Congestion Control Routing Using Optimal Channel Assignment Mechanism in Wireless Mesh Network

Arslan Musaddiq[*], Yousaf Bin Zikria[*], Rashid Ali[*], Illa Ul Rasool[*], Sung Won Kim[*+]

[*] Department of Information and Communication Engineering, Yeungnam University, South Korea

arslan, yousafbinzikria, rashid, illaulrasool@ynu.ac.kr, swon@yu.ac.kr

Abstract— Multi-Radio Multi-Channel (MR-MC) Wireless Mesh Network (WMN) can increase network coverage area and capacity. The assignment of non-overlapping channels can efficiently reduce the link congestion and co-channel interference. Network experiences a channel switching delay and overheads caused by Channel Assignment (CA). In this paper, we propose a mechanism to avoid channel switching delay caused by CA procedure, using Dijkstra's algorithm. The proposed method keeps a record of congested channels in the form of a table and uses this information to assign a non-negative weighted score to the pair of nodes for efficient routing with less switching delay and overheads.

Keywords—Channel Assignment; Mesh Network; Congestion; Channel switching

I. INTRODUCTION

IEEE 802.11s standard is for Wireless Mesh Network (WMN) which is made up of mesh routers and mesh clients [1]. The mesh routers are the stationary access points which propagate the traffic from various routes to the gateway node that is connected to the internet, in a multi-hop fashion [2]. The multihop communication scenarios do not need a centralized control system. The out of range nodes transmits the packets using intermediate nodes. Therefore, the transmission power and thus interference effect can be reduced. IEEE 802.11s standard utilizes almost all the properties of IEEE 802.11 protocols. There are 12 non-overlapping channels in IEEE 802.11a protocols. An interference is produced if the nearby radios are operating on the same channel which results in congestion in the logical links. The nature of the congestion in MR-MC WMN is different to that in a wired network. The capacity of a wireless node highly depends on the transmission between its neighbors. The frequency channels are limited; therefore, the nearby radios may communicate on the same channel that causes the interference. This interference from a nearby node highly affects the network capacity; hence, results in network congestion. Efficient Channel Assignment (CA) scheme is needed to optimize the network performance [3] [4] [5].

During CA procedure, network undergoes a channel switching phenomenon. The switching from one channel to another produces switching overheads, needs tight time synchronization and produces a considerable amount of switching delay. IEEE 802.11 protocol states the physical channel switching time as 224μs [6]. The real delay is the addition of physical channel switching time, hardware registers reconfiguration time and MAC layer packets processing time.

In this paper, the concept of Dijkstra's algorithm has been used to avoid the congested links and reduce channel switching delay. We introduced a routing technique which is based on a congested link weighted score. In this regard, when the link becomes congested the node undergoes a channel switching procedure. The proposed algorithm saves the congestion information in the form of a table. Then, this congestion information is used using Dijkstra's algorithm to assign a non-negative weighted score and generate link ranks. The traffic is routed based on the link ranks.

WMN has gained much popularity because it can increase network coverage area with less cost and complexity. CA is an active research area to increase the network capacity and performance by utilizing the frequency spectrum efficiently. IEEE 802.11 protocol provides a limited number of orthogonal frequency channels, therefore, some nearby radios may operate on the same frequency band. In MR-MC system, assigning the channels to the radios by keeping an interference and congestion to the minimum level is very challenging. However, during CA; network faces a channel switching delay and overheads which affect the overall network performance. Assigning multiple channels to the number of nodes without increasing delay caused by channel switching is a key challenge in WMN. This motivates us to highlight the importance of CA approach for enhancing the network performance by avoiding the congested links and employing efficient routing technique.

In this paper, we present an effective solution using the channel selection technique which is based on congestion table information. Also, special emphasis is placed on provisioning appropriate algorithm for alleviating overhead and performance degradation resulting from continuous switching and computational complexity. In particular, the concept of Dijkstra's algorithm to utilize the multi-path function by avoiding the weak links has been used. Moreover, the simulation setup to conduct the analysis is delineated.

The rest of this paper is structured as follows. Section II provides the related work of channel assignment techniques in

[+]Corresponding author.

MC-MR WMN. The system model and problem statement are given in Section III. Section IV explains the overview of channel assignment in WMN and explains the proposed protocol. Section V describes performance evaluation and simulation results followed by the last section VI that concludes the paper.

II. RELATED WORK

CA research in WMN is based on either centralized or distributed manner. A centralized node is responsible for making CA decision and controls all maintenance functions in a centralized approach. Similarly, in a distributed scheme, each node is responsible for channel allocation to its corresponding nodes. There are a number of CA approaches that have been proposed to increase network goodput [7]. For better routing, Raniwala et al. [8] proposed centralized Load Aware Channel Assignment (LA-CA) protocol which balances the load distribution on each virtual links to avoid any bottleneck in the network. It assigns the channel in such a way that load on the link is less than its capacity. Raniwala and Chiueh [9] proposed a distributed scheme called Hyacinth, in which each node divides the Network Interface Card (NIC) into UP-NICs and DOWN-NICs. CA is done only at DOWN-NICs. This scheme uses a load-aware algorithm which only assigns the least used channel in the neighborhood without causing a ripple effect and channels oscillation.

Kodialam and Nandagopal [10] proposed two centralized schemes called Balance Static Channel Assignment (BSCA) and Packing Dynamic Channel Assignment (PDCA). BSCA assign a time slot to each link that uses a particular channel. The channels that are assigned to each link are fixed and cannot be changed until next time slot. Similarly, PDCA performs link channel assignment and allows every link to switch channel in time slots. Lin et al. [11] also proposed a centralized scheme which is based on Genetic Algorithm (GA). The radios and channels are represented as a chromosome-like data structure. Each chromosome is assigned a fitness value using roulette wheel selection technique. A. Hamed et al. [12] proposed a scheme to optimize CA and congestion control problem called Distributed Congestion Aware Channel Assignment (DCACA) algorithm. In this scheme, channels are assigned based on congestion measure at every time slot in a distributed manner. Makram and Gunes [13] introduced the centralized Cluster Channel Assignment (CCA). Mohammad et al. [14] proposed interference reduction approach by using Improved Gravitational Search Algorithm (IGSA).

The link scheduling scheme in CA is proposed by Andrew et al. [15] called. The scheme uses a centralized approach and partitions the WMN in a number of subnetworks using stability and matroid theory. Similarly, Alicherry et al. [16] also proposed a centralized scheme for joint CA, routing and link scheduling problem called RCL. Some other schemes are discussed elsewhere to solve the CA problem in WMNs [17], [18], [19], [20], [21], and [22].

III. SYSTEM MODEL

The proposed MR-MC WMN is designed as a static network with graph G (V, E, C) where; $V, E,$ and C represents wireless

Table I. Key Notations

Parameters	Description
V	Set of wireless nodes
E	Wireless Links
C	Set of channels
c'	Least congested channel
n	Number of packets
λ	Packet size
U	Set of radios
H	Link capacity
β	Queue threshold level
Q_L	Queue length
f	Data flow
W	Gateway
α	Channel switching message
Z_r	Channel assignment matrix
Z_l	Link radio matrix

nodes, logical links, and a number of channels, respectively. If two radios are within each other transmission range and utilize same frequency channel $c_i \in C$; a logical link E is created between them. A node $v_i \in V$ can have a number of U_n NICs radios operating simultaneously. The load on each logical link L is less than the data rate of the link $e \in E < d$. Each access point transmits n packets of size λ bytes. It is assumed that all the data flows f to the gateway W, therefore traffic at W is f x n.

We want to reduce the channel switching delay in a logical link $e_i, \forall e_i \in E$, in WMN by efficiently routing the traffic after assigning the orthogonal frequency channels C to the wireless nodes V. Table 1 provides the list of notations used in this paper.

IV. CONGESTION CONTROL CHANNEL ASSIGNMENT IN WMN

Channel assignment serves as a promising approach to compensate for the shortcomings of classical channel assignment mechanisms, as well as queuing procedures. It ensures a reduction in link congestion and co-channel interference which is one of the main reasons of network performance degradation in WMN.

MR-MC play a pivotal role in the infrastructure of WMN because they can provide more coverage area and capacity. The capability of channel switching can help in reducing congestion and interference in the network. Channel switching introduces non-negligible delay, which is 224μs [6]. However, the total delay is the sum of physical channel switching time, hardware registers reconfiguration time and MAC layer packets processing time. Therefore, channel switching incurs an additional delay because wireless NIC does not receive and send the packets during the switching period. The concept of Dijkstra's algorithm can be used to reduce frequent channel switching and utilize the multi-path function by avoiding the weak links. Algorithm 1 illustrates the proposed Congestion

Algorithm 1: Congestion Control Channel Assignment. To be executed by each wireless node.
Input: $G(V, E, C)$
Output:
1. Form the ripple free logical topology using algorithm proposed in [9].
A. Channel switching:
2. At any time slot $t \in T$, **do**
3. Measure congestion level based on equation (1)
4. **if** equation 1 satisfied, **then**
B. Channel selection and scheduling:
5. Initialize congestion table for, $u_i \leftrightarrow u_j \in U$
6. Calculate c' for link between $u_i \leftrightarrow u_j \in U$
7. u_i inform u_j by exchanging α message.
8. Assign the channel
9. **while** equation 1 is satisfied, **do**
C. Congestion avoidance:
10. Assign c_w to link $e \in u_i \leftrightarrow u_j$
11. Apply Dijkstra's algorithm
12. calculate least congested path for $u_i \leftrightarrow u_j$
13. **end while**
21. **end if**

Control Channel Assignment (CCCA) mechanism. The detail description of CCCA procedure is explained as follow.

A. Channel Switching

The switching process at each node is triggered each time when following equation is satisfied.

$$Z_l = \begin{bmatrix} & u_2 & u_3 & u_4 & u_5 & u_6 & \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 \end{bmatrix} \begin{matrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \end{matrix}$$

$$Q_{L(i,j)} > \beta \qquad (1)$$

Where $Q_{L(i,j)}$ is the queue length of node i which is connected to node j and β shows the queue threshold level. The node will switch its channel when its queue size reach a certain threshold level β. If there is an interference, the congestion will occur in the links and the algorithm will initiate the channel switching procedure. The switching process at each node is triggered each time equation (1) is satisfied. After triggering the switching process, the corresponding radio $u_i \in U$ coordinates with its neighboring radio by broadcasting a channel switching message α that contains the queue size and new channel number c_n to its neighboring radio u_j. The neighboring radio u_j sends back the *ACK* packet after receiving the change channel request. We assume that all radios are operating on the IEEE 802.11a protocol, which support 12 non-overlapping channels.

Table II. Congestion History Table

Nodes	v_i			v_k		v_j			v_l	
Radios	**1**	**2**	**3**	**1**	**2**	**1**	**2**	**3**	**1**	**2**
Channel 0	1	3	5	6	2	0	4	3	1	0
Channel 1	3	1	3	5	2	5	0	2	0	2
Channel 2	1	4	2	4	7	3	0	2	3	5
Channel 3	3	6	5	5	0	4	2	0	4	1
Channel 4	2	7	0	0	2	5	5	1	6	3
Channel 5	5	0	8	1	4	0	6	0	1	0
Channel 6	0	0	2	3	1	0	7	8	3	0
Channel 7	4	2	4	2	2	8	2	5	4	2
Channel 8	9	9	1	0	3	1	3	4	2	3
Channel 9	1	1	3	5	4	2	1	3	0	4
Channel 10	2	2	0	2	6	7	0	0	1	7
Channel 11	0	3	6	1	10	3	2	1	3	1

$$Z_r = \begin{bmatrix} c_0 & c_1 & c_2 & c_3 & c_4 & c_5 & c_6 & c_7 & c_8 & c_9 & c_{10} & c_{11} & \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{matrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{matrix}$$

The relationship between nodes and their corresponding CA can be explained using matrix Z_r of size $u \times c$, where c is the number of channels and u represents the radios. The entry in the uth row and the cth column of Z_r is equal to 1, if the radio u is assigned with channel c; otherwise, the entry is 0. From the matrix Z_r, it is shown that the radio u_1, u_2, u_3 and u_4 are operating on the channel number 0, 11, 5 and 8 respectively. Therefore, $Z_r(u_1, c_0), Z_r(u_2, c_{11}), Z_r(u_3, c_5)$ and $Z_r(u_4, c_8)$ are equal to 1.

Similarly, If a radio wants to exchange a channel switching message with another radio, whether there is a link (i, j) between radio u_i and u_j or not, it can also be represented by a matrix Z_l. The matrix Z_l shows that radio u_1 can exchange a channel switch message with radio u_3 and u_6. Similarly, u_6 can communicate
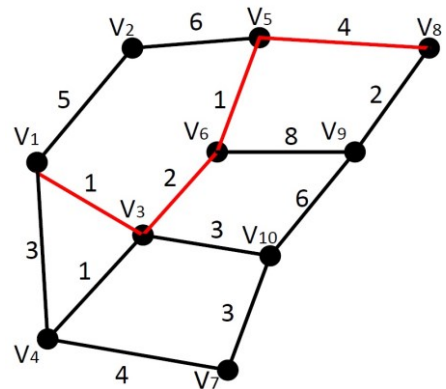

Fig 1. Congestion Avoidance Procedure

Parameter	Value
Carrier frequency	5 GHz
Network size	1500 m x 1500 m
Data rate	54 Mbps
Number of nodes	30
WLAN type	IEEE 802.11
Max queue size	45
Queue threshold size	25
Number of orthogonal channels	3/12
Packet Size	536 Bytes
Routing protocol	OLSR
Mobility type	Stationary

Fig 2. Suitable Threshold Value

with u_1, u_4 and u_5. Therefore, we can say that $Z_l (u_1, u_3)$ and $Z_l (u_1, u_6)$ are set to 1. Similarly, $Z_l (u_6, u_1)$, $Z_l (u_6, u_4)$ and $Z_l (u_6, u_5)$ are equal to 1.

B. Channel Selection and Scheduling

In the proposed mechanism, we assume that whenever a pair of nodes is assigned a new channel, no channel switching is required at any other node. Hence, nodes can independently switch channels without increasing switching overheads. In the proposed CA technique, we propose a congestion table mechanism for optimal channel selection.

Each radio maintains it congestion history table and utilizes it for next channel switching. Durinh the channel switching phase; least congested channel is selected first, and highly congested channels are avoided. Table II shows an example of optimal channel selection procedure using a congestion history. Suppose we have four nodes v_i, v_j, v_k and v_l. Node v_i and v_j use three radios while nodes v_k and v_l operate using two radios. If the queue at node v_l reaches a threshold level, the link $v_i \leftrightarrow v_l$ needs to switch to a new channel that is less congested. There are 12 non-overlapping channels in IEEE 802,11ah. The values shown in Table II represents the number of times a particular channel is congested. For example, channel 0 in radio 1 of node v_i is congested 1 time.

Similarly, channel 0 on radio 1 of node v_k is also congested 6 times and so on. The least congested channel, in this case, is channel 9, which is congested in total for 1 time. To avoid broadcast message conflict, if channel 9 is already in use by the neighboring nodes, the algorithm switches to another channel and selects the second least congested channel, which is channel 0 in our example.

C. Congestion Avoidance

The proposed channel selection mechanism can be used to predict the congestion to avoid congested link. We use Dijkstra's algorithm for congestion prediction and overflow avoidance. In a graph of $G (V, E)$, Dijkstra's algorithm solves the shortest path problem, assigns a non-negative weighted score c_w to the link between a pair of nodes $v_i \leftrightarrow v_j$ and generates a link rank based on the weighted score. The weight is the number of times the channel becomes congested. The algorithm repeatedly chooses the path for p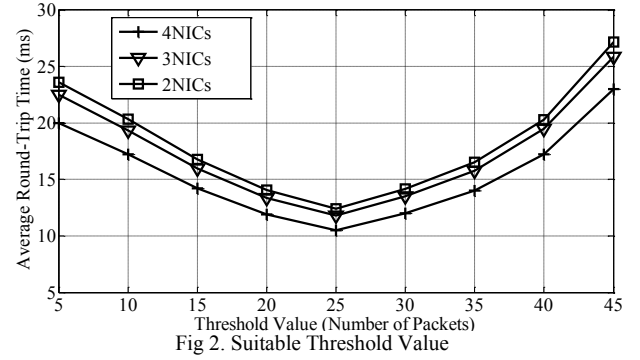acket transmission that has minimum congestion weight. This can reduce the channel switching overheads and link delay. The end to end delay depends on the transmission delay, propagation delay, packet processing delay and queuing delay.

Considering the example of Fig. 1; the number of the links represents the congestion weight. For example, link $v_1 \leftrightarrow v_2$ is congested 5 times. We assume that the links with high congestion weight are likely to be congested again and undergoes a channel switching phenomenon. In propagating the packets from $v_1 \leftrightarrow v_8$ through the paths $v_1 \leftrightarrow v_2$, $v_2 \leftrightarrow v_5$, and $v_5 \leftrightarrow v_8$, we assume that each pair of node undergoes channel switching phenomenon once. IEEE standard defines the switching delay as 224 µs [6]. Using the aforementioned path, if there are four times switching, the total switching delay is 4x224 µs. The maximum range an IEEE 802.11a router can provide is 120 m in an outdoor environment. Therefore, we assumed that the distance between each node in grid topology is 100 m. The one hop propagation delay is 0.33 µs, which is much lower than the one-time switching delay. Therefore, in Fig 1, if the propagation distance increases to avoid the congested node, the overall end to end delay is still be lower as compared to the delay caused by the switching procedure.

V. PERFORMANCE EVALUATION

The performance of proposed Congestion Control Channel Assignment (CCCA) protocol is evaluated in a simulation environment using OMNET++ version 4.3.1 [23]. We used INET version 2.2.0 simulation framework. The modeling of the proposed model involves 30 WMN nodes placed in the form of grid topology. In the grid topology, each node at the corner of the grid serves as a gateway node. IEEE 802.11a and IEEE 802.11b provides 12 and 3 orthogonal channels with an operating frequency of 5 GHz and 2.4 GHz, respectively. We used TCP flows as a traffic source with the packet size of 536 bytes. The optimal queue size is set to 45 packets, with a threshold value of 25 packets. Our logical topology is based on the Hyacinth ripple effect free WMN algorithm [9]. Nodes are chosen randomly as a source node and the gateways serve as a sink node. The chosen sink for the node is the one with minimum hop path away.

The number of TCP flows in the grid varied from 5 to 30. Table III summarized the parameters used in the simulation. We varied the number of radios from two to four at each node. The results are evaluated with respect to the decision parameters including a number of TCP flows and a number of radios (NICs).
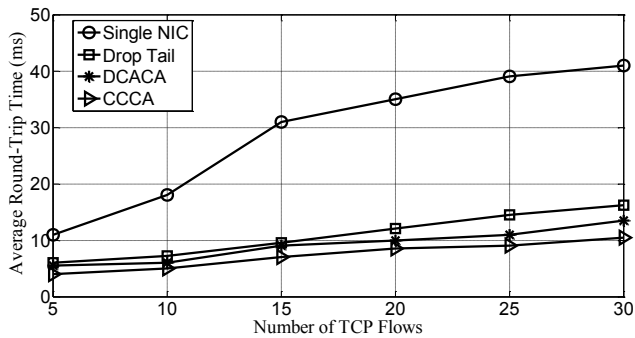
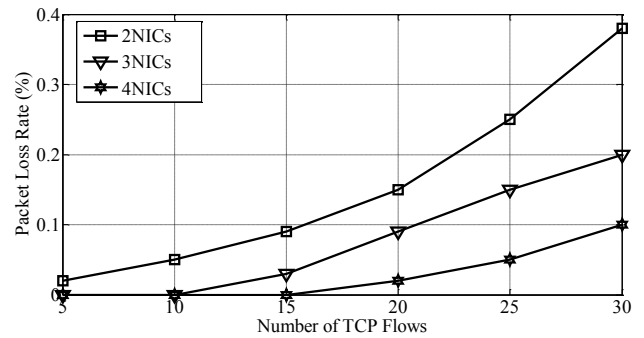Fig 3. Number of TCP Flows versus average round-trip time

Fig 4. Number of TCP flows versus packet loss rate

The channel switching in CCCA is based on suitable queue threshold value as explained in Section IV. Which suitable threshold value to be selected is one of the most important parts of the protocol.

A. Suitable Threshold Value

The simulation parameters, including Round-Trip Time (RTT) and packet loss rate, depends on the threshold level. In order to find the suitable threshold value, the threshold level is varied from 5 to 45 packets. At threshold level 5, the RTT of 20 ms, 22.5 ms and 23.6 ms using 4NICs, 3NICs and 2NICs, respectively, is obtained. After the threshold level 25, the RTT in the network started to increase until it reached the maximum value at level 45 as shown in Fig. 2. This is due to the fact that when the threshold level is lower, the radio goes under continuous channel switching phenomenon.

Due to this continuous switching, the switching overheads results in high RTT. The probability of disconnectedness and link failure also increases. Similarly, when the threshold level is higher than 25, packets wait longer in the queue and the radios do not perform the beneficial channel switching. Therefore, the probability of packet loss and queue waiting time increases RTT in the network.

B. The impact of varying number of TCP flows on average Round-Trip Time

The impact of varying number of TCP flows on average RTT using grid topology is shown in Fig. 3. The performance of the proposed mechanism is compared with previously proposed distributed congestion-aware channel assignment (DCACA), drop tail queueing management and a single channel network. It can be seen that the network becomes highly congested when a single NIC is used. Increasing the number of traffic flows increases the RTT. However, this can be controlled using more NICs per node. By using 4 NICs, the average RTT is maintained significantly; hence, congestion is avoided.

C. The Performance Impact of TCP Flows on Packet Loss Rate

Increasing the number of TCP flows may cause TCP retransmission timeouts. The relationship between TCP flows and packet loss rate is shown in Fig. 4. Increasing the TCP flows may cause network congestion which results in TCP retransmission timeouts. CCCA switches the channels using the

mechanism explained in Section IV and prevents the packets loss rate. The packet loss rate using 4NICs at 30 TCP flows is about 0.10%. Similarly, its 0.20% and 0.38% by using 3NICs and 2NICs, respectively.

VI. Conclusion

WMN is an emerging communication network that can be used for connectivity in the remote areas, broadband home automation, building connectivity and wide area networking. Thus, this paper provides an overview of the significance of using efficient CA technique in WMN as a performance improvement approach to enhance the network quality. The proposed CA scheme discusses an efficient queuing procedure and link congestion mitigation mechanism, which is one of the main reasons of network performance degradation in WMN. MR-MC play a pivotal role in the infrastructure of WMN because they can provide more coverage area and capacity. The capability of channel switching can help in reducing congestion and interference in the network. To reduce the channel switching overheads, the queue length threshold level in each wireless node is used as a congestion measure parameter. This queue threshold level is also used to prevent the packets drop. Further, congestion table is introduced for optimal channel selection mechanism using Dijkstra's algorithm.

In future, we plan to study the possibility of using two different channels for data and control packets to reduce the probability of disconnectedness.

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