Fair Channel Assignment in Multi-Hop Wireless Networks

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***Abstract*—In Multi-hop Wireless Networks (MWNs), the end-to-end performance degrades exponentially with hop counts and the degree of traffic aggregation at each hop. Fair allocation of bandwidth among nodes is one of the challenging problems in multi-hop wireless networks. The IEEE 802.11 Distributed Coordination Function (DCF) standard stipulates long-term equalization of throughput among stations by giving the same number of transmission opportunities regardless of their individual bit rates. A transmission between two nodes is affected by three main factors: i) its distance from the gateway, ii) number of nodes interfering with it and iii) its traffic load. This paper presents a Fair Channel Assignment Algorithm (FCAA) that increases fairness and throughput and decreases delay in a multi-hop wireless networks. FCAA starts by constructing an interference graph from the multi-hop wireless network. From the generated interference graph, it builds a matrix of all noninterfering nodes in the wireless network. Last, FCAA uses the generated matrix in addition of nodes individual traffic load to generate various sets of nodes. Nodes belonging to the same set are later assigned distinct nonoverlapping channels to transmit their packets. We show that FCAA maximizes fairness and individual nodes throughput. In addition, it increases the overall network throughput and decreases delay.**

I. Introduction

MWNs have been studied significantly and deployed considerably for a variety of applications including Mobile Ad Hoc Networks (MANET), Wireless Sensor Networks (WSN), and WMN. Nodes in MWNs intermediate nodes receive and forward packets using Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA). This fact make them difficult to analyze due to their complex dynamics. Whereas the performance modeling of a single-hop 802.11 MAC protocol is well perceived [1], the MAC performance in multi-hop is still up for debate among researchers.

The end-to-end throughput between a pair of nodes in a MWN depends on various physical and environmental factors. Physical factors include their distance, transmission power, and data rate. These factors include noise, path loss, and fading.

The DCF in IEEE 802.11 networks inclines to provide equal long-term transmission opportunities to the stations in the network. Thus, each station has the same *number* of opportunities to transmit a frame, regardless of its bit rate. Consequently, low bit rate stations hold the channel longer than a high bit rate station and both achieve approximately the same throughput but experience different delays. This is referred to as throughput-based fairness [2].

It has been shown that multi-hop Wide Area Networks (WAN), aggregate throughput and the throughput of high bit rate stations are negatively affected by channel holding time of the low bit rate stations, while transmitting an equal amount of data [3].

To address the deficiency associated with delay and throughput-based fairness problem in MWN, two major challenges must be addressed. First, we need a way to identify the position of a station with respect to the other stations along the path towards a gateway in the presence of exposed and hidden nodes. The problem of exposed and hidden nodes is described in details in [4]. Second, we need to be able to estimate the load that each node is carrying on its and other nodes behalf. By doing so, we can match closely noninterfering nodes to various sets where all nodes in the same set can use the same channel to transmit at the same time.

In this paper, we propose a new centralized algorithm that assigns non-overlapping channels to stations in MWNs. The algorithm maximizes individual nodes and overall network throughout and minimizes the delay. The main contributions of our work are summarized as follows:

- Formulate and model the MWN as a graph representing nodes are vertices and wireless links as the edges.
- Generate the corresponding interference graph based on nodes spacial positions in the MWN.
- Construct compatibility matrix to include all noninterfering nodes in the network.
- Create an algorithm that is capable of generating sets of nodes that are compatible to transmit using the same channel.
- Run detailed simulation of the new algorithm under heavy loads
- Show that the new algorithm outperforms the default system in terms of individual nodes through-

put, the overall network throughput and end-to-end delay.
- Discuss open issues, and possible improvements to the algorithm.

This paper is organized as follows: Section II briefly covers major research work in fair bandwidth allocation in multi-hop wireless networks. Section III explains the network model and the formulation of the problem. Section IV describes the Fair Channel Assignment Algorithm (FCAA). Section V presents the simulation implementation, assumptions, and performance results. Last, Section VI discusses some open issues with FCAA, future work and the conclusion.

II. Previous Work

A contention window based algorithm has been introduced in [5]. It distinguishes different medium access rates for different nodes by varying their contention window sizes.

So et al. [6] presented a routing and channel assignment protocol for MWNs suitable for nodes with single network interface. The protocol discovers multiple routes to various access points allowing them to choose different channels based on traffic load information. However, the protocol has several limitations as indicated by the authors.

In [7], a distributed algorithm has been used to show the capability of achieving fairness without any modifications to the transport protocol. It has been demonstrated that by applying the distributed algorithm, a near-perfect fairness can be achieved with high throughput for both CSMA and CSMA/CA. However, the topology used was restricted to a static mesh network with only a single chain of nodes and already known traffic patterns.

In [8], the capacity of WMNs has been formulated in terms of collision domain, which was defined as the set of nodes that need to be inactive in order for the wireless link to transmit successfully. It has been shown that the effective load on a collision domain is less than or equal to the sum of traffic on its links. A constant effective MAC capacity has been assumed in this study which may not be realistic due to the interference and other physical limitations in multi-hop wireless networks.

Fairness disparity between upstream and downstream traffic in 802.11 has been investigated in [9]. This disparity limits the network capacity in the context of voice traffic and not the radio bandwidth.

It has been observed in [10] that, in multi-hop wireless networks, flows with the same hop count may experience different throughput (symmetrical unfairness). The authors proposed a distributed routing algorithm to improve this symmetrical unfairness. However, it is not clear if the algorithm can be used to remove spatial bias.

A distributed slot allocation algorithm has been used in [11] to improve fairness in MWNs. While the scheme did not make any assumption about the existence of a centralized coordination of traffic patterns, a 2-hop interference region has been assumed. This is not necessarily the case in WMNs.

In [12], the authors analytically presented the existence of starvation in MWNs in a linear topology. They carried their work on a simplified linear topology consisting of only two nodes. Also some unrealistic assumptions were made such that two hops away nodes do not interfere with each other and they are not in the same carrier sensing range.

The authors in [13] introduced a rate limiting approach to solve the problem of fairness in WMNs. They showed that by limiting the rates of nodes that are 1-hop away from the gateway in order to give more transmission opportunities to all other nodes. However their method requires determining the optimal rate allocation offline using analytical models.

The work in [14] introduces an Adaptive Contention Window Algorithm (ACWA) that assigns variable contention window sizes to nodes in the mesh network based on their distances from the gateway and on the number of hidden nodes affecting their transmissions. Results show improvement in terms of individual throughput, the overall throughput, and the average end-to-end delay. Although fairness was improved but it was not significant.

In [15] a Fair Share Algorithm (FSA) was presented. FSA assists each node in computing a fair packet size and a fair contention window based on their location in the mesh network. FSA accomplishes better fairness and better individual throughput however, the overall system throughput decreased.

The authors in [16] proposed a distributed and jammer channel assignment algorithm capable of collecting information from neighbors to help each device make a decision on to stay on current channel or switch to another.

The authors in [17] suggested channel assignment and topology control approach for WMNs. The procedure assigns channels in an order determined dynamically during the execution of the channel assignment procedure and is based on the target objective.

III. System Model and Problem Formulation

We assume that the multi-hop wireless network is a set V of communicating stations (nodes). The stations send and forward traffic on behave of their neighbors. The communication graph is a graph $G = (V,E)$, where V is the set of the n submitting stations in G and E is the set of links between them. The transmission range between nodes in G is t, and the interference (sensing) range is r. The interfering range is usually not the same as the transmission range. Usually $r > t$. Two nodes u and v in G share an edge and are able to communicate with each if they are in the same transmission range i.e. if the Euclidean distance $\parallel u - v \parallel \leq t$. In 802.11, nodes in the same transmission range are aware of each other [18]. Thus each node can exchange its location information with its neighbors. Consequently, a node can determine its number of hops it is from the gateway. By sending the information to the gateway, the gateway is able to implement the algorithm presented in this paper.

We build the Interference graph I_G from G as follows: Two vertices u and v in I_G share an edge $e(u,v)$ in I_G if their Euclidean distance $\| u-v \| \leq r$. The set of all edges in I_G is called $E(I_G)$. M is the Interference matrix of I_G where rows and columns in M correspond to vertices in I_G. M is constructed as follows:

$$M(u,v) = \begin{cases} 1 & \text{if } e(u,v) \in E(I_G) \\ 0 & \text{otherwise} \end{cases}$$

We define $d[u]$ to be the degree (which includes traffic intensity) of node u in I_G. $h[u]$ is defined as the number of hops away u is from the gateway, and $Comp[u]$ is the set of nodes compatible with u generated from M.

Algorithm 1 shows how to compute the interference matrix, the compatibility set, and the nodes degree.

Algorithm 1 Interference Matrix, Compatibility Set, and Nodes Degree Computation

for $v \in V(I_G)$ **do**
  for $u \in V(I_G)$ **do**
    $M(u,v) = 0$
  end for
end for
for $v \in V(I_G)$ **do**
  $d[v] = 0$
  for $u \in V(I_G)$ **and** $u \neq v$ **do**
    if $\| v-u \| \leq r$ **then**
      $M(u,v) = 1$
      $d[v] = d[v] + M(v,u)$
    else
      $u \in Comp[v]$
    end if
  end for
end for

A node's throughput is primarily affected by its hops away from the gateway h and secondarily by its traffic intensity or degree d. Nodes closer to the gateway with lower degree have higher throughput than those farther away [7], [15]. In addition, nodes with the *same number of hops* from the gateway but with lower degree have also higher throughput than their neighbors as shown in [10]. We associate with each vertex v a variable we call a Dominance Rank $DR[v]$. Vertex v with the **lowest** $DR[v]$ is the **dominant node** and it is the one closest to the gateway and with minimum degree. To compute the dominance ranks DR of nodes in the network, we first sort the nodes by their hops h from the gateway. Of course, nodes closer to the gateway are ranked higher. Algorithm 2 describes the algorithm to finding the Dominance Rank of all nodes in the network.

Algorithm 2 Finding Dominance Ranks

for $v \in V(I_G)$ **do**
  $DR[v] = h[v]$
end for
We assume h is sorted
Set all nodes $\in V(I_G)$ as unprocessed
$i = 1$
for $u \in V(I_G)$ s.t u is unprocessed & u has the minimum h **do**
  mark u as processed
  for $v \neq$u$\in V(I_G)$ s.t v is unprocessed **do**
    if $h[u] = h[v]$ **then**
      mark v as processed
      if $d[u] < d[v]$ **then**
        $DR[v] = DR[u] + i$
      else
        if $d[u] > d[v]$ **then**
          $DR[u] = DR[v] + i$
        else
          $DR[u] = Dr[v]$
        end if
      end if
    end if
  end for
  $i = i + 1$
end for

IV. FCAA

The objective of our algorithm is to divide noninterfering nodes into sets that can transmit simultaneously using the same channel in such a way that maximizes fairness and improves throughput.

If node u is scheduled with node v where u is much more dominant than v, this may result in a noticeable increase in u throughput and small increase in that of v. In this case, the Negative Effect $NE(u,v)$ of u over v becomes high and the fairness $F(u,v)$, among u and v becomes low. This issue is further discussed in section VI.

We would like to find a scheduling algorithm that increases $F(u,v)$ among nodes in the same set and decreases $NE(u,v)$. By intuition, high ranked noninterfering nodes must to be scheduled to transmit together using the same channel, and lower ranked noninterfering nodes must be scheduled together using another nonoverlapping channel. [1] This way, we minimize the negative effect that nodes have on each other and we increase fairness. Our algorithm is a greedy algorithm that starts by picking the node u with the lowest DR that has not been scheduled (processed) yet and schedules it with node v s.t $v \in Comp[u]$, and v has the lowest $DR[v]$ between all nodes in $Comp[u]$ set. The algorithm then marks them as processed. Then it moves to the next highest ranked (lowest DR) unprocessed node and finds its compatible node which has the lowest DR, etc. FCAA is shown in 3.

[1]This was proved through intense simulations but we are unable to include the results here due to space constraints.

Algorithm 3 Fair Channel Assignment Algorithm (FCAA)

We assume that nodes are sorted based on the DRs
Set all nodes $\in V(I_G)$ as unprocessed
$l = 0$
while not all vertices are processed **do**
    $s_l = \emptyset$
    $found = 0$
    Find unprocessed vertex $u \in V(I_G)$ s.t. u has the lowest DR
    Mark u as processed
    Add u to s_l
    while not all nodes in $Comp[u]$ are processed **or** $found \neq 0$ **do**
        Find unprocessed vertex w in $Comp[u]$ s.t. w has the lowest DR
        Mark w as processed
        Add w to s_l
        $found = 1$
    end while
    $l = l + 1$
end while

We have now l sets

A. Example

Consider the network in Figure 1. In this network, node N_1 is assumed to be the gateway, thus it is not included in the computation. Nodes N_4, and N_5 send their traffic to node N_2 which in turn forwards it to the gateway. Node N_8 transmits its traffic to node N_7, and node N_7 transmits to node N_3. The latter then transmits them to the gateway. The

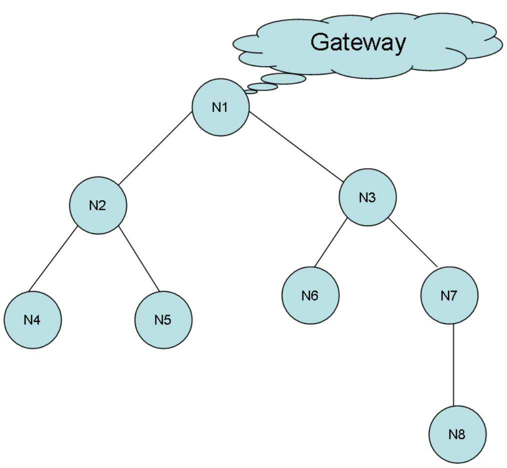

Fig. 1: Initial Graph G of the Multi-Hop Wireless Network

compatibility matrix M for graph I_G is as follows:

$$M = \begin{array}{c} \\ N2 \\ N3 \\ N4 \\ N5 \\ N6 \\ N7 \\ N8 \end{array} \begin{array}{c} \begin{array}{ccccccc} N2 & N3 & N4 & N5 & N6 & N7 & N8 \end{array} \\ \begin{pmatrix} 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 \end{pmatrix} \end{array}$$

The resulting interference graph I_G along with each node degree, number of hops from the gateway, and its DR are shown in Figure 2. Nodes with the same color forms sets that later transmit using the same channel.

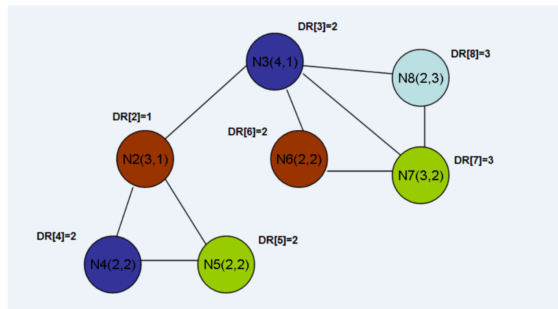

Fig. 2: Interference Graph I_G of Graph G with each node DR

Proposition 1. *The algorithm has the greedy property.*

Proof. Suppose that $S = \{u, v\}$ is a set of noninterfering nodes where u has the lowest DR and v has the lowest DR in $Comp[u]$. Suppose that a scheduling solution S' exists where set (u, v) are not included in S' but instead (u, w) in set S' where w is also in $Comp[u]$. This implies that $NE(u, w) > NE(u, v)$ because $DR[v] < DR[w]$ and thus $F(u, w) < F(u, v)$. Therefore, by replacing v by w in S' yields a better solution. $\square$ $\square$

V. Simulations Assumptions and Experiments

We implement the algorithms on the network shown in Figure 3. Number of nodes generating traffic (n) is 7.

We assume that *mobile_node_*7 is the gateway. *mobile_node_*2, and *mobile_node_*3 send their traffic to *mobile_node_*0 which in turn forwards it to the gateway. *mobile_node_*6 transmits its traffic to *mobile_node_*5, and *mobile_node_*5 and *mobile_node_*4 transmit their packets to *mobile_node_*1. The latter then transmits them to the gateway. The gateway does not generate any traffic.

The default scenario called *MyFairness_Try*1 but we caption it as *Default*. In this scenario, we let the nodes transmit packets using default channel assignment as chosen by the simulator. We duplicate the default and create a second scenario which we implement on it our FCAA. The new scenario is called *MyFairness_level_Assignment* and we caption it as *FCAA*. The buffer size of all nodes is set to 10300

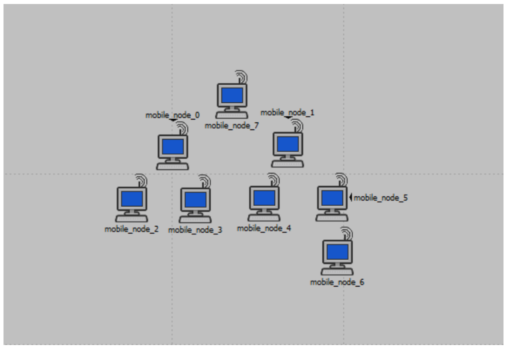

Fig. 3: Wireless Multi-Hop Network

bits. We set the transmission range is set such that nodes 2-hops away from each others interfere with each other transmissions. We use static routing to inflict one way routing and we assume all nodes are fixed. The speed of the channel is set to 1 Mbps, and the packet size (s) is set to constant 1024 Bytes. We use the IEEE 802.11g network protocol implemented in Riverbed Modeler (version 17.5) simulation software to evaluate the performance of the algorithm on the network. We assume that the traffic is homogeneous and it exponentially distributed. The inter-arrival time (τ) to 0.001 second. The simulation time is set to 30 minutes. The traffic ON state is set to 100 sec and the OFF state is 0.1 sec. Thus the total load ρ is given by:

$$\rho = \frac{\text{ON}}{(\text{ON+OFF})} * \frac{(\text{s*n}) * 8(\text{Bytes})}{\tau} \approx 57.3\text{Mbps}$$

By running FCAA on network of Figure 3, it returns the following sets: s_1={*mobile_node*_1, *mobile_node*_2}, s_2 = {*mobile_node*_0, *mobile_node*_4}, s_3 = {*mobile_node*_3, *mobile_node*_5} and s_4 = {*mobile_node*_6}.

Thus, we manually (using the channel set nodes *mobile_node*_1 and *mobile_node*_2 to transmit using channel 1. *mobile_node*_0 and *mobile_node*_4 use channel 6 to transmit. *mobile_node*_3 and *mobile_node*_5 are set to use channel 11 and *mobile_node*_6 uses channel 14.

A. *FCAA Performance*

In the next two Sections we show the simulation results we obtained by running our algorithm on the network shown in Figure 3. We then compare the obtained results with the results obtained from the same network but without implementing FCAA on it.

1) Overall Network Results: The simulation results show noticeable improvements on the network when FCAA is implemented over the network without it. As shown in Figure 4, the overall throughput of FCAA is significantly higher than the default network. The network overall delay is shown in Figure 6. The MAC delay is also presented in Figure 7. As shown in all Figures, FCAA shows better throughput and shorter delay.

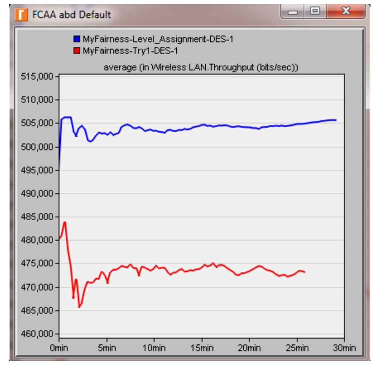

Fig. 4: Overall Network Throughput FCAA and Default

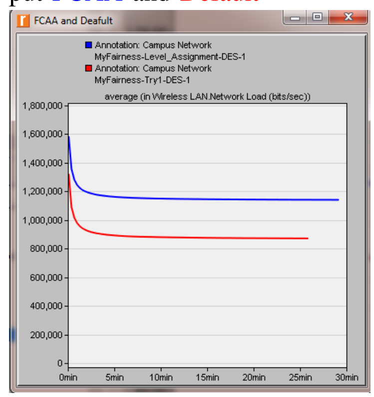

Fig. 5: Overall Network Load FCAA and Default

2) Individual Nodes Simulation Data: In this section we present the simulation results of individual nodes in the network. Since the space here is not enough to include all results for all nodes, we opted to show only a subset of the results. As shown in Figure 8, all nodes are able to send much more traffic in the network compared to the default one. Individual traffic sent by each node is shown in Figures 9, 10, 13, 12, 14, and 15. Also notice the traffic sent by farther nodes in the network improved significantly. In addition, as shown in Figures 16,17,18, nodes in the same set are able to send nearly the same amount of traffic unlike in the case of the default scenario where the gap between sent traffic is significant.

VI. Conclusion and Future Work

Multi-hop networks based on IEEE 802.11 suffer from providing fair access to flows traveling with an increasing number of hops. In this paper, we present a centralized Fair Channel Assignment Algorithm (FCAA) to improve throughput and fairness. In FCAA the gateway assigns nonoverlapping channels to various sets of nodes in the network based on their location and their aggregate traffic load. Preliminary simulation results show that

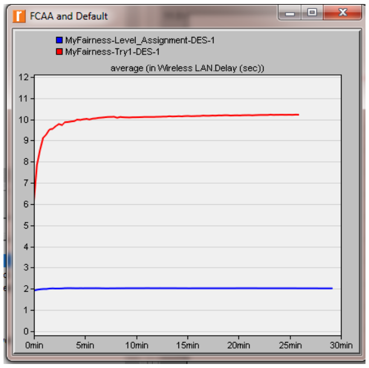

Fig. 6: Network Delay FCAA and Default

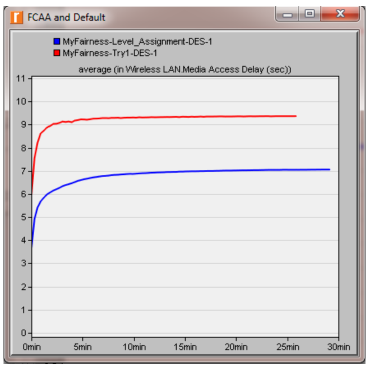

Fig. 7: MAC Delay FCAA and default

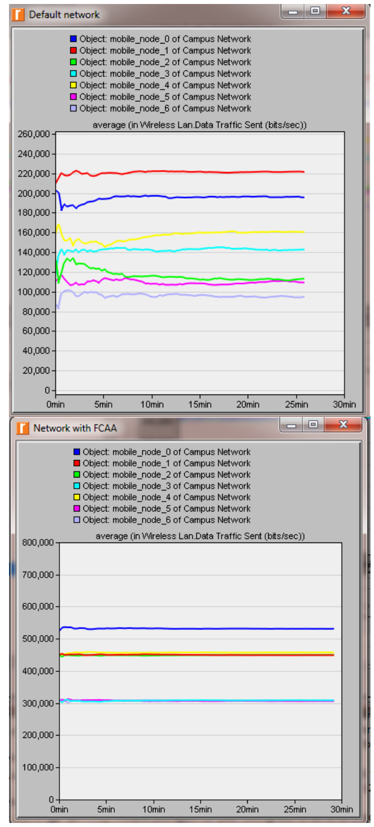

Fig. 8: All Nodes Sent Traffic- Default (top) and FCAA (bottom) Networks

FCAA outperforms the default in terms of individual nodes' throughput, fairness, overall network throughput, and the average end-to-end delay. The limitation of the FCAA is that the sets of nodes assigned the same channel is confined to two. While it is true that scheduling any permutation of only two noninterfering nodes improves the throughput and fairness for both nodes, it may not achieve the maximum fairness if it is done randomly. For instance, if node u is scheduled with node v where $DR[u] \ll DR[v]$ (i.e u is much more dominant than v), that may result in a noticeable increase in u throughput and little increase in that of v. In this case, u will have a negative impact on v and the fairness among u and v becomes low. We recognize that in large networks, assigning different channels for only two nodes would not be practical. We also assume that nodes are not mobile, however we believe that FCAA will work equally the same on mobile stations. In this case FCAA needs to be run every time nodes change their location which will obviously cause an overhead. Future work includes testing FCAA on various topology to investigate further its optimality in context of nodes selection in the noninterfering sets.

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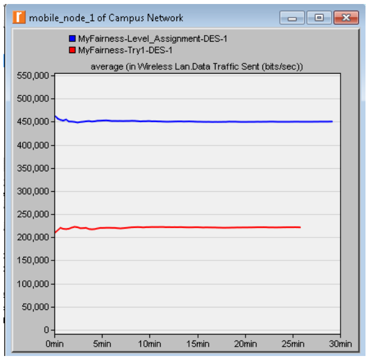

Fig. 9: *mobile_node*_1 Sent Traffic FCAA and Default

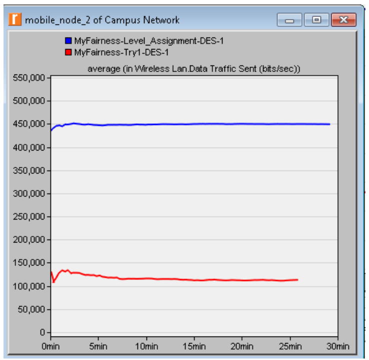

Fig. 10: *mobile_node*_2 Sent Traffic FCAA and Default

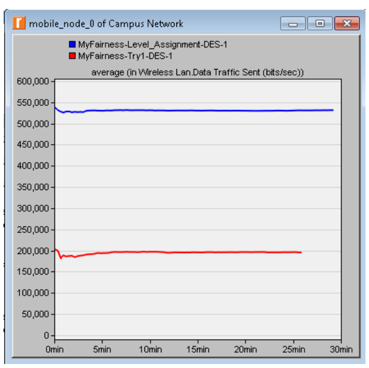

Fig. 11: *mobile_node*_0 Sent Traffic FCAA and Default

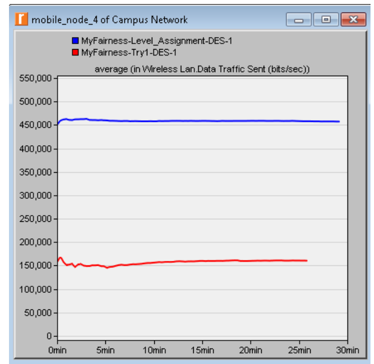

Fig. 12: *mobile_node*_4 Sent Traffic FCAA and Default

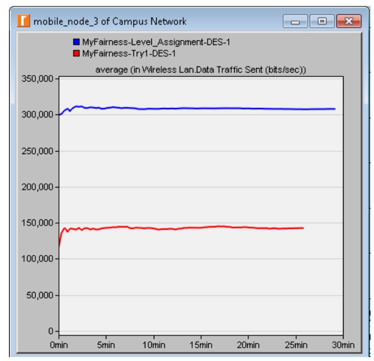

Fig. 13: *mobile_node*_3 Sent Traffic FCAA and Default

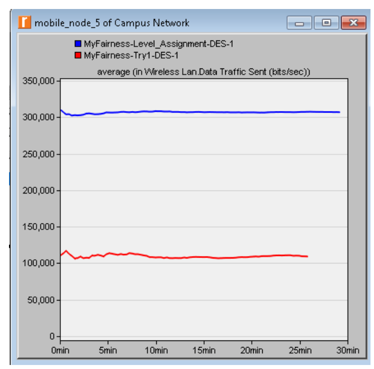

Fig. 14: *mobile_node*_5 Sent Traffic FCAA and Default

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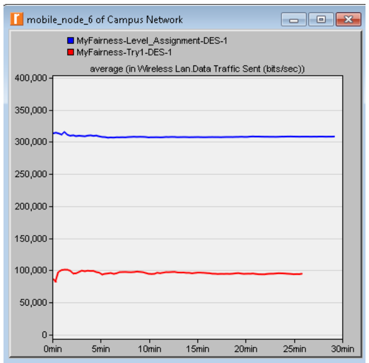

Fig. 15: *mobile_node_6* Sent Traffic FCAA and Default

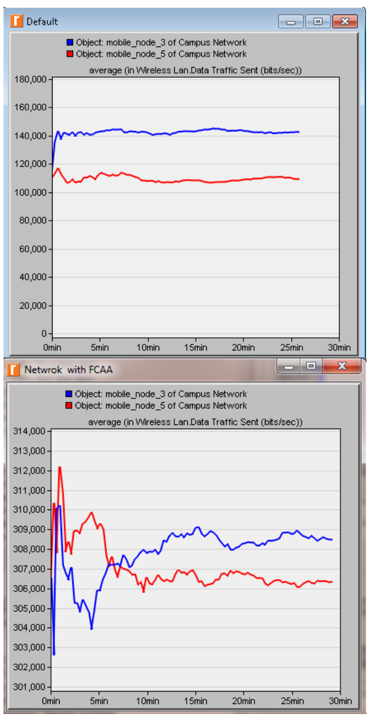

Fig. 16: *mobile_node_3* and *mobile_node_5* - Sent Traffic b/s. Default (top) and FCAA (bottom) Networks

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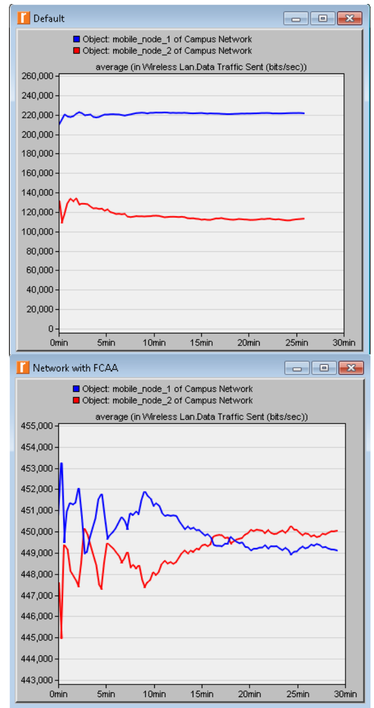

Fig. 17: *mobile_node_1* and *mobile_node_2* - Sent Traffic b/s. Default (top) and FCAA (bottom) Networks

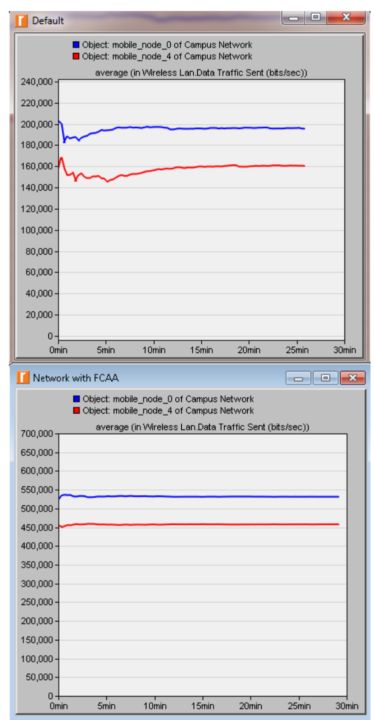

Fig. 18: *mobile_node_0* and *mobile_node_4* Sent Traffic b/s. Default (top) and FCAA (bottom) Networks