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Channel quality and utilization metric for interference estimation in Wireless Mesh Networks☆

Saleem Iqbal[a,c,*], Abdul Hanan Abdullah[a], Kashif Naseer Qureshi[b]

[a] Faculty of Computing, Universiti Technologi Malaysia, Johor Bahru, Johor, Malaysia
[b] Department of Computer Science, Bahria University, Islamabad, Pakistan
[c] University Institute of Information Technology, PMAS-AAUR, Pakistan

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ABSTRACT

Wireless Mesh Networks have emerged as an architectural shift from traditional wireless networks for providing ubiquitous coverage. The mesh routers equipped with multiple 802.11 commodity network cards provide high throughput by maximizing the simultaneous transmissions on multiple channels. However, the selection of a channel is affected by various factors and it requires accurate knowledge of channel conditions. In addition, an imprecise selection of the channel requires channel reassignment, which significantly reduces the network performance. The existing schemes have suffered to gratifying the aggregate effect of interference. In this paper, we propose a Channel Quality and Utilization Metric (QUAM) that selects less interfering channels. The QUAM employs MAC specification parameters to acquire utilization awareness of various channels in the vicinity. The channel utilization helps to cater the effect of co-channel interference, whereas, to accommodate the impact of adjacent channel interference; the channels are further quantified by considering the channel quality. The proposed metric is evaluated through extensive simulations experiments. The simulation results demonstrated the validation of QUAM with a significant improvement in terms of network throughput and a decline in network delay and packet losses.

1. Introduction

Wireless Mesh Network (WMN) is a key backhaul technology used in 802.11 networks to provide ubiquitous coverage to isolated areas which require high-speed connectivity. The multi-radio feature has enabled the mesh routers to derive the full benefit of available multiple channels for providing parallel transmissions and thus increasing the overall network carrying capacity. However, in addition to the benefits, the WMNs pose challenges in channel assignments due to the interference and network dynamics [1]. The selection of a new channel is critical to the overall throughput of the network because it depends on the awareness of surrounding knowledge where the channel is likely to be used. The underestimation of such knowledge leads to a less optimal selection of a channel and again requires a channel switching. Such channel switches, rather than becoming the basis of throughput gain, badly affect the system performance due to traffic disruptions.

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* Corresponding author at: PCRG Lab, Faculty of Computing, Universiti Technologi Malaysia, Johor Bahru, Johor, Malaysia.
E-mail addresses: isaleem2@live.utm.my (S. Iqbal), hanan@utm.my (A.H. Abdullah).

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In close vicinity, the simultaneous assignment of limited channels creates collisions and leads to interference. Such interference is either controlled by the background media access mechanisms (such as Carrier-Sense Multiple Access with Collision Detection - CSMA/CD) or through frequency reuse [2]. The CSMA/CD restricts parallel transmission on a single channel and thus limits the overall capacity of links, whereas, the frequency reuse restricts that the nearby assignments should be far away from each other to reduce the interference. The IEEE 802.11 based WMN operates in 2.4 and 5 GHz bands and there are always possibilities that more than one network are operating in the same geographical area. These IEEE 802.11 based co-located networks create interference for WMN [3]. The surrounding knowledge includes the working and usage of a channel by these co-located networks. In the case of co-channel, the existence of such networks shares the airtime of a channel and as a result, the channel is overutilized; thus leaving no or minimum capacity for WMN. Whereas, in the case of adjacent- channel, such networks degrade the channel quality.

For the channel evaluation, the previous researchers have mostly focused on the effects of internal interference. However, for mesh networks, the co-located wireless networks operating on the same channel, are the major causes of external interference [4]. With the introduction of converged networks, such scenarios will be seen commonly in the near future. The external interference is uncontrolled and cannot be completely removed since their sources are out of the administrative control of WMN. However, the effect of such interference can be minimized, if it is correctly measured and accordingly alternative channels are used in the WMN.

In this work, channel quality and utilization metric are proposed for assignment of best channels to the bottleneck links. The contributions of this paper are threefold:

- In the first phase, channel's internal utilization is considered. In most of the previous approaches, all the interfering links, which are tuned to the same channel, are uniformly considered for investigating the channel utilization. However, all such interfering links may not be communicating at all the time. Therefore, the interfering links that are used for traffic in the previous interval are considered as true interfering links in the proposed approach.
- The second phase deals with the utilization of channel by the external IEEE 802.11 networks. In previous research works, the channel utilization is based on packet size and the packet arrival rate. The data rate represents the packets that are received. Practically, the physical data rate is usually different because there may be some packets which are not received due to severe environmental conditions. The proposed approach extracts the channel utilization parameter from the beacon frames, which more accurately represents the channel utilization.
- The third phase encounters the effect of interference by the non-IEEE 802.11 networks by giving due weight to the packet with errors and the packets that are dropped during transit.

The rest of the paper is organized as follows; Section 2 provides the literature review. The design of proposed metric is discussed in Section 3. Section 4 explains in detail the formulation of QUAM. For evaluation of QUAM, the complete scenario and the channel assignment algorithm is presented in Section 5. Performance and Simulation are presented in Section 6.

2. Literature review

The wireless medium is restricted by the limited available channels, such as three and twelve channels in 802.11b/g in 802.11a respectively. Moreover, the wireless medium comparatively is more prone to interference and noise. The interference also affects the carrying capacity of channels in WMNs. In the case of single-channel single-radio WMNs, the impact of interference is more severe, thus leaving no option to deal with. Similarly, the increase in a number of radios also increases the magnitude of the problem.

In channel assignments, the major pitfall is the inaccurate measurement of channel conditions which are evaluated at the time of channel selection for wireless links. A channel is affected by its environmental dynamics and underestimation of such environmental factors leads to less optimal or invalid selection of channels. Therefore accurate estimation of interference is critical for selecting the better channels. In most of the proposed approaches, the links in a 2-hop distance of an incident link are considered as interfering links [5]. In standard Carrier Sense Multiple Access (CSMA), the channel's air-time is shared between these interfering links of a network. However, in practical cases, all such links are generally not active at the same time and therefore the contention rate is low.

The 802.11 based WMNs operate in 2.4 and 5 GHz bands and there is always the probability that more than one network is operating in the same geographical area [6]. For better channel selection, the surrounding knowledge also includes the working and usage of the channel by these co-located wireless networks. With the existence of such networks, the airtime of the single channel is shared with the co-existed network. As a result, the channel is over utilized and thus leaving no or minimum capacity for WMN. This research also considers the existence of such co-located networks.

Riggio et al. [1] have presented Interference and Traffic aware Channel Assignment (ITACA) scheme that considers the channel utilization as a measure of channel condition. The utilization is calculated by considering the packet size and the data rate of the received packets of other networks. The channel utilization reveals the air-time of channel for which it remained occupied by the other network. The data rate employed in this scheme is based on the average of number of packets received during the scanning interval; however, the actual physical rate may vary, because there may be the packets that are not received by the sensing unit due to a high level of disturbance on the channel. Therefore, the method of calculating the channel utilization also becomes doubtful. Similarly, in [7] author proposed an External Interference aware Channel Assignment (EICA) that utilizes channel occupancy to measure the channel conditions. For channel occupancy calculation, carrier sensing mechanism is employed which monitors the carrier for a particular time in order to get statistics of the number of times when the channel is found busy. The calculated value of channel occupancy is compared against a threshold and accordingly channels are selected.

Shah et al. [8] proposed a dynamic and distributed channel assignment protocol that measures the interference based on the channels being used in the neighborhood. For channel assignment, each node maintains two types of tables: (i) Channel Usage Table (CUT) that maintains the records of interfaces bonded to which neighbors and on which channels and (ii) Neighbor's Channel Usage (NCU) that records the exchange of control messages with the neighbors. A mesh router obtains two hop neighbors information using NCU. A ranking is derived based on the channel usage records from both the tables and accordingly channels are assigned. However, this algorithm does not maintain the record regarding to what extent a channel is being used by its neighbor(s). This makes the solution less attractive due to two reasons (i) according to CSMA/CA standard, channel's airtime is shared between multiple mesh routers, so same channel may be used in more than 2-hop distance and (ii) the neighbor mesh router's transmission on the channel may or may not be uniform.

Theoretically, minimal interference based channel assignment schemes may be obligated for particular WMN, such as the conflict graph approach for non-interfering links [9,10]. But, practical deployment of WMN also faces the external interference and noise that have a severe impact on its performance. Similarly, the approaches that account for management frames (i.e. ETT, ETX) do not provide accurate results. In these methods, each mesh router broadcasts a probe frame in every second, and the neighbor mesh routers record the number of probe frames received in a periodic interval (usually last 10 s) and estimate a loss rate. These probe frames are sent at a basic data rate which is different than the rate at which data packets are sent and considering symmetric links, the same rate is considered for both directions. The estimate is based on just 10 readings, which is too small to get accurate loss rate [11].

The channel utilization or channel occupancy alone cannot capture the effect of interference completely. Zengen et al. [12] have highlighted the fact that the channel selection metric with no relation with the Channel Quality (CQ) is not able to identify a better channel. The CQ is a measure of interference in the vicinity [13] and is based on packet losses and delay [14]. In [15], the Bit Error Rate (BER) is used in a channel quality and load aware routing mechanism to measure the CQ. The BER represents the packets that are corrupted during the transmission due to environmental impairments [16]. Such packets are identified at the OSI link layer through Cyclic Redundancy Check (CRC). The packets with CRC failed are considered as packets with errors and are dropped by the receiver [17]. However, Jakubczak and Katabi [18] in their study highlighted that interference causes packet losses and high bit errors during the transmission. Therefore, packets with only bit errors do not correctly depict the interference, unless the actual packet drops are also given due weight. The dropped packets are the packets which are transmitted by the sender but are reached at the receiver [19].

The literature reveals that another not fully addressed part of channel assignment is the operation of WMN in co-existence of other networks. Since the WMN make the use of IEEE 802.11 that operates in the unlicensed band, there is no guarantee that other networks do not use the same band while WMN is operating. Therefore, internal influencing factors of interference single handedly cannot accurately model the real-world scenarios. Similarly, another overlooked aspect is the accurate knowledge of saturation that is also the main source of capacity degradation. The IEEE 802.11 MAC protocol does not provide a direct method for accessing network saturation information. The evaluation of existing approaches also does not disclose any proper mechanism for getting this information and impart a systematic approach is needed for it. Consequently, due to the unavailability of such information, the existing channel assignment approaches also fail to mitigate the interference effectively. For this reason, efficient approaches are needed to fairly approximate the channel assignment solution.

3. Formulation of QUAM

In a collision domain, the channel is shared by WMN's internal mesh routers and the co-located network routers that are out from the administrative control of the WMN. These both types of routers contend for access (airtime) of the channel by utilizing Distributed Coordination Function (DCF). Therefore, the less traffic generated by the co-located network, the more airtime is available for WMN routers. The traffic load of co-located network routers on a channel cannot be restricted; however, the precise awareness of channel utilization by these co-located networks enables more optimal channel selection for WMN. This research aims for utilizing off-the-shelf hardware in a simple and efficient manner. However, with classical mesh routers and due to the unavailability of communication mechanism with co-located networks, it is hard to measure the exact amount of interference generated by these networks. However, the QUAM provides a good estimate of channel utilization and quality by measuring the captured frames. Table 1 represents the common notations and their meanings.

3.1. QUAM preliminaries

The selection of channel requires modeling the interference relationship between wireless links. The links in WMN interfere with their neighbor links in the WMN or with the links of co-located wireless networks. The following sub-sections discuss both the scenarios.

3.1.1. Link Interference Matrix

The interference between the wireless links of WMN is represented through Link Interference Matrix (LIM) [20,21]. The LIM is an N × N binary matrix, which represents the interference as a binary value; so either two links interfere or do not interfere. This LIM is generated by considering two-hop interference model. Therefore, if the two links in the two-hop neighborhood are assigned to the same channel, they will be considered as interfering links. The mesh gateway is designated as a Channel Assignment Server (CAS), which maintains the Interference Matrix for having a global view of interfering links. Consider an example of six mesh routers which are connected to each other, by considering links calculation formula n (n−1) / 2, the total links will always be less than or equal to 15. For each of the links, the interference matrix is maintained by CAS. Table 2 presents Link Interference Matrix example.

3.1.2. Interference estimation

The interference from the co-located networks is estimated through passive scanning using the monitor mode - Radio Frequency MONitor (RFMON) of the radio interface. Both management frames and data frames are captured to estimate the CEU and CQ accordingly. The monitor mode only captures the traffic that consists of IEEE 802.11 frames. However, this fact has to be taken into account that the RFMON can only capture the traffic that is received at the receiver of the radio interface. Traffic may also exist that the interface cannot listen due to limited carrier sensing range of the receiver. The drawback of using RFMON on a radio interface is that the interface becomes unavailable for transmission and reception for the duration in which monitor mode is active. To minimize this negative impact, the monitoring activities are performed after the specific periodic interval. This leads to another challenge of the time duration required to perform the monitoring measurements. Less duration may lead to underestimation and increases the risk that the bursty traffic may not be captured and similarly, the overestimation may become the reason of radio unavailability. To get awareness of the channel conditions of all the supported channels of a mesh router, simultaneous monitoring of each channel is not possible. Therefore, the RFMON of a single radio interface is turned on periodically for each of the supported channels for a specified duration of time.

3.2. QUAM computation

The computation of QUAM involves three elements: (i) Channel Internal Utilization, (ii) Channel External Utilization and (iii) Channel Quality measurement. The following sub-section discusses the calculation of each unit in detail.

3.2.1. Channel Internal Utilization (CIU)

Multiple links that simultaneously operate on the same channel in a single collision domain create Co-Channel Interference (CCI). Such multiple accesses are restricted by the use of DCF. The network performance can be increased by minimizing the usage of co-channels in the vicinity. The CIU refers to the awareness of the supported channels that are being used in the collision domain of an incident link. The key idea of maintaining utilization information is to allow parallel transmissions by using non-overlapping channels and minimizing the use of co-channels.

In the first step, links in the collision domain are identified through LIM, this includes the links of target mesh router's other radio connections. For example, a WMN that is formed by a set of n mesh routers where ∀n ∈ N, each mesh router n is connected to its neighboring mesh routers with bidirectional link l, where ∀l ∈ N. For neighbor y, the link between mesh routers x and y is represented as $l_{x\leftrightarrow y}$. Interfering Links (IL) of a bi-directional link $l_{x\leftrightarrow y}$, includes the links of all the routers that are in the 2-hop distance of the incident router (e.g. x, y); excluding the link $l_{x\leftrightarrow y}$ itself, as represented in Eq. 1 below:

$$IL(l_{x\leftrightarrow y}) = \left(\sum_{i=0}^{2hop(x)\ -\ y} l_i + \sum_{j=0}^{2hop(y)\ -\ x} l_j \right) - (l_x \cap l_Y) \tag{1}$$

In the second step, True Interfering Links (TIL) are identified, which is the subset of IL ($TIL \subseteq IL$) and represents the IL on which Traffic Load (TL) is observed during the previous interval as represented in Eq. (2).

$$TIL(l_{x\leftrightarrow y}) = \forall l | l \in IL(l_{x\leftrightarrow y}),\ TL(l_{x\leftrightarrow y}) \rangle\ TH \tag{2}$$

The TL information is obtained from the traffic profile and Threshold (TH) is set equal to data rate of individual mesh router. In order to have updated knowledge of interfering links, the TIL list is refreshed after each periodic interval. The above discussed scenario is graphically presented in Fig. 1. For reference transmission on link $l1$ from node n1 to node m1, the 2-hop IL list includes the links $l2$ to $l9$, However, the TIL list only includes the links $l3$, $l4$, $l8$ and $l9$.

3.2.2. Channel External Utilization (CEU)

The IEEE 802.11 based WMNs use shared medium that operates in the non-ISM band within the 2.4 and 5 GHz range. The use of non-overlapping channels with CSMA/CA technique helps to minimize the effect of interference. In addition to the internal interfering links, there are some other sources of network traffic that cause CCI because the same frequencies and same channel access mechanism are used by these co-located networks.

The Channel External Utilization (CEU) refers to the utilization of a channel by 802.11 based co-located networks, which a mesh router is able to hear. In IEEE 802.11 networks, the routers periodically transmit the beacon frames to announce

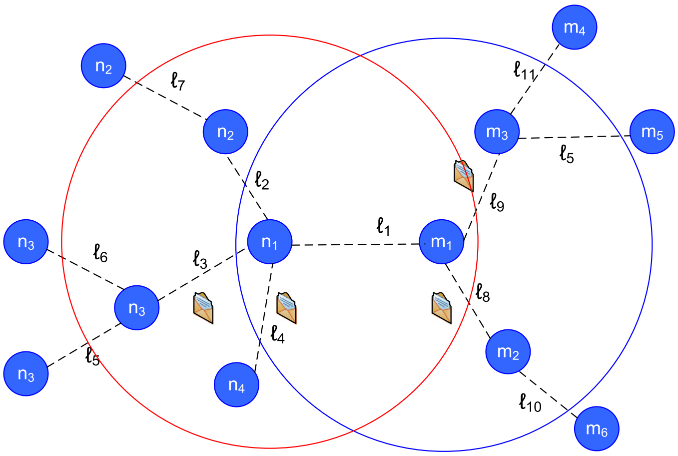

Fig. 1. Identification of true interfering links.

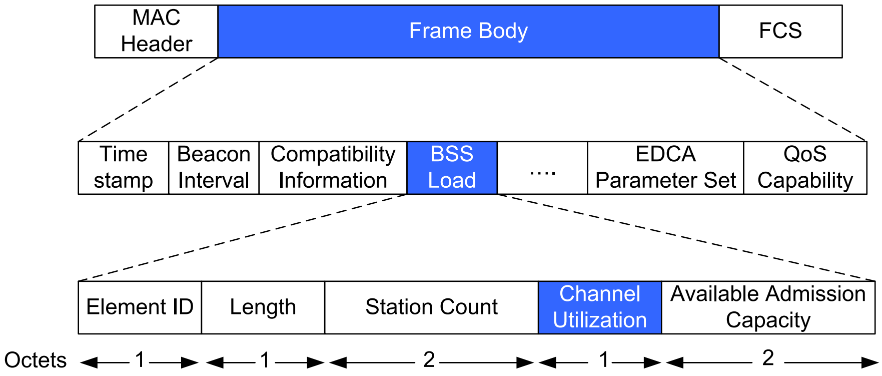

Fig. 2. IEEE 802.11 beacon frame.

their presence to the other nodes in the network. In the beacon frames, the router appends the BSS load element that provides channel load information of the router. In WLAN, for association with the router, the intended node analyzes the received beacons and selects the best route based on the load on that particular router [22]. In QUAM, while the monitor mode is turned on, the radio interface uses these beacon frames and extracts the BSS load element. The eight-bit channel utilization metric of BSS load element is inspected that represents the amount of time where a channel remains busy when it is sensed by the target router. Fig. 2 shows a typical beacon frame by highlighting the BSS load element and relevant channel utilization field.

The channel utilization calculation by the radio interface of a target router is mathematically presented in Eq. (3) [23].

$$CEU_{\mathrm{r}}^{\mathrm{Ch}} = \frac{BT_{\mathrm{r}}^{\mathrm{Ch}}}{\mathrm{BI}_{\mathrm{r}}^{\mathrm{Ch}} \times \mathrm{BP}_{\mathrm{r}}^{\mathrm{Ch}} \times 1024} \times 255 \tag{3}$$

The Ch and r denote the target channel and radio. The *BT* indicates the channel busy time in which target interface sensed the medium and found it busy, this is defined in microseconds. Whereas, the *BI* and *BP* denote the number of beacon intervals and the beacon period per beacon interval respectively. The IEEE specification defines the channel utilization as the percentage of time that is scaled to 255 which defines 100%. The overall utilization of a channel by all the co-located networks is calculated using Eq. (4).

$$CEU^{Ch} = \frac{\sum_{i=0}^{r} CEU(\mathrm{Ch}, \mathrm{r})}{r} \tag{4}$$

3.2.3. Channel Quality measurement (CQ)

The disruption on a channel is derived from the link-layer header contents such as Bit Error Rate (BER) and signal strength. These contents vary for different type of network interfaces, the SNR thresholds are hardware dependent [24] and BER is based on the modulation schemes used at the PHY layer [25]. Furthermore, it works only for the frames that are received at the receiver interface. However, based on the intensity of interference, there are such frames that are not received at all. Thus, in QUAM, the CQ is used that illustrates the packet loss ratio. This ratio is calculated from the sniffed traffic and

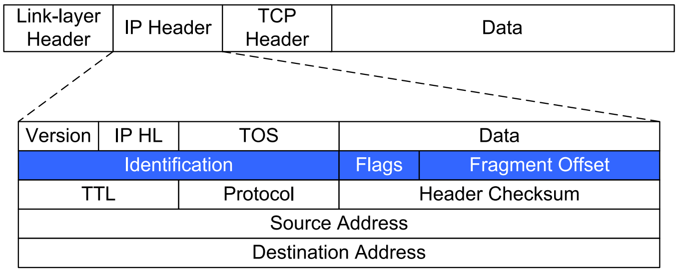

Fig. 3. Identification field in 802.11 IP header.

192.168.1.4	162.159.241.165	0x4d79 (19833)
162.159.241.165	192.168.1.4	0xc8a8 (51368)
162.159.241.165	192.168.1.4	0xc8a9 (51369)
162.159.241.165	192.168.1.4	0xc8aa (51370)
192.168.1.4	162.159.241.165	0x4d7a (19834)
162.159.241.165	192.168.1.4	0xc8ab (51371)
162.159.241.165	192.168.1.4	0xc8ac (51372)
162.159.241.165	192.168.1.4	0xc8ad (51373)
192.168.1.4	162.159.241.165	0x4d7b (19835)
192.168.1.4	162.159.241.165	0x4d7d (19837)
192.168.1.4	162.159.241.165	0x4d7f (19839)
192.168.1.4	162.159.241.165	0x4d80 (19840)
192.168.1.4	162.159.241.165	0x4d81 (19841)
162.159.241.165	192.168.1.4	0xc8ae (51374)
162.159.241.165	192.168.1.4	0xc8af (51375)
162.159.241.165	192.168.1.4	0xc8b0 (51376)
192.168.1.4	162.159.241.165	0x4d83 (19842)
162.159.241.165	192.168.1.4	0xc8b1 (51377)
162.159.241.165	192.168.1.4	0xc8b2 (51378)

Fig. 4. Wireshark packet capturing snapshot representing identification values.

reflects the effect of interference on the quality of a channel. The packet loss refers to the failure of one or more packets that were transmitted from the source but failed to reach the destination [26]. Due to limited sniffing time, packet loss ratio may not be an exact gauge but is a good estimator for measuring the interference on a channel.

Fig. 3 shows a typical 802.11 IP header, where 16-bit identification field is provided to store the individual packets that the sender transmits [27]. On the receiver side, this field is used for assembling the datagram fragments. The sender increments identification number for every packet it transmits. The identification number is specific to each individual source-destination pair, for a conversation two different identification sequences are enumerated during packet analysis as shown in Fig. 4. For proof of concept, the missing identification numbers are highlighted in a snapshot obtained from the wire-shark software as shown in Fig. 4. The first and second column of the Fig. highlights the source and destination IP addresses, respectively, whereas the third column shows the identification values in Hex format. However, 16 bits provide only 65,536 maximum identification values and then it is automatically reset to the first value.

While tracing the captured traffic, the identification numbers are observed from the sequence of received packets and missing/dropped packets are counted accordingly, to calculate the FLR. The FLR is the percentage of frames that should be received but are not received by the MAC layer of a radio interface. From the captured frames, interfering radios of the co-located network are identified by comparing the MAC addresses of the captured frame with the stored entries of Address Resolution Protocol (ARP) cache of the mesh router. Eq. (5) mathematically represents the frame loss ratio.

$$FLR^{Ch} = \frac{\sum_{i=0}^{r} m_{\mathrm{r}}^{\mathrm{Ch}}}{\sum_{i=0}^{r} S_{\mathrm{r}}^{\mathrm{Ch}}} \times 100 \tag{5}$$

The m denotes the number of missing packets while δ is the total packets sent on channel Ch by the co-located network radio r over a period of time. The packets with a duplicate identification number are also sometimes received by the interface that is operating in monitor mode (RFMON). For such packets the, three-bit Flags field and thirteen-bit Fragment Offset field of the IP header are further analyzed. This situation persists when the original IP datagram is fragmented into small packets by the sender. Table 3 shows a similar scenario where an original IP datagram is fragmented and all the resultant fragments contain a similar identification number. In this case, the proposed approach confirms the fragmentation from More Fragments (MF) bit of Flag and counts the missing Fragment Offset numbers instead of counting the missing identification numbers. The frame loss ratio also includes the frames that have not passed the Cyclic Redundancy Check (CRC) at the link layer and resultantly dropped. CRC is a data integrity check that detects communication errors. The last 4 bytes of the frame represent the CRC.

3.2.4. Channel rankings

The CEU is the air-time in which the channel remains occupied by the co-located 802.11 networks and is not available for inside use of the WMN. Therefore CEU helps in catering the CCI. The FLR is the CQ that represents, how much interference affected the channel. A channel with very high FLR hampers the communication, an acceptable frame loss depends on the type of data being sent but the typical threshold is less than 30% [28], thus, in the proposed solution the channels with $0 < FLR^{Ch} < 30\%$ are only used. The mathematical representation of rank calculation at mesh router is shown in Eq. (6).

$$Rank_{x}^{Ch} = \frac{1}{CEU_{x}^{Ch} + FLR_{x}^{Ch}} \tag{6}$$

The rank of a channel over the link is calculated by taking average ranks of both end mesh routers that are forming the link as represented in Eq. (7). The higher combined rank shows that the channel is more prone to interference and utilization.

$$\mathrm{Rank}_{x\leftrightarrow y}^{Ch} = \frac{Rank_{x}^{Ch} + Rank_{y}^{Ch}}{2} \tag{7}$$

4. Design of proposed metric

The proposed metric QUAM is divided into three phases, in the first phase, channel internal utilization is considered. In most of the previous approaches, all the interfering links, which are tuned to the same channel, are uniformly considered for investigating the channel utilization. However, all the interfering links may not be communicating all the time. Therefore, the interfering links that are used for traffic in the previous interval are considered as true interfering links in the proposed approach. The second phase deals with the external utilization of channel by the other IEEE 802.11 networks. In previous research works, the channel utilization is based on packet size and the packet arrival rate. The data rate represents the packets that are received. Practically, the physical data rate is usually different because there may be the packets that are not received due to severe environmental conditions. The proposed approach extracts the channel utilization parameter from the beacon frames, that more accurately represents the channel utilization. The third phase encounters the effect of interference by the non-IEEE 802.11 networks by giving due weight to the packet with errors and the packets that are dropped during transit. To evaluate the proposed metric, it is jointly used with a channel assignment approach.

The flowchart of QUAM is shown in Fig. 5 that represents the measurement of channel utilization and quality. One of the radio interfaces of each mesh router performs a passive scan of every Supported Channel (SC) for a defined period of time. The MAC address of the received frame is inspected to identify that the frame belongs to WMN or co-located network. In the case of co-located network, the frame is further categorized into management frame or data frame. The data frames are used to measure Channel Quality (CQ). For each received data frame, the QUAM extracts the identification numbers of packets from frame header and observe the sequence of received packets. The missing/dropped packets are accordingly counted to calculate the Frame Loss Ratio (FLR). For each received management frame, the beacon frames are observed for Channel External Utilization (CEU). In beacon frames, the QUAM extracts the Basic Service Set (BSS) load element that contains the traffic utilization parameter [22]. The channels with FLR greater than 30% [28] are discarded and the FLR of remaining channels is grouped with their CEU to form a channel rank.

The interference is also created by the links inside the WMN, The links in the 2-hop distance of the incident link and assigned the same channel are considered as the internal interfering links. However, the interference has different intensity on different links, therefore; Channel Internal Utilization (CIU) only considers the 2-hop active links as interfering links. The 2-hop interfering links are identified through Link Interference Matrix (LIM) [20,21] and active links, termed as True Interfering Links (TIL), are the links which are used for traffic communication in the previous interval. The highest rank channel that is not listed in TIL channels is selected as a new channel.

The Channel Selection procedure is represented in Algorithm 1, which takes the MCG, True Interfering Links (TIL), The FLR and Channel Ranks, Link Error Matrix and Traffic Profiles as input as represented. The Q is a priority list from MCG that contains an ordered list of bottleneck links. For each vertex in Q, the algorithm iteratively checks all the supported channels for which the FLR of both end mesh routers is less than the predefined threshold (TH). Such channels are then arranged in their decreasing order of ranks, as shown in line 5–10 of the algorithm. A channel with very high FLR hampers the communication; therefore the algorithm does not consider such channels for assignment.

At line 10 of the algorithm, the CAS finds the TIL for the selected vertex through LIM and traffic profiles. The TIL includes the neighboring interfering links of the incident link. Line 11–16 represents the selection of a new channel, the algorithm visits each all the ranked channels in their set order unless it finds a channel that is not in the list of TIL.

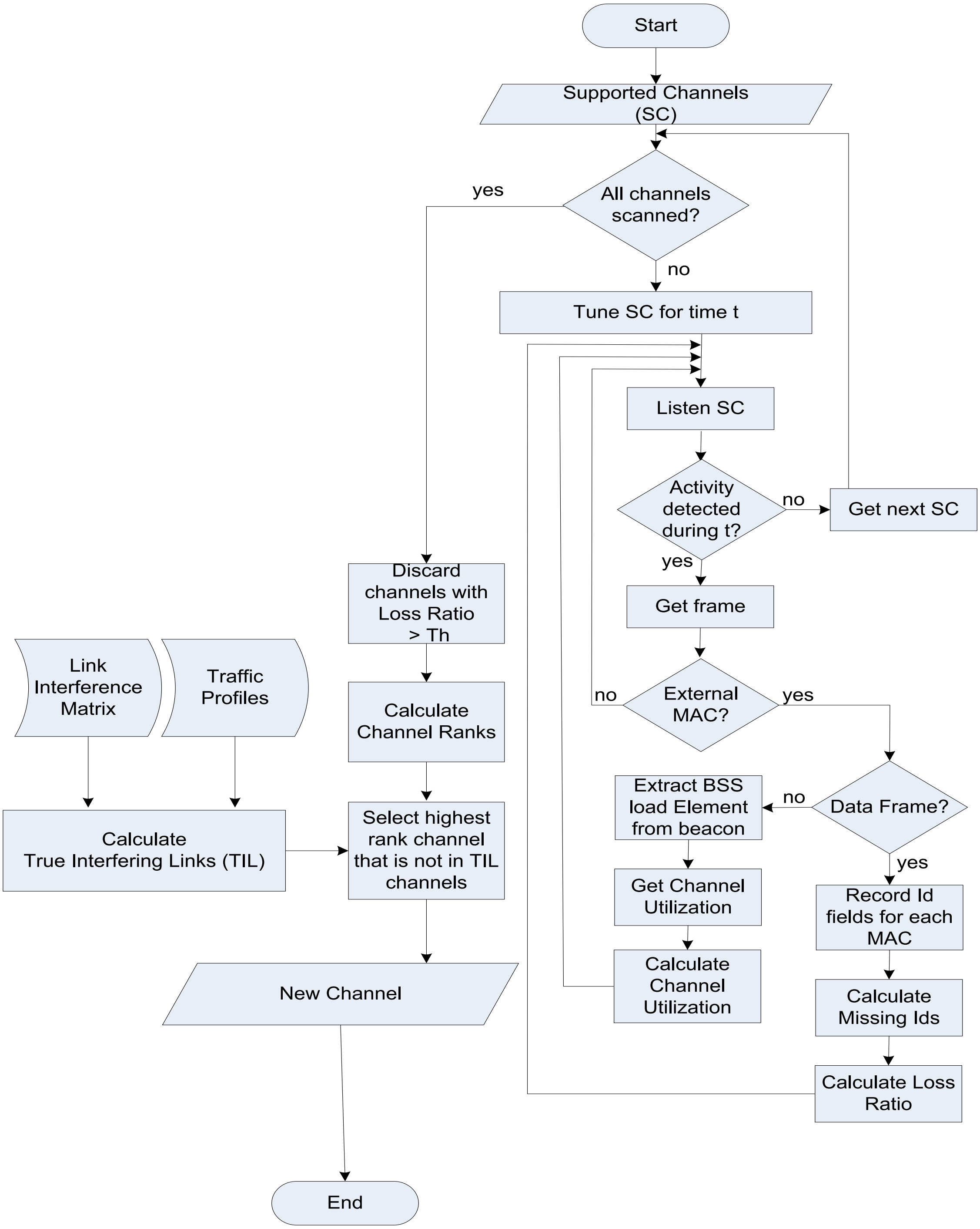

Fig. 5. Flowchart of QUAM.

5. Channel assignment

In order to assess the effectiveness of QUAM, it is applied in a centralized channel assignment scheme that assigns the channel according to high priority links. Such links can be identified by applying the critical link identification algorithms [1,29]. For each of these bottleneck links, the QUAM suggests the priority of less interfering channels that do not have a conflict with the neighbor assignments of the incident link. Fig. 6 shows the system diagram of the complete working of QUAM in a centralized channel assignment algorithm.

Algorithm 1. QUAM based channel selection algorithm.

```
Input: MCG, True Interfering Links (TIL), Frame Loss Ratio (FLR), Channel Ranks, Link Interference Matrix (LIM), Traffic
   Profile
1:   Let Q ← list of vertices of MCG ordered by their priority
2:   while Q not empty do
3:     v_current ← pull_highest_priority (Q)
4:     for all supported channels do
5:       If FLR(Selected channel) at v_current(both radios) < TH then
6:         arrange channels in decreasing order of ranks
7:       end if
8:     end for
9:     TIL ← LIM, Traffic Profile
10:    while all arranged channels not visited OR channel selected = false
       do
11:      pick channel in order of their rank
12:      if the channel is not in the list of TIL then
13:        channel selected = channel
14:      end if
15:    end while
16:  end while
```

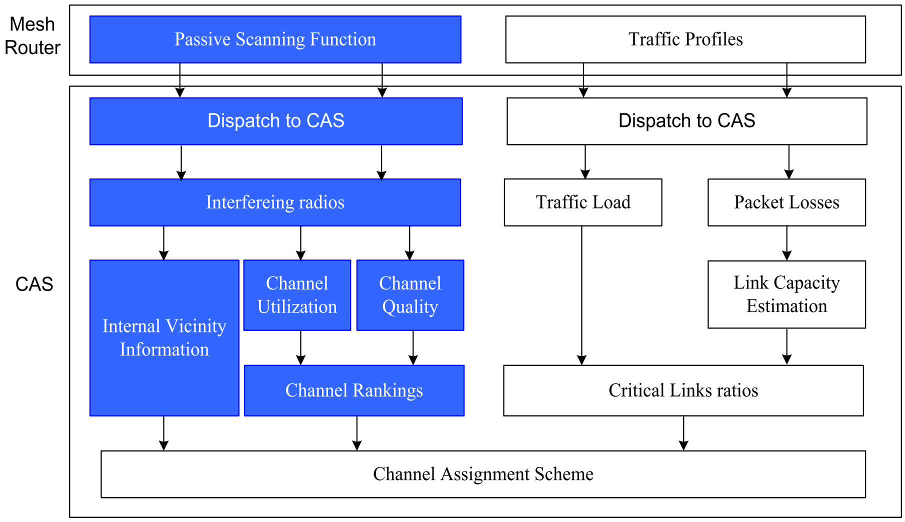

Fig. 6. System diagram of QUAM.

At the network initialization, all the non-default radios of mesh routers are assigned a single channel. The QUAM based channel selection algorithm takes the MCG, True Interfering Links (TIL), Frame Loss Ratio, Link Interference Matrix (LIM), Traffic Profile and Channel Ranks as input as represented in Algorithm 2. Two lists are associated with the MCG, the V list contains all the (links) vertices whereas, the Q is a priority queue that contains ordered list of bottleneck links. For each of the vertex in q, the algorithm iteratively checks the PDR of both the end MRs of the selected vertex have PDR less than the pre-defined threshold (TH1) and arrange such channels in their decreasing order of ranks, as represented in line 5–10 of the algorithm. A channel with very high FLR will hamper the communication if the same channel is selected and used for WMN. At line 10 of the algorithm, the CCAS maps the TIL of interfering links with the Interference Matrix (LIM) to find the current channel assignment of TIL [ch] links.

Line 11–16 represents the selection of a new channel, the algorithm visits each all the ranked channels in their set order unless it finds a channel that does not is in the list of TIL [ch]. If no such channel is found, the algorithm selects any random channel from the ranked channels. In line 20–21, the newly selected channel is assigned to the vertex and its visited flag is set to true. The channel switching of a vertex subsequently may lead to ripple effects and force several channel switches. To cater such ripple effects and to ensure that only one channel is assigned to one radio, the protocol after coloring a vertex immediately looks for other vertices that contain either radio of the current vertex and also mark it as visited. These other verities may belong to the critical links that are prioritized for the next channel switch, thus, reducing the number of channel switches required as represented in lines 22–30.

Algorithm 2. Channel assignment algorithm.

```
Input: MCG, True Interfering Links (TIL), Frame Loss Ratio. Channel Ranks, Link Interference Matrix (LIM), Traffic Profile
    Let V ← list of all vertices of MCG
    Let Q ← list of vertices of MCG ordered by their priority
    while Q not empty do
            channel selected = Select Channel()
      If channel selected == false then
         the channel selected = select random channel from ranking
      end if
      AssignChannel (v_current, channel selected)
      visited(v_current) = true
      for all z | z belongs to V and contains either radio of v_current and visited(z) = false do
         AssignChannel (z, channel selected)
         visited(z) = true
         If z is also in Q then
            remove z from Q
            v_current = z and
            Go to step10
         end if
      end for
    end while
```

Table 1
Notations and their meanings.

Notations	Meanings
N	Total mesh routers in the WMN such that $n \in N$
L	Total Links in the WMN such that $\in L$
$^{l}x\leftrightarrow y$	Bidirectional link between mesh router x and y
IL	Interfering links
TIL	True Interfering links
TL	Traffic load
TH	Threshold
$CEU^{Ch}{}_{r}$	Utilization of channel Ch by co-located network radior
CEU^{Ch}	Utilization of channel Ch by all by co-located networks
FLR^{Ch}	Frame loss ratio on channel Ch at a particular mesh router
$Rank^{Ch}{}_{x}$	Rank of channel Ch at mesh router x
$Rank^{Ch}_{x\leftrightarrow y}$	Rank of channel Ch at link $^{l}x\leftrightarrow y$

6. Simulation and analysis of results

The QUAM is implemented in a simulation environment using OMNeT++. Each mesh router is equipped with three radio interfaces for backbone connectivity [1,8]. Among these interfaces, two interfaces are reserved as data interfaces (termed as non-default radios) and remaining one is for both control and data purposes (termed as default radio). The default radio is permanently assigned a fixed CC, whereas the proposed approaches are for assigning channels to the non-default radios. The link redirection procedure is also implemented that is used during the channel switch process. In redirection, before switching the channel, the mesh router broadcasts ‘Link Down’ message to all the neighboring mesh routers in order to inform them about time duration during which the incident interface will not be available for reception of data [1].

Different simulation experiments are performed by varying mesh router densities over a field size of 1000 m × 1000 m. The interference estimation is obtained by simulating the RFMON mode, where one of the non-default radio interfaces temporarily suspends its normal communication and listens to the media for capturing the data and management frames. During the listening period, link redirection procedure is used as discussed above. The duration of management frames is set to 100 ms and for interference estimation; the listening period is set to 3 s after every 10 min. For dynamic channel assignment of non-default radios, the need for channel switch of the links is in accessed every 10 min, while channel switch delay is set to 0.03 s [1]. The remaining simulation parameters are listed in Table 4.

For benchmarking the QUAM, it is compared with the channel selection method of ITACA [1] and EICA [7]. The ITACA and EICA are also implemented in the same simulator. To ensure the effectiveness and performance of QUAM compared to the existing ITACA and EICA, the same simulation setup is used. The ITACA and EICA are the channel assignment schemes that in addition to internal interfering links also consider the existence of co-located networks. For assessment of channels, both the ITACA and EICA considers 2-hop neighbors as interfering links, however, for co-located networks, ITCA uses channel utilization while EICA uses channel occupancy. To certain the efficiency and performance gain of proposed approaches from the previous work, the homogeneous deployments of simulation scenarios are made. The simulation results can be affected by different factors. To reduce the effects of errors, and random results, the consistency, and reproducibility are determined through repetitive analyses of traces obtained through 10 runs of each scenario.

Table 2
An example of link interference matrix.

Mesh routers							
Mesh routers		**1**	**2**	**3**	**4**	**5**	**6**
	1		1	1	0	1	0
	2	1		1	0	1	0
	3	1	1		0	1	1
	4	0	0	0		1	0
	5	1	1	1	1		0
	6	0	0	1	0	0	

Table 3
Use of Fragment Offset instead of identification number in case of datagram fragmentation.

Sequence	Identification	Total length	DFMay / Don't	MF Last / More	Fragment offset
0	345	5140	0	0	0
			(a) Original IP Datagram		
Sequence	**Identification**	**Total length**	**DF May / Don't**	**MF Last / More**	**Fragment offset**
0–0	345	1500	0	1	0
0–1	345	1500	0	1	185
0–2	345	1500	0	1	370
0–3	345	1500	0	0	55
			(b) IP fragments		

Table 4
Simulation Parameters.

Parameters	Values
World size	1000 m × 1000 m
No. of mesh routers	20, 40, 60, 80, 100
Traffic type	UDP
Packet size	512 bytes
Physical standard	IEEE 802.11a
Physical transmission	Fixed at 12 Mbps
Channels	12
Traffic load	CBR
Traffic flow	5–14 for 20 nodes
Data rate	100 pps
No. of radios	3
Simulation duration	30 min
Interference estimation cycle	Every 10 min
Interference estimation duration	3 s
Management frame cycle	Every 100 ms
Channel assignment cycle	Every 10 min
Channel switch delay	0.03 s

6.1. Experimental analysis

Five sets of simulation experiments of QUAM are conducted for evaluating the performance. The first set of experiments presents a comparison of achieved throughput by both the schemes in a relationship with the hop distance. The second set of experiments examines the effect on achieved throughput over the time. In the third set of experiments, throughput in a multi-hop environment is examined to observe the impact of different flows. In the fourth set of experiments, the effect of the end-to-end delay is analyzed in a multi-hop environment with varying the number of concurrent flows. In the last experiment, the packet delivery ratio is investigated in a multi-hop environment by varying the number of mesh routers. To minimize the effects of errors and random results, all the experiments are repeated ten times with different locations of mesh routers and an average is presented in the graphs.

6.2. Performance evaluation

To evaluate QUAM, three performance metrics are considered. The sub-sections discuss the three performance metrics including throughput, end-to-end delay, and packet delivery ratio.

6.2.1. Throughput

The throughput of a network is greatly affected by the number of mesh routers in between the source and the sink. This multi-hop comparison helps to quantify the effect of interference between the wireless links effectively. Twenty-one mesh

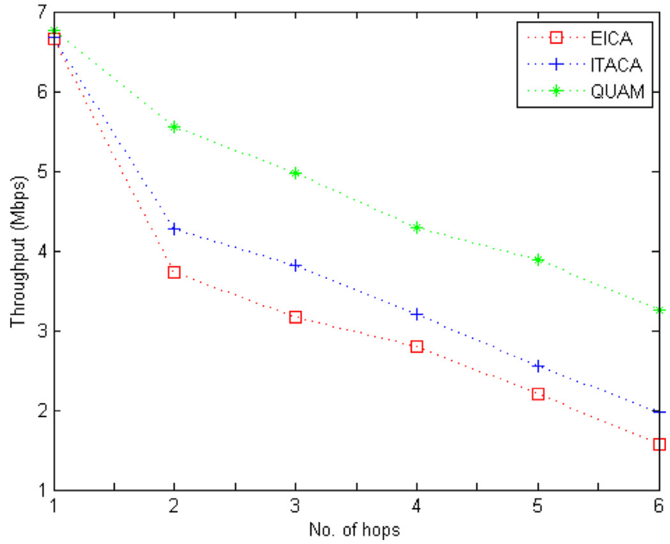

Fig. 7. Throughput effect as the number of hops increases.

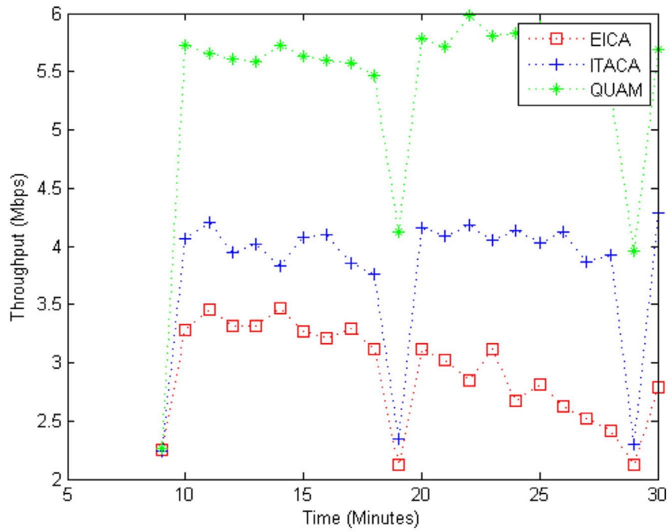

Fig. 8. Throughput effect over time.

routers topology is considered; one mesh router is declared as mesh gateway and remaining 20 act as normal mesh routers. In this topology, all the flows from normal mesh routers are directed to the gateway through intermediate mesh routers. Twelve random flows are initiated between the routers and gateway.

Fig. 7 shows the comparison graph of average throughput of the network topology for all the three approaches. In this graph, average throughput in all the three cases is affected, as the number of hops is increased. Due to this increase, the possibility of interference between the intermediate hops from source to sink becomes high. At the 1-hop distance, almost all the approaches behaved similarly and produced maximum throughput. However, as the distance between the source and sink is increased with just 2-hops of distance, the average throughput suddenly decreases to almost 21%. However, comparatively, to the ITACA and EICA, the use of QUAM noticeably increases the throughput. The average throughput achieved by QUAM, ITACA, and EICA is 4.78 Mbps, 3.74 Mbps, and 3.35 Mbps respectively. This means the QUAM provides 27.80% and 42.68% higher throughput than ITACA and EICA respectively. This is due to the reason that the interference effect on supported channels is accurately assessed and accordingly the critical links are provided better channels that ultimately mitigates the interference.

Fig. 8 shows the second experiment, where the measured throughput at a distance of 3-hops is plotted over the first 22 min of the experiment. The graph shows sudden downward spikes around the 10th, 20th and 30th min. These fluctuations are due to the sensing mechanism for interference estimation that is turned on every 10 min. During this time, one of the radio interfaces becomes in-active for traffic forwarding for almost 3 s. However, to minimize the effect of packet

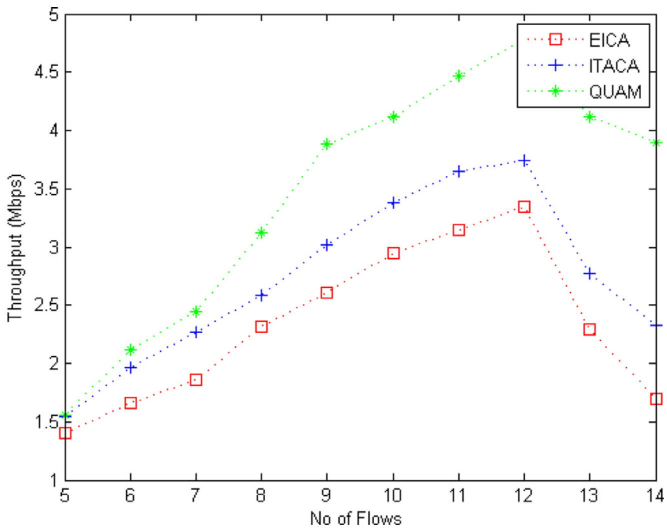

Fig. 9. Throughput effect as the number of flows increase.

drops or delay, link redirection mechanism is implemented as discussed earlier. This slightly lowers the throughput, but in comparison of performance gain, this is negligible.

In the third experiment, the effect of multiple flows on network performance is analyzed. The main objective of this experiment is to verify the optimal distribution of channels between the wireless links under different traffic loads. The same 21 mesh routers topology is considered. The number of active mesh routers is varied from 5 to14 at different timings. Fig. 9 shows a graph, where all the three approaches, till flow 12, provide increased throughput as the flows are increased. The reason is that the delivery of flows is done through a sparse network of 20 mesh routers where the interference between the flows is very less. However, the throughput in case of QUAM is comparatively high and logarithmic from flow 7 to 12. This is due to the reason that the interference effect on supported channels is accurately assessed and accordingly, the actual bandwidth starved links are provided better channels that ultimately mitigates the interference.

Furthermore, when more flows are induced as flow 13 and onward, the throughput decreases due to increase in interference. However, the throughput of QUAM is still higher than the ITACA & EICA and QUAM comparatively sustained in higher interference also. The average throughput achieved by QUAM, ITACA, and EICA is 3.45 Mbps, 2.72 Mbps, and 2.32 Mbps respectively. This means the average throughput achieved by QUAM is 26.83% and 48.70% higher than ITACA and EICA respectively.

6.2.2. *End-to-end delay*

The objective of this experiment is to examine the effect of interference and saturation under different traffic loads. The same topology is considered as discussed in the previous section. Fig. 10 shows the end-to-end delay as a function of the load on the network. It is observed that performance of ITACA and EICA remains almost similar with a minor difference. On the other hand, due to better channel assignment, the QUAM produced less end-to-end delay from the start. In all the approaches, the delay till flow 12 is nominal due to the sparse topology and less number of concurrent transmissions; therefore, the packets faced minimal interference and delay for propagation during transit.

However, as the network saturation tends to increase from flow 12 onward, the QUAM faced considerably less delay. The average end-to-end delay faced by the QUAM, ITACA, and EICA is 0.28 s, 0.39 s and 0.43 s respectively. This means that the QUAM more effectively dealt with the interference by a factor of 28.20% and 34.88% than ITACA and EICA respectively.

6.2.3. *Packet delivery ratio*

In this experiment, the performance of QUAM is examined through packet delivery ratio (PDR) by varying the mesh router density. This PDR is affected by both the interference and the number of hops. Fig. 11 shows a plot of PDR with varying the number of mesh routers. During this experiment, the number of active flows is kept exactly half of the total mesh routers. The PDR in this experiment represents the gateway traffic profile. The graph shows that, when the mesh router density is less, the QUAM works almost similar to the ITACA and EICA and yield PDR above 95%. However, as the number of packets increases in the network due to the rise in mesh router's density, the PDR starts decreasing. The main reason for this drop is that the increase in density also increased the contention between the links, thus more routers now contend for getting access to the shared channel.

Although all the three approaches use the same number of channels, the fact that QUAM more effectively captures the effect of interference, helps the channel assignment algorithm to use better channels for saturated links. The average PDR

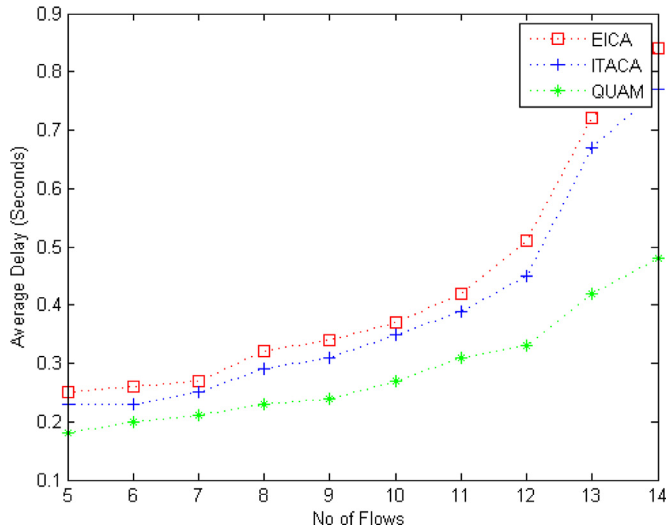

Fig. 10. End-to-End delay as the number of flows increase.

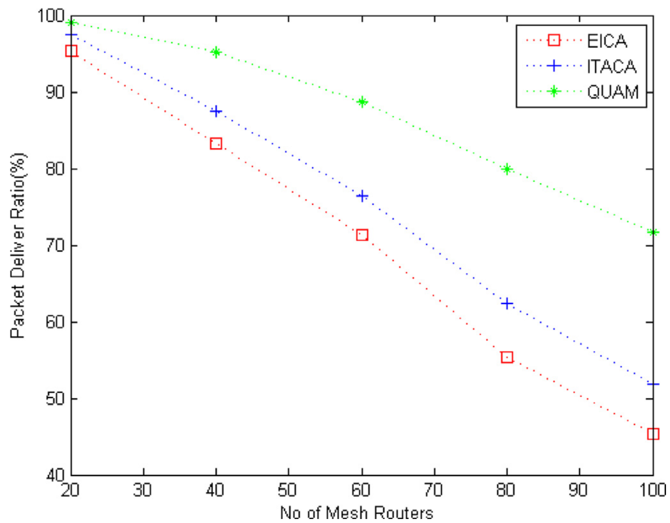

Fig. 11. PDR Comparison as the number of mesh routers increase.

achieved by QUAM, ITACA, and EICA is 86.84%, 75.10%, and 70.13% respectively. This shows that packet delivery of QUAM is 15.63% and 23.82% higher than ITACA and EICA respectively.

7. Conclusion and future work

The main focus of this research is to improve the performance of WMN while taking into consideration the high and dynamic effects of interference. A measurement-based metric (QUAM) is presented that helps to assign better channels to the bottleneck links in a WMN. This metric provides more accurate knowledge about the surroundings by critically assessing the utilization and quality of a channel. The benefit and accuracy of this metric are ensured by applying it in a centralized channel assignment scheme and by performing rigorous testing over multiple scenarios. The simulation results reveal performance improvements in dense networks with multi-hop deployments. The real test-bed implementation would better reveal the performance of the proposed metric, however, due to time and budget factors, it has been left as future work. The results of the achieved throughput in multi-hop traffic flows indicate that QUAM performs 27.80% and 42.68% better than ITACA and EICA respectively. In the case of increasing the traffic load while keeping the intermediate hops fixed, the results show that QUAM excels 26.83% and 48.70% higher throughput and approximately 28.20% and 34.88% less delay than ITACA and EICA respectively. Similarly, in the scaled network, the QUAM's delivery ratio is almost 15.63% and 23.82% better than ITACA and EICA respectively. The proposed metrics and channel assignment scheme have been implemented for centralized scenarios; however, in some scenarios the centralized approaches are not feasible. Therefore, in future the proposed approaches will be extended for distributed WMN.

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Saleem Iqbal received Ph.D. degree from PCRG Lab, UTM, Malaysia in 2015. He is Assistant Professor at University Institute of Information Technology, PMAS-AAUR, Pakistan. Previously, he was with the COMSATS as a Lecturer from 2003 to 2007. Saleem worked for four years with Pakistan Federal Government for deployment of ICT projects. His research interests include medium access control and network layer for heterogeneous wireless networks.

Abdul Hanan Abdullah received the Ph.D. degree from Aston University, Birmingham, U.K., in 1995. He is currently a Professor with the Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia. From 2004 to 2011, he was the Dean of the Faculty of Computing. He is currently heading the Pervasive Computing Research Group, UTM. His research interests include wireless sensor networks, mobile ad hoc networks, network security, and next-generation networks.

Kashif Naseer Qureshi received his Ph.D. degree from the Department of Computer Systems and Communications in University of Technology Malaysia (UTM). He has received his MS Degree in Information Technology in 2012 from IM Sciences Peshawar Pakistan He is Assistant Professor at Bahria University Islamabad, Pakistan. He has been as a reviewer for various reputable academic Journals.

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