Multi-Class Traffic Analysis of Single and Multi-band Queuing System

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***Abstract*—To facilitate higher bandwidth for multimedia traffic, modern mobile routers support simultaneous multi-band communication, leading to less interference, higher capacity and better reliability. However, there exists no quantitative evaluation to judge whether multi-band is better than single band router in realistic scenario. Our main objective in this paper is to find performance of different class of traffic under single and multi-band system with respect to utilization. In this paper, we have used different scheduling algorithms for multi-band routers which transmits different classes of traffic through different frequency bands in order to achieve improved performance. We have provided analytical and simulation results for average queue occupancy, average delay, throughput, and packet drop rate. We show our results comparing multi-band and single band mobile router performances based on different circumstances. It is evident from our results that one of them is not always better than the other. Our work can help ...**

***Index Terms*—Analytical modeling, scheduling algorithm, queuing system, real-time traffic, next generation mobile routers.**

I. INTRODUCTION

A. Why multi-band routers / Importance

In recent years, there have been explosive growth of mobile users accessing large multimedia files (such as, high definition audio, video, images, etc.) over the Internet. Therefore, the bandwidth demand for mobile Internet access is increasing exponentially [1]. To satisfy such a higher bandwidth requirement, today wireless routers are available commercially with simultaneous multi-band support of 2.4 and 5 GHz. Future IEEE 802.11ad (WiGig) tri-band enabled devices, operating in the 2.4, 5 and 60 GHz bands, are expected to deliver data transfer rates up to 7 Gbps [2]. The benefit of using multi-band router is to have *less interference, higher capacity and better reliability*. Exploitation of rarely-used frequency bands in wireless networks reduces interference in heavily-used frequency band, e.g., 2.4 GHz, thereby increasing total capacity of the wireless network.

B. Problem Statement

Current simultaneous multi-band MRs make use of two different bands (2.4 GHz and 5GHz) for different types of devices in a home network. However, they do not attempt to exploit the under-utilized frequency band while other one is flooded with data. The multi band router system is a heterogeneous multi server system which means each server rate is different than each other. Heterogeneity of system arises a question which arrived packet should be distributed to which servers, namely allocation policy, to have high throughputs or increase performance [3]. The question getting complex while different class of packets has been considered because some of the traffic type (such as, real-time) has some strict delay constraints associated with it; some other signaling traffic (required for mobility management) are crucial for maintaining Internet connectivity of the mobile users. Therefore; flexibility levels of each class and each server; which class can be served by which server or which servers can serve which class, and priority of class; which class will be served first if a server can server more than one class, can be added to multi server system to make the system more complex. Therefore, it is not only essential to propose appropriate scheduling and queue management scheme for the multi-class traffic to ensure maximum possible utilization of the system resources in multi-band mobile routers [4] but also performance of multi band system should be compared with single band system with different approaches. The aim of this work is to propose a scheduling algorithm for multi-band routers and compare single-band and multi-band system with different multi band allocation policies and find out under which circumstances single band or multi band better by using real routers service rates and buffer sizes.

C. Previous works

There have been voluminous research about multi heterogeneous servers system in the literature. These research subjects can be classified under four questions. (1) How many servers are needed? (2) What should be the allocation policies? (3) What should be flexibility level of each server? (4) What should be flexibility level of each class? A review of detail related literature can be found in [5]. There have been also several research works [1], [2], [4], [6]–[9] reported in the literature that attempt to extend current single band technology through the use of multiple frequency bands, leading to increased bandwidth while reducing interference. Even though multi band usage has been widely investigated in cell networks [7], [8], it is relatively new concept in wireless networks. Verma and Lee [9] explain possible Wi-Fi architecture with multiple physical and link layers to support multiple frequency bands simultaneously. Singh et al. [1] proposed a method to assign end-devices different bands based on their distances from the access router. In [2], [6], authors proposed the use of 60 GHz frequency band (having low range) to attain faster data transfer rate in wireless networks. However, none of these works [1], [2], [4], [6]–[9] propose any scheduling algorithm for multi-band system considering multi-class traffic, neither do they perform any comparison between multi and single bands.

D. *Differences with previous works*

To the best our knowledge, there has been no earlier works on scheduling and queue management for multi-band mobile routers that attempts to maximize utilization of available bands. Moreover, no previous work exists that proposed the sharing of multiple bands to transmit different classes of traffic. This is a *novel work* that aims at attaining maximum possible band utilization with different allocation policies while using band sharing in multi-band and compare obtained performance with single-band performances.

E. *Objective*

The *objective* of this work is to compare the performance of proposed multi band routers with single band router with respect to band-wise and class-wise analysis based on extensive simulation results.

F. *Contribution*

The *contributions* of this work are: (i) proposing a band-sharing router architecture and a novel scheduling algorithm to ensures maximum possible utilization of the system, (ii) Comparing the multi band router with single band router with realistic simulation.

Our proposed algorithm considers multi-class Internet traffic and schedules them through alternate under-utilized frequency bands, thereby reducing packet loss and delay.

G. *Results* ****

Results show the packet drop rate and throughput are significantly improved in proposed band-sharing architecture of the mobile router. Moreover, multi-band router can suffer low band utilization under light traffics.

H. *Uses*

Our proposed scheme and related analysis will help network engineers build next generation mobile routers with higher throughput and utilization, ensuring least packet loss of different classes of traffic. Our work also helps decide what kind of routers are suitable under which conditions.

I. *Organization of the paper*

The rest of the paper is organized as follows. In Section II, we explain the typical architecture of single-band mobile routers, followed by the proposed multi-band architecture in Section III. Section IV presents analysis of model to derive different performance metrics of the proposed architecture. In Section V, we present the simulation results which show performance of queue and class differences for single and multi band architectures. Finally, Section VI has the concluding remarks.

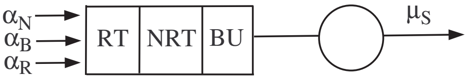

Fig. 1. Single-band mobile router architecture.

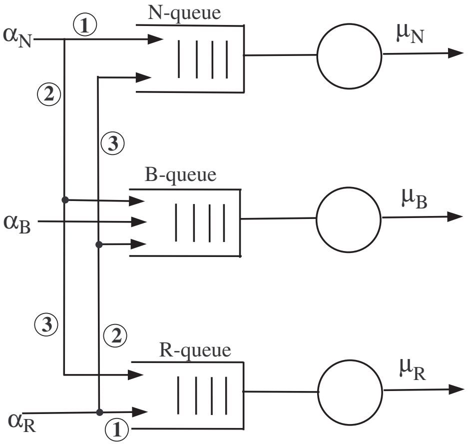

Fig. 2. Proposed architecture of a simultaneous multi-band mobile router.

II. SINGLE BAND ROUTER ARCHITECTURE

Traditional single-band MRs use only one frequency band for all types of traffic. Fig. 1 shows the architecture of a single band MR with arrival rates of different class of traffic: signaling traffic or Binding Update (BU), non-real time (NRT), and real-time (RT) traffic with α_B, α_N and α_R arrival rates. All the traffic are queued and served by the single server with rate (μ_S) based on the priority level of each class. Generally accepted priority order of packet classes from highest to lowest is BU, NRT, and RT [10]. Disadvantage of priority of classes in single-band architecture is one type packet can be served continuously while other type of packets suffer from not being served. To answer that needs a threshold is used for each class. However, identify optimum threshold is another problem. In our model, absolutely non-preemptive priority is assumed for each class.

III. PROPOSED MULTI-BAND ROUTER ARCHITECTURE

Commercial mobile routers available today makes use of two different bands (2.4 GHz and 5GHz) simultaneously for different types of devices in a home network. Laptops may connect to 2.4 GHz network while WiFi-enabled TV, gaming devices may connect to 5 GHz network. This reduces interference with the heavily-used 2.4 GHz network (as cordless phones, microwave oven use similar band). In addition, video streaming can be done through the high frequency band. Future IEEE 802.11ad (WiGig) tri-band enabled devices, operating in 2.4, 5 and 60 GHz bands, are expected to deliver data at a much higher rate (up to 7 Gbps) [2].

The simultaneous multi-band routers available today do not allow sharing of bands among the traffic classes. In this section, we explain our proposed architecture of multi-band

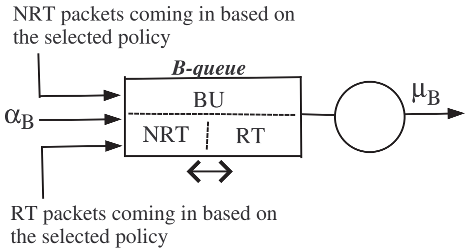

Fig. 3. Queue corresponding to BU band.

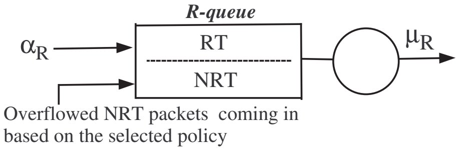

Fig. 4. Queue corresponding to RT band.

MRs that promotes sharing of bands to maximize system utilization. We have considered three different queues (shown in Fig. 2), each of which corresponds to a frequency band of a simultaneous tri-band Mobile Router. We name them as B-queue, N-queue and R-queue as they are designated to carry BU, NRT and RT traffic, respectively in usual case where the traffic arrival is much less than the capacity of the queue. The three queues and their corresponding arrival rates and service rates are shown in Fig. 2.

In our proposed architecture, traffic of one class can flow through other queues provided the other queues have empty slots, thereby ensuring better utilization of buffer spaces available. For example, if the B-queue has some empty spaces available and a bursty RT traffic comes in, the overflowed RT traffic can be queued in the B-queue and subsequently served (or sent) through the B-server (transmitter).

A. Time and space priority

The time and space priority for the three queues of the proposed architecture are explained in Figs.3, 4 and 5. For B-queue, BU packets have the highest priority; RT and NRT packets have dynamic priority based on arrival rates (see Eqns.(1) and (2)). Regarding space priority, BU packets are queued in front of B-queue and if there are empty spaces available, other types (RT and NRT) can be accommodated as shown in Fig. 3.

R-queue can have only RT and NRT packets as shown in Fig. 4. RT traffic has higher priority over NRT traffic. Therefore, R-queue can have NRT packets only if RT packets cannot fill the R-queue at any instant and there are NRT packets overflowed from the N-queue.

Finally, Fig. 5 shows the N-queue which is designated for NRT traffic. However, if there are empty spaces available in this queue, overflowed RT traffic out of R-queue can be enqueued in N-queue (see Fig. 2).

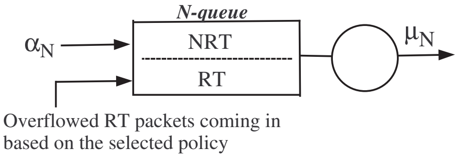

Fig. 5. Queue corresponding to NRT band.

B. Allocation Policy

We have considered the following two crucial factors to ensure improved performance of the multi-band MR:

- The unused buffer space of one queue (or band) can be used for other traffic types, thereby reducing the idle time of the system.
- Priorities of different traffic classes are also considered while selecting a particular type of packet over others. Priority has an inverse relation with the arrival rate.

Two types of allocation policies are used in the proposed architecture:

- Fastest server first (FSF).
- Least Utilization First (LUF).

Queue allocation policies are explained as follows:

- Different class of traffic are first tried to be sent through the designated frequency band.
- If there is overflow of RT or NRT packets from R-queue or N-queue, they are forwarded to other server on the basis of two principles: faster server first or lower utilization server (computed by α_B / μ_B for B-queue, α_N / μ_N for N-queue, and α_R / μ_R for R-queue).
- If there is no space available in the chosen queue, the packets are queued in the third queue (if there is space in it). Otherwise, packets are dropped from the system.
- The race between different class of traffic are resolved based on priority explained in Section IV-C.
- Similar policy is enforced while dealing with each class of traffic.

IV. ANALYSIS

In this section, we explain in some details how various metrics are computed in our multi-band proposed architecture and for single-band architecture.

A. Assumptions

To make the model analytically tractable, the following assumptions have been made.

- Packet arrival follows Poisson distribution.
- Type of queue discipline used in the analysis is FIFO with non-preemptive priority among various traffic classes.

B. Notations

The notations used in the analysis are listed below. To simplify our notation, we use T as the common notation for different traffic class types, and $T \in \{$ B, N, R $\}$.

N_T	Queue size of T-queue in the MR,
α_T	Total packet arrival rate at T class of i-th MN,
μ_T	Service rate at T-queue of i-th MN,
$\sigma_{T_{BQ}}$	Priority of class T traffic in B-queue,
$E(D_T)$	Average delay of class T packets,
$E(n_T)$	Average occupancy of class T packets,
P_{dT}	Drop probability of class T packets,
γ_T	Throughput of class T,
$E(D_{TQ})$	Average delay of packets in T queue,
$E(n_{TQ})$	Average occupancy of packets in T queue,
P_{dTQ}	Drop probability of a packet in T queue,
γ_{TQ}	Throughput in T queue,
$E(D^T_{TQ})$	Average delay of class T in T queue,
$E(n^T_{TQ})$	Average occupancy of class T in T queue,
P^T_{dTQ}	Drop probability of class T in T queue,
γ^T_{TQ}	Throughput of class T in T queue.
$E(D_{sys})$	Average delay of packets in system,
$E(n_{sys})$	Average occupancy of packets in system,
P_{dsys}	Drop probability of a packet in system,
γ_{sys}	Throughput in system.

C. Priority

Priorities of different classes are taken into account while allowing traffic into B-queue. Priority of B packets in B-queue is $\sigma_{B_{BQ}}$ = 1. Priorities of other classes of traffic in B-queue are measured as follows:

$$\sigma_{N_{BQ}} = \frac{\alpha_R}{\alpha_B + \alpha_R + \alpha_N} \tag{1}$$

$$\sigma_{R_{BQ}} = \frac{\alpha_N}{\alpha_B + \alpha_R + \alpha_N} \tag{2}$$

D. Alternative way of deriving metrics using M/M/1/N formula

We may have used M/M/1/N formula rather than simulations to derive metrics for while analyzing performance of multi-band by using total arrival rates of each class, total service rate and total buffer sizes of each bands. However, the analytical formulation will not reflect the real scenario. This is because in heterogeneous multi-server system and for LUF case, packets may remain in the queue of slower server, thereby increasing the packet delay and occupancy of the system.

It can be noted that all the system performance metrics (e.g., average occupancy, packet delay, drop rate, throughput) can be obtained (or approximated) only for the FSF policy under the heavily loaded (server) condition. This cannot approximate when the servers remain idle or for the LUF policy.

For the FSF policy (with heavy traffic), it can be computed as follows:

$\alpha_{All} = \alpha_B + \alpha_N + \alpha_R$
$\mu_{All} = \mu_B + \mu_N + \mu_R$
$N_{All} = N_B + N_N + N_R$
$\rho_{All} = \alpha_{All}/\mu_{All}$

Therefore estimated occupancy of multi-band system can be obtained using the following standard equation of M/M/1/N [11]:

$$E(n_{sys}) = \begin{cases} \frac{\rho_{All} - (N_{All}+1)\rho_{All}^{N_{All}+1} + N_{All}\rho_{All}^{(N_{All}+2)}}{\left(1-\rho_{All}\right)\left(1-\rho_{All}^{N_{All}+1}\right)} & \text{, if } \rho_{All} \neq 1 \\ \frac{N_{All}}{2} & \text{, if } \rho_{All} = 1 \end{cases} \tag{3}$$

The packet drop probability of multi-band system can be obtained using standard M/M/1/N formula as follows [11]:

$$P_{dsys} = \begin{cases} \frac{\rho_{All}^{N_{All}}(1-\rho_{All})}{1-\rho_{All}^{N_{All}+1}} & \text{, if } \rho_{All} \neq 1 \\ \frac{N_{All}+1}{2} & \text{, if } \rho_{All} = 1 \end{cases} \tag{4}$$

However, performance metrics for each class cannot be approximates similar way because the system can be only heavily loaded by one type packet. By using similar approach as above, it is not possible to understand which type packet has more influence on system. To answer that problem, our past work (**** cite technical report****) will be solution for a particular case in multi band system. On the other hand, average occupancy, delay, drop rate and throughput of each class can be measured by using approximation formulas in single band. There are some previous work in the literature to do so. In [12], drop rate of each class and [13], average class occupancy and delay have been analytically formalized for non-preemptive priority. However, non of work has been justified by a simulation. Therefore, excessive simulation is used to compare both single and multi band systems to obtain reliable results. We will give some alternative approximation result under some cases for FSF allocation policy:

Case 0: As a general assumption, assume that BU packets are not overflowed at any time.
Case 1: Only NRT type packets are overflowed.
Case 2: Only RT type packets are overflowed.
Case 3: Both N and R types packets are overflowed.

We will go through only one case because we can use similar methodology to approximate metrics formulas based on the allocation policy.

1) Case1: Assume that only NRT type packet are overflowed and $\mu_R > \mu_B$. In that case, following approximations can be done to evaluate performances of each class.

$$E(n_T) = E(n^T_{TQ}) = \begin{cases} \frac{\rho_T - (N_T+1)\rho_T^{N_T+1} + N_T\rho_T^{(N_T+2)}}{\left(1-\rho_T\right)\left(1-\rho_T^{N_T+1}\right)} & \text{, if } \rho_T \neq 1 \\ \frac{N_T}{2} & \text{, if } \rho_T = 1 \end{cases} \tag{5}$$

and

$$P_{dT} = P^T_{dTQ} = \begin{cases} \frac{\rho_T^{N_T}(1-\rho_T)}{1-\rho_T^{N_T+1}} & \text{, if } \rho_T \neq 1 \\ \frac{N_T+1}{2} & \text{, if } \rho_T = 1 \end{cases} \tag{6}$$

From $E(n_T)$ and P_{dT}, delay and throughput for BU and RT type packet can be found as

$$E(D_T) = E(D^T_{TQ}) = \frac{E(n_T)}{\alpha_T} \tag{7}$$

and

$$\gamma_T = \gamma_{TQ}^T = \alpha_T(1 - P_{dT}) \tag{8}$$

where $\rho_T = \alpha_T/\mu_T$ and T can be B and R.

However, performance evaluation for NRT type is different than BU and RT type packets because overflow NRT type packets will be forwarded to B-queue and R-queue. Therefore, overflow packets should be considered while finding performance metrics for NRT type packets.

$$P_{dNQ} = \begin{cases} \frac{\rho_N^{N_N}(1-\rho_N)}{1-\rho_N^{N_N+1}} & \text{, if } \rho_N \neq 1 \\ \frac{N_N+1}{2} & \text{, if } \rho_N = 1 \end{cases} \tag{9}$$

To find NRT packet occupancy in multi-band system, we have to know average occupancy of NRT packets in R-queue and B-queue. From assumption which made above (FSF allocation policy is used and $\mu_R > \mu_B$), it is known that overflow NRT packets are forwarded to firstly R-queue and then B-queue. Therefore; average overflow NRT packets can be measured as follow:

$$Overflow\,NRT\,packets = \alpha_N(P_{dNQ}) \tag{10}$$

To find average occupancy of NRT type packets in R-queue, total occupancy of R-queue measured as follows;

$$E(n_{RQ}) = \begin{cases} \frac{\rho_R^{'} - (N_R+1)\rho_R^{'\,N_R+1} + N_R\rho_R^{'\,(N_R+2)}}{\left(1-\rho_R^{'}\right)\left(1-\rho_R^{'\,N_R+1}\right)} & \text{, if } \rho_R^{'} \neq 1 \\ \frac{N_R}{2} & \text{, if } \rho_R^{'} = 1 \end{cases} \tag{11}$$

where $\rho_R^{'} = \frac{\alpha_N(P_{dNQ})+\alpha_R}{\mu_R}$. Then average occupancy of NRT type packets in R-queue will be $E(n_{RQ}^N) = E(n_{RQ}) - E(n_R)$. To find the occupancy of NRT type packets in B-queue, overflow NRT packets from R-queue should be measured by considering non-preemptive priority because NRT packets have second priority in R-queue. By using formula in [12], P_{dRQ}^N can be measured. Therefore; average overflow NRT packets from R-queue can be calculated as follow:

$$Overflow\,NRT\,packets\,from\,R - queue = \alpha_N P_{dNQ} P_{dRQ}^N \tag{12}$$

To find average occupancy of NRT type packets in B-queue, total occupancy of B-queue measured as follows;

$$E(n_{BQ}) = \begin{cases} \frac{\rho_B^{'} - (N_B+1)\rho_B^{'\,N_B+1} + N_B\rho_B^{'\,(N_B+2)}}{\left(1-\rho_B^{'}\right)\left(1-\rho_B^{'\,N_B+1}\right)} & \text{, if } \rho_B^{'} \neq 1 \\ \frac{N_B}{2} & \text{, if } \rho_B^{'} = 1 \end{cases} \tag{13}$$

where $\rho_B^{'} = \frac{\alpha_N P_{dNQ} P_{dRQ}^N + \alpha_B}{\mu_B}$. Then average occupancy of NRT type packets in B-queue will be $E(n_{BQ}^N) = E(n_{BQ}) - E(n_B)$. Therefore; $E(n_N) = E(n_{NQ}) + E(n_{RQ}^N + E(n_{BQ}^N$. Again by using formula in [12], P_{dBQ}^N can be measured. Actually $P_{dN} = P_{dBQ}^N$ because only NRT packets dropped from system is NRT paclets which dropped from B-queue. By using $E(n_N)$ and P_{dN}, delay and throughput can be calculated as

$$E(D_N) = \frac{E(n_N)}{\alpha_N} \tag{14}$$

and

$$\gamma_N = \alpha_N(1 - P_{dN}) \tag{15}$$

Similar approaches can be done for other cases. Because of page limitations, other cases are omitted.

E. Utilization

Utilization is the percentage of time the server is busy (or not idle which means, 1 - probability of state 0). We have computed the band utilization through simulations by using the ratio of amount of time server found busy to the total time of simulation in each run.

F. Average queue occupancy

We have taken average of the three queue occupancies of multi-band architecture in order to compare multi band system with single-band.

Total average queue occupancy of multi-band architecture (in all queues) can be computed as follows:

$$E(n_{Total}^{MB}) = E(n_B) + E(n_N) + E(n_R) \tag{16}$$

G. Computing drop probability

For multi-band system, we have computed the packet drop rate of system (in simulations) as follows after finding each drop rate of packet type:

$$P_{d(avg)}^{MB} = \frac{P_{dB} * \alpha_B + P_{dR} * \alpha_R + P_{dN} * \alpha_N}{\alpha_B + \alpha_N + \alpha_R} \tag{17}$$

H. Throughput

The total throughput of multi-band architecture can be obtained as follows:

$$\gamma_{All}^{MB} = \gamma_B + \gamma_N + \gamma_R \tag{18}$$

I. Average packet delay

Average delay of each packet in the multi-band architecture can be obtained as follows:

$$E(D_{avg}^{MB}) = \frac{\gamma_B E(D_B) + \gamma_N E(D_N) + \gamma_R E(D_R)}{\gamma_{All}^{MB}} \tag{19}$$

V. RESULTS

We have written discrete event simulation programs in MATLAB environment by taking into account the assumptions and scheduling policies mentioned in Sections II and III. We have followed M/M/1/N and M/M/3/N [11] procedures for the implementation of simulation programs. We have kept equal buffer length (50 packets) for each multi-band queue. Buffer lengths are kept small [14] as in real routers to decrease packet delay. However, to be fair to single band, total buffer length for multi-band (150 packets) is used. RT and NRT packets are assumed to be 512 bytes [2], [15] whereas the BU packets are assumed to be 64 bytes. The service rates of the B, N and R-queues are kept 27, 75 and 132 packets/sec which is proportional to service rates of multi-band routers [2]. Single band routers can only have one band therefore the highest

service rate of band in multi band (132 packets/sec) is used for service rate of single band. We ran each simulation with 100000 samples for 20 trials having different traffic class arrival rates as follows:
$\lambda_B(i)$ = { i }, $\lambda_N(i)$ = { 3i }, $\lambda_R(i)$ = { 18i }

where i = 1, 2, 3, …, 20. We have run simulations with increased arrival rates of all types of traffic to observe the impact of heavy traffic on the multi-band system. The arrival rate of B-queue and N-queue are increased slowly in each trial whereas the RT traffic arrival rate are increased at a much higher rate. This will saturate the R-queue and we explain the impact of this overflow on different performance parameters of our proposed system and typical existing system.

A. Queue-wise Analysis

We present five set of results to show queue-wise analsyis.

1) Utilization: Band utilization results for each experiment are given in Figures 6, 7, and 8. Single band utilization is lower than $N-queue$ and $R-queue$ multi bands for low arrivals but, when arrival rates are increased, single band utilization sharply increases. $B-queue$ utilization is the lowest because of low arrival rates of BU packets. When system is under heavy traffic, all bands utilization is going to be similar. Band utilization is similar for Fastest Server First (FSF) and Lowest Utilization First (LUF) until no overflows. There are some differences between FSF and LUF when there are overflows packets from RT traffic. Overflow packets from RT packets use generally $N-queue$ based on FSF and $B-queue$ based on LUF allocations until NRT packets overflow. Therefore, utilization of $B-queue-LUF$ is higher than utilization of $B-queue-FSF$ and utilization of $N-queue-LUF$ is lower than utilization of $N-queue-FSF$. After both NRT ad RT traffic overflow, they are forwarded to $B-queue$. Thus, utilization of $B-queue$ is similar for both FSF and LUF allocations.

2) Average queue occupancy: Average queue occupancies results for each experiment are given in Figures 9, 10, and 11. Single band and multi band occupancies are low under light traffic. When arrival rates are increased, single band occupancy sharply increases. At 6 trial arrival rates are BU 3, NRT 30 and RT 90, which means total arrival is 123. And at 7 trail arrival rates are BU 4, NRT 35 and RT 105 which means total arrival is 144. Also the priority of service is BU, NRT and RT packets therefore occupancy increases sharply after 7^{th} trial. However, multi band occupancies slowly increases trial 10^{th}. Both single and multi band reach maximum point of occupancy under heavy traffic. There is occupancy differences between FSF and LUF allocation policy because overflow RT packets use generally $N-queue$ based on FSF and $B-queue$ based on LUF allocations until NRT packets overflow. Therefore, average occupancy of LUF is higher than average occupancy of FSF and occupancy.

3) Average queue delay: Average queue delay results for each experiment are given in Figures 12, 13, and 14. Single band and multi band delays are low under light traffic. When arrival rates are increased, single delay sharply increases and fixed after when it reaches its maximum capacity. Multi band delay slowly increases. After RT and NRT packets overflow, they are forwarded to $B-queue$. $B-queue$ has the slowest service rate and because of priority which first BU then based on our formula (NRT and RT). Even if forwarding, the average delay of multi band is two times better than single band because total service rate of multi band is two times service rate of single band.

4) Packet drop probability: Average queue drop rate results for each experiment are given in Figures 15, 16, and 17. Drop rate of single band and average drop rate of multi bands are same while arrival rates are low. However, under heavy traffic average drop rate of multi bands is lower than single band because total service rate of multi band is higher than single band. It is also interesting to see that FSF drop rate is higher than LUF drop rate.

5) Throughput: Total queue throughput results for each experiment are given in Figures 18, 19, and 20. Throughput of both single and multi bands increases while arrival rate increases and reaches the maximum points after services reaches the maximum service capacity. Total throughput of multi band is higher than single band throughput under heavy traffic as it is expected.

6) Summary of queue-wise analysis: According to queue-wise analysis results, following observations are obtained

- Performance of multi band is better than performance of single band under heavy traffic.
- Multi band system does not use band efficiently as single band while system is under low traffic.
- Although FSF allocation was expected to have the best performance, performance of LUF allocation is the best in multi band allocations.

B. Class-wise Analysis

1) Average class occupancies: Average class occupancies results for each experiment are given in Figures 21, 22, and 23. BU and NRT traffic occupancies are low both single and multi band because of low arrival rates and priority in single band. When RT arrival rates are increased, RT occupancy sharply increases in single band. However, it slowly increases in multi band for FSF and LUS allocations. When NRT traffic rates began to close to service rate of $N-queue$, occupancies of RT traffic begin to decrease because forwarded RT packets to $N-queue$ is dropped or not being accepted by $N-queue$. There is small RT occupancies difference between FSF and LUF allocations.

2) Average class delays: Average class delays results for each experiment are given in Figures 24, 25, and 26. BU and NRT traffic delay are low both single and multi band because of low arrival rates and priority in single band. When RT arrival rates are increased, RT delay sharply increases in single band. However, it slowly increases for multi bands. Although total service rate is multi band almost two times higher than single band, the delay for multi band is only 1/3 delay of single band after NRT and RT traffics are increased.

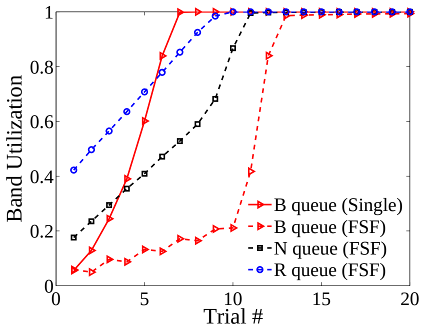

Fig. 6. FSF vs Single.

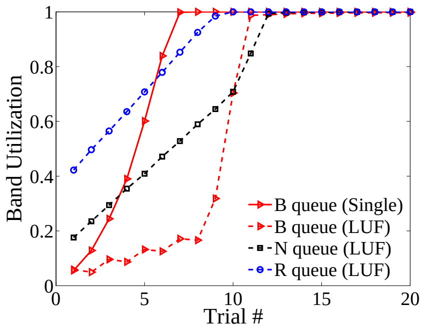

Fig. 7. LUF vs Single.

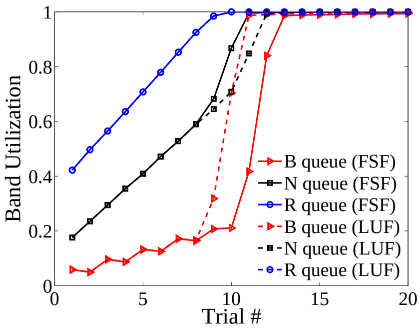

Fig. 8. FSF vs LUF.

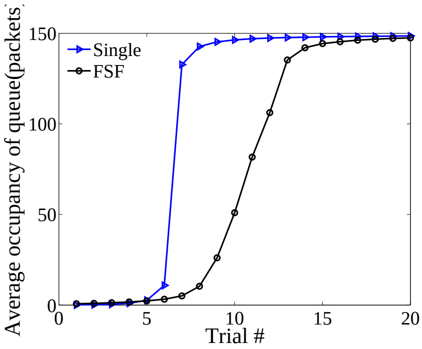

Fig. 9. FSF vs Single.

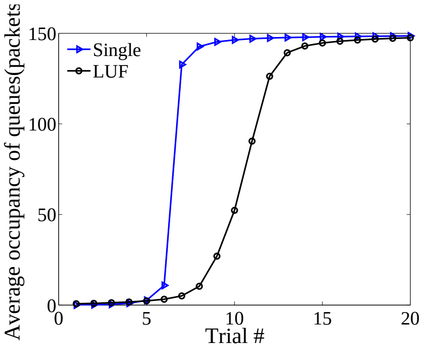

Fig. 10. LUF vs Single.

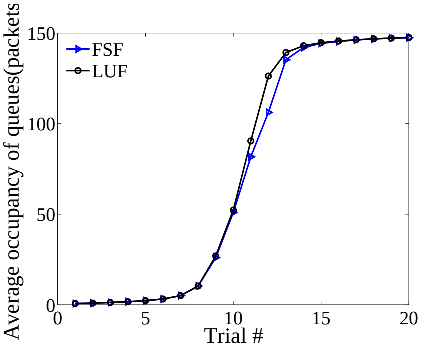

Fig. 11. FSF vs LUF.

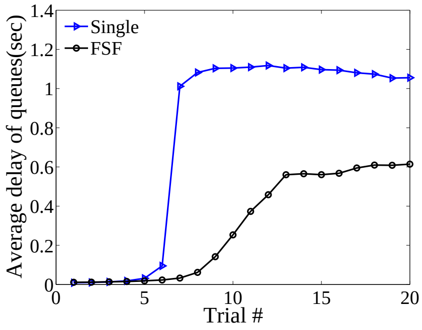

Fig. 12. FSF vs Single.

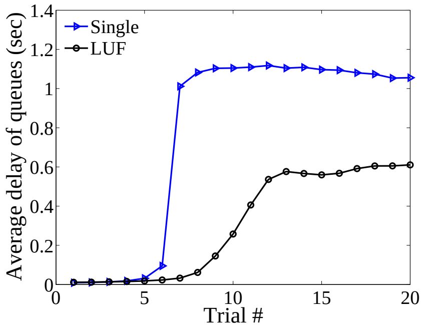

Fig. 13. LUF vs Single.

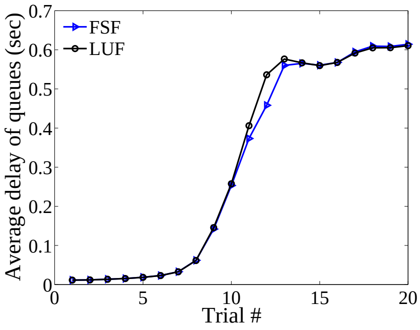

Fig. 14. FSF vs LUF.

Similarly, RT occupancy, there is small RT delay difference between FSF and LUF allocations.

3) Average class drop rate: Average class drop rate results for each experiment are given in Figures 27, 28, and 29. BU and NRT traffic drop rates are low both single and multi band because of low arrival rates and priority in single band. When RT arrival rates are increased, RT drop rate increases in single band. However, it slowly increases for multi bands because overflow RT packets can be forwarded to $N-queue$ and $B-queue$. Although single band buffer size is equal to total buffer size of multi bands, total service rate is multi band almost two times higher than single band. Hence, the drop rate of RT traffic for multi band only 1/2 drop rate of single band.

4) Average class throughput: Average class throughput results for each experiment are given in Figures 30, 31, and 32. BU and NRT traffic throughputs are increasing both single and multi band while arrival rates increased. When RT arrival rates are increased, RT traffic throughput is going to be lower for single band after NRT traffic arrivals are increased to 35. However, RT traffic throughput in multi band has higher throughputs and increasing until NRT traffic reaches the service rate of $N-queue$ which is 75. After NRT traffic arrival passed the service rate of $N-queue$, RT throughput is decreased and will be a constant after some point. It is also interesting that there is not much performance differences between FSF and LUF.

5) Summary of class-wise analysis: According to class-wise analysis results, following observations are obtained

- The highest priority class in single band can have less delay than same class in multi band.
- Under heavy traffic, the lowest priority class waits in

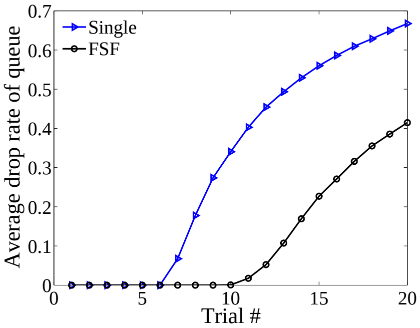

Fig. 15. FSF vs Single.

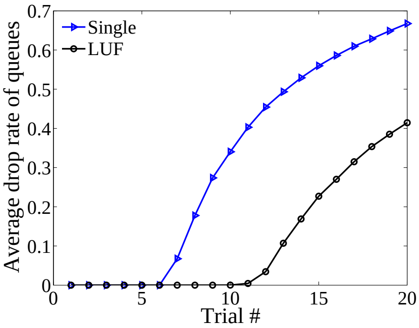

Fig. 16. LUF vs Single.

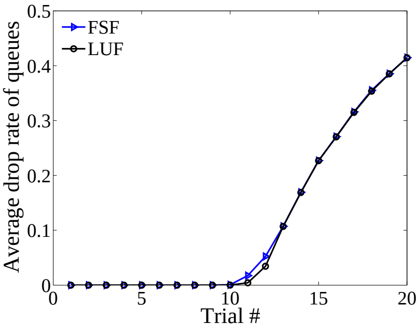

Fig. 17. FSF vs LUF.

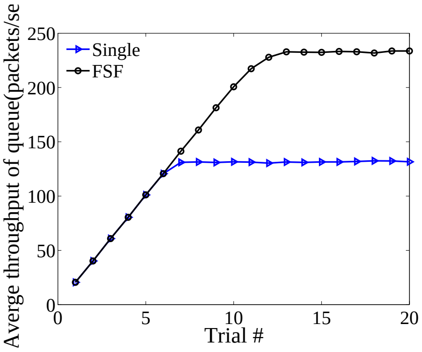

Fig. 18. FSF vs Single.

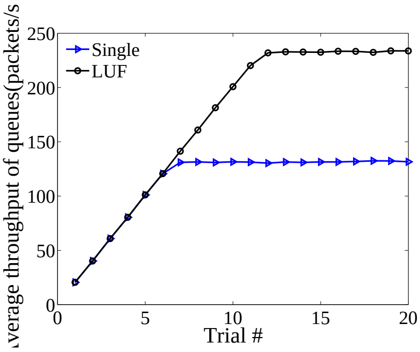

Fig. 19. LUF vs Single.

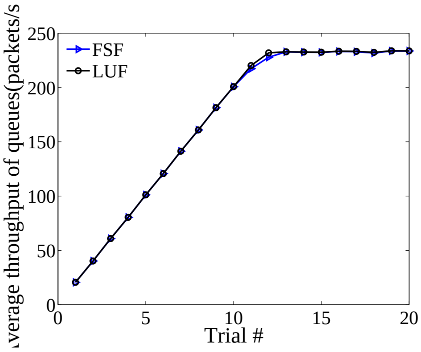

Fig. 20. FSF vs LUF.

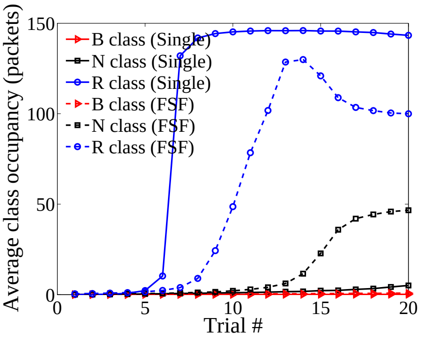

Fig. 21. FSF vs Single.

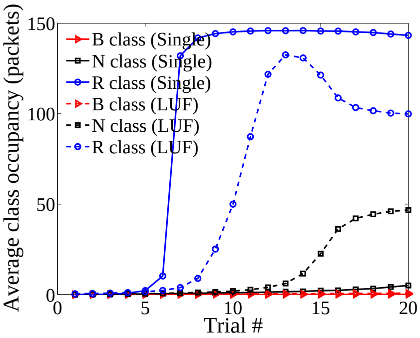

Fig. 22. LUF vs Single.

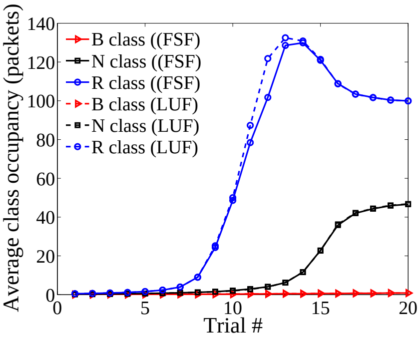

Fig. 23. FSF vs LUF.

queue more than it waits in multi band.

- Performance of LUF and FSF allocation policies can behave differently under different circumstances.

VI. CONCLUSION

In this paper, we have proposed a novel scheduling algorithm for multi-band mobile routers that exploits band sharing. Analytical model of proposed multi band system are derived by going through cases for FSF allocation. Extensive simulation has been developed to compare multi band and single band system under realistic scenario. After analyzing the both system based on class-wise and queue-wise performances, following observation are obtained:

- Single band priority system is recommended for low traffic system.
- Multi band system is recommended for heavy traffic systems.
- The class priority in single band definitely plays important role in class performance.
- Priority in multi band system does not significantly affect the system performance in proposed management algorithm.

The results which are obtained in this paper can help not only engineers to have more efficient routers but also users to have more appropriate routers for their networks.

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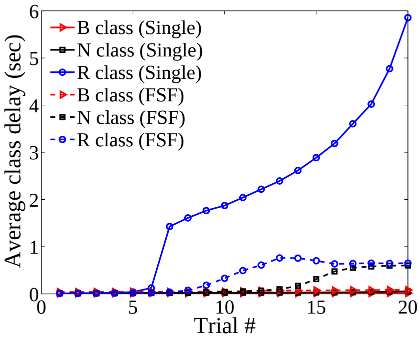

Fig. 24. FSF vs Single.

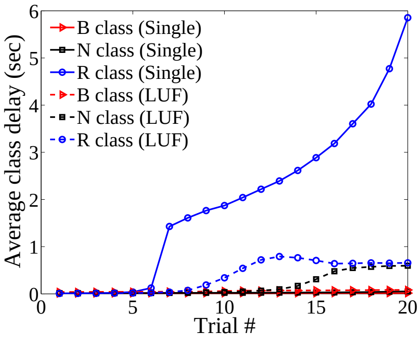

Fig. 25. LUF vs Single.

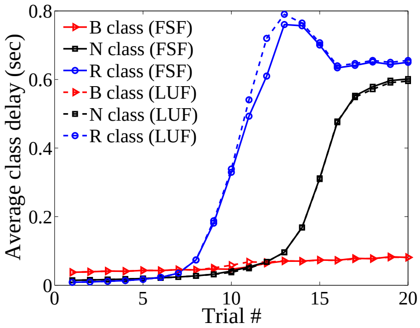

Fig. 26. FSF vs LUF.

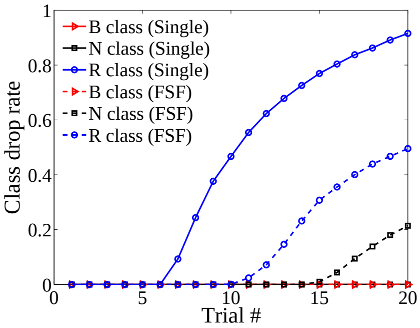

Fig. 27. FSF vs Single.

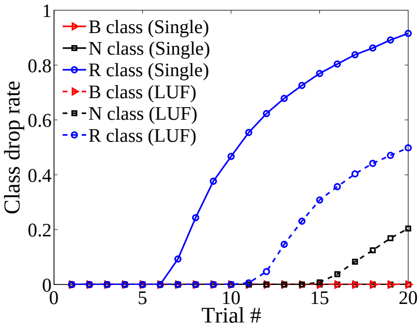

Fig. 28. LUF vs Single.

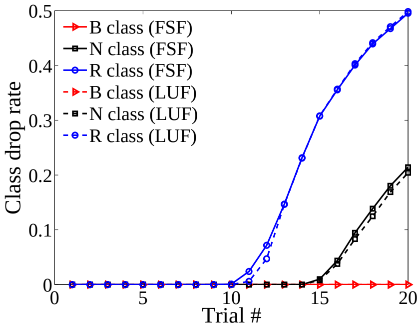

Fig. 29. FSF vs LUF.

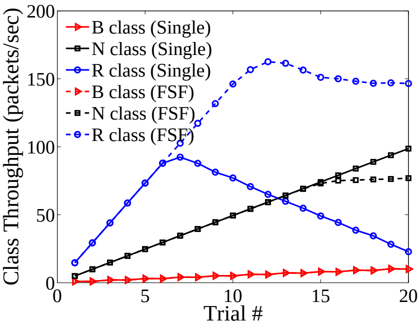

Fig. 30. FSF vs Single.

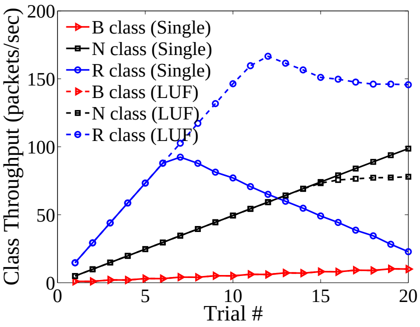

Fig. 31. LUF vs Single.

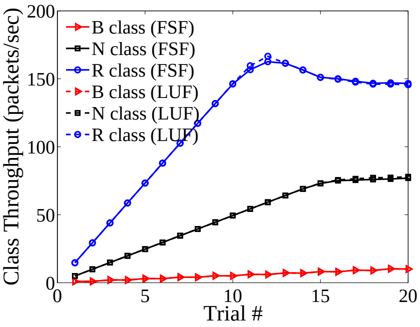

Fig. 32. FSF vs LUF.

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