Multi-Band Multi-Hop WLANs for Disaster Relief and Public Safety Applications

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***Abstract*—Calamities like tsunami and flood cause communication outage by damaging the communication infrastructure and power supply. As an alternate communication facility, multi-hop relay networks are deployed. Deploying these networks is quick and easy, however, the performance is deteriorated due to the use of relays in such environments. Similarly, given the surge in bandwidth hungry applications, performance parameters such as high throughput and low end-to-end delay are also daunting challenges in the traditional one-hop wireless LANs (WLANs). In this context, simultaneous transmission over multiple bands has the potential to improve the capacity of relay networks and accommodate the future unforeseen bandwidth-hungry applications. Manipulating the attributive diversity of different bands will yield prolific gains in terms of performance. However, for multi-hop transmissions in such multi-band networks, channel conditions and bit-rates over different bands, different links tend to be different. This causes significant degradation in the performance in terms of throughput and end-to-end delay. To address this problem, considering the channel conditions and bitrates of each band on either side of the relay, we exploit Shapley value to distribute the load in such a way that maximizes throughput and minimizes end-to-end delay in multi-band networks. Illustrative numerical results demonstrate the effectiveness of our proposed scheme.**

***Index Terms*—WLAN, end-to-end delay, disaster area networks, multi-band transmission**

I. Introduction

Post-calamity, restoring communication facility is the most important function of disaster management to assess the damage and expedite the recovery measures. For this purpose, multi-hop relay networks are deployed to coordinate and aid the relief efforts in the catastrophe stricken area [1]. However, relaying information over multiple hops in such networks causes deterioration in the network throughput and end-to-end delay [2]. Similarly, with the proliferation of bandwidth-intensive applications, future wireless networks are expected to accommodate the inexorable rise in the demand for high data rates, low latency, efficient utilization of spectrum and high throughput. To meet this formidable demand, various advanced tools and techniques have been adopted in the current technologies such as beamforming, spatial multiplexing, bandwidth aggregation and massive Multiple-Input Multiple-Output (MIMO) [3]. However, the envisioned requirements such as multi-Gbps throughput and ultra-low latency are already daunting. In this regard, we envision multi-band wireless LANs to improve the performance of the relay networks and to meet the surging bandwidth demand in the traditional WLANs. We propose a network model where the communicating nodes are capable of operating over multiple bands simultaneously, to transmit and receive the data frames to improve throughput and end-to-end delay. By providing each node with multiple bands, we can exploit the inherent characteristics of different bands and utilize more of the radio spectrum.

We consider multiband, multi-hop relay-based WLANs that form a coalition among the bands. In these networks, the bands over different links differ by channel condition, bit-rates and the performance that they can offer. This can result in channel under-utilization, frame losses and buffer overflow. For this reason, the end-to-end delay increases and throughput declines significantly. To address the problem, we first estimate the performance of different bands based on their channel conditions. Considering the performance of each band on either side of the relay, we exploit Shapley value technique to find the traffic load each band can transmit while satisfying certain constraints. The Shapley value is a technique used to optimally distribute both profit and costs among multiple entities working together in the form of a coalition [4].

By distributing the load according to the performance of the bands, the end-to-end delay is minimized and throughput is maximized. The technique is first applied on the single-hop WLAN and then an extension is developed to incorporate the relay nodes.

Rest of the paper is structured as follows. Following a brief literature review in Section II, we describe our system model and present formal problem formulation in Section III. The

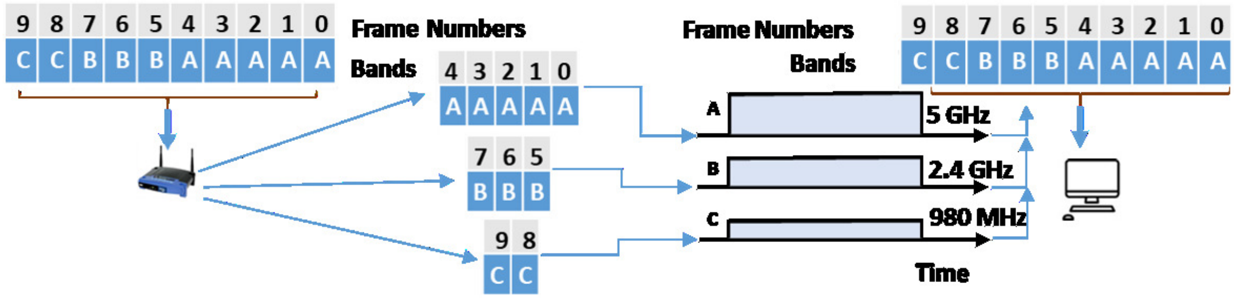

Fig. 1. A simplified model of the considered multi-band Wireless LAN

proposed traffic load distribution technique to minimize the end-to-end delay and maximize the throughput is discussed in Section IV followed by performance evaluation of the proposed scheme in Section V. Finally, we conclude the paper in Section VI.

II. Literature Review

The idea of multi-band transmission in WLANs is not entirely new. To date, many researchers have considered multi-band transmission. In many cases, multiple bands are used by switching between the bands [5]. For instance, the authors in [6] proposed an architecture for multiband transmission in cellular networks. The authors performed band switching by designating a node as primary node responsible for band switching. When a primary node changes the band, all the secondary nodes change their bands accordingly. However, the mechanism for choosing appropriate target band is still missing in the work and the architecture does not cater for multi-hop networks. Multi-band multi-hop wireless network has been considered in [7], [8] and [9]. To make up for the frame losses that results from performance mismatch between sender-relay and relay-destination links, the authors of [7] and [8] have proposed adaptive bit-rate schemes.These works were supplemented by [9] with adaptive channel selection method where instead of lowering the bitrate, a channel with higher SINR (if available), is selected in the first attempt. Otherwise, bitrate is adjusted in the second attempt. In all these schemes, the band is always switched at the relay nodes regardless of the channel conditions with an aim to bring about spectral efficiency, albeit at the cost of increased processing delay. On the contrary, we propose to use multiple bands simultaneously instead of switching between the bands. Whenever there is a change in channel condition or traffic load of a band, instead of switching the band, we switch the load from one band to another.

III. Assumed Scenario and Problem Formulation

In this section, we present our system model and discuss the factors affecting the throughput and end-to-end delay to estimate the performance of the bands. Keeping in view these factors, we formulate an integer linear program that minimizes end-to-end delay and maximizes. Fig. 1 shows a simple illustration of our assumed multiband WLAN system. The system is capable of operating over multiple bands simultaneously. The data frames are coming to the multiband-enabled access point which are then divided into three segments according to the performance metrics of the bands on the outgoing link. The three segments are transmitted simultaneously. Upon reaching the destination, the frames in each segment are re-arranged and then forwarded to the application after necessary processing.

A. Factors Affecting Throughput and End-to-End Delay

In multi-band simultaneous transmission, throughput and end-to-end delay is affected by the following factors.

1) Number of users per channel: We denote the number of users per channel by (U). The number of users per channel is inversely related to throughput and end-to-end delay.

2) Interference: We use interference ratio (I) to incorporate the effect of interference. Let Th be the throughput when there is no interference, i.e., throughput under zero interference and let Th_f be the throughput in the presence of some interference. Interference ratio (I) is given by Th_f/Th. The value of I always remains between 0 and 1 where value closer to 1 means lesser interference in the network and I equals to 1 means zero interference.

3) Packet re-ordering delay: Packets arrived out of order will either be kept in the buffer or discarded depending on the magnitude of the out of order packets as TCP can allow packet reordering by a maximum of two positions only [10]. Therefore, the impact of packet re-ordering delay is twofold. The time taken to put the received packets in correct order increases the packet's end-to-end delay. Likewise, TCP transmission window is reduced which leads to the under-utilization of capacity which results in the drastic degradation of application throughput.

4) Switching delay: Despite of distributing traffic load according to the performance of the bands, change in the channel conditions or traffic load of the bands calls for switching the traffic load between the bands. Since the bands have different characteristics, the data frames must be made conformable to the band in which they are being transmitted. It is worth noting that the time taken by this process along with the interface switching delay is not negligible [11]. Therefore, the goal is to switch maximum switchable traffic in the minimum number of rounds. Switching delay (Δ) is the sum of frames processing delay (P_d) and interface switching delay (I_d) whose value is taken as 130 μs [12].

5) Bitrate: There is always an optimal bitrate (B) for the given channel conditions such that a bitrate greater than the optimal bitrate leads to congestion in the network, which in return leads to increased bit error rate. On the other hand, for a bitrate less than optimal bitrate, the network resources such as channel capacity are under-utilized. Assuming that throughput is the number of bits per second successfully received, we obtain optimal bitrate by iterating all the bitrates and finding the one giving highest throughput that is, ($B \times S$), where S is the bit success rate.

6) Residual capacity: Both throughput and end-to-end delay are in an inverse relationship with residual capacity. Here our goal is twofold: we need to keep the residual capacity minimum to improve the throughput. Secondly, the ratio of residual capacity to the total capacity of all the bands must be equal to ensure equal delay.

With the number of users per channel (U), interference ratio (I), bitrate (B) and bit success rate (S) given, the end-to-end delay (D) for a particular amount of traffic load (L) can be obtained as follows.

$$D = \frac{L}{\sum_{i=1}^{3} (B \times U \times S \times I)_i} + \sum_{j=1}^{n} \Delta_j + \Theta \qquad (1)$$

Δ is the switching delay while Δ_j indicates the delay for carrying out j number of switches and Θ is the sum of queuing delay, slot synchronization delay and transmission delay. For the sake of simplicity, we have relaxed these delays and leave them for future work.

B. Problem Formulation

With Bitrate (B) and bit success rate (S) optimally chosen (section III-A5), the next job is to optimally allocate the load to the bands. For this purpose, we formulate the problem as an integer linear program (ILP);

$$\text{minimize } D$$

Subject to:

1) Delay of all the bands are equal.

$$D_a = D_b = D_c \; ... \qquad (2)$$

Here D_a is the delay of band a, D_b is the delay of band b and so on.

2) Ratio of the residual capacity to total capacity of all the bands are equal.

$$\frac{\zeta_a^r}{\zeta_a^t} = \frac{\zeta_b^r}{\zeta_b^t} = \frac{\zeta_c^r}{\zeta_c^t} \; ... \qquad (3)$$

Here ζ_a^r and ζ_a^t are respectively the residual and total capacity of band a, ζ_b^r and ζ_b^t are respectively the residual and total capacity of band b and so on.

With the above ILP, we can have optimal capacity utilization, throughput and end-to-end delay. To solve the ILP, we develop a technique based on Shapley Value that takes D_i of each band i in the coalition and allocates traffic load according to their performances. As a result, delay of all the bands are equal, which means that no band is faster or slower, the traffic load that they carry however, vary according to their capacities.

IV. Traffic Load Assignment

In this section, we propose a solution to the formulated problem using Shapley value [4]. The Shapley value optimally assigns profits and costs to the entities working in the form of a coalition. It represents a share of an individual entity in the coalition when the total utility generated by coalition is divided among its members following a certain distribution technique. This distribution corresponds to the contribution of the individual entity in the coalition. The purpose of distribution is to estimate the utility contributed by an individual band by averaging its marginal contribution over all possible permutation of the bands.

To elaborate further, consider a coalition given by a pair (N, v) where $N = \{1, 2, 3, ..., q\}$ is the number of entities and $v : 2^{[N]} \rightarrow \mathbb{R}$ is a characteristic function that takes every coalition of entities and assigns it a value. Here $2^{[N]}$ is the set of all possible subset of N. With a given characteristic function, every possible combination of entities is considered and contribution of each entity in the combination is calculated as if they are producing utility one-by-one one after another in turns. We use this fact to design a traffic load assignment algorithm that calculates the possible contribution of the individual band in the coalition. The contribution of the band in the coalition is actually the load it will be assigned.

The proposed technique is summarized in Algorithm 1. In step 1, we calculate the delay of all the bands in order to get the benchmark value as shown in step 2. The benchmark value obtained in step 2 is used to calculate the maximum possible marginal contribution that every band can offer. Maximum marginal contribution of band i denoted by C_i^{mm} is the maximum load transferred by other bands in the same amount of time as compared to the band with least delay (refer to step 3 for calculating maximum marginal contribution). In step 4, we perform the maximum number of permutation of the three bands. The purpose of permutation is to weigh the individual contribution of the band by different possible ways of coalition. The total number of permutation for the three bands is 6. In step 5, for each set of the three bands in a given permutation, we calculate the actual marginal contribution of each band (C_i^{am}) for the given order in the permutation. Actual marginal contribution serves as characteristic function to map the contribution of the individual bands. Finally, we get the load share of an individual band by averaging its total actual marginal contribution over the different ways according to which the grand coalition could be built. Mathematically, we can express the load share as follows.

$$\text{Load of Band } (i) = \frac{1}{N!} \sum_{\pi \epsilon \prod_N} C_{i,\pi}^{am} \qquad (4)$$

where $\prod_N$ is the set of all the permutation that we performed for N users and $C_{i,\pi}^{am}$ is the actual marginal contribution of band i in permutation π, the value of which we obtain using step 5 in Algorithm 1.

Algorithm 1 Traffic Load Share

Input: Offered Load (OL), $(BUSI)_i$ of band i
Output: Load Share
1. Calculate delay D_i of band i where $D_i = \frac{L_i}{(B \times U \times S \times I)_i}$
2. Benchmark (K) = minimum of D_i
3. Calculate maximum marginal contribution of every band i, $(C_i^{mm}) = K \times (BUSI)_i$
4. All possible permutation of individual bands
5. **for each** Permutation do
 {
  Load Left (LL) = OL
  for each band in the permutation order do
   {
    While$(LL > 0)$
    {
     $C_i^{am} = Min\,(LL, C_i^{mm})$
      LL = LL - C_i^{am}
     } } }
6. $\frac{\sum C_i^{am}}{N!}$

We explain the aforementioned algorithm with the help of the following example. Let the total incoming load be 80Mbps, which is to be distributed among three bands A, B and C with $B \times U \times S \times I$ (BUSI) values of 8 Mbps, 5 Mbps and 3 Mbps respectively. Using Eq. 2, their individual delays are 10 seconds, 16 seconds and 26.67 seconds, respectively, rendering benchmark value of 10 being the least of the delays among the three bands. For a benchmark value of 10, maximum marginal contribution of A, B and C will be 80, 50 and 30 Mbps, respectively. The six possible permutations are given in table I. In the first row, the order of the band is ABC, thus actual marginal contribution of first band that is, A is 80 Mb (10×8). Here 10 is the benchmark value while 8 is the BUSI value of band A. Since no traffic load is left after 80 Mb went to A, therefore, the entries in the corresponding cells of bands B and C are Zero. In second row again, A is the leading band. Therefore, 80 Mb will go to A and zero to the rest of the two bands. In third row, B has now become the leading band. Its actual marginal contribution is 50 Mb (5×10). The rest of the 30 Mb will go to band A, being second in the order. C will not get any load as all of the 80 Mb load is already distributed. In row 4, the extra 30 Mb will go to band C instead of A because of being second in the order. In fifth row, 30 Mb (3×10) will go to band C. Rest of the 50 Mb is given to band A in row 5 and C in row 6 depending upon their position in the permutation. The total actual allocated load to the bands are the average of their total actual marginal contribution over six permutations.

TABLE I
MARGINAL CONTRIBUTION OVER EVERY PERMUTATION AND RESULTING LOAD SHARE

	A	B	C
ABC	80	0	0
ACB	80	0	0
BAC	30	50	0
BCA	0	50	30
CAB	50	0	30
CBA	0	50	30
Share	40	25	15

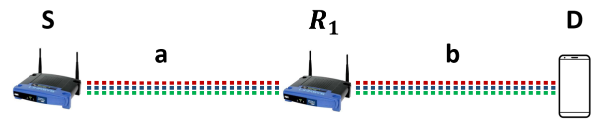

Fig. 2. Incorporating Relay Nodes in the Assumed Multiband WLAN.

A. Incorporating Relay Nodes

Consider a relay node between source and destination as shown in Fig. 2. Assuming that loads are fairly shared at the source node based on the performance of the bands, it is safe to assume that the delay of all the three bands for their corresponding loads are equal. However, channel conditions at relay-destination link tend to be different. Furthermore, additional relay nodes may be attached to the relay node in question. If relay nodes are also transmitting data via R_1, the load at R_1 will be different than at S. For these two reasons, constraint 1 above is violated. In such case, we need to switch a particular amount of load from the band experiencing increase in the delay to the rest of the bands to keep the delays equal.

Suppose on a particular band B_o, the amount of load L_o is increased or $BUSI$ value $(BUSI)_o$ is decreased due to which it is incurring more delay than the other bands. Therefore, we switch some of its traffic load to the other two bands. Let L_s be the total amount of traffic load that will be switched to the rest of the two bands to make the delay equal. Using Eqn. 1 and 2, L_s can be incorporated as following.

$$\frac{(L_o - L_s)}{(BUSI)_o} = \frac{(L_{n1} + L_{sa})}{(BUSI)_{n1}} + \frac{\Delta}{2} = \frac{(L_{n2} + L_{sb})}{(BUSI)_{n2}} + \frac{\Delta}{2} \quad (5)$$

Where $(BUSI)_{n1}$ and $(BUSI)_{n2}$ are the $BUSI$ values of the bands other than $(BUSI)_o$ and L_{n1}, L_{n2} are their respective loads. The load L_s is subtracted from the current band and distributed proportionally among the bands with BUSI values $(BUSI)_{n1}$ and $(BUSI)_{n2}$ depending upon their performance. The total switched load $L_s = L_{sa} + L_{sb}$. L_{sa} and L_{sb} are the load assigned to the other two bands while Δ is the traffic switching delay. The maximum amount of traffic L_s, that will go to the other two bands is given by Eqn. 7.

L_s obtained from Eqn. 7 is subtracted from the band experiencing increase in the delay and added to one of the other two bands, However, adding L_s to the new band distorts the balance of the two bands. Therefore, we again have to

$$L_s = \frac{L_0 \left\{ (BUSI)_{n1} + (BUSI)_{n2} \right\} - \left\{ (L_{n1} + L_{n2}) (BUSI) \right\}_0 - \Delta \left\{ (BUSI)_0 + (BUSI)_{n1} + (BUSI)_{n2} \right\}}{(BUSI)_0 + (BUSI)_{n1} + (BUSI)_{n2}} \tag{6}$$

$$L_{s2} = \frac{\left\{ L_{n1} (BUSI)_{n2} - L_{n2} (BUSI)_{n1} \right\} - \Delta \left\{ (BUSI)_{n1} + (BUSI)_{n2} \right\}}{(BUSI)_{n1} + (BUSI)_{n2}} \tag{7}$$

TABLE II
EVALUATION SETTING

Parameter	Value
Number of Radios	3 at each Node
Bands Used	920 MHz, 2.4 GHz, 5 GHz
Bitrate	As per SNR
Noise Level	90 dB
Bandwidth	
920 MHz Band	1 MHz
2.4 GHz Band	20 MHz
5 GHz Band	20 MHz
EIRP	30 dB
Modulation Scheme	QAM-64
Inter-node Distance	20 meters
Packet Length	512 Bytes
Interface Switching Delay	130 μs

adjust the load between the two bands as follows. Let L_{s2} be the load to switch from slower band to faster. L_{s2} can be obtained using Eqn. 8.

L_{s2} is subtracted from the slower band between the two and added to the final one. In this way, the load between the two bands is adjusted. The three bands have once again equal delay.

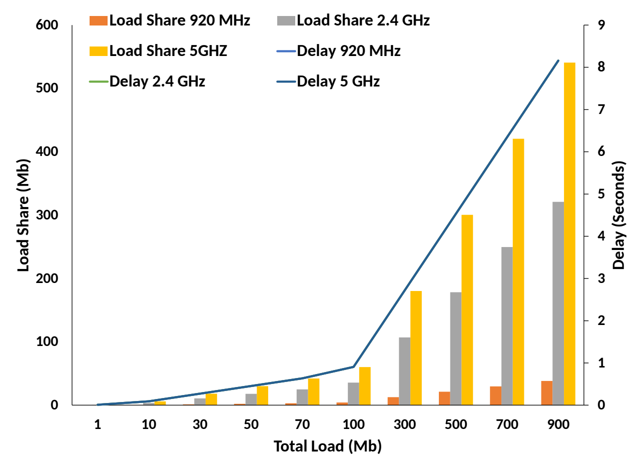

Fig. 3. Delay and Load Distribution Performance with respect to Incoming Load.

V. PERFORMANCE EVALUATION

In this section, we mathematically evaluate the proposed mechanism. We show the end-to-end delay of the three bands for varying load to see if they are equal. We also show the ratio of residual capacity to total capacity in order to verify the share-fairness of the scheme. Finally, we compare the traffic switching delay when the traffic is switched from one band to another. We compare the switching delay with the Truncated Decode and Forwarding (TDF) scheme used in [7]–[9]. Recall that TDF switches all the traffic from one band to another band regardless of the channel conditions.

A. Environment and Parameters Settings

Parameters used in this paper are listed in Table II. For topology, initially directly connected source and destination pair are considered to show the load distribution and corresponding delay of the incoming load. Later, relay nodes are added that results in multi-hop relay network as shown in Fig. 2. It is worth noting that in the figure only one relay node is shown, however, multiple relay nodes can be deployed in the same manner. In such a case, a node w (where $1 < w < d$, d referring to the destination) receives a packet from $w - 1^{th}$ node and forwards it to $w + 1^{th}$ node until the frame reaches d^{th} node, i.e., the destination node. The nodes are 20 meters apart and are equipped with three 802.11 based radios, all operating on three different bands given in the Table II.

B. Results

1) Load Distribution: In Fig. 3, we show the load distribution and delay performance of our proposed algorithm with respect to the incoming traffic load. 5 GHz takes the highest share of the incoming traffic load followed by 2.4 GHz. 920 MHz has better fading characteristics as compared to the 5 GHz and 2.4 GHz. The 920 MHz band suffers the least path loss among all the three bands, however, given the lesser bandwidth that it can have, the amount of traffic load it shares is meagre as compared to other two bands. From the figure, we can see that three curves for the delay of three bands coincide each other appearing to be a single curve. For every load distribution, the delays of the three bands are same. This phenomenon implies that all the frames arrive simultaneously, thus, avoiding the re-ordering delay.

2) Capacity Utilization: In Fig. 4, we show the capacity utilization performance for the same load and scenario. The ratio of residual capacity to total capacity is decreasing initially until the total load is less than the total capacities of the three bands. Once the total load exceeds the total capacities, the ratio tends to increase. In the figure, we can see that ratio of residual capacity to the total capacity is same for all three bands. The curves coincide each other, which implies that the load distribution is not only fair but the ratio of residual

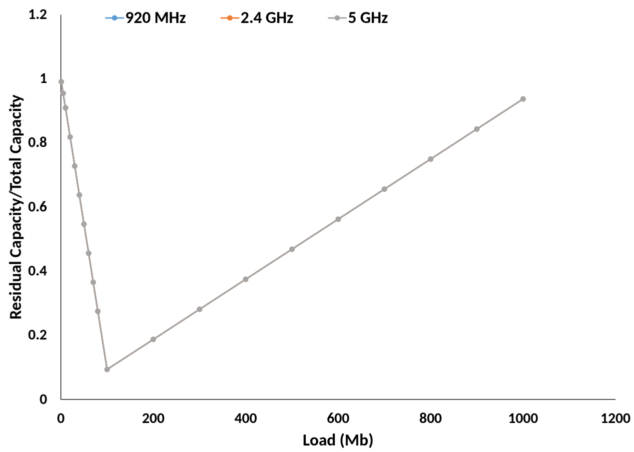

Fig. 4. Ratio of Residual Capacity to Total Capacity of the three Bands.

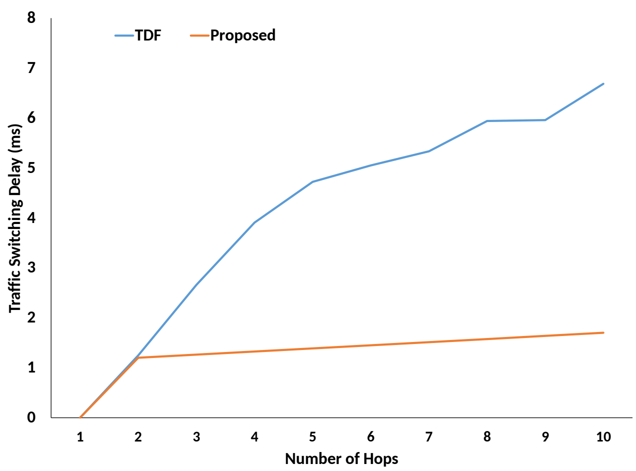

Fig. 5. Switching Delay with respected to number of hops.

capacity to the total capacity is equal for all the three bands substantiating the fact that load is optimally divided.

3) Traffic Switching Delay: In Fig. 5, we have compared switching delay of our proposed scheme with that of TDF. Here, the packet arrival rates is taken to be Poisson with average of 100. The figure shows that traffic-switching delay of TDF is increasing significantly with the increase in the number of hops whereas the switching delay for the proposed scheme is increasing slightly, as we add number of relay nodes. The curve for the proposed scheme is a straight line because only a minute portion of the traffic load is switched from one band to another. Total switching delay for TDF scheme is well above 6 ms whereas it is only 1.5 ms for our proposed scheme.

VI. Conclusion

We worked on simultaneous transmission over multiband multi-hop WLANs. Channel conditions on different bands, different links in these networks, are prone to be different. This difference among the bands drastically impact the throughput and end-to-end delay. Having highlighted the causes of decline in throughput and increase in end-to-end delay, we estimated the performance of the bands. Further, considering the performance estimates, we used Shapley value technique to find the load each band can assume. Numerical results showed that end-to-end delay of all the three bands were equal, capacity was optimally utilized and switching delay was minimized. In future, we plan to add additional parameters such as jitter, packet loss ratio, useful packet ratio etc. Finally, simulations can be performed to include different types of packets such as voice and video.

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