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Abstract. One of the most promising wireless technologies are *Wireless Mesh Networks* (WMN). The aggregate capacity of wireless mesh networks can be improved significantly by equipping each node with several Wireless Network Interfaces (WNICs) and by using multiple channels in order to minimize the interference and to provide high performance in such networks. However, multiple WNICs in each node requires a channel assignment planning. The channels have to be assigned in such a way, that interference is decreased and performance is increased at the same time. Since the number of available channels is limited, it is desired to allocate and reallocate channels dynamically on-demand.

In this paper, a dynamic channel assignment, is proposed to the aforementioned problem which is adaptive to the load in the wireless mesh network. The algorithm add or select a channel for heavy loaded nodes, based on the local information of the neighbor nodes. The selected or added channel minimizes the interference and insures the network connectivity.

1 Introduction

The next generation of networks will be build by the integration of wired and wireless networks. *Wireless Mesh Networks* (WMN), *Mobile Ad-hoc Networks* (MANET), *Wireless Sensor Networks* (WSN), *Cellular Networks*, and existing fixed networks will be integrated and they will be based on IP to finally melt in the *Internet of Things* [2, 3]. This environment will provide the user with the capability to communicate at any time, anywhere, and with anything. In such an internetworked environment original new applications will be created and applied. These applications demand for high data rates and low latency. At the same time, the number of users which gain access to the network will increase, too. An important requirement of these future applications is the demand for quality of service (QoS) guarantees, e.g., for real time multimedia applications and Internet connections. However, current available wireless technologies have several limitations in this respect.

Recently, wireless mesh networks are in the focus of academia and industry research. The reason is that WMNs have several favorable characteristics, such as self-organization, self-configuration, reliable service, and Internet connectivity. A WMN is a multihop wireless network which consists of mesh gateways, mesh routers and mesh clients. Mesh routers have minimal mobility and form the backbone for the mesh clients which can be either stationary or mobile. In the wireless backbone, the radio channel becomes a bottleneck due to the high usage of such a channel. Furthermore, nodes cannot receive and forward data at the same time using a single channel. To overcome these limitations multiple channels and multiple network interfaces can be equipped for each router.

The wireless standards specifications of the IEEE 802.11 family provide several non-overlapping channels, e.g., IEEE 802.11b/g provides 3 and IEEE 802.11a provides 12 non-overlapping channels, respectively. The standards provide also a higher number of partial overlapping channels. These channels can be used to transmit data in parallel. This is also the case with a node with several network interfaces in which each network interface is bound to a different channel. However, the binding of network interfaces to channels has to be done in such a way that connectivity of the network is ensured and the performance does not suffer. Eventually, the channel assignment of the backbone of the mesh routers becomes a challenge in large installations, since the state of the wireless backbone may change over time depending on the number of flows and user activity.

1.1 Motivation and Contribution

Today, there are new developments of physical and MAC layers in wireless networks since IEEE 802.11x standards provide multiple channels, which could be used simultaneously. For this the mesh-router can use multiple channels to communicate with its neighbors. Recently, routing algorithms do not take into account the quality of the wireless link, channel usage, channel diversity, and other metrics. Therefore, such information from MAC layer could be used to choose the appropriate route. Since the routing protocol not only needs to select the shortest path between different nodes, it also has to select an appropriate channel or radio on the path which satisfies the QoS requirements. Furthermore, it has to take into account interferences between channels and how many channels are assigned to the node which can enable the node to transmit via multiple paths. In addition, one important problem that still faces wireless networks is the capacity reduction due to the interference of neighboring nodes using the same channel. For this, a new mechanism is required to assign channels based on the expected traffic load and minimize the interference.

As a consequence, an adaptive channel assignment mechanism should be designed in relation of routing and aware of the properties of WMNs. We summarize the consideration of channel assignment [5, 7]:

- The number of distinct channels that can be assigned to a node must be less or equal to the number of Wireless Network Interfaces (WNIC) of that node.
- The channels should be selected based only on locally available information.
- The assignment of the channel should be based on the physical structure of the network rather than on the dynamic network condition.
- The change in channel assignment should not frequently alter the connectivity between nodes, rather providing a stable channel environment for the end-to-end routing mechanism.

Our contributions are to develop an adaptive channel assignment, where a node selects a channel that minimizes the interference and maximizes the throughput using local information. We provide a practical channel assignment solution where the nodes are equipped with limited number of WNICs, it is desired to allocate and reallocate channels dynamically. In addition, our solution provides a good balance between two conflicting goals of channel assignment, network connectivity, and channel diversity. Furthermore, it balances the load and utilizes the channels efficiently.

1.2 Structure of the paper

The remainder of the paper is organized as follows. In Section 2, we describe the architecture of wireless mesh networks (WMNs) and introduce the terminology used throughout the paper. Subsequently, Section 3 reviews the related work. Section 4 presents the adaptive channel assignment approach called *Neighborhood Nodes Collaboration to support QoS* (NNCQ) in detail. Section 5 evaluates the performance of NNCQ. Finally, Section 6 concludes the paper and discusses future work.

2 SYSTEM MODEL AND PROBLEM FORMULATION

2.1 Wireless Mesh Network Architecture

In [13] an architecture for Wireless Mesh Networks is introduced which we are going to refer to in this paper, see Figure 1. According to this architecture a WMN consists of mesh gateways, mesh routers and mesh clients. Some of the mesh gateways are connected to the Internet by wire, which is indicated by solid lines. They provide Internet access to the backbone of mesh routers. Mesh gateways can use WiMAX IEEE 802.16, since WiMAX has potential to provide high data rate with a large transmission range (50km in rural areas). Mesh routers provide access to the mesh clients and both of them can use WiFi IEEE 802.11(a, b and g).

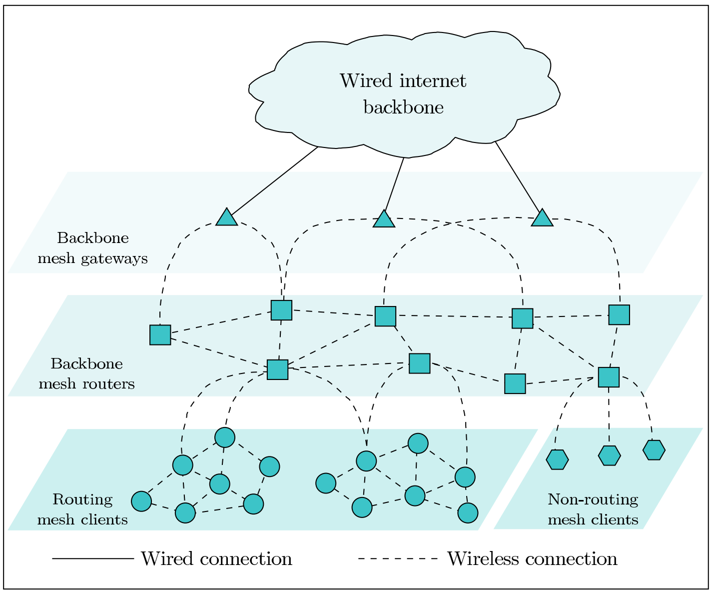


Fig. 1: The considered Wireless Mesh Network architecture

To illustrate the problem considered in this work we refer to Figure 2. The mesh routers $v_1, \ldots, v_7$ build the wireless backbone of the considered wireless mesh network. The router v_6 is connected to the Internet and mobile clients can connect to every router to gain access to the Internet. The figure shows an example of unbalanced load since the router v_1 has heavy load where the router v_5 has less load. We assume that each mesh router has multiple *wireless interface cards* (WNIC). Each WNIC is assigned to one channel and communicates with at least one of the neighbors on a common channel. One of the node's WNICs is used to communicate with the client nodes in its service range on a specified channel. The rest of the WNICs are used to communicate with its neighbors on diverse channels. Our algorithm will only operate on the latter ones, the WNIC for the clients is not part of the algorithm. Furthermore, the mesh routers which constitute the wireless backbone are static and do not move. However, there is some dynamic in the WMN due to spatial and temporal diversities.

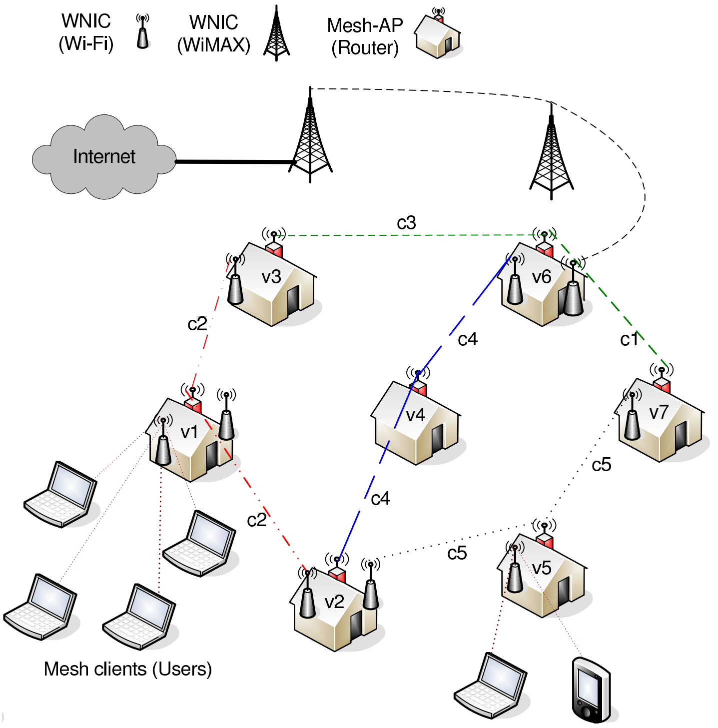


Fig. 2: Model of a Wireless Mesh Network with multiple wireless network interfaces

In single-radio mesh network, each mesh-node has only one interface card (NIC) and all nodes can communicate by using one radio channel. The motivation of using multi-radio, multi-channel per mesh router in WMNs, can be obvious shown in Figure 3. The throughput is reduced by every hop when using a single channel. By using dual-channel, the throughput is increased and much increased with multi-channel comparing with single-radio mesh network.

2.2 Network Model

The considered wireless mesh network (WMN) constitutes a graph $G(V, E, C)$, where $V = \{v_1, v_2, \ldots, v_n\}$ is the set of nodes, $C = \{c_1, c_2, \ldots, c_k\}$ the set of available channels, and $E = \{(v_i, v_j, c_r) | v_i, v_j \in V \land c_r \in C\}$ the set of virtual wireless links between the nodes v_i and v_j on channel c_r. For the sake of simplicity

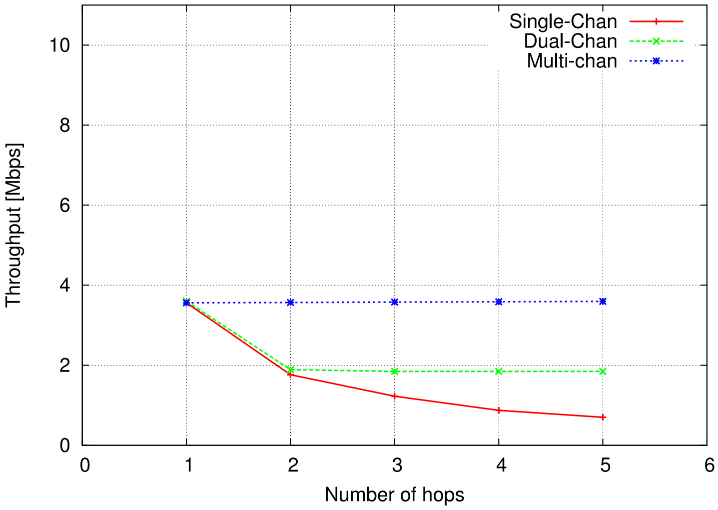


Fig. 3: Multi-channel performance

we will denote $l^a_{i,j} = (v_i, v_j, a) \in E$ as the wireless link between node v_i and v_j on channel $a \in C$. The set $L_i = \{l^a_{i,j}\}$ describes all wireless links of the node i. A node v_i with m_i wireless network interfaces may allocate up to m_i different channels, if available. The set of assigned channels to node v_i is denoted as $C_i = \{c_{i_1}, c_{i_2}, \ldots, c_{i_u}\}$, $u \leq m_i$. Furthermore, N^a_i denotes the one step neighbors of node v_i on channel a and all neighbors are given by $N_i = \bigcup_{a \in C_i} N^a_i$. Based on the previous terms the channels of all neighbors of node v_i are given by $C_{N_i} = \bigcup_{j \in N_i} C_j$.

2.3 Traffic Load Estimation

Our approach requires the information about the current load on a wireless link $l^a_{i,j}$ and the quality of the link.

The approach we deploy is based on the packet loss probability. For this, each mesh router v_i counts all sent packets $s(l^a_{i,j}, t)$ and acknowledgment packets received $r(l^a_{i,j}, t)$ for the sent packets on the link $l^a_{i,j}$, where the channel is a, during a specified time interval t. The packet loss probability on link $l^a_{i,j}$ from the point view of node v_i is given by:

$$P(\text{loss on } l^a_{i,j}) = 1 - \left(\frac{r(l^a_{i,j}, t)}{s(l^a_{i,j}, t)} \right) \tag{1}$$

There are many reasons for packet loss. These reasons include the high usage of the channel, hidden terminal problem, and interference from nearby nodes.

The node v_i shares this information with its neighbors v_j. Notice, that all these calculations are done locally on each node and only represent the view of the network from the point of view of node v_i, since wireless links show strong asymmetry.

3 Related Work

3.1 Joined Routing and Channel Assignment Approaches

Various approaches have discussed routing and channel assignment for WMN in previous years. In this section we will discuss some of these approaches.

So et al. [11] propose a load balancing routing protocol where each node is equipped with only one network interface. They propose a routing protocol that finds routes to balance load among channels while maintaining connectivity. They assume that neighboring APs are assigned different channels, and each node selects the less load route to an access point. The drawback is that they do not consider the varying channel conditions and it happens that neighboring APs use the same channel due to the limited number of channels. Bahl et al. [4] propose the dynamic switching of channels in such a way that the neighbors meet periodically on a common channel to communicate. The advantage of the approach is that it neither requires the modification of the MAC protocol nor multiple network interfaces. The drawback is the synchronization of the nodes, which is difficult to achieve. So et al. [10] propose that the nodes which have packets to transmit negotiate with the destination who sends in a specific time window. This approach assumes also that all nodes are synchronized. Wu et al. [12] suggest to divide the overall bandwidth in $n+1$ channels, one channel for control information and the other n to transmit data packets.

All the approaches discussed until now operate with one network interface per node. There are also approaches which assume multiple interfaces per node.

Raniwala et al. [8] propose a distributed channel assignment joined with routing. They represent a WMN as multiple spanning trees, and assume that a node can join multiple spanning trees to distribute the load among the trees. In their channel assignment approach nodes positioned higher in the tree hierarchy get a higher priority, since they are connected to the Internet. The nodes lower positioned in the tree hierarchy get lower priority in choosing channels and that may result in discriminating these nodes which can affect their communication performance negatively.

3.2 Channel Assignment Approaches

Several research approaches discuss channel assignment for WMNs. The main focus of these approaches is to enhance the overall network performance by reducing interference and maximizing the capacity.

Ramachandran et al. [6] propose a centralized channel assignment algorithm which is performed by a central server that periodically collects dynamically changing channel interference information. Shin et al. [9] show that optimal channel assignment is NP-hard, and propose to assign as many distinct channels as possible to a node to improve the performance while satisfying the constraints of limited NICs and available channels. The channel selection to particular network interfaces is done randomly. Ko et al. [5] assume that a node can transmit on a single channel but can listen to all available channels within its local domain at the same time. In this approach, the nodes select the channel which minimizes the interference cost from the set of nodes within their interference range.

4 Neighborhood Nodes Collaboration to support QoS

4.1 Approach Assumptions

In the beginning we assume that the initial channel assignment is already done and all routers have a connectivity matrix of the network. This matrix is static. Our approach never invalidates old links or becomes aware of newly created links. Hence there is no need to update this matrix during runtime. Based on the matrix all routing within the wireless backbone is done. For the routing, a router creates a set of link-disjoint paths to its destination. Initially, the shortest path is used. Regardless of the channel switching, the routing is always valid, hence there is no routing overhead incurred in a channel switch.

After this initialization phase, each router periodically estimates the load of all its communication links and exchanges this information with its neighbors. We have mentioned earlier that we will rely on the measurement of the probability of loss of a link to estimate the current load. There are two methods to exchange the information of the link status and channel usage. Either the router periodically sends out broadcast messages to its neighbors or it sends this information on demand as soon as one of its neighbors announces a channel switch. The first solution is more reliable and saves the overhead of the data collection prior to a channel switch but it creates a relatively high network overhead. We chose the second possibility since channel switches are not assumed to happen frequently.

Algorithm 1 NNCQ Channel selection

```
if $\left((|C_i| < m_i) \wedge (\exists j \in N_i, |C_j| < m_j)\right)$ then
    {/*Both partners have an unused WNIC*/}
    $c_x \in C \setminus (C_i \cup C_{N_i})$
    Allocate channel $c_x$ to $v_i$ and $v_j$
else if $(|C_i| < m_i) \wedge (\nexists j \in N_i, |C_j| < m_j)$ then
    {/*Only router i has a free WNIC*/}
    $c_x = \min\{C_{N_i}\}$
    Allocate channel $c_x$ to $v_i$
else
    {/*No unused WNICs are available*/}
    $c_x = min\{C_i \cap C_{N_i}\}$
    Send switch-request to neighbor who offers $c_x$
end if
```

4.2 NNCQ

Based on the above assumptions and using the terminology defined in Section 2.2, we describe our algorithm called *Neighborhood Nodes Collaboration to support QoS* (NNCQ) in detail. Generally the algorithm has two phases: the monitoring phase and the channel switching phase. During the monitoring phase the NNCQ instance on each router monitors the links to all its neighbors and records the probability of loss $P(\text{loss on } l^a_{i,j})$ for each of its links.

If the router i experiences a loss rate $P(\text{loss on } l^a_{i,j}) \geq \sigma$ on a currently used link $l^a_{i,j}$, it proceeds to the channel switching phase. During this phase the router tries to locally modify the channel assignment to minimize the experienced loss rate and thereby maximize the overall performance. The channel switching phase is described in the following.

Based on the connectivity matrix, the router calculates all node disjoint paths to its destination. If it discovers an additional unused path using neighbor $k \neq j$, it checks its local assignment table to find the channel b so that $l_{i,k}^{b} \in L_i$. If $a \neq b$ the router simply activates the newly found path in its routing table and starts using the multiple paths according to the route selection algorithm (see Section 4.3).

If there are additional paths but none of them uses a different channel, the router compiles a *CH_ REQUEST* message and sends it to the possible next hops to its destination. The *CH_ REQUEST* message contains the channels C_i currently used by router i and their loss values. The message also indicates whether an unused WNIC is available on i. The destinations of this message first check whether they can reply. A router k can reply with a *CH_ REPLY* message, if it has an unused WNIC, the free WNIC flag of the request is set, or $C_i \cap C_k \neq \{b\}$, if b denotes the channel currently used to communicate. The router then compiles the *CH_ REPLY* message adding his list of channels from C_k with their respective loss values. Equivalent to the *CH_ REQUEST* message it also indicates whether it still has an unused WNIC.

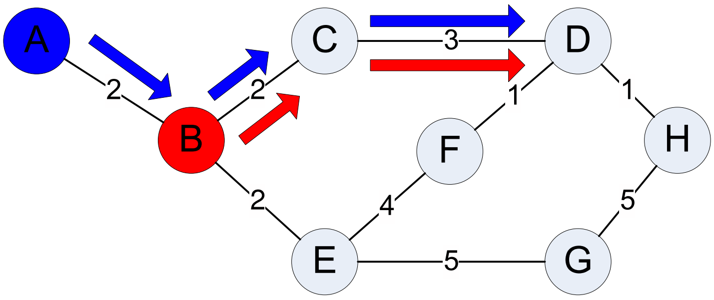
After gathering the *CH_ REPLY* messages of its neighbors router i starts the channel selection algorithm as depicted in Algorithm 1. In the algorithm it is assumed that channels are never double assigned, meaning two WNICs never operate on the same channel inside a router. It follows that $|C_i| = m_i$ means that all WNICs on the current router are used. Throughout the algorithm the expression $\min\{<\text{ set of channels }>\}$ denotes the channel with the minimal loss probability. Lines 1 to 4 describe the case in which the requester and at least one neighbor have unused WNICs available. In case that a previously unused channel is selected and assigned to the unused WNICs. If only the requester has a free WNIC (lines 5 to 8), then the selected channel is the one with the lowest loss probability within the neighborhood. The selected channel is assigned to the unused WNIC at the requester. Probably the most common case that no additional WNICs are available is handled in lines 10-12. The set of available paths is constructed as an intersection of the channels C_i and C_{N_i}, meaning the channels the router i and its neighbors use. From this set the channel with the lowest loss probability is selected. The construction of the channel selection algorithm guarantees that existing network links are never invalidated.

After the algorithm selected a suitable channel and neighbor, it informs the neighbor of the channel switch using a *CH_ SWITCH* message and executes the channel switch. It then awaits a *CH_ ACK* message from the neighbor acknowledging the switch.

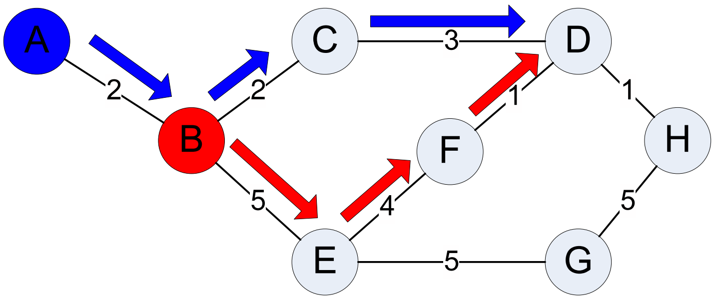
As a last step of the channel switching phase the router updates its routing tables. Since it now has multiple paths to its destination the router has to perform a route selection algorithm. This is detailed in the following section. It has to be mentioned that since the routing is source routing based on the locally available connectivity matrix no network overhead is generated by route searches or the activation of routes.

4.3 Route Selection

In our approach we considered two possible mechanisms for the route selection: round robin and single path. Round robin uses each of the multiple paths one



(a) Before using NNCQ



(b) After using NNCQ

Fig. 4: Example network scenario to illustrate NNCQ

after the other. The routes vary from packet to packet thereby possibly creating many out of order events on the higher network layers (e.g. TCP). Nevertheless it might be useful to distribute the load over several paths.

Single path uses only one path to the destination. Directly after a channel switch the newly created path is preferred. After a certain damping time $t_{wait} = 10s$ another path might be chosen according to the loss rate of the first links, the path length or any weighted combination of both. The waiting time t_{wait} is introduced to prevent alternating channel assignments and route changes.

4.4 Example

The approach is demonstrated in the scenario in Figure 4. There are 8 nodes (mesh routers) $A, B, \dots, H$ and each router has three WNICs. In this example there are 5 available channels and the initial assignment is shown in Figure 4a.

We assume that routers A and B are used by a sufficiently large number of users to overutilize the connection between B and C. At some point the probability of packet loss $P(\text{loss on}l^2_{B,C})$ will exceed the threshold σ and the NNCQ instance on router B will switch from the monitoring phase to the channel switch phase.

As its first step it will calculate the node disjoint paths to D and discover the additional path $E - F - D$. Since this path uses the same channel on its first hop like the currently used one it cannot be used directly. Therefore B sends a *CH_REQUEST* message to E. It will contain the information about the currently used channels $C_B = \{2\}$ and the loss probability $P(\text{loss on } l^2_{B,C})$. Since we assumed that every node has more than one WNIC, it will also flag that an unused WNIC is still available.

According to our approach router E will answer with a CH_REPLY message. The reply message contains the channels in use by node E and their respective loss values. Then the channel selection algorithm is started on B. According to Algorithm 1 one of the channels $\{2, 4, 5\}$ has to be selected. For our example we will assume that channel 5 is the one with the lowest loss rate. Consequently, B sends a CH_SWITCH to E and waits for the CH_ACK. After the successful reception of the CH_ACK the new route is available for routing and will be used according to the route selection algorithm.

5 PERFORMANCE EVALUATION

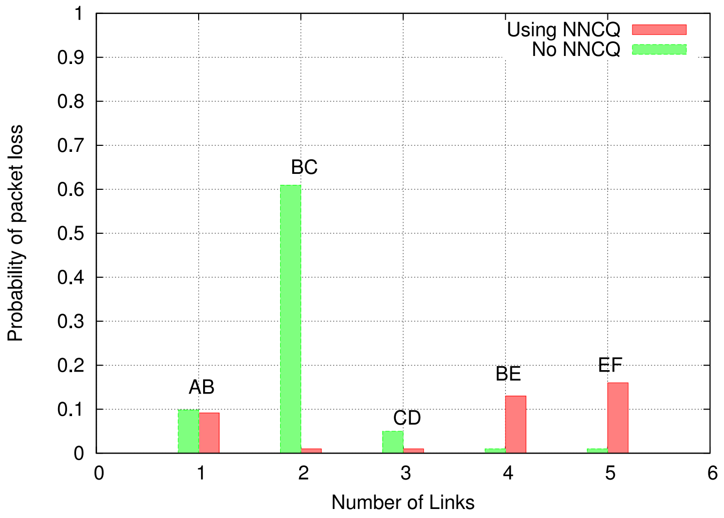


Fig. 5: Probability of packet loss versus links

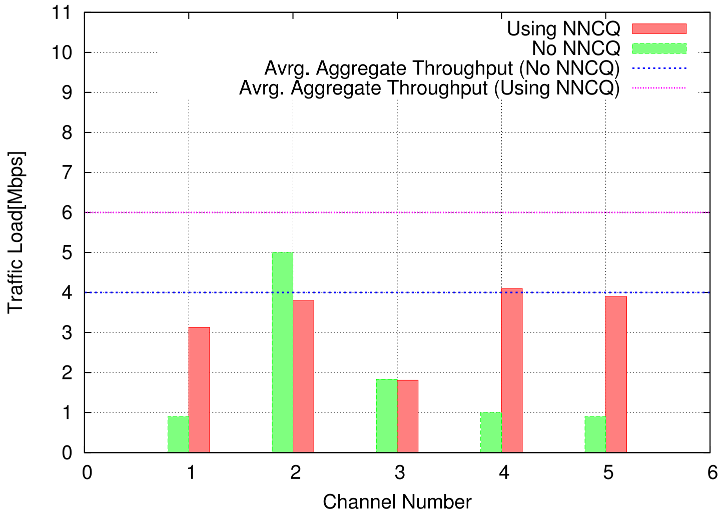
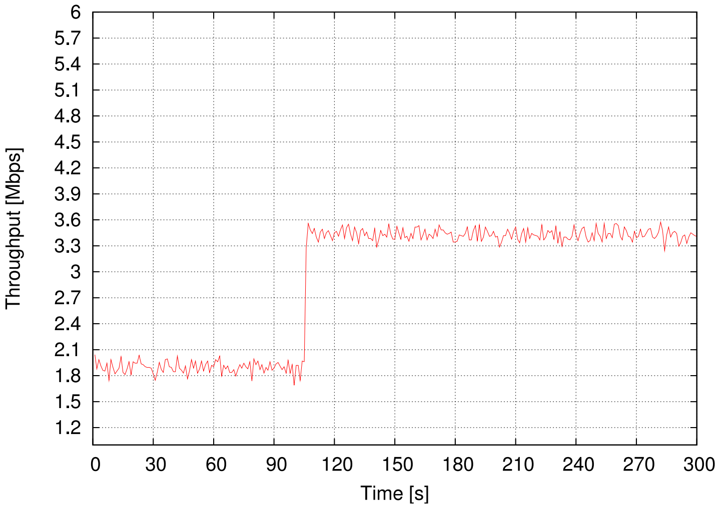
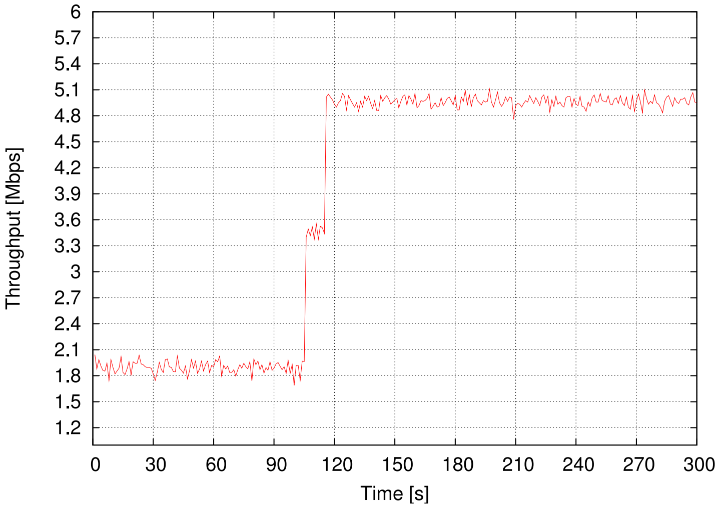


Fig. 6: An efficient utilization of channels using NNCQ



(a) Round-robin multiple paths



(b) Single path routing

Fig. 7: NNCQ performance

We have performed simulations using ns-2 simulator [1] to evaluate the performance of the proposed approach. A simulation area of $1000 \times 1000m$ is divided into twelve quadrants. The routers are placed at the center of each quadrant. To illustrate the simulation we refer to Figure 4. The physical and MAC layers of ns-2 are set up to simulate 802.11b with a maximum bitrate of 11Mbps.

To demonstrate our approach, clients are attached to routers A, B, G and E generating a traffic load of 2Mbps, 3Mbps, 1Mbps, and 1.1Mbps respectively. The destination of all flows is router D except the source E where the destination is F. In this case, router B has to transmit the traffic from its clients and also to forward the traffic from A to the destination. In this scenario high load occurs on router B, since it use only one channel where the other routers has less load. This will eventually result in an increased packet loss rate on router B, since it has only one channel to forward the traffic to the next hop C for the shortest

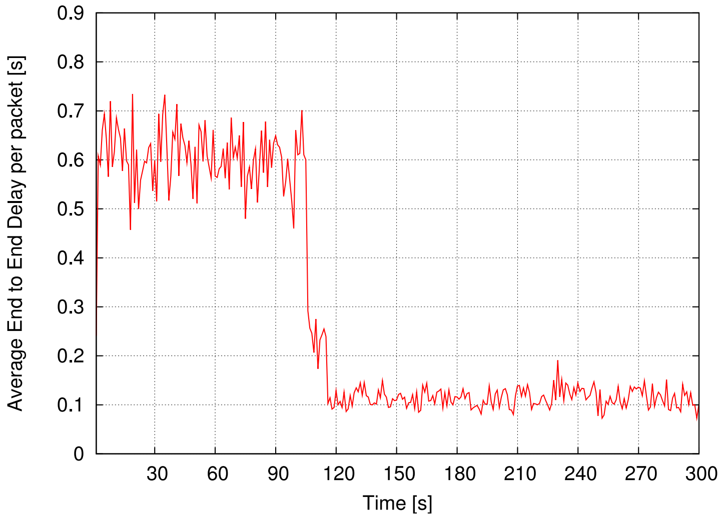


Fig. 8: End to End Delay

path $C - D$. We set the duration of the simulation to 300 seconds, and after 100s our approach is enabled.

Using this scenario, we compare the throughput and the traffic load with and without NNCQ. Figure 5 shows the bottleneck on link BC (See Figure 4a. Due to the high usage of channel 2, the packet loss on this link is very high where the packet loss on other links are low. After NNCQ is enabled at $t = 100s$, the new channel 5 is added to the router B. The new channel (5) is assigned to the link BE where the old channel 2 is canceled. Now, after using NNCQ, nearly there is no packet loss on link BC where the loss is increased a little bit on other links. In Figure 6, we measure the average of aggregate throughput of all flows in the network. It is obvious that the total throughput with NNCQ is increased with approximately 70%. We also measure the total traffic load on each channel and it shows after using NNCQ the high traffic load is distributed over the channels. Figure 7 shows the throughput measured at the destination D. It is clear, that after NNCQ is enabled the throughput improves substantially.

We also consider the route selection algorithm used and its impact on the throughput. The comparison of Figure 7a and Figure 7b shows the importance of choosing the right route selection algorithm. Using a round-robin approach in which all paths are used in turn increases the throughput by more than 70%. Using a single path increases the bandwidth even more so that in the long run both routers can transport the offered load completely. We conclude that the originally overloaded link $l^2_{B,C}$ remains the bottleneck if round-robin routing is used. The reordering of packets was not considered here but could also lead to decreased performance when using round-robin routing.

The end-to-end delay is shown in Figure 8. It is clear that after NNCQ is enabled at $t = 100s$, the average of end-to-end delay for all flows is much lower than before.

As a bottom line, NNCQ achieves significantly higher throughput than a network without dynamic channel assignment.

6 Conclusions and Future Work

In this paper, we have presented a novel approach for dynamic channel assignment which is adaptive to the traffic load. The simulation results show that our approach can successfully improve the throughput. NNCQ is an efficient local optimization strategy for wireless mesh networks and does not require changes in the MAC layer, since it can be completely realized in the application layer.

Channel switching in general and NNCQ in particular always incurs some drawbacks. During the channel switch the link cannot be used. With NNCQ this time is minimized because no existing links will be invalidated and hence no routing overhead is generated. The control messages generate only minimal network overhead since they are only send on-demand, no periodic broadcasting of information is needed. Since NNCQ always uses local information it is not guaranteed to find a globally optimal solution. If clients move fast, the channel assignment adapts too slowly, because of the concentration of channels at the previous traffic hot-spot.

As future work we plan to build a hybrid central/local assignment strategy to overcome these challenges. We also plan to implement it in our testbed presented in Section 2.1.

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