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Combine and Conquer: Simultaneous Transmission Over Multiband Multi-Hop WLAN Systems

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ABSTRACT Multi-hop relay networks are deployed to restore communication environment in the catastrophe stricken area. Deployment of these networks are fast and easy but performance is low due to the relay nature of the networks. Given the surge of bandwidth hungry application, performance such as high data rates, high throughput and ultra-low latency is a concern in traditional one-hop Wireless Local Area Networks (WLANs) as well. Simultaneous transmission over multiple bands is a compendious solution that has the potential to significantly boost data rates and flexibility. It will enhance the network utilization and performance of high-bandwidth applications effectively and efficiently. However, there are certain challenges that need to be addressed before taking full advantage of simultaneous transmission over multiple bands. In this work, we outline the factors affecting the performance such as throughput and end-to-end delay in multiband multi-hop WLANs. Considering these factors, we design an end-to-end traffic scheduling technique that minimizes end-to-end delay and maximizes throughput. We design a mixed integer linear program (MILP) that optimizes end-to-end delay and maximizes throughput. Illustrative numerical results show that proposed technique effectively minimizes end-to-end delay and maximizes throughput.

INDEX TERMS Disaster area networks, multiband, multi-hop communication, simultaneous transmission, packet reordering.

I. INTRODUCTION

Deploying multi-hop relay networks to extend the coverage area of the networks in scenarios such as catastrophe or military tactical communication, has received a lot of attention during the last decade [1]. In these cases, rehabilitation services are needed but communication infrastructure either is demolished or does not exist a priori. Therefore, multi-hop relay networks are deployed to restore communication environment. For these networks, the deployment is quick and easy, however, relaying information over multiple hops cause drastic deterioration in network performance such as throughput and end-to-end delay [2]. Therefore, we need a Wireless Local Area Networks (WLANs) system where performance such as capacity, throughput and end-to-end delay is not affected by relaying data over multiple hops.

Similarly, for traditional one-hop WLANs, bandwidth demand has been growing at a staggering pace. The compound annual growth rate of WLAN traffic from 2016 to 2021 is 47% [3] which implies 1000 times more capacity relative to the current level of capacity in next few decades. 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. Furthermore, as the benefits of wireless connectivity transcend beyond smartphones and tablets, additional utility devices will require wireless services, which give us a glimpse of the bandwidth that we need in next few years.

To meet this formidable demand, various advanced tools and techniques have been adopted in the current technologies such as beamforming, spatial multiplexing, bandwidth aggregation, massive multiple-input multiple-output (MIMO) and dense deployment of devices [4]. However, performance expected from next generation wireless networks such as providing orders of magnitude more capacity to address the burgeoning demand in bandwidth, is already daunting. To this end, we envision multiband WLANs to enhance the

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performance of the relay networks and to meet the requirements of high-bandwidth applications.

We envision a system where nodes are capable of operating over multiple bands simultaneously, for example, 5 GHz, 2.4 GHz and 980 MHz. The considered system uses all three bands synchronously for transmitting and receiving the data to increase the throughput. We believe simultaneous transmission over multiple bands will prove a productive way to meet the traffic demand of future networks. Keeping in view that different bands have different responses to the physical conditions such as distance and interference, by providing each node with multiple bands, we can exploit the inherent characteristics of different bands. We can utilize more of the radio spectrum simultaneously. Whereas the performance of the wireless networks is limited by the multiple hops [5], it will provide multi-Gbps throughput to end users in a cost-effective way. Simultaneous transmission over multiple bands will serve as a powerful platform for the provision and construction of emerging as well as future unforeseen applications and services. Multiband transmission will be hallmark of the upcoming 6G mobile networks as well [6].

In this paper, we consider single-hop where the end-user is directly connected to the access point as well as multi-hop WLAN system where the sender and the receiver are not in direct contact with each other that is, there is only one source-destination pair while all other nodes assist the transmission. Multi-hop networks are mostly deployed to extend the coverage area of the networks in exhibitions, conferences or areas where connection to a network is not available a priori. Scenarios where relay networks are deployed include disaster-hit area for rescue operation where rehabilitation services are needed but network infrastructure is completely demolished post-catastrophe and in military tactical communication for fast establishment of communication infrastructure during deployment of forces in a foreign territory [7].

However, before realizing true benefits of multi-band WLANs, there are certain issues that needs to be overcome. Performance such as throughput and end-to-end delay in multi-band multi-hop WLAN systems are affected by several factors such as link condition at pre- and post-relay links, packet loss, channel under-utilization when certain channel has more capacity then relay nodes is transmitting and buffer overflow when the relay node or the link after relay node cannot accommodate the incoming traffic. Similarly, packets traversing multiple hops and traffic switching frequency from one band to another band affect the end-to-end delay.

The main contributions of this paper are summarized as follows:

- We first study how various parameters affect the end-to-end delay and throughput. Subsequently, we attempt to optimize these parameters whenever possible. After taking care of all the parameters and incorporating their impact, we estimate the performance of each band.
- Once we have performance estimate of every band, we formulate a mixed integer linear program (MILP) and design an end-to-end traffic scheduling technique that minimizes end-to-end delay and maximizes throughput. The MILP is designed for single-hop directly connected users. Later on, we develop an extension to incorporate the relay nodes.
- Considering the performance of the links, the proposed technique distributes the incoming traffic among the bands in such a way that their capacities are optimally utilized, and load over bands is varied in such a way that delays of all the bands are made equal, thereby completely avoiding packet re-ordering at the receiver's end.

Rest of the papers is organized as follows. In following section, we will have a brief literature review. In Section III, we describe our considered architecture where we shall discuss our system model and the factors affecting the end-to-end delay and throughput. In Section IV, we formulate our problem exploiting multi-band transmission over multiple radio. Section V contains our proposed solution. Later, in Section VI, we incorporate relay nodes to formulated problem and solution. We show results of our proposed scheme in Section VII. Conclusion is given in Section VIII.

II. LITERATURE REVIEW

Multi-band WLAN is a promising solution guaranteed to improve the capacity of relay networks and meet the bandwidth demand of traditional WLAN user. Manipulating the attributive diversity of different bands will yield prolific gains in terms of performance of these networks.

Capacity improvement through channel switching with in a band has been extensively studied. Some valuable insights into channel switching within a single band are provided in [8]–[11], [12]. To date, many researchers have considered the idea of multiband transmission in WLANs and cellular networks. Venkataraman *et al.* [13] proposed a band switching mechanism in cellular networks. In the proposed architecture, when a primary node (a node responsible for switching the band) changes the band, all the secondary nodes (that are not allowed to switch the band unless instructed by the primary node to do so), change their bands accordingly. However, the mechanism for choosing appropriate target band is still missing in this work and the architecture does not cater for multi-hop networks. Multi-hop multi-band wireless network have been considered in [14]–[16] and [17]. Authors in [14] have given an analytical model that guides the channel switching between multiband system. The authors have appraised the health and location of the channel; based on which bitrate is varied and/or channel is reassigned depending upon the availability and condition of the channel.

Multiple bands have been used in [15] and [16] with an aim to enhance spectral efficiency. Using multiple bands, however, introduce packet processing delay which has been addressed by the authors. Moreover, given the fact that bitrate on source-relay link may be different from relay-destination link, results in the buffer overflow and loss of data frames; in the aforementioned papers, the authors proposed adaptive bitrate schemes to make-up for this performance mismatch between sender-relay and relay destination links. These works have been extended in [17] and [18] where the authors have supplemented the previous works with adaptive channel selection method to minimize the transmission delay where instead of lowering the bitrate, a channel with higher SNR, if available, is selected in the first attempt. Otherwise, bitrate is adjusted in the subsequent attempt. In all these schemes, regardless of the channel conditions, the band is always switched to bring about spectral efficiency, which introduces significant delay that adversely impact the end-to-end delay and throughput, as delay caused by band switching is not negligible [19].

To fill the gaps, in [20] we envisioned multiband multi-hop relay networks which instead of switching between the bands, simultaneously transmit over multiple bands namely, 5 GHz, 2.4 GHz and 980 MHz band. These networks use all three bands synchronously for transmitting and receiving the data to enhance the performance in terms of throughput and end-to-end delay. We presented an integer linear program (ILP) to maximize end-to-end delay and throughput. However, in [20] several important parameters are not incorporated into the given ILP. Moreover, a detailed analytical framework of the presented work is also missing.

III. CONSIDERED ARCHITECTURE

In this section, we describe our assumed WLAN system that operates on multiple bands and multiple hops employing relay nodes. We also discuss the factors that affect the throughput and the end-to-end delay.

A. SYSTEM MODEL

We consider a WLAN that forms a coalition among the bands to simultaneously transmit the incoming traffic load instead of switching between bands. Figure 1 shows a simple illustration of our assumed system model. The considered multi-hop relay-based WLAN system operates on three bands namely 5 GHz, 2.4 GHz and 980 MHz. As shown in the figure, the source, relay and destinations nodes are denoted by S, R and D respectively whereby S and R are stationary while node D is a mobile station. Furthermore, the source-relay link is indicated by 'a' while relay-destination link is indicated by 'b'. For the sake of simplicity, a single source, relay and destination is shown. However, there can be multiple relay nodes assisting the transmission between source and destination.

Given the three bands on the links, the data frames at source node are divided into three segments depending upon the performance of individual bands on out-going links. The three segments of frames are transmitted simultaneously. Upon reaching the destination, the frames in each segment are re-arranged and forwarded to application after necessary processing at lower layers as shown in Figure 2.

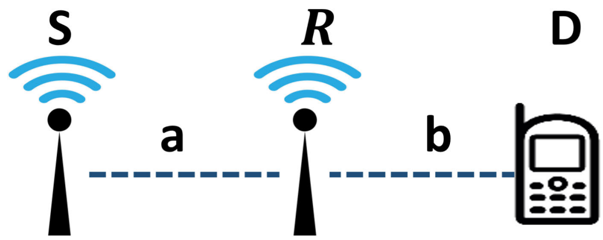


FIGURE 1. A simplified model of assumed relay-based WLAN.

In the following section, we discuss the factors affecting the throughput and delay before incorporating their impact in the proposed model.

B. FACTORS AFFECTING PERFORMANCE

1) NUMBER OF USERS PER CHANNEL

Improving channel assignment is out of scope of this work; however, we incorporate number of users per channel as follows. Let number of users U on channel i be $U(CH_i)$. The impact of number of users per channel is calculated as follows.

$$U(CH_i) = \frac{1}{\text{Number of users on channel } i} \tag{1}$$

For single user on channel i, Channel Utilization $U(CH_i)$ is 1. For 2 users on channel i, $U(CH_i)$ is 0.5 and so on.

2) BIT SUCCESS RATE

We define throughput as the number of bits per second successfully received. It follows that throughput and thence, system delay appertains to bit success rate. We find bit success rate on the basis of the SNR of the signal for given modulation scheme. The objective here is to maximize number of bits successfully received per unit of time.

3) INTERFERENCE

Reducing interference is out of scope of this work; however, we incorporate the impact of interference using interference ratio as follows. Let Th be the throughput when there is no interference i.e., throughput under zero interference and let Th_f be the throughput when there is interference of some kind that is, throughput under interference. Let I be the interference ratio which is obtained as follows.

$$I = \frac{Th_f}{Th} \tag{2}$$

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.

With number of users per channel (U), interference ratio (I), bitrate (B) and bit success rate (S) given, delay (D_i) of band i for a particular amount of load (L_i) can be calculated as follows.

$$D_i = \frac{L_i}{B \times U \times S \times I} \tag{3}$$

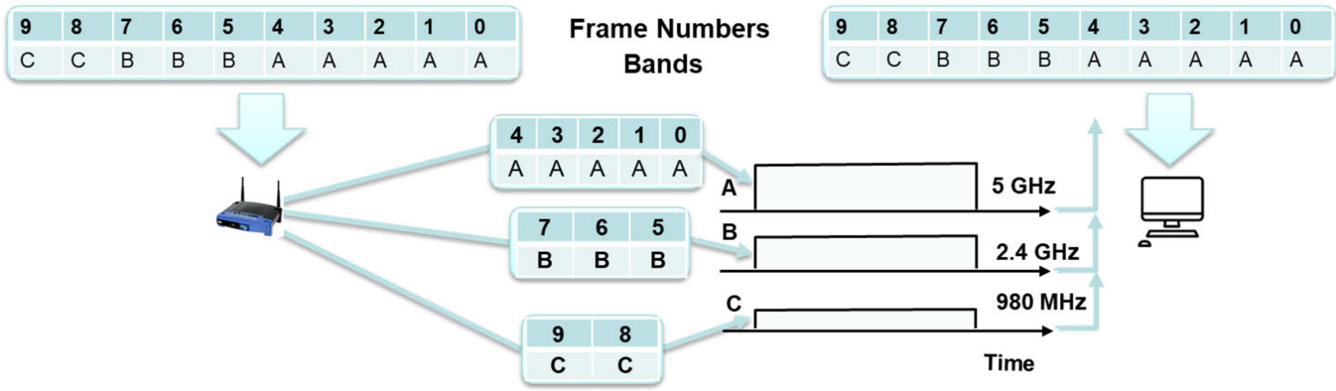


FIGURE 2. A simple illustration of the considered multi-band wireless LAN.

4) BITRATE

Unlike [15]–[17], we do not adapt the bitrate. We attempt to keep the bitrate as high as possible. However, a higher bitrate does not always lead to higher throughput. There is always an optimal bitrate for given channel condition. Equation (3) shows that delay depends upon bitrate which is a function of success rate. Therefore, we can write (3) as follows.

$$D_i = \frac{L_i}{B \times U \times I} \times f\left(\frac{1}{S}\right) \tag{4}$$

Bit success rate in return is a function of $(B \times S)$. Therefore, we can re-write (4) as follows.

$$D_i = \frac{L_i}{B \times U \times I} \times f\left(\frac{1}{B \times S}\right) \tag{5}$$

Assuming that channel utilization and interference have been taken care of, to find optimal bitrate we differentiate (5) with respect to B and equal it to 0.

$$\frac{d\left(D_i\right)}{dB} = \frac{d}{dB}\left[\frac{L}{UI}\left(\frac{1}{B}f\left(\frac{1}{S}\right)\right)\right] = 0 \tag{6}$$

$$\frac{L}{UI}\left(-\frac{1}{B^2}f\left(\frac{1}{S}\right) + \frac{1}{B}\frac{d\left(f\left(\frac{1}{S}\right)\right)}{d\left(\frac{1}{s}\right)}\frac{d\left(\frac{1}{S}\right)}{dB}\right) = 0 \tag{7}$$

$$\left(-\frac{1}{B^2}f\left(\frac{1}{S}\right) + \frac{1}{B}\frac{d\left(f\left(\frac{1}{S}\right)\right)}{d\left(\frac{1}{s}\right)}\frac{d\left(\frac{1}{B \times S}\right)}{dB}\right) = 0 \tag{8}$$

$$\left(f\left(\frac{1}{S}\right) + \frac{1}{B \times S}\frac{d\left(f\left(\frac{1}{S}\right)\right)}{d\left(\frac{1}{s}\right)}\right) = 0 \tag{9}$$

$$f\left(\frac{1}{S}\right) = -\frac{1}{B \times S}\frac{d\left(f\left(\frac{1}{S}\right)\right)}{d\left(\frac{1}{s}\right)} \tag{10}$$

S in (10) is the optimal bit success rate. Equation (10) shows that there exists an optimal bit success rate, supported by the negative sign in the equation which indicates the decrease in success rate after optimal point, as we increase $(B \times S)$. It follows that there exists an optimal bitrate (B_{opt}) that gives the highest throughput. For $B > B_{opt}$, we have congestion and packet errors increase the delay. For $B < B_{opt}$, resources are under-utilized and if lower bitrate is because of the factors other than SNR, error rate may still increase because of the longer transmission time as a result of lowered bitrate [21]. We obtain optimal bitrate by iterating all the bitrates and finding the one giving highest channel level throughput that is, $(B \times S)$. Mathematically, for a channel m, its throughput (Th_m) can be expressed as follows;

$$Th_m = B_m \times S_m \quad m \in [1, n] \tag{11}$$

where S_m is the bit success rate for bitrate B_m on channel m and the product $B_m \times S_m$ is the highest for all bitrates and bit success rate from 1 to n. Therefore, optimal bitrate is the one giving highest value for (11).

5) PACKET RE-ORDERING DELAY

When allocating the traffic load to the bands if the load is not proportionally allocated, some bands will take more time transmitting the data while others having already been transmitted their share of data load, assuming that performance of each band is different. The time during which the faster bands are idle, could have been used to deliver more data. The mismatch in the delay of the individual bands is a significant contributor to the end-to-end delay of the system. Furthermore, the delay mismatch will render the transmitted data useless as transmission control protocol (TCP) forward the data to applications according to the sequence numbers of packets.

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 re-ordering by a maximum of two positions only [22]. Overwhelming the slower band and putting the total data in correct order increases the overall end-to-end delay. Bringing data packets back in order, consumes a significant amount of time, which causes packets of real-time application to miss their respective deadlines and get discarded. Therefore, to avoid packet re-ordering delay, we make end-to-end delay of individual bands equal. This is possible by distributing the data load in such a way that commensurate their performance. In case of change in performance, we vary the load accordingly. Eventually, the delays of the all bands are same but the traffic load that they transmit vary.

6) UNDER-UTILIZATION OF CAPACITY

Receiving data out-of-order has other implication as well. TCP treats packet re-ordering beyond two positions as a loss, attributing this to worsened channel conditions. This results in the reduction of the transmission window. Consequently, the aggregated capacity will be under-utilized and the application throughput may drop drastically. Similarly, when data is disproportionally allocated, some bands will be overwhelmed while some have data considerably lesser than their capacity. The extra residual capacity is essentially the under-utilization of capacity, which can be used to deliver more data. Therefore, the goal is to distribute the load in such a way that minimizes residual capacity of the bands.

7) SWITCHING DELAY

At source node, the data frames are divided into three segments depending upon the channel condition of the three bands on the outgoing links. However, the same channel conditions may no longer hold post-relay node. If additional nodes are attached to relay node, the amount of load at relay node may be different from that at source node. This might result in the bands having disproportional data load. Therefore, unlike single-radio where bitrate is adapted and channel is switched according to the channel condition, here pro rata load instead, is switched between the bands. Furthermore, the bands have different characteristics, therefore the data frames must be made conformable to the targeted band in which they will be transmitted after switching. During this process, generally the signal is demodulated to convert it into bits, which are then de-interleaved to undo any encoding that spreads error over data stream. De-interleaved bits are de-punctured, followed by viterbi decoding. Finally, the bits are passed through cyclic redundancy check (CRC) check to correct any errors. For transmission, this process is repeated in reverse order that is, CRC followed by convolutional encoding, puncturing, interleaving and finally, modulation. This processing time along with the interface switching delay is not negligible [19]. The more we switch the traffic, the more will be the delay incurred. Therefore, maximum switchable traffic needs to be switched in a single round to avoid frequent traffic switching between the bands. Switching delay (Δ) can be obtained as follows.

$$\Delta = P_d + I_d \tag{12}$$

where P_d is frames processing that is, encoding and decoding delay and I_d is interface switching delay whose value is taken as 130 μs [23]. Further details on pro rata load and optimizing switching delay are given in section 6.

Once number of users per channel (U), interference ratio (I), bitrate (B) and bit success rate (S), and traffic switching delay (Δ) are estimated, the end-to-end delay (D) of the total load (L) can be obtained as follows.

$$D = \frac{L}{\sum_{i=1}^{3} (B \times U \times S \times I)_i} + \sum_{j=1}^{n} \Delta_j + \Theta \tag{13}$$

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.

IV. PROBLEM FORMULATION

Keeping the above factors into account, we formulate the problem. We first formulate integer linear program (ILP) for directly connected source-destination pair. Later we extend the model to multi-hop relay networks. We write the objective function as;

$$\text{minimize } D$$

Subject to the following constraints.

$$B = B_{opt} \tag{14}$$

$$\sum_{i=1}^{N} h_i = 1 \tag{15}$$

$$h_i \geq 0 \tag{16}$$

$$h_i > 0 \quad \forall L > 0 \tag{17}$$

$$0 < B_i \leq \zeta_i \tag{18}$$

$$\frac{L_i}{(B \times U \times S \times I)_i} = \frac{L_j}{(B \times U \times S \times I)_j} \tag{19}$$

$$\frac{\zeta_i^r}{\zeta_i^t} = \frac{\zeta_j^r}{\zeta_j^t} \tag{20}$$

Equation (14) represents optimal bitrate constraint. Based on the discussion on the significance of optimal bitrate, bitrate (B) of the individual bands should be optimal (B_{opt}). Constraint in (15) specifies that sum of share ratio of all the bands should always be equal to 1. This constraint ensures that sum of load shares of all the bands do not exceed the total load on the link. Where h_i in the equation is the share ratio of an arbitrarily chosen band i. We call this as share ratio constraint.

Similarly, positive share-ratio constraint is shown in (16). This constraint specifies that share-ratio of any band cannot be negative, as physically it is not possible that a band has a negative load. Also, if traffic load exists, individual share cannot be zero. This is to ensure that all the bands must contribute to ultimate objective of the system. We call this as load share constraint and is given in (17). Where L in the equation is the traffic load.

Like positive share-ratio constraint, bitrate should be always positive, and cannot be greater than capacity of the band i. Physically, it is not possible to have negative bitrate. At the same time, the bitrate cannot exceed the physical capacity of the link. We call this as bitrate constraint and is given in (18). Where B_i in the equation is the bitrate of the arbitrarily chosen band i and ζ_i is the capacity of the band i.

Constraint in (19) states that delay of all the bands must be equal. We call this as delay constraint. This is a very crucial constraint to ensure in-order delivery of the data frames. In case of unequal delay, the packets will arrive out-of-order. Thus, giving rise to packet re-ordering delay. In the equation, i and j are arbitrarily chosen bands. Finally, residual capacity constraint is given in (20). This constraint states that ratio of residual capacity to total capacity of all the bands must always be equal. This constraint ensures that loads are fairly shared while optimally utilizing the band capacities. In the equation, ζ_i^r and ζ_j^r are the residual capacities of arbitrarily chosen bands i and j while ζ_i^t and ζ_j^t are the total capacities of band i and j.

The above integer linear program caters for all the factors and parameters highlighted above. Upon solving the integer linear program, we can have most optimal capacity utilization, throughput and end-to-end delay with all the delays being equal. However, the formulation turns out to be mixed integer linear program (MILP) as variables can take non-integral values such as delay and capacity. And because variables are independent of each other, in other words, they are not connected, therefore the MILP is non-deterministic polynomial-time hard (NP-hard).

V. PROPOSED SOLUTION

In order to solve the problem in polynomial time, we solve the MILP in two stages. We first find optimal load shares and then in second stage, we assign the loads to the bands.

A. FINDING THE LOAD SHARES

The technique used to find three random load shares is summarized in algorithm 1 below. In step 1, we calculate $B \times U \times S \times I$ ($BUSI$) value of three bands. In step 2, we calculate load share ratio. Finally, load shares are calculated in step 3.

Algorithm 1 Finding Optimal Load Shares

Input: B, U, S, I of all the three bands
Output: Load Shares
1. Calculate ($BUSI$) values of all three bands.
   // Finding Share Ratio (h_i) for all the three bands
2. $\sum_{i=1}^{N} h_i = 1,$ therefore,
   $h_i = \frac{(BUSI)_i}{\sum_i^N (BUSI)_i}$
   // Finding a load share
3. An arbitrary load share L_i will be
   $L_i = (B \times U \times S \times I)_i \times h_i$

Once we have calculated load shares, next job is to assign L_i to appropriate band B_i in a way that will optimize the delay.

B. LOAD ASSIGNMENT

Here the job is to allocate exactly one load share to one band that is, one load goes to exactly one band and one band gets exactly one of the three load shares in such a way that total delay is minimized. For this purpose, we form a 3 x 3 matrix and assign delays as shown in Table 1. On the top, the $BUSI$ values are written column-wise in increasing order while on the left side of the matrix, load shares are written row-wise in increasing order. Let 1, 2 and 3 be the delay of the three load shares. We populate the matrix with the delays as follows. In first row, we write 1 in first column, followed by 2 and 3 in second and third column, respectively. In second row, we write one in the second column, followed by 2 in third column and 3 in first column. In the third row, we write 1 in third column, 2 and 3 in first and second column respectively. If C_{ij} is the associated delay when load i is assigned to band j, our goal is to minimize total delay.

TABLE 1. Initial 3 × 3 matrix for load allocation.

	$(BUSI)_1$	$(BUSI)_2$	$(BUSI)_3$
L_1	1	2	3
L_2	3	1	2
L_3	2	3	1

Before formulating the load assignment problem, let us define an assignment variable A_{ij} such that;

$$A_{ij} = \begin{cases} 1, & \text{if load } i \text{ is assigned to band with } BUSI\ j \\ 0, & \text{otherwise} \end{cases}$$

Now, the mathematical formulation of the considered load allocation problem is as follows.

$$\text{minimize} \sum \sum C_{ij} A_{ij}$$

subject to

$$\sum_{j}^{3} A_{ij} = 1 \quad \forall i \tag{21}$$

$$\sum_{i}^{3} A_{ij} = 1 \quad \forall j \tag{22}$$

$$A_{ij} = 0, 1 \quad \forall i, j \tag{23}$$

Equation (21) indicates that a load goes to exactly one band while (22) indicates a band gets exactly one of the loads.

To achieve the objective function, we proceed as follows. We subtract the smallest value in every row from every element in that row. For example, 1 happens to be the row minimum of row 1. Therefore, we subtract 1 from every element in row 1. We repeat this process until we get first zero. The process of subtraction is repeated for row 2 and 3. The resultant matrix is shown in Table 2 below.

TABLE 2. Resultant 3 × 3 matrix after necessary computation.

	$(BUSI)_1$	$(BUSI)_2$	$(BUSI)_3$
L_1	0	1	2
L_2	2	0	1
L_3	1	2	0

The load is assigned to band where they intersect each other at 0 in the resultant matrix. For example, L_1 intersect $(BUSI)_1$

at zero. Therefore, L_1 is assigned to $(BUSI)_1$. Similarly, L_2 goes to $(BUSI)_2$ and L_3 goes to $(BUSI)_3$. By calculating the delays of the bands using equation 3, we find out that they are same, substantiating the fact that load was fairly shared.

C. PROOF OF OPTIMALITY

The proof of load share and subsequent allocation being optimal, will connote the throughput and end-to-end delay being optimal. For proving the optimality, we have to prove certain theorems which are as follows.

Theorem 1: h_i is the optimal load ratio

Proof of Theorem: Let total load be 1 Mb and load shares be l, m, n. Where $l + m + n = 1$. Our goal is to maximize, that is, to further enhance ratios h_1, h_2 and h_3, if they are not the optimal. For this purpose, we exploit Nash Bargaining solution technique [24] that maximizes the product of the gains of the entities involved. Nash Bargaining solution is proven to be optimal [25]. Using the bargaining technique, our goal is to maximize the product of the load shares z, that is;

$$\text{maximize } z = (l - h_1)(m - h_2)(n - h_3) \tag{24}$$

In order to maximize z, in other words to find optimal h_i, we differentiate z with respect to l, m, n and equaling to 0, we get

$$mn - mh_3 - nh_2 + h_2h_3 = 0 \tag{25}$$
$$ln - lh_3 - nh_1 + h_1h_3 = 0 \tag{26}$$
$$lm - lh_2 - mh_1 + h_1h_2 = 0 \tag{27}$$

Upon solving equation (25), (26) and (27), we obtain same h_1, h_2 and h_3 which shows that all the three ratios are optimum a priori.

Theorem 2: Subtracting arbitrary numbers u_i, v_j from matrix A does not impact the solution but reduces the cost.

Corollary: Subtracting or adding any number will not change the solution because all of them have uniformly increased or decreased the costs.

Proof of Theorem: Let C'_{ij} be the costs in resultant matrix and $C'_{ij} = C_{ij} - u_i - v_j$ for all $i, j = 1, 2 \ldots n$ and u_i, v_j be real numbers.

$$\Rightarrow \sum\sum C'_{ij}A_{ij} = \sum\sum \left(C_{ij} - u_1 - v_j\right) A_{ij} \tag{28}$$

Since $\sum_j^3 A_{ij} = \sum_i^3 A_{ij} = 1$, we can write

$$= \sum\sum C_{ij}A_{ij} - \sum u_i - \sum v_i \tag{29}$$
$$\therefore \sum\sum C_{ij} - \sum u_i - \sum v_i \tag{30}$$

Equation (29) shows that optimal solution of the newly formed objective function and the original one is same, as $\sum u_i$ and $\sum v_i$ are independent of A_{ij}. In other words, they are like slack variables that add nothing to objective function.

Theorem 3: When $C_{ij} \geq 0$, if we have a feasible solution with $\sum\sum C_{ij}A_{ij}$, then it is optimal.

Proof of Theorem: The proof is quite intuitive. Since $A_{ij} = 0, 1$ and $C_{ij} \geq 0$. Therefore, minimum value of the objective function cannot be negative. That means it should be greater or equal to zero. But, since the minimum value is equal to zero, it means that A_{ij} is giving the optimal solution.

TABLE 3. Parameters and their obtained values.

Parameters	Obtained Values		
Bands	980 MHz	2.4 GHz	5 GHz
B	6	48	78
U	1	1	1
S	0.78	0.82	0.85
I	1	1	1
$BUSI$	3.68	39.36	66.3
Share Ratio	0.04241	0.3567	0.6008
Load Share	**0.4241**	**3.5671**	**6.0087**

TABLE 4. Initial 3 × 3 matrix for load allocation.

	4.68	39.36	66.3
0.04241	1	2	3
0.35671	3	1	2
0.60087	2	3	1

TABLE 5. Resultant 3 × 3 matrix after computation.

	4.68	39.36	66.3
0.04241	0	1	2
0.35671	2	0	1
0.60087	1	2	0

Example: We obtained B, U, S, I for the two nodes operating over three bands that are 20m apart. We calculated their $B \times U \times S \times I$ ($BUSI$) values, as shown in Table 3 below. Next, we calculated load shares as per $BUSI$ values of the bands for a total load of 10 Mb. It is noteworthy that there are only two users, therefore, channel utilization (U) and interference ratio (I) both are taken to be 1.

We form 3 × 3 matrix as shown in Table 4 below, where we write the $BUSI$ values column-wise in increasing order at the top of the matrix and load shares row-wise in increasing orders at the left of the matrix. The matrix is populated as shown in Table 4.

1 being row minimum in all the rows, will be subtracted from every entry in their respective rows. This operation results in table 5. By looking at the table, we see that load 0.0424 coincides with the band having $BUSI$ Value 3.68, the load 0.3567 coincides with the band having $BUSI$ value of 39.36. Finally, the load 0.6008 coincides with the band having $BUSI$ value of 66.3.

The coincided loads are allocated to the corresponding bands. Upon calculating the delay of all the bands, we notice that they are same which indicates that load was fairly shared.

VI. INCORPORATING RELAY NODES

Assuming that loads are fairly shared at the source node based on the performance of the bands, we can safely assume that the delay of all the three bands for their corresponding loads are equal. That is,

$$D_5 = D_{2.4} = D_{980} \tag{31}$$

where D_5 is the delay of the 5 GHz band, $D_{2.4}$ is the delay of 2.4 GHz band and D_{980} is the delay of 980 MHz band. Using

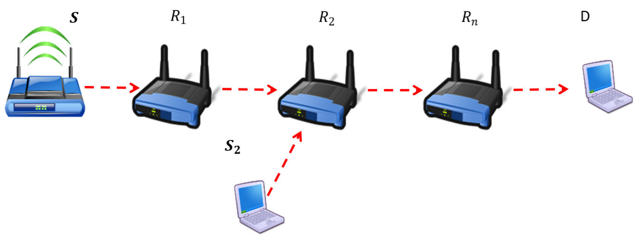


FIGURE 3. A simplified scenario where an additional node is transmitting via relay node.

equation (3), we rewrite the above as follows.

$$\frac{L_5}{(BUSI)_5} = \frac{L_{2.4}}{(BUSI)_{2.4}} = \frac{L_{980}}{(BUSI)_{980}} \tag{32}$$

However, the bands at relay nodes do not necessarily have the same $BUSI$ values as at source node. Moreover, additional nodes may be attached to the relay nodes that give rise to extra traffic load at the relay node, as shown in Figure 3. Finally, traffic at relay node may be different due to losses. These conditions result in violation of the constraints stated in above MILP which leads to the delay of the bands being unequal. That is,

$$\frac{L_5}{(BUSI)_5} \neq \frac{L_{2.4}}{(BUSI)_{2.4}} \neq \frac{L_{980}}{(BUSI)_{980}} \tag{33}$$

Therefore, when a particular band experience an increase in the load or decrease in the $BUSI$ value, we need to switch maximum load in the minimum number of switches, so as to keep the switching delay as low as possible. As an elaboration, consider the traffic and capacities on different bands in the Figure 4.

Traditionally, 5 Mb load from band a will be switched to band b. However, Band $b's$ capacity is much better than band a. It may be advisable to switch all the traffic to band b.

Let t is the total traffic of band a with a delay of D^t_{oc} where oc refers to old channel which happens to be the channel used at band a. If we switch s amount of traffic from t, we will be left with $t - s$. It follows that we have three options for the traffic t under question, which can be expressed mathematically as follows.

$$\text{Delay}D = \begin{cases} 1.\ D_{t,oc} \\ 2.\ D_{t-s,oc} + D_{s,nc} + \Delta \\ 3.\ D_{t,nc} + \Delta \end{cases} \tag{34}$$

In the first option, the system decides not to switch the traffic at all. Let the band handle its traffic. In such a case, the delay incurred is shown in case 1 above. In the second option, we partially switch the traffic. In this case, incurred delay is $D_{(t-s),oc} + D_{s,nc} + \Delta$. Here $D_{(t-s),oc}$ is the delay of the traffic left after switching s amount of traffic on old channel and $D_{s,nc}$ is the delay of the switched traffic on "new channel". Finally, Δ is the traffic switching delay. In third case, we switch all the traffic to new channel. In this case, incurred delay $D_{t,nc}$, which is the delay of the total traffic on the new channel. The goal is to find which option will have the least delay, given the performance and traffic estimates. In case of option 2, how much traffic to switch to new band to have the least delay. There is trade-off between traffic switching and the capacity gain. There should be an upper limit to traffic switching and number of switches made. Therefore, the goal is to optimize the traffic switching and the corresponding delay. This can be done by maximizing the switchable traffic and minimizing the number of times the traffic is switched in such a way that total end-to-end delay of all the band is reduced and equal. Consequently, for load switch problem formulation at relay nodes, in addition to constraints defined in the MILP, we shall add one more constraint for switching the traffic, which is;

$$\begin{gathered} \text{maximize } L_s \\ \text{subject to} \\ \frac{L_{s,n}}{(BUSI)_n} + \Delta = \frac{L_{s,o}}{(BUSI)_o} \end{gathered} \tag{35}$$

Here L_s is the switchable traffic load, $L_{s,n}$ refers to the switchable traffic load on the new band and $L_{s,o}$ refers to the switchable traffic load on old band. Similarly, $(BUSI)_n$ and $(BUSI)_o$ refer to the $BUSI$ values of new and old bands. The above implies that the delay of switched traffic on new band along with the switching time should be less than delay of same traffic on old band. Our goal is to find the maximum traffic of the current band whose delay would be lesser on the new band. We resolve this problem as follows.

Suppose on a particular band B_o, the amount of load L_o is increased or $BUSI$ value $(BUSI)_o$ is decreased and it is incurring more delay than others are. Therefore, we switch some of its traffic load to the other two bands. We incorporate these changes into (32) to obtain (36), as shown at the bottom of the next page. $(BUSI)_{n1}$ and $(BUSI)_{n2}$ in (36) are the $BUSI$ values of the bands other than $(BUSI)_o$ and L_{n1}, L_{n2} are their respective loads. $L_s = L_{sa} + L_{sb}$ 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 (37), as shown at the bottom of the next page, which is obtained by resolving (36).

We subtract L_s from $(BUSI)_o$ and add it to the band having higher $BUSI$ value. Reason for adding L_s to the band with higher $BUSI$ value is that it suffers lesser queuing, transmission and slot-synchronization delay because of higher capacity and bitrate. This gives us the opportunity to transfer lesser amount of load and to make a smaller number of switches in future. However, adding L_s to that band will distort the delay balance of the rest of the two bands, thereby making the band with higher $BUSI$ value slower. We again have to adjust the load between the two bands as follows. Let $(BUSI)_{n1}$ be the band with higher $BUSI$ value to which L_s was added. Thereupon, $(BUSI)_{n1}$ got slower. Therefore, we have to find another switchable load, say L_{s2}, that is to be subtracted from $(BUSI)_{n1}$ and added to $(BUSI)_{n2}$. L_{s2} is obtained using (38), as shown at the bottom of the next page.

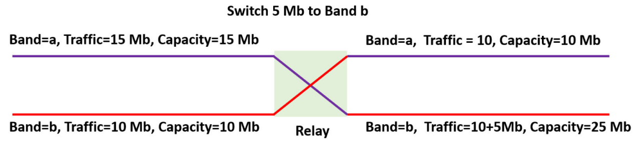


FIGURE 4. A simplified scenario where traffic load must be switched between the bands.

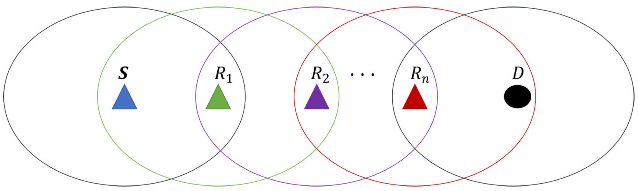


FIGURE 5. Assumed scenario for performance evaluation.

We subtract L_{s2} from $(BUSI)_{n1}$ and add it to $(BUSI)_{n2}$. In this way, the load between the two bands is adjusted. The three bands have once again equal delay. Thus, totally avoiding the ordering delay. Having similar delay values are crucial for orderly arrival of packets.

VII. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed multi-hop transmission in multiband WLAN systems. We first show the load share and corresponding delay for the three bands and then ratio of residual capacity to total capacity is shown to show the share-fairness of the scheme. We will also show the impact of number of end-users and number of relay nodes between source and destination. We also compare the switching delay with Truncated Decode and Forwarding (TDF) scheme used in [15]–[17]. Recall that TDF switches all the traffic from one band to another band regardless of the channel conditions with an aim to bring about spectral efficiency. Finally, we will also compare throughput achieved with our proposed SNR-based bitrate scheme with that of non-SNR based schemes that decides bitrate on the basis of the factors other than SNR.

To analyze the traffic switching delay, we have varied the number of relay nodes between source and destination. The extension of our proposed technique shown in section VI, is applied at relay nodes to estimate the traffic switching delay based on the switchable traffic derived in (37) and (38).

TABLE 6. Parameters setting.

Parameter	Value
Number of Radios	3 at each Node
Bands Used	980 MHz, 2.4 GHz, 5 GHz
Bitrate	As per SNR
Noise Level	90 dB
Bandwidth	
980 MHz Band	1 MHz
2.4 GHz Band	20 MHz
5 GHz Band	20 MHz
$EIRP$	30 dB
Modulation Scheme	QAM-64
Packet length	512 bytes
Inter-node Distance	20 meters
Interface Switching Delay	130 μs [23]

A. ENVIRONMENT AND PARAMETERS SETTING

Parameters used in this paper are given in Table 6. The assumed topology is shown in Figure 5. The nodes are 20 meters apart and are equipped with three 802.11 based radios all operating on three different bands as given in the table. Access points (source node and relay nodes) are assumed to be static while end-node is assumed to be mobile, following random walk. Capacity of the bands, bitrate and bit success rate are calculated as per SNR obtained at the receiver, for Quadrature Amplitude Modulation (QAM)-64 modulation scheme. Effective Isotropic Radiated Power (EIRP) is kept at 30 dB for all nodes. We assume uniform traffic loads for distribution and delay performance analysis and Poisson distribution for switching delay analysis. Load shares for uniform traffic are calculated using Algorithm 1.

Initially, only one source and destination pair is taken to show the load distribution, fair-shareness and corresponding delay of the incoming load with no traffic switching. Later, relay nodes are added resulting in source-relay, relay-destination with multiple relay-relay pairs between them as shown in Figure 5. The actual source and destination are

$$\frac{(L_o - L_s)}{(BUSI)_o} = \frac{(L_{n1} - L_{sa})}{(BUSI)_{n1}} + \Delta = \frac{(L_{n2} - L_{sb})}{(BUSI)_{n2}} + \Delta \tag{36}$$

$$L_s = \frac{L_0\left\{(BUSI)_{n1} + (BUSI)_{n2}\right\} - \left\{(L_{n1} + L_{n2})\,(BUSI)\right\}_0 - \Delta\left\{(BUSI)_0 + (BUSI)_{n1} + (BUSI)_{n2}\right\}}{(BUSI)_0 + (BUSI)_{n1} + (BUSI)_{n2}} \tag{37}$$

$$L_{s2} = \frac{\left\{L_{n1}\,(BUSI)_{n2} - L_{n2}\,(BUSI)_{n1}\right\} - \Delta\left\{(BUSI)_{n1} + (BUSI)_{n2}\right\}}{(BUSI)_{n1} + (BUSI)_{n2}} \tag{38}$$

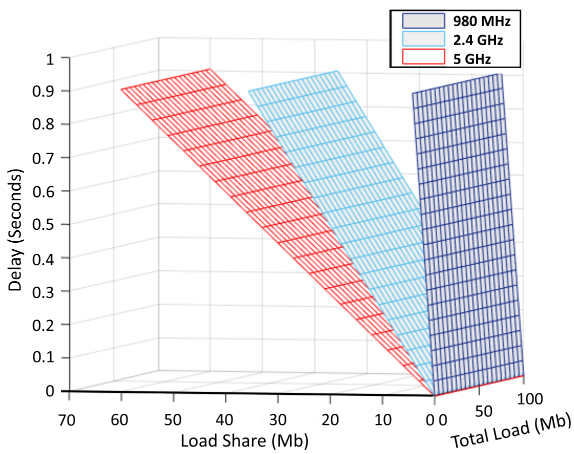


FIGURE 6. Comparison of delay, load share and total load.

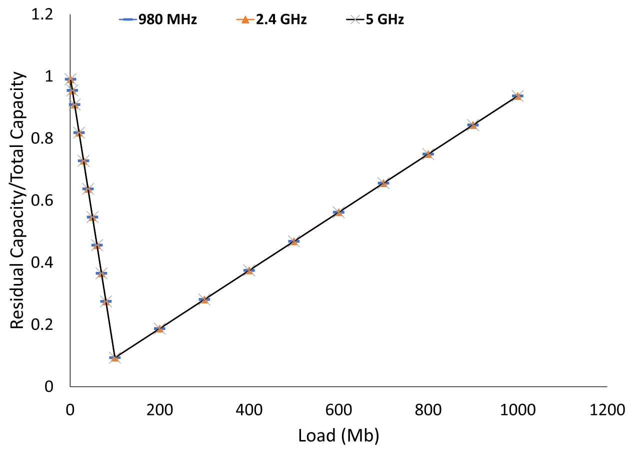


FIGURE 7. Ratio of residual capacity to total capacity.

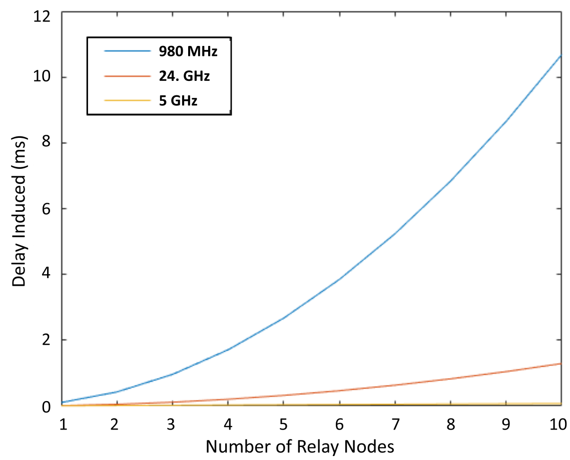


FIGURE 8. Delay induced by addition of relay nodes.

the first node and last node, respectively whereas the other nodes assist the transmission between source and destination. In other words, a node k (where $1 < k < n$, n referring to the destination) receives a packet from $k-1^{th}$ node and forward it to $k+1^{th}$ node until the frame reaches n^{th} node, that is, the destination node.

B. RESULTS

1) LOAD DISTRIBUTION ANALYSIS

In Figure 6, we have shown the distribution of load and delay performance of our proposed algorithm with respect to incoming traffic load. 5 GHz takes the highest share of the incoming traffic load followed by 2.4 GHz. 980 MHz has better fading characteristics as compared to 5 GHz and 2.4 GHz. It 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 meager comparing with other two bands. From the figure, we can see that regardless of the load assumed by the bands, their respective delays are same. Delays of all the three bands increase uniformly with the increase in the incoming load. Whatever the incoming traffic load is, and as a result, whatever the load distribution is, delays of the three bands are same, which implies that all the frames reaching at same time, thus; absolutely avoiding any possible re-ordering delay.

2) CAPACITY UTILIZATION ANALYSIS

In Figure 7, we have shown capacity utilization performance for the same load and scenario. The ratio of residual capacity to total capacity tends to decrease with the increase in total load. When total load exceeds the total capacities of all three bands, this ratio begins to increase. 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 was not only fair, but the ratio is equal for all the three bands substantiating the fact that load was optimally divided.

3) IMPACT OF RELAY NODES

In Figure 8 we show the impact of relay nodes on delay. The delay increases as we increase the number of relay nodes. As we increase the number of relay nodes, the delay performance of 980 MHz band is considerably affected as compared to 2.4 GHz and 5 GHz bands. In order to make up for this difference, we used the technique described in section VI to adjust the load between the three bands. This is the reason that we added L_s to the band with higher *BUSI* value as it is less affected by relay nodes. Figure 9 shows the adjusted load share with respected to relay nodes. In the figure, the curve for 980 MHz is leaned slightly towards left and curves for 2.4 GHz and 5 GHz are leaned right. The change in opposite direction of curves show that the traffic load from 980 MHz band is switched to 2.4 GHz and 5 GHz bands in order to make the end-to-end delay equal. Addition of relay nodes will change the load of each band but delay of all the bands are equal.

4) IMPACT OF NUMBER OF END-NODES

In Figure 10, we have compared load share with respect to increasing number of end-users. Channel utilization is

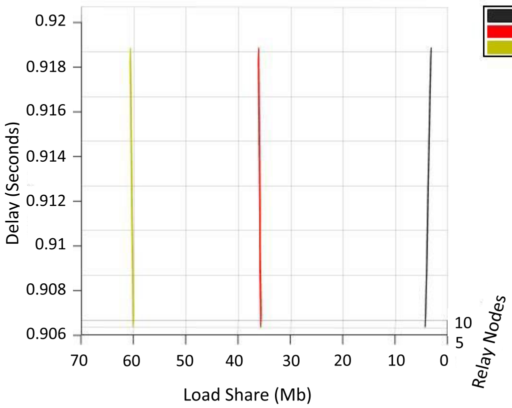


FIGURE 9. Change in band load with respect to relay nodes.

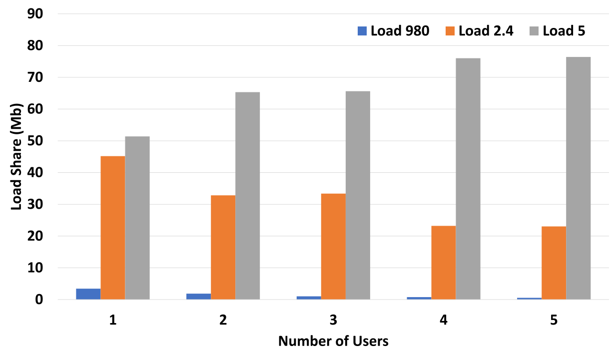


FIGURE 10. Change in band load with respect to number of users.

calculated on the basis of the number of channels the bands have, while interference is calculated on the basis of the position of the nodes from access points and each other assuming random walk model is followed by the mobile users. 5 GHz has consistent performance for having enough number of orthogonal channels. As we increase the number of nodes, it takes more load than 2.4 GHz and 980 MHz. The load share for 2.4 GHz and 980 MHz decreases gradually as we increase the number of end-users.

5) SWITCHING DELAY

In Figure 11, we have compared switching delay of our proposed scheme with that of Truncated Decode and Forwarding (TDF), when relay nodes were added. For calculating switching delay, packet lengths are kept at 512 bytes and the arrival rates is taken to be Poisson with average of 100 packets per second. The techniques used in [15], [16] and [17] switch the traffic from one band to anther regardless of the condition on the channel of each band whereas our proposed scheme switch only the traffic which is needed to be switched. In other words, the extra load that is causing more delay on particular band. 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

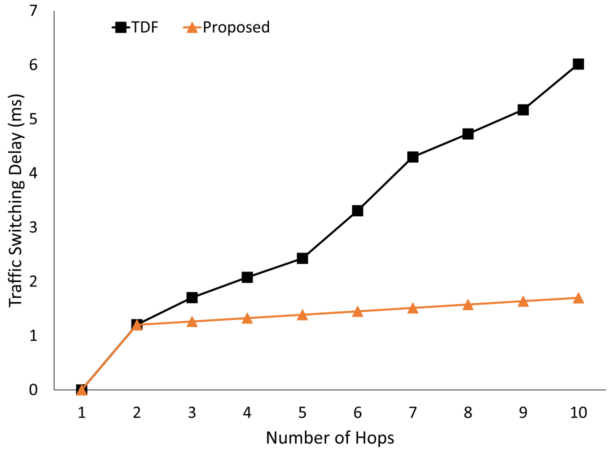


FIGURE 11. Switching delay with respected to number of hops.

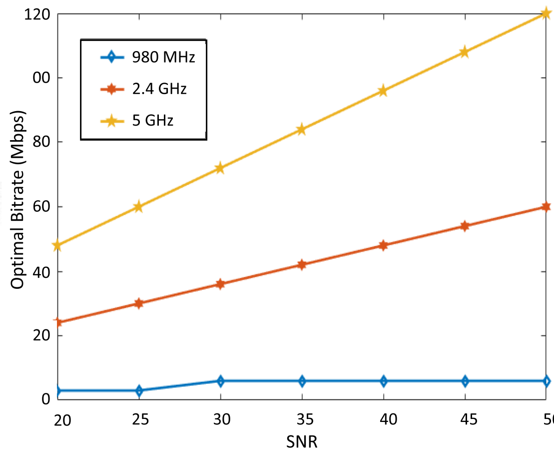


FIGURE 12. Comparison of optimal bitrate.

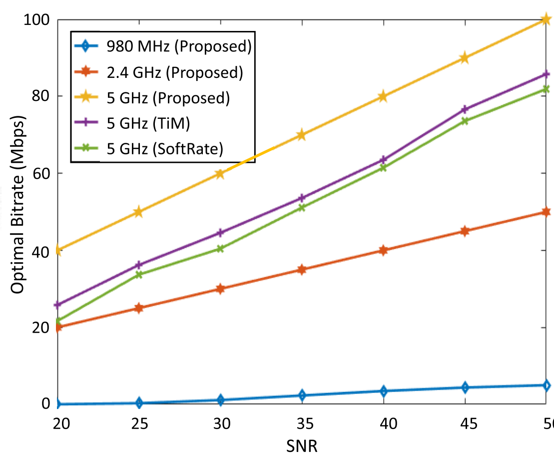
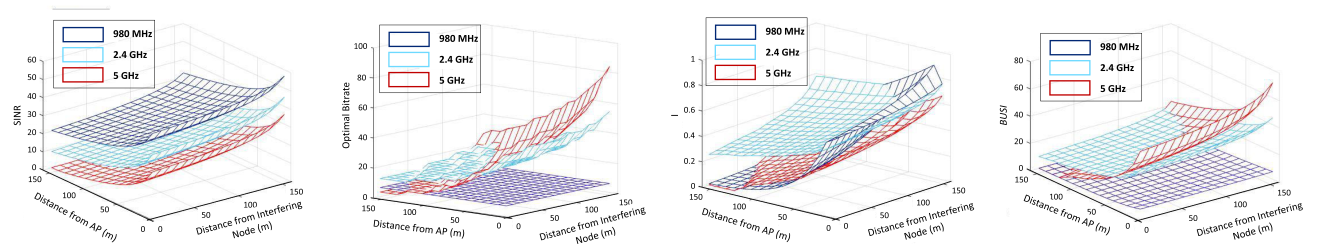


FIGURE 13. Comparison of throughput.

scheme is slightly increasing, 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



(a) Impact on $SINR$. (b) Impact on optimal bitrate. (c) Impact on interference ratio. (d) Impact on $BUSI$.

FIGURE 14. Impact of interference on various parameters.

from one band to another. Significant portion of this delay is the interface switching delay as per equation (12), while the actual frame processing delay is almost negligible due to which the curve is appearing to be a straight line. Total switching delay for TDF scheme is well above 6 μs whereas it is only 1.5 μs for our proposed scheme.

6) OPTIMAL BITRATE ANALYSIS

Figure 12 shows the optimal bitrate with respect to SNR. Generally, optimal bitrate increases in direct proportion to SNR for all the bands, however, 5 GHz has twice the bitrate of 2.4 GHz while optimal bitrate of 980 MHz gets saturated at 6 Mbps.

7) THROUGHPUT COMPARISON

We compare maximum throughput achieved for our proposed scheme with that of non-SNR based schemes that decides bitrate on the basis of the factors other than SNR. Other than SNR, packets are lost due to interference, medium access control (MAC) inefficiencies, buffer size etc. Deciding bitrate other than SNR may lead to wrong results. The same is reflected in throughput given by non-SNR based schemes as shown in Figure 13 where the throughput of our proposed technique is compared with Softrate [21] and TiM [26].

8) INTERFERENCE ANALYSIS

As the interfering nodes move away, interference decreases which results in the increased signal-to-interference-plus-noise Ratio (SINR), bitrate and *BUSI* values. As the node move closer to access point, *SINR* and *SNR* overcomes the Interference. Therefore, *SINR*, bitrate and *BUSI* value increase because of the signal strength. Generally, 5 GHz supports higher bitrate but is most affected by distance and interference. It follows that at higher interference and longer distance from access point, 2.4 GHz outperforms 5 GHz. Similarly, 980 MHz is the least affected by distance from the access point and interference. The impact of interference on various parameters is shown in Figure 14.

VIII. CONCLUSION

In this paper, we treated multiple bands in multi-hop WLAN systems. We showed multiband transmission over single-hop as well as multiband transmission over multiple hops. Multibands transmission is a cost effective and high-capacity solution to disaster area relay networks and to cater for the exponential increase in data traffic demand. However, we needed to address several research challenges before realizing the true benefit these types of networks. As a proof-of concept, we worked on minimizing the end-to-end delay and maximizing throughput. We studied different parameters that affect throughput and delay in multiband multi-hop scenario and attempted to choose their optimal values according to the channel conditions. Further, realizing that delay is the function of the incoming load and considering the parameters that affect the delay and throughput, we formulated a mixed integer linear program to distribute the incoming load among the bands in such a way that minimized the end-to-end delay and maximized the throughput. Mathematical results showed that proposed technique made the delay of the three bands equal, thereby avoiding the re-ordering delay. Furthermore, the ratio of residual capacity to total capacity was equal highlighting the fact that load was fairly shared and that capacity was optimally utilized, this in return substantiates the optimal throughput achieved with our proposed technique. We conclude that switching the traffic between the bands, keeping the delay of the band equal and choosing optimal bitrate are feasible solution to maximizing throughput and minimizing end-to-end delay.We believe multiband simultaneous transmission will not only meet the traffic challenges faced by disaster area networks but also that of the expected traffic volumes for traditional networks for years to come.

IX. OPEN RESEARCH ISSUES

Simultaneous transmission over multiband in multihop relay networks will prove to be a promising avenue for improving the capacity of disaster-area and military tactical networks. However, in order to take full advantage of using multiple bands at the same time, there are certain challenges that needs to be addressed. In this section, we outline several research challenges for designing a multi-band relay networks that transmit simultaneously. Considering the work done as a proof-of-concept, future research work can be conducted in the following areas.

A. DESIGNING INTEGRATED MULTIPLE ACCESS CONTROL (MAC)

How will the traffic from the three bands be merged together to form the amalgamated chunk of data consists of a big research challenge. Furthermore, how to carry out parallel processing is also an open research problem. Given the different inherent characteristics of the bands, how to allocate resources to the incoming traffic should also be considered. These are the questions that need to be addressed in the future. An integrated MAC protocol for simultaneous transmission over the next generation relay-based networks needs to be carefully designed to address the aforementioned issues.

B. CAPACITY OF MULTI-BAND RELAY NETWORKS

In the future, research work needs to be conducted on measuring the upper and lower bounds of performance of the multi-band relay networks. For instance, suppose that there is only a single active source-destination pair while all other nodes assist this transmission. Analysis on the capacity gain if we use all the three (or even more) bands simultaneously needs to be performed.

C. PROCESSING AND SWITCHING DELAY

A packet, when received is demodulated, de-interleaved, de-punctured, Viterbi decoded, and made to pass through frame error checking. Processing three different types of packets simultaneously can be a cumbersome job. This becomes even worse when a packet has to travel over multiple hops and at every node, similar process is carried out. Moreover, when there is an imbalance in the delay of the bands, a certain amount of traffic load has to be switched from one band to another one. Different bands have different bandwidths leading to different frame sizes. Switching packets to the new band requires making packets conformable to the targeted band that incurs significant processing delay. Therefore, we need to reduce the processing and band switching delays.

D. INCORPORATING ENERGY EFFICIENCY

We need to design a multi-band operation that enables selecting an optimum interface based on the nature of the communication and channel conditions in multiple bands and switch the rest of the interfaces to sleep mode, if the base station or the relay nodes are not used to their peak capacities.

E. RE-ORDERING DELAY

In our proposed method, we avoided the out-of-order reception of frames by equaling the delay of the bands. However, out-of-order packet arrival may still occur because of the frame losses and heterogeneous MAC protocols for the multiple bands at the receiving ends. Therefore, out of order packet reception needs to be investigated in depth, and a thorough problem and solution need to be formulated in order to reduce re-ordering delay of any kind.

F. SELECTIVE TRANSMISSION

Considering the re-ordering delay discussed above, one way to reduce re-ordering delay is to have selective transmission. In other words, we must ensure that we send the most important piece of information in the next frame. However, we need to investigate, how to send a selected frame? What should be the transmission order of the selected frame so as not to deteriorate the order of the rest of the transmitting data? Which band should be chosen for this selective transmission? These questions apply also to the acknowledgement of the frames. Suppose that a node has received four out-of-order data frames. Which three should the node acknowledge in the next selective active acknowledgement in order to maximize the throughput in the multi-band relay scenario?

G. MULTI-BAND TO SINGLE BAND AND BACK

Finally, not all devices are multi-band enabled. We must consider the legacy nodes while designing a multi-band operation. Work can also be done on optimally placing the multi-band enabled D2D nodes and base stations between legacy access points to maximize the throughput and minimize the communication delay.

ACKNOWLEDGMENT

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