Traffic and interference aware channel assignment for multi-radio Wireless Mesh Networks

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1. Introduction

The proliferation of broadband wireless technologies, coupled with the development of smart devices and multimedia applications has brought us closer to realizing *network utopia* – a world of "smart, intercommunicating everything" [1]. The next generation of wireless communication systems are envisaged to provide high-speed, high-bandwidth ubiquitous connectivity to end-users through a *converged network* of different technologies, like third (3G) and fourth-generation (4G) mobile cellular systems, IEEE 802.11 (WiFi) based wireless local area networks (WLAN), and emerging broadband wireless technologies like IEEE 802.16 (WiMaX).

One of the key components of such *converged networks* is wireless mesh networks (WMNs), typically consisting of wireless mesh routers, equipped with one or more radio interfaces which communicate with each other and to an Internet gateway over multi-path wireless links. As elucidated in [2], WMNs have emerged as a promising candidate for extending the coverage of 'WiFi islands' and providing flexible, high-bandwidth wireless backhaul for converged networks. WMNs can provide significant advantages in deploying cost-efficient, highly flexible and reconfigurable backhaul connectivity over large areas. Incumbent with the inherent benefits of WMNs, specific challenges have also opened up, such as routing and topology deployment issues (see [3] for a survey).

The capacity provided by a mesh network has a significant impact on the overall performance. Current state-of-art mesh networks, using off-the-shelf 802.11 based network cards, are typically configured to operate on a single channel on a single radio. This configuration adversely affects the capacity of the mesh due to interference from adjacent nodes in the network, as identified in [3]. Various schemes have been proposed to address this capacity problem, based on modified medium access control (MAC) protocols adapted to WMNs [11], utilizing channel switching on a single radio [13][14], and the use of directional antennas [3]. While directional antennas and modified MAC protcols make practical deployment of such solutions infeasible over a wide scale, the main issue in using multiple channels with a single radio is that dynamic channel switching requires tight time synchronization between the nodes.

Equipping each node with multiple radios is a promising approach for improving the capacity of WMNs. First, the IEEE 802.11b/g and IEEE 802.11a standards respectively provide 3 and 12 non-overlapping frequency channels, which can be used simultaneously within a neighborhood leading to efficient spectrum utilization and increasing the effective bandwidth available to the network. Secondly, the availability of cheap, off-the-shelf commodity hardware also makes multi-radio solutions economically feasible.. Moreover, the spatio-temporal diversity of radios operating on different frequency with different sensing-to-hearing range, bandwidth, and fading characteristics can be leveraged to improve the capacity of the network.

Although multi-radio mesh nodes have the potential to significantly improve the performance of mesh networks, efficient channel assignment is a key issue in mitigating the adverse effects of interference from the limited number of channels available to the network. A WMN node needs to share a common channel with each of its communication range neighbors with which it wishes to set up a *virtual link* or connectivity (where a *virtual link* between two nodes is defined as a possible direct communication link between them). However, to reduce interference, a node should minimize the number of neighbors with whom to share a common channel. Therefore, there exists a trade-off between maximizing connectivity and minimizing interference as illustrated in **Fig. 1**. In this figure, the maximum connectivity that can be achieved is that shown in **Fig. 1(a)**. In both **Fig. 1(b)** and **(c)**, there are four available channels but only three can be assigned to the radios in **Fig. 1(b)** so that connectivity is maximized, while the four of them can be exploited simultaneously if the only goal was to minimize interference, as shown in **Fig.1(c)**.

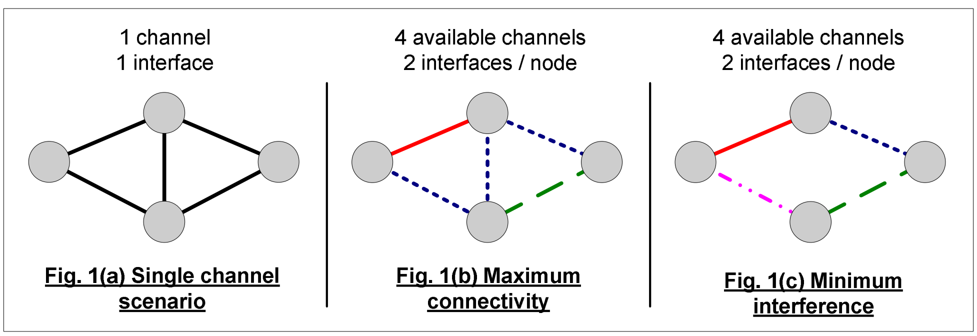

Fig. 1 – The trade-off between connectivity and interference

MesTiC is a static, centralized channel assignment scheme based on a ranking function that takes into account traffic, number of hops from the gateway and the number of interfaces per node. We present an overview of the performance of *MesTiC* in terms of network throughput on a comparative simulation platform.

2. *MesTiC: A Mesh* based *T*raffic and *i*nterfere aware *C*hannel assignment scheme

As elucidated earlier, the central goal of channel assignment for multi-radio mesh networks is to improve the aggregate throughput of the network, factoring in the effects of traffic and interference patterns, as well as maintaining topological connectivity. The problem of optimally assigning channels in an arbitrary mesh topology has been proven to be an NP- hard based on its mapping to a *graph-coloring* problem [4]. Therefore, many channel assignment schemes predominantly employ heuristic techniques to assign channels or *color* nodes in the network. Based on our observations on the impact of traffic pattern and network connectivity on the performance of a wireless mesh network, we propose below a novel technique, called *MesTiC*, having the following salient features:

- It is a fixed, rank based, polynomial time, greedy algorithm for centralized channel assignment, which visits every node once, thereby mitigating any *ripple effect* in channel assignment;
- The *rank* of each node is computed based on its link traffic characteristics, topological properties and number of network interface cards on a node;
- Topological connectivity is ensured by a common default channel deployed on a separate radio on each node which can also be used for network management purposes.

It may be mentioned here for completeness, that the algorithm has been designed for a mesh network with a single gateway node, but can be easily extended for cases with multiple gateways with minor modifications to the basic scheme.

2.1 Proposed Channel Assignment algorithm

The central idea behind *MesTiC* is to assign channels to the radios of a mesh node based on ranks assigned a priori to the nodes. The *rank, R,* of a node determines its priority in assigning channels to the links emanating from it. The rank encompasses the dynamics of channel assignment and is computed based on three factors:

a) The aggregate traffic at a node based on the traffic pattern of the mesh network which is computed as in [4].
b) The distance of the node, measured in the minimum number of hops from the gateway node.
c) The number of radio interfaces available on a node.

Note that the gateway node is assigned the highest rank as it is expected to carry the highest traffic. The rank *R*, for the rest of the nodes is given by:

$$Rank(node) = \frac{Aggregate\ Traffic(node)}{\min\ hops\ \ from\ the\ gateway\ (node) * number\ of\ \ radios\ (node)} \qquad (1)$$

Clearly, the aggregate traffic flowing through a mesh node has an impact on the channel assignment strategy. The rationale driving this observation stems from the fact that if a node relays more traffic, assigning it a channel of least interference will increase the network throughput. Thus, aggregate traffic in the numerator in Eqn. (1) increases the rank of a node with higher traffic. Also, due to the hierarchical nature of a mesh topology, the nodes which are nearer to the gateway should have higher preference (rank) in channel assignment as they are more likely to carry higher traffic. At the same time, the number of radios on a node gives flexibility in channel assignments and should inversely affect its priority (i.e., lower the number of radios, higher is the priority in channel assignment). The aggregate link traffic matrix is a key factor in computing the rank of the node. Such a measure is subject to temporal variability due to randomness of the wireless channel, routing protocols and application layer traffic profiles. We envisage traffic characterizations aggregated from a large number of network flows change over longer periods of time, wherein *MesTiC* can re-assign channels based on new traffic characteristics.

Once the rank of each node is computed, the algorithm traverses the mesh network in the decreasing order of R, assigning channels to the radios. **Fig. 2** presents the pseudo-codes of *MesTiC* which begins with a set of input parameters. In line 2, the connectivity graph represents an undirected graph where a pair of nodes has a link between them if they are located within the transmission range of each other. Line 3 refers to the aggregate link traffic matrix between nodes within transmission range. The multi-radio conflict graph [10], which represents the potential interference between the multi-radio links in the connectivity graph based on the interference model of the network, is input in the algorithm in line 4. Based on these inputs, the rank R of each node is computed in line 8. The main channel assignment steps are described in lines 13-51. While visiting a node and its radios, the algorithm assigns channels to its links in the order of decreasing aggregate link traffic, thus trying to minimize the potential interference as computed on the basis of the multi-radio conflict graph.

Let us illustrate the working principle of *MesTiC* by considering a simple example shown in **Fig. 3(a)** where the input connectivity graph and estimated link traffics are shown. Also, the network is configured with 3 channels and 2 interfaces per node. Assuming node **b** to be the gateway node, the rank of the remaining nodes, in decreasing order, are **d**, **a**, **c**. The algorithm starts by visiting node **b** first, assigning channel **C1** to the link between **b-a** (which carries the highest traffic of 120), and then moves on to assign channel **C2** to the link **b-d**. Now, while assigning a channel to link **b-c**, it has a choice between **C1** and **C2**. However, as **C1** carries more traffic than **C2**, it assigns **C2** to link **b-c**. Similarly, at node **d**, it assigns a previously unassigned channel **C3** to the link **d-c,** and as **C3** carries less traffic than **C2** (90 + 80 =170) **or** C1 (120), it assigns **C3** to the link **d-a**. The algorithm proceeds until all links and radios are assigned channels as shown in **Fig. 3(b)**.

```
Input:
-     Connectivity graph
-     Traffic matrix
-     Multi-radio conflict graph
-     Number of radios at every node
-     Number of non-overlapping channels

Ranking function:

Output:
      The assignment of channels to radios

Pseudo-code:
/* MesTiC visits every node based on its rank, the higher the Rank, the earlier a node is visited */
For each node V in the Rank order
/* For every link in the connectivity graph a channel has to be assigned to the link between the two nodes which both have a radio assigned a common channel */
For each unassigned incident link (V,W)
          If both V and W have a radio with a common channel C
                Assign C to link (V,W)
                Update the interference matrix
/* Now for every link not assigned a channel yet, MeTtiC will pick the link estimated to carry higher traffic first */
While V has an unassigned incident link
          Pick a neighbor W with whom V has the highest traffic in the Traffic matrix
/* If the visited node V has a radio still uncolored then its radio is either assigned a least used channel among those previously assigned to its neighbor W  if W has assigned all its radios. If not, both V's and W's unassigned radio are assigned the least used channel in the vicinity*/
          If V has an unassigned radio
                If W has all its radios assigned
                      Pick the least used channel C among those assigned to the radios at W
                      Assign C to a radio at V
                      Assign C to the link (V,W)
                      Update the interference matrix
                Else if W still has an unassigned radio
                      Pick the least used channel C within the vicinity
                      Assign C to a radio at V
                      Assign C to a radio at W
                      Assign C to the link (V,W)
                      Update the interference matrix
/* Similarly If all V's radios are already assigned a channel and W still has an unassigned radio, then W is assigned from among the radios already assigned to V */
          Else if V has all its radios assigned
                If a radio at W is still unassigned
                      Pick the least used channel C among those assigned to the radios at V
                      Assign C to a radio at W
                      Assign C to the link (V,W)
                      Update the interference matrix
/* Note that If the radios of both V and W are all assigned channels then MesTiC will not do anything because connectivity is already ensured with a radio dedicated to a common channel*/

For each node V in the network
     For each unassigned radio
          Pick a neighbor W with whom V has the highest traffic in the Traffic matrix
          Pick the least used channel C among those assigned to the radios at W
          Assign C to a radio at V
          Assign C to the link (V,W)
          Update the interference matrix
```

Fig. 2 The *MesTiC* algorithm

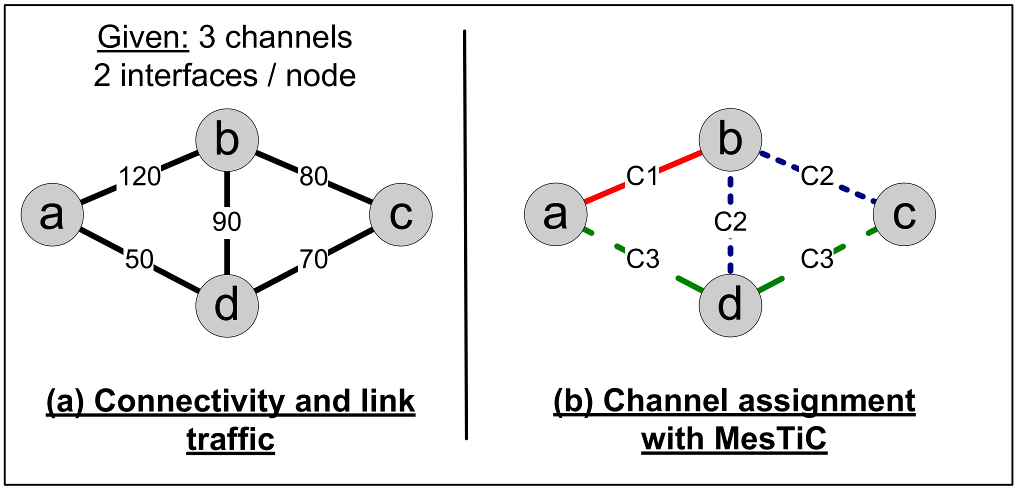

Fig. 3 – Example illustrating how MesTiC works

In this manner, *MesTiC* assigns channels to the radio interfaces of the nodes in a wireless mesh network, while the connectivity of the network is ensured through a default radio on a separate channel. The cost dynamics of 802.11 based hardware and the availability of 12 non-overlapping channels in the IEEE 802.11 standard make a default connectivity scheme feasible under current scenarios for community mesh networks.

3. Performance Study

In this section, we study the performance of the proposed channel assignment scheme, *MesTiC,* in terms of overall throughput on a wireless mesh network. We present the details of the simulation platform and comparison results with the traffic-aware centralized scheme based on the *Hyacinth architecture* [9], C-HYA.

3.1 Simulation Platform

In order to build a common platform for comparative study, we developed our simulation on a modified version of the ns2 software, which incorporates support for multiple wireless radios and configurable routing protocols such as dynamic source routing (DSR) and ad-hoc on demand distance vector routing (AODV). The simulation experiments were performed on a 5 X 5 grid topology[1] where each node could potentially communicate with 4 neighbors, with randomly generated traffic profile, the traffic between any ingress-egress pair being chosen between 0-3 Mbps. Ns2 was configured to emulate the traffic profile by running constant bit rate (CBR) UDP-flows between the ingress-egress node pairs. The conflict graph was created based on interference-to-communication ratio set to 2, and the experiments reported in this paper were performed

[1] Although experiments can be conducted on larger networks, we report on a 25 node mesh network as community mesh networks are envisaged to contain typically 25-30 mesh routers unlike cellular systems where over 100 cell-sites are deployed in a coverage area.

based on the DSR routing protocol. As mentioned earlier, the centralized CA scheme based on *Hyacinth* architecture (C-HYA), accounts for the link traffic matrix in their channel assignment algorithm. Moreover, their simulation analysis is based on a similar ns-2 based platform with similar settings. Thus, in this paper we report our experimental results based on comparisons performed against C-HYA. However, our simulation platform can be easily extended to incorporate different routing and channel assignment schemes for mesh networks.

3.2 Experimental Results

The WMN was simulated on ns-2 with the number of radios on each node set to 3, with 12 non-overlapping channels. The simulation was performed for 100 secs for a given set of traffic profile and ns-2 was configured to report the aggregate throughput obtained in the network as well as the number of active flows. The experiments were conducted on the mesh network topology with channel assignments generated by *MesTiC*, and repeated for the channel assignments generated by C-HYA. **Fig. 4** reports the dynamics of the network in terms of aggregate throughput and active flows.
As observed from **Fig. 4,** the simulation stabilizes around 40 secs from start of simulation run after which *MesTiC* reports a sustained higher aggregate throughput for the mesh network.

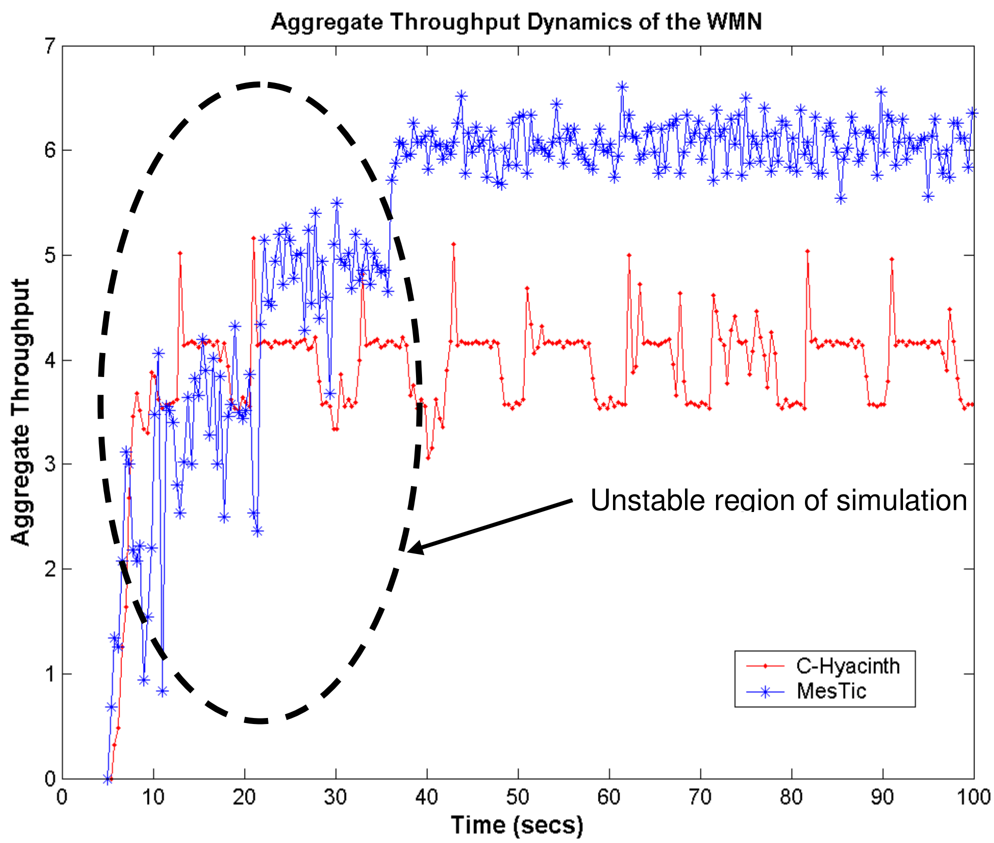

Fig. 4 – Aggregate throughput dynamics of *MesTiC* vs. C-HYA

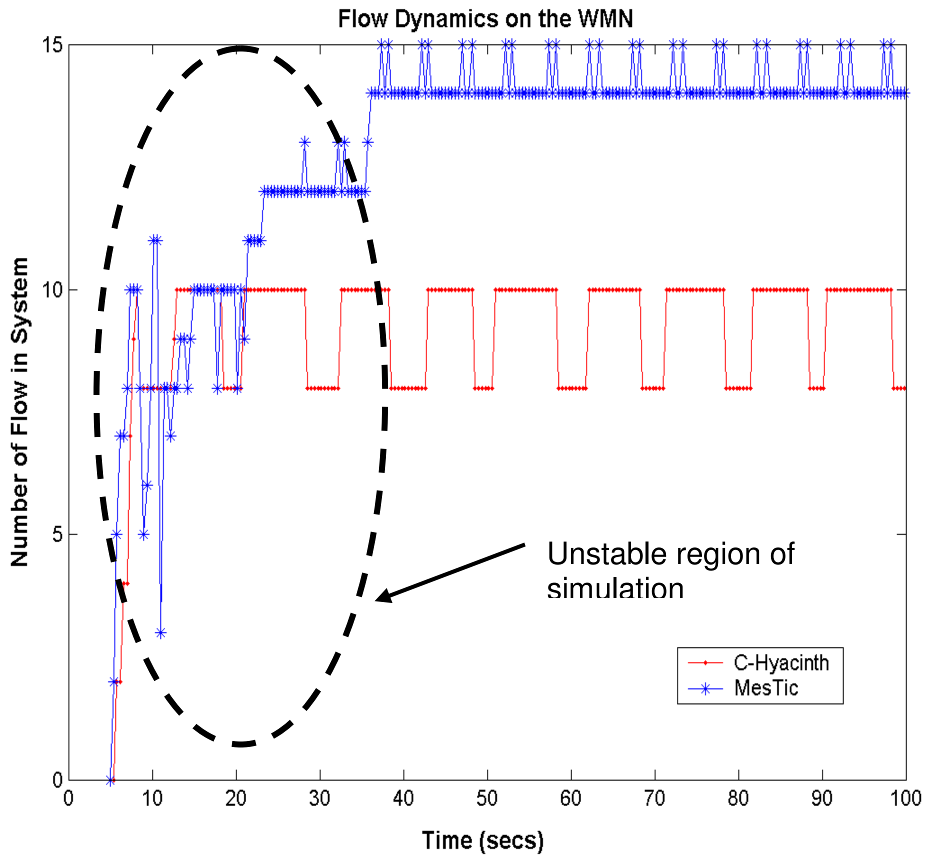

Fig. 5 – Flow dynamics of *MesTiC* vs. C-HYA

Similarly, at the stable region, *MesTiC* supports larger number of active flows in the system, with an average value of 14 flows against an average of 9 flows in C-HYA, as seen from **Fig. 5**. Based on these observations, we conclude that *MesTiC* gives significant improvement in aggregate throughput over C-HYA while sustaining more than 1.5 times the number of active flows in the network.

In another experiment, we have measured throughput for different network topologies for both MesTiC and Hyacinth as illustrated in **Fig. 7**. We observe that for seven different topologies MesTiC outperforms Hyacinth sometimes very significantly as in topology number 6 (5 times higher throughput).

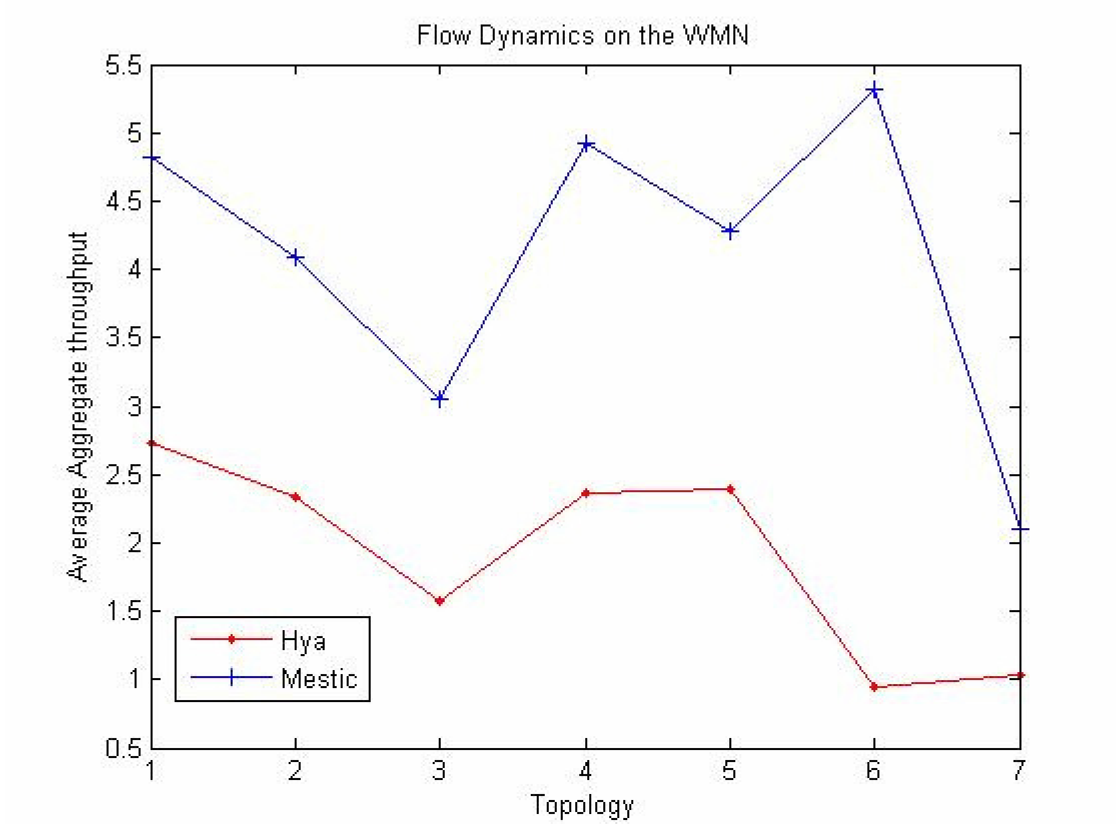

Fig. 7 – Aggregate throughput versus network topologies – comparison between *MesTiC* and Hyacinth

Note that although the simulation experiments were performed with 3 radios per node, *MesTiC* essentially operates its channel assignment scheme on 2 radios, with the third one configured on a default channel for connectivity. Thus, even with a lower degree of freedom in terms of radio flexibility, *MesTiC* was able to improve the overall network performance in terms of aggregate throughput.

4. Conclusion

In this paper, we have analyzed the key challenges associated with assigning channels to radio interfaces in a multi-radio wireless mesh network. After presenting a taxonomy of channel assignment schemes, we have developed a novel CA algorithm, *MesTiC*, that incorporates traffic pattern and network topology in ranking the nodes for channel assignment. Since the problem of defining optimal routes in a mesh network is closely coupled with the channel assignment scheme, we are currently studying the impact of channel assignment schemes on the performance of the routing protocols on wireless mesh networks.

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