can not be scheduled in the existing groups, network controller would make a new group for it if there is sufficient number of available slots in CTAP period. Otherwise, the transmission request of flow j would be declined. If r_j is in 2.4/5 GHz band, the network controller would repeat above process and schedule it in CTAP period. The interference-free concurrent transmission condition for two mmWave links is that any transmitter is outside the beamwidth of the other receiver or does not direct its beam to the other receiver if it is within the beamwidth of the other receiver. The concurrent transmissions in 2.4/5 GHz band is bounded by the number of antennas on each node. Since the transmission rate of 2.4/5 GHz band is much lower than that of mmWave band, the flows over 2.4/5 GHz band need to be allocated more number of time slots to provide the required throughput. The pseudo code for space-time scheduling is presented in Algorithm 1.

Algorithm 1 Space-time Scheduling

BEGIN:

1: Network controller receives r_j requesting $n(j)$ time slots
2: **if** Flow j is over mmWave band **then**
3:   **for** All non-empty group (G_b! = Null) **do**
4:     **if** Flow j does not conflict with all existing flows in G_b **then**
5:       **if** r_j requires extra slots, $n(i, j) - n(b) > 0$ **then**
6:         **if** Available slots $L \geq n(j) - n(b)$ **then**
7:           Schedule r_j in group G_b;
8:           Update $G_b = G_b \bigcup \{r_j\}$;
9:           Update the available slots $L = L - [n(j) - n(b)]$;
10:           Update $n(b) = n(j)$;
11:           Update the allocated slots for r_j;
12:           Go to END;
13:         **else**
14:           Go to line 28;
15:         **end if**
16:       **else**
17:         Schedule r_j in G_b;
18:         Update $G_b = G_b \bigcup \{r_j\}$;
19:         Update the allocated slots for r_j;
20:         Go to END;
21:       **end if**
22:     **end if**
23:     Next Group;
24:   **end for**
25:   **if** The number of available slots is larger than $n(j)$ **then**
26:     Start a new group $G(y) = \{r_j\}$;
27:   **else**
28:     Decline request r_j;
29:   **end if**
30: **else**
31:   GO to line 3;
32: **end if**

END;

VI. Performance Evaluation

In this section, performance evaluation settings and simulation results are described for the proposed multi-radio band integration mechanism.

In a typical indoor environment of large office, i.e., a square area of $30 \times 30\ m^2$, network controller is placed in the center of the room and 40 wireless nodes are randomly distributed in the room. Each node can communication with all the other nodes in the room in both mmWave band in directional antenna and 2.4/5 GHz band in omni-directional antenna. Each node supports beamforming with steerable directional antennas at mmWave band with a beamwidth of $45°$ for both transmission and reception. Because the gain of the main lobe of typical directional antennas is more than 100 times than the gain of sidelobes, we apply ideal "flat-top" model for directional antenna, i.e., unit gain within the beamwidth and zero outside the beamwidth. At the reference distance d_{ref}, the corresponding path loss is denoted as PL_0. We set up various numbers of flows with constant bit rates (CBR) and randomly select the source and destination nodes for each flow. The running time for each traffic flow is normally distributed between 1 min. and 3 min. The simulation parameters are listed in Table I.

TABLE I
SIMULATION PARAMETERS

Parameters	Symbol	Value
Channel bandwidth at mmWave	W_{mm}	1200 MHz
Channel bandwidth at 5GHz	W_L	160 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	10μs
Beacon period	T_{BEA}	50 μs
Random access period	T_{RAP}	80000 μs
Channel time allocation period	T_{CTAP}	500 ms

We evaluate the performances of multi-radio band integration mechanism in terms of link connectivity ratio and the number of flows supported in the network, in comparison with relaying mechanism and single hop transmission. The relaying mechanism selects an intermediate node as relay if the LOS link between the source node and the destination node is blocked. The single hop transmission does not use relaying node or alternative radio band even if the transmission rate is reduced significantly due to human blockage.

Fig. 4 shows the network connectivity ratio with various number of flows in the network. We use the single hop transmission at mmWave band as the baseline for comparison. The single hop transmission at mmWave band can be blocked if people move to the LOS link. Relaying mechanism can reduce the link outage probability by replacing the blocked link with an alternative path with two hops. However, it is possible that the hops in the alternative path are blocked, which also results in the blockage.

The number of flows supported successfully in the network is shown in Fig. 5. The proposed multi-radio band integration mechanism can support much more number of flows by transmitting data over multi-radio bands. By properly selecting the relay node [1], the relay mechanism can utilize network resources more efficiently than single hop transmission, thus it can support more number of flows than single hop transmission.

VII. Conclusion

In this paper, integration mechanism of multi-radio bands is proposed to deal with the link blockage for indoor mmWave networks. It focuses on scheduling concurrent transmissions with multi-radio bands in TDMA-based MAC, aiming to

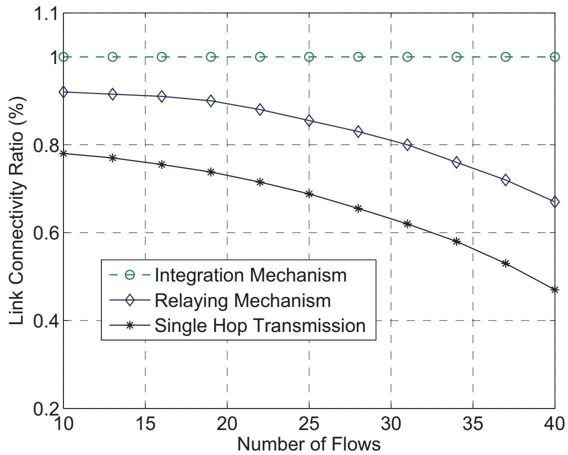

Fig. 4. Network Connectivity Ratio

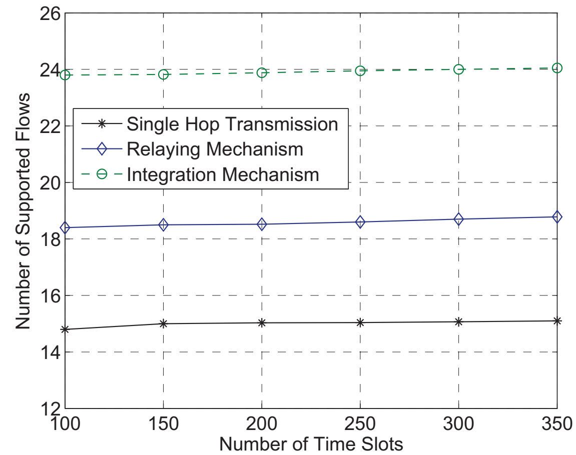

Fig. 5. Number of Scheduled Flows

provide guaranteed performance on flow throughput to support multimedia applications requiring multi-Gbps throughput. We first propose radio band selection scheme considering both the channel status and network load status to support more traffic flows. Considering the unique features of mmWave communication and the recent advances on WLAN in 2.4/5 GHz band, a concurrent transmission scheduling algorithm free of multiuser interference is proposed to exploit spatial reuse. We show that the proposed multi-radio band integration mechanism is successful in providing robust connectivity in indoor environment with people movement. It would provide a fundamental role in mmWave indoor networks to keep network connectivity and extend the network coverage. Our future work therefore focuses on extending the proposed multi-radio band integration framework into other layers and it is also of interest to evaluate the performance in other aspects, such as delay and jitter for multimedia applications.

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