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# A novel interface selection scheme for multi-interface wireless mesh networks

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***Abstract*—Wireless mesh networks suffer of scalability problems when the number of nodes grows. To solve this issue, multi-interface wireless mesh networks were introduced. In such networks it is possible to use multiple channels to implement spatial reuse of frequencies. However, channel assignment schemes make this kind of networks complex to manage and limit their applicability in presence of mobile nodes. In this paper a novel technique is introduced for the optimization of resources allocation in a multi-interface wireless mesh network where channel assignment is fixed. With this technique the scalability of the network is improved and the support for mobility is easily granted.**

## I. INTRODUCTION

Recently IEEE 802.11 mesh networks have been an active field of research. In such networks a coordinator is not required and the network intelligence is spread on every single node. This feature produces some interesting consequences such as: high reliability, easy network maintenance, fast reconfiguration and coverage extension. These characteristics can be extremely useful to offer connectivity in infrastructureless zones or situations in which the coverage is needed for a short period of time (i.e. incident area networks and ad-hoc networks).

On the other hand the performance of a mesh network suffer of scalability limits. A transmitting node must share the radio resources with all the other devices in its proximity. It has been shown that the performance of a single link of a mesh network decreases drastically with the number of nodes that form the network [1].

In order to improve network performance, several proposals have been developed based on multi-radio approach in which devices forming the mesh are equipped with more than one interface. These solutions offer a huge throughput improvement but, as a consequence, they increase the complexity due to the need of a policy to decide channel assignment (CA). A very effective approach, that allows a good improvement in terms of throughput, is to assign channels in advance in order to reduce interference between adjacent nodes and maximize spatial reuse of frequencies. While this policy has been widely adopted in the past for cellular networks it is very difficult to apply in absence of a centralized infrastructure. In particular a few issues arise:

- the problem of assigning frequencies to the links of a mesh network can be described as a variant of the well-known graph coloring problem [2]. The algorithms to solve this problem are np-hard so that with a limited number of devices and orthogonal channels available, it is extremely hard to find a distributed way of solving it.
- If the interfaces are distributed over different channels, a node can reach only a subset of its neighbors depending on how many common channels their interfaces are tuned to. The degree of the graph representing the network decreases so the failure of a link can make a node unreachable, or a piece of the network disconnected.
- Given an initial channel assignment state, upon a link failure or topology change, a reconfiguration is needed which may propagate to links far from the failed one. In general there is no guarantee that a re-configuration to an equally efficient state will need less effort than the first assignment.

If the nodes support mobility, the network will be constantly reconfiguring the channel assignment scheme so that the second and third issue outlined become an important limitation. Moreover to keep connectivity roaming nodes should have at least a common channel to discover each other.

In this paper we present an algorithm that performs a packet-based interface selection that supports mobility. In our scenario interfaces are assigned statically for each node, i.e. if every node has three radio interfaces they will be statically tuned on the same channel (i.e. 1,6,11 in IEEE 802.11) for each node. In practice we have a three-layer mesh network that makes the network always connected and needs no reconfiguration. In this paper we will characterize this kind of network and we will introduce a packet-based policy to perform device selection. We will show that such a policy do not just multiplies the total capacity of the network by a factor of 3, as expected, but strongly improves scalability still allowing node mobility.

## II. MULTI-INTERFACE WMN

Single-interface wireless mesh networks performances are limited by interference, each transmitting node interferes with all its neighbors and, before transmitting, has to contend the resource with a number of nodes that can be huge in a dense network. If devices are equipped with 802.11 interfaces, the access is granted by a CSMA/CA which provides poor performance in presence of hidden terminals, exposed terminals and high interference. Consequently, link capacity may decrease linearly with the number of interfering nodes [3].

The idea of spatial reuse is that several nodes can transmit simultaneously without a collision if they don't use the same channel. This is possible thanks to multiple orthogonal channels available with IEEE 802.11 as shown in 1.

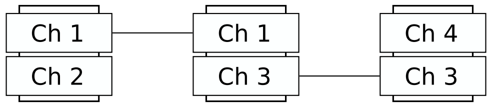


Figure 1. spatial reuse example: each node is equipped with two interfaces tuned to different channels

The problem of assigning channels to a mesh network maximizing frequency reuse and minimizing interference can be approximated as a particular case of a graph coloring problem. These families of problems have been shown to be np-hard (see [2]) so that in large networks made of tens of nodes it is extremely difficult to find an optimal solution. This is even harder if the problem must be resolved in a distributed environment without a central authority. Two more issues arise: the first is that at each change of the network the problem must be solved again (note that changing a single link could produce a completely different configuration). For this reason it seems unlikely to use such an approach in a network with mobile hosts, that is constantly changing its topology.

The second is the relationship between channel assignment and routing. If a node can not communicate with all its neighbors because it does not share a channel with all of them, the mesh is not completely connected and the average length of end-to-end routes is higher. Longer routes produce more traffic in the network and partially lower the advantages given by multiple interfaces.

To simplify network management, hybrid solutions have been proposed with devices sharing a common channel. Additional radios are used to achieve spatial reuse [4]; this approach avoids connectivity problems, but complexity remains.

The approach introduced in this paper is to assign the channels statically to each interface, with the same assignment for each node, as represented in fig. 2. Hence the network is made up of a three-layer mesh network, connectivity is guaranteed even with mobility and there is no reconfiguration. Each time a node has to transmit a frame to a neighbor it will choose on which interface. The contribution given by this paper is to introduce an efficient policy of interface selection; the rest of the paper will show that using a random selection the network scales exactly as a single interface mesh, but with the proposed algorithm the performance can be greatly improved.

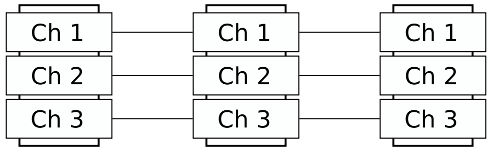


Figure 2. static channel assignment example

## III. Previous Works

Many schemes have been proposed to manage multiple interfaces for performance improvement in wireless networks. These papers can be ideally divided in 2 classes: the first considers the joint problem of channel assignment and routing, the second treats the two problems separately. Given a network topology and the traffic patterns between couples of nodes, channel assignment and routing both influence the performance of the network. Joint channel assignment and routing (as in [5] [6] [7]) gives the best throughput improvement, but on the other hand requires a high complexity. Such a strategy can be subject to continuous updates, since CA depends on the traffic patterns which are variable. All these works propose an algorithm to find the best CA according to a given metric that takes into account flow distribution. For example [7] defines a metric, *CCM*, that takes into account both interference due to hidden terminals and channel utilization; variations to the traffic patterns imply an update of the metric and subsequent reorganization.

If CA is performed separately from routing, as in [2] [8] [4] channel assignment isn't routing dependent, hence complexity can be reduced. In [2] the authors develop a distributed CA algorithm, called *SAFE*, that avoids partitioning through the usage of a skeleton links system that grants at least minimal connection for all nodes in the network. Skeleton connections must be decided *a priori* with the knowledge of the whole network topology, such a requirement is not compatible with mesh networks architecture. The authors suggest that SAFE could work properly even in mobility conditions with marginal penalties, but this topic is not deeply inspected. In [4] the authors use a hybrid scheme where a fixed channel is used to receive data and switching interfaces to send data to neighbors. This scheme is mostly aimed to static wireless mesh networks, tha same stands for [8].

If the considered scenario is a mobile wireless mesh network, the conditions are significantly different. Topology changes are frequent, so that frequent re-organization will impact the overall performance. Moreover, solutions in which nodes do not share a common channel are difficult to port to mobility scenarios. Since there is no direct way to send a broadcast *hello* frame that will be received by all neighbors, it is hard to discover topology changes and avoid network partitions.

Lastly, an intrinsic limit of any frequency-reuse scheme is that non-overlapping channels are limited to 3 and 12 respectively for 2,4 and 5 GHz spectrum for IEEE 802.11, which limits its applicability in dense networks.

Our contribution is focused on a solution that will be easily applicable to mobile wireless mesh networks, using a different approach from the ones present in literature.

## IV. Random interface selection

In a three-layer mesh network as the one in figure 2 each time a packet has to be forwarded, the routing layer will choose the node that will be the next-hop. Due to the presence of multiple links to every neighbor, a channel selection strategy will chose one among the available interfaces. Our final goal is to improve network performance studying an effective interface selection strategy. We define a switching vector $P_i = (p_i(1), p_i(2), p_i(3), ..., p_i(N))$, where $\sum_{j=1}^{N} p_i(j) = 1$ for each node *i* in the network. Given the next hop *i* will choose one of its interfaces following the probability distribution given by $P_i$ where $N$ is the total number of interfaces it owns. Many policies can be studied to define the switching vector. In this paper we will introduce one that allows reservation of resources to most congested nodes that behave as bottlenecks.

A basic interface selection policy is random choice, the probability vector will be the same for all nodes $P_i = (1/N, 1/N, ..., 1/N))$. Since there is no standard approach to the management of a multi-layer mesh network and schemes present in literature do not focus on mobility, this approach will be used as a basic meter to evaluate RAMEN performance.

The first simulations have been performed using one, two and three interfaces for each node with a 4x4 static grid topology. Distance between nodes is 150 meters, each device can only communicate with adjacent nodes inside its transmission range. Routing is based on a geographic shortest path algorithm. Simulations have been performed also with a more dense network (the distance between nodes set to 100m), since results are perfectly compatible we omit to report them for brevity.

Traffic is made up of UDP flows at constant bit rate (64 Kbps and framesize = 1280 bit). Given a number of traffic flows, 20 simulations have been performed with random source, destination and start time. The simulations have been performed on OMNet++ simulation environment with INET framework.

Figure 3 reports the sum of the average throughput of every traffic flow, when all the flows are active. It's possible to evince that maximum throughput increases approximately linearly with the number of available interfaces. Basically the network behaves as the sum of multiple overlapped and independent sub-networks. As we can qualitatively appreciate in figure 4, showing the number of packets lost by each terminal, central nodes have a higher packets loss compared to the others. Packets are discarded because the output queue is full or the maximum number of retry is reached. This is due to two factors, the first is that central nodes have a larger set of neighbors, so they suffer of a higher interference. The second is that the simple geographic distance vector routing chosen overloads central nodes. It must be noted that another routing algorithm based on another metric might have produced less concentration of traffic but also longer routes, thus increasing interference and contributing to the first factor. Our aim is to keep the benefit of a shortest path algorithm and introduce a strategy to reserve a larger amount of resources to overloaded nodes in order to reduce packets losses gap with external devices. In particular, we aim at improving performances in the saturation region, to make the network more scalable. Note also that the strategy introduced in next chapter is independent by routing, so it could be paired also with a link-state algorithm.

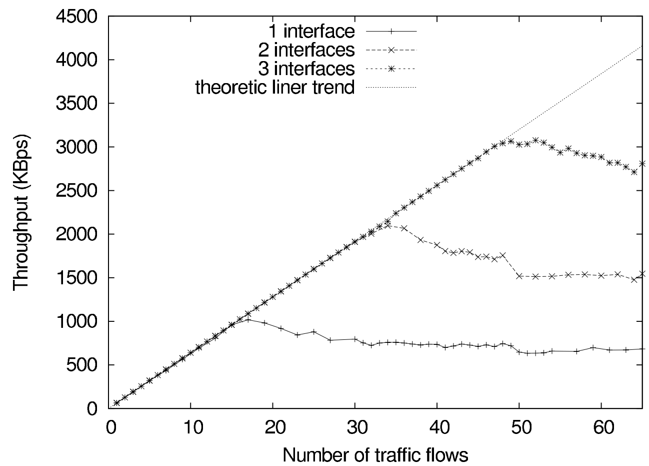


Figure 3. Throughput with multiple interfaces

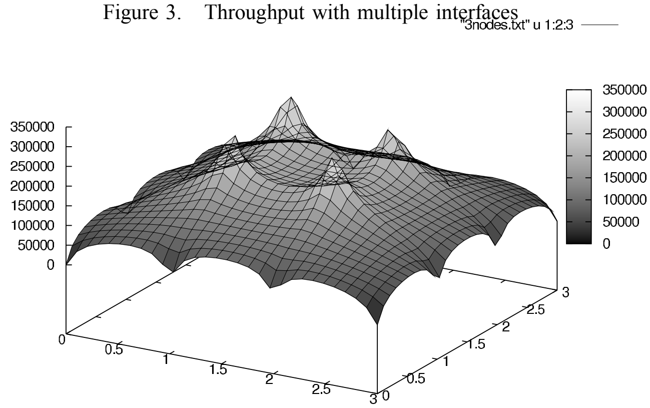


Figure 4. Packet loss distribution

## V. RAMEN

In the previous chapter we have described how central nodes need a larger amount of resources in order to manage their data traffic. To achieve this aim we have developed a distributed algorithm called *RAMEN* (Resource Allocation for MEsh Networks). The main idea behind the proposed algorithm is to reserve more resources to nodes routing a large amount of data. Each node has been equipped with 3 radio interfaces, tuned on three different channels. Only the most heavy-loaded ones will be able to transmit on all interfaces, while other nodes will be able to use a number of channels proportional to their managed data traffic. To determine how many interfaces a device can get it must be informed about the amount of traffic each neighbor manages in order to estimate its load factor compared to its interfering neighbors. In our scenario, traffic is made up of constant bit rate flows, hence, to determine the amount of traffic that crosses each node it's enough to count the number of flows that cross every node. Nodes transmit a broadcast message containing this information that each neighbor receives and stores. In the next part of this paper we will refer to this number as $\alpha$. In a more general scenario where traffic flows are not CBR, $\alpha$ could be generalized using a more complex metric, as the one defined in [9]. Once each node knows $\alpha$ for all of its neighbors, it will chose the number of available interfaces by computing the parameter B:

$$B = \alpha * \frac{N-1}{max_\alpha - 1} + \frac{max_\alpha - N}{max_\alpha - 1} \quad (1)$$

where $N$ is the maximum number of interfaces and $max_\alpha$ the highest value of $\alpha$ received from the neighbors. B must assume positive values, then the constraint $max_\alpha \geq N$ must be respected. Using $\alpha$ as defined before (number of flows that cross every node), it's needed to have more than $N$ flows that cross the most charged node; the constraint is easily accomplished in our scenario, anyway it can be respected in all conditions changing $\alpha$ definition.

In practice, $B$ is an integer representing the number of available interfaces with a linear assignment scheme. Each node can transmit on a number of interfaces proportional to its own $\alpha$ from a minimum of 1 interface to the maximum of N. The most loaded nodes (considering a scale that includes all the neighbors) for which $\alpha = max_\alpha$ will use all three interfaces, nodes with $2 \leq B < 3$ will use only two interfaces and the remaining nodes only one.

The rationale behind this strategy is that nodes in the peripheral regions need less resources then central nodes and will be assigned only one interface to transmit, while receiving on any. This way the interference domain for the central nodes is reduced and the peaks in figure 4 are smoothed. Note that this strategy is particularly suited for a shortest path algorith, since the central nodes are overloaded. Since a high number of paths pass through this bottleneck, it is the main limit to the capacity of the network. Note also that with a different routing algorithm, but with the same topology, this situation would proabably persist. This is due to the fact that even if the routes do not cross the central nodes, the peripheral nodes interfere in any case with the central ones.

Once determined how many interfaces to use, which interface to use is another important factor. This choice should be made in order to spread all the traffic uniformly on every channel, but that's very hard to achieve since nodes do not have a global view of the network. The easiest strategy, that has been chosen, is to use random assignment, but we believe there is room for improvement in this area.

Figure 5 shows the throughput achievable by RAMEN algorithm compared to random interface selection; each set of simulations has been repeated with both RAMEN and random assignment. It can be seen that:

- the maximum throughput is increased
- the behaviour of the network under saturation is consistently improved. When the network is routing 65 connections the performance is improved of almost 15%

Packets loss distribution is spread more uniformly through the network since the variance is lowered to 60% with RAMEN. As wanted, the redistribution of packet loss reduces the bottleneck effect into the central nodes and the network scales better then a three-layer mesh network. This is due to the fact that without RAMEN, the performance of each connection are extremely variable, a few of them hardly transmit and a few other maintain their performance, depending on the path over the network. With RAMEN the performance of each connections degrades more gently and fairly. It can be noted that before saturation RAMEN performance is lightly lower then random choice. This is due to the fact that in that phase network capacity is sufficient so there is no real need for resource limitations. This suggests the introduction of a hybrid scheme, that will be a topic of future research.

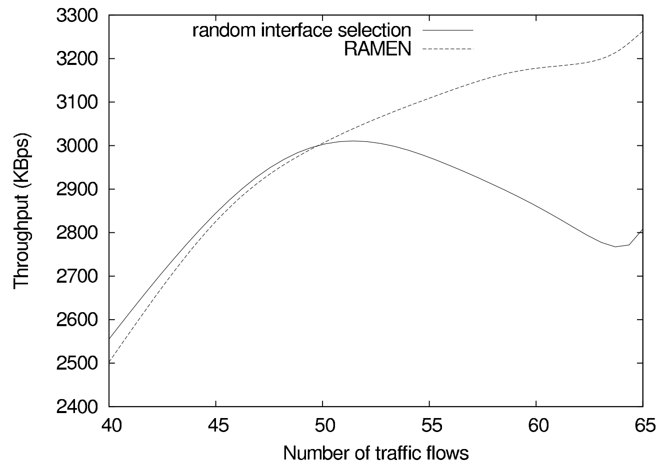


Figure 5. Throughput with three interfaces in a 4x4 grid with 150 meters distance; RAMEN compared to random selection

Another positive effect is that a more fair resource allocation strongly reduces mean end-to-end delay, as shown in figure 6; the use of RAMEN permits to reduce delay in saturation condition by almost 40%. Additionally the number of actives flows (flows that have a non zero end-to-end throughput) is appreciably improved and it increases with an increased data load, as shown in figure 7.

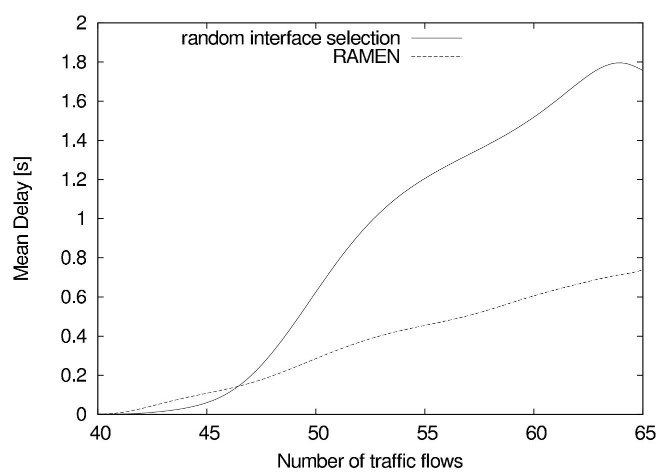


Figure 6. Mean delay in a 4x4 grid with 150 meters distance; RAMEN compared to random selection

Simulations have been performed also with mobile nodes. The core of 4 central nodes have been kept stable to guarantee network connectivity, while the other 12 roam with a random

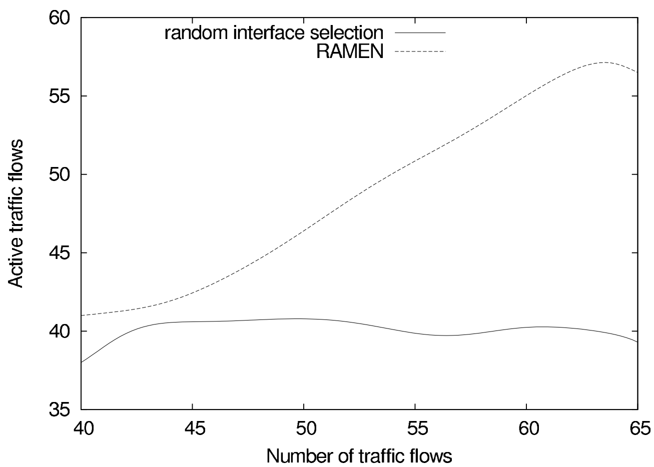


Figure 7. Number of active flows in a 4x4 grid with 150 meters distance; RAMEN compared to random selection

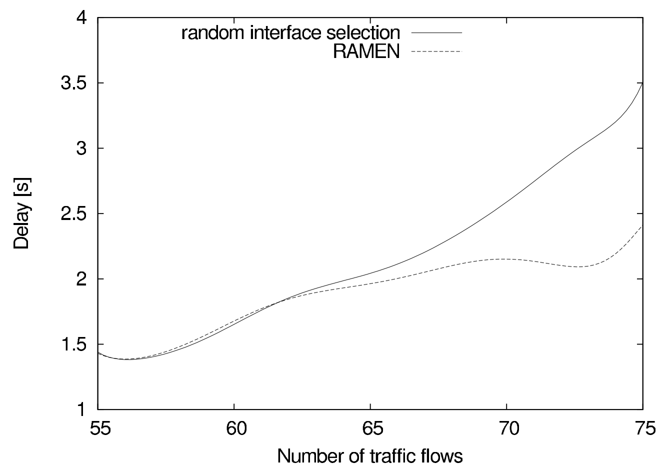


Figure 9. Mean delay with multiple interfaces in mobility scenario; RAMEN compared to random selection

way-point model and constant speed (1 m/s). With mobility, where any channel allocation scheme encounters difficulties, RAMEN performs smoothly and produces a significant gain over random choice; maximum saturation throughput is increased by 11% (figure 8).

This positive results shows that our approach is topology independent. Every node decides resources allocation basing its decision only on local information, that is enough since it is concentrated in its own collision domain. More simulations performed with different speed (2,5 m/s) did not produce relevant changes to the performance of the algorithm. Even mean end-to-end delay measurements are fully compatible with the static scenario and the gain with RAMEN is still about 40% in saturation (figure 9).

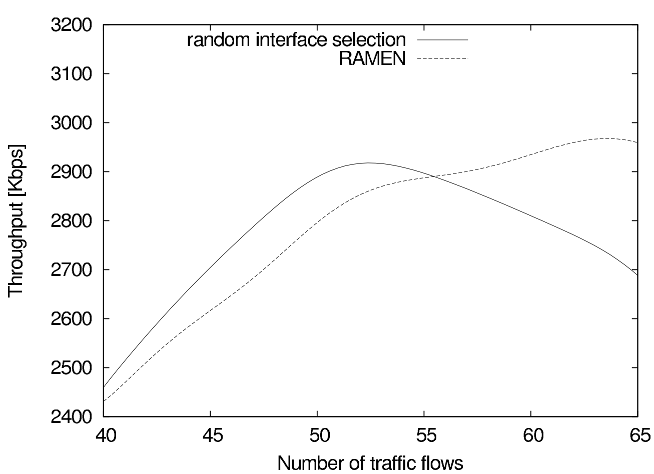


Figure 8. Throughput with multiple interfaces in mobility scenario; RAMEN compared to random selection

## VI. Conclusions

In this paper it has been introduced a model of multi-interface wireless mesh network that greatly enhances the scalability of a 802.11 wireless mesh network. The protocol used produces a lightweight resource allocation scheme that makes the network more stable, fair, and performant under heavy loads. The simplicity of the scheme make it applicable to mobile wireless mesh networks, where all the channel allocation schemes analyzed in literature are hardly usable.

There is large room for improvements, our focus will be concentrated into non-linear allocation schemes, non-random channel selection and the introduction of more complex $\alpha$ metrics.

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