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Interaction between P2P, Channel Assignment and Routing in Wireless Mesh Networks

Case Study Final Report

*Abstract***—Wireless mesh networks are an emerging paradigm for future broadband wireless access networks, with many application areas ranging from content distribution over community networking and providing backhaul networking for sensor devices. In wireless mesh networks, clients connect to wireless routers which are equipped with one or more wireless cards and relay the packets over the wireless links towards internet gateways or the destination. Peer-to-Peer applications are an important class of applications which contributes nowadays to the majority of internet traffic. Therefore, it is important to provide high capacity in the mesh network to support them. However, the capacity of wireless mesh networks depends on many factors such as network topology and size, traffic volume and pattern, interfaces per node and channel assignment scheme used, modulation schemes, routing approaches, etc. In this paper, we develop an analytical framework which allows to estimate the achievable capacity of a wireless mesh network when peer-to-peer applications download many flows simultaneously. The model is based on the collision domain concept and incorporates various channel assignment, replication and peer selection strategies. We investigate the achievable capacity for various scenarios and study the impact of different parameters such as the number of channels or radios used.**

I. INTRODUCTION

Wireless mesh networks (WMNs) provide a low cost and easy to deploy solution to build broadband wireless access networks, thereby ensuring connectivity to remote locations. WMNs consist of a backbone of quasi-stationary mesh routers forming a multi-hop wireless networks, in which mesh routers wirelessly relay traffic on behalf of others. Typical application scenarios are community networks, city networks, public safety or the extension of WLAN hotspots. Currently, mesh routers have been equipped with multiple radios, which allow sending and receiving on multiple frequency bands in parallel and consequently increase network capacity.

P2P (Peer-to-Peer) networking represents the next frontier to wireless communication, as wireless users might expect to use the same services which are already available on the Internet, like P2P multimedia resource sharing. Therefore, a deploying P2P networks over WMNs represents exciting possibilities, but at the same time several challenges need to be investigated. In P2P scenarios, typically network capacity is assumed to be quasi unlimited while having always connectivity. Those assumptions make resource sharing in wireless scenarios a challenging task as wireless links suffer from environment noise and interference problems. Such problems are even greater in WMNs, as adjacent hops on the same path and neighboring paths can cause additional interference to each other. As a consequence, the capacity in a mesh network is limited and depends on many factors such as the location of the node, network topology and size, traffic volume and pattern, interfaces per node and channel assignment scheme used, modulation schemes, routing approaches, etc.

Content replication has been an effective approach for reducing the overhead and increasing the accessibility and performance in distributed systems. When deploying P2P overlay networks over WMNs, the replication of an object (such as a specific content, e.g. “movie”, “music file” or a service that is in digital format), can reduce communication overhead as the peers requesting such object (*requester peer*s) can retrieve it from *a set of* replicated candidates (*source peers*) and not just from a single entity. Such multiple paths to different replicas allows effective load-balancing and, combined with multiple radios and channels a significant increase in capacity. In order to make a decision about the *best source peer* to be selected, important issues such as channel assignment and routing in WMNs need to be considered but also questions regarding *where to put the replicas* need to be considered.

Peer selection, routing and channel assignment are not independent problems. To solve the peer selection problem requires the knowledge of the routing and the end-to-end available bandwidth between the peers. Changing the peer selection will result in different load in the network which might require a different channel assignment or routing. The available end-to-end bandwidth depends on the selected routing and channel assignment strategy. In addition, solving the routing problem requires also a solution for the channel assignment, as the channel assignment algorithm determines the set of links sharing the same channel and accordingly their available link bandwidth. In the same way, solving the channel assignment requires the flow rate expected on the network links, which is determined by the routing. Thus, peer selection, routing and channel assignment are closely inter-dependent problems that must be jointly solved.

In this paper we evaluate the inter-dependency of peer selection, replica placement, routing and channel assignment approaches for multi-channel multi-radio mesh networks. The contribution of this paper is a set of numerical models, which allow to estimate available capacity for a given peer selection, channel assignment and routing approach based on the collision domain concept. While such collision domain model has been applied before to estimate achievable capacity in a mesh network (e.g. [1]) this work is the first attempt to extend this concept to include peer selection and replication strategies for multi-channel multi-radio WMNs. Based on four peer selection schemes, two channel assignment algorithms and two replication strategies, we study achievable throughput and fairness and analyze the benefit of increasing the number of channels and radios.

The rest of this paper is structured as follows. In Section II we give an overview on the related work. In Section III, we present our system model and problem formulation. Section IV describes routing and channel assignment strategies used in this work. Section V presents the problem formulation and models used for peer selection. Numerical results are presented in section VI and the paper concludes in section VII.

II. RELATED WORK

A variety of algorithms and solutions for WMNs have been proposed under the scope of optimization problems, ranging from gateway placement [2] to multi-layer joint optimization techniques [3], [4], [5], [6]. A joint channel assignment and routing is studied in [4], where the goal is to assign channels that lead to minimum interference and contention based on expected load information on each link. Using genetic algorithms, [5] also focuses on channel assignment and routing problems in order to achieve a max-min fair throughput allocation. [7] can be considered quite related to this work, where a linear programing model is used to calculate the aggregated throughput for P2P services over WMNs. Differently from [7], which considers only single radio approaches and assumes a perfect scheduling-based MAC using TDMA, in our work we model the network using the more realistic collision domain concept where channel access is shared among mobile routers on a given channel. In addition to that, we also study the interaction between peer selection, routing and channel assignment in terms of throughput and fairness while using multiple channels and multiple radios.

III. SYSTEM MODEL AND CAPACITY FORMULATION

In this section we present our system model and discuss several considerations we have made in order to study the peer selection and replica placement in conjunction with channel assignment and routing.

A. System Model

We consider multi-channel multi-radio WMNs composed of quasi-stationary wireless mesh routers that provides connectivity to mobile clients within their coverage range. The wireless mesh routers form a multi-hop mesh network among themselves in order to relay traffic to and from mobile clients. Some of the wireless mesh routers can serve as gateways between the WMN and the Internet. The wireless routers are equipped with multiple network interface cards, which are tuned to a particular radio channel for a relatively long period of time (e.g. several minutes or hours). We assume that a channel assignment algorithm determines which radio is tuned to what channel. For two nodes to communicate, they need to share a common channel.

We model the WMN as an undirected graph $G = (V, E)$, where *V* represents the nodes i.e. mesh routers and *E* denotes the set of edges $e = \{i, j\} \in E$ which are the links between nodes i and j such that i and j are within the transmission range of each other and there is at least one common channel to both. A link $l \in L$ is represented by $l = (e \in E, c)$ to indicate that nodes of link *e* can communicate using channel *c*. Each node is assumed to have *k* network interface cards (NICs) and *c* available channels. The channel assignment algorithm allocates channels to radio interfaces of each node, and it is represented by the matrix *X* of the form $X\,(n, k) = c$ to indicate that node *n*'s k^{th}interface is transmitting using channel *c*. Obviously, *L* can be deduced from *E* and matrix *X*.

Furthermore, the network is composed by a set of nodes $R = \{(u, f) : u \in V,\ f \in F\}$ (*requester nodes*) which request a given set of files *F*, located at a set of nodes $S = \{(v, f) : v \in V,\ f \in F\}$ (*source nodes*). In case of resource replication, a requester node may find the requested file *f* located at different source nodes. The routing protocol is responsible for establishing the end-to-end paths between each requester node and its respective source nodes.

B. Capacity in Wireless Mesh Networks

In order to derive the capacity of multi-channel multi-radio WMNs, we need to derive the capacity of each link taking into account interference from parallel packet transmissions of nodes nearby. We make use of the concept of collision domains (CDs) introduced by [8] and later on generalized by [1]. Basically, the collision domain C_l of a link *l* transmitting at a given channel *c* is the set of all the links *k* which can not be active in parallel while link *l* is transmitting on channel *c* because the interference from a transmission on a link *k* would be strong enough to disturb a parallel transmission on link *l*. The nominal load of a given collision domain can then be defined as the sum of the rates of the flows routed on links of the collision domain. As only one link in the collision domain can be active at a given time, the total flow in any collision domain will be bounded by the nominal MAC throughput *B*. As a result, the maximum capacity of a given collision domain is limited by the nominal MAC layer throughput. The outcome of the collision domain model is a set of inequalities. It is easy to see that there exists a *bottleneck* collision domain, which is the collision domain which carries the maximum load (or forwards the maximum amount of traffic [8]). Therefore, the bottleneck collision domain can serve to derive the strongest bound on achievable throughput and thus on nominal network capacity. [8] validates the collision domain model using simulations that match closely analytical results.

In general, a network might have several bottleneck collision domains. Similar inequalities can be written for every collision domain, and it is straightforward to extend the same analysis to regular two-dimensional or arbitrary topologies [1]. In general, the steps are the following: first, one needs to calculate the expected load on each link in the network, taking into account source/destination pairs and routing protocol considerations. Then, all collision domains have to be identified for the whole network. Assuming a homogeneous network, where the available bandwidth of all collision domains is the same, the bottleneck collision domain C_B can be identified as the one having the highest load. Finally, an upper bound for the traffic within C_B can be determined, which depends on the routing and channel assignment strategies used. It is important to note that the model does not take into account the benefits of variable transmission rates, transmission power, interference from nodes far away, etc. However it can be extended to make their use.

As summary, we can define the collision domain C_l of link $l_{i,j,c} = (\{i, j\}, c) \in L$ between nodes i and j at channel c by:

$$\begin{aligned} C_l = \{l_{x,y,c} :\ d_{ab} \leq I,\ ab = ix, iy, jx, jy, \\ ij \neq xy,\ l_{x,y,c} \in L,\ x, y \in V\} \cup \{l_{i,j,c}\} \end{aligned}$$

where i,j and x,y are the nodes forming the links $l_{i,j,c}$ and $l_{x,y,c}$ on channel c and I is the interference range of the node.

IV. ROUTING AND CHANNEL ASSIGNMENT IN MULTI-CHANNEL MULTI-RADIO WMNS

We want to model the achievable capacity for P2P based file download in a multi-channel multi-radio mesh network. We assume that a number of requester nodes *r* issue look-up commands to locate objects or files *f* they are interested in. The lookup operation returns a list of source peers *s* which hold the resource in question. While such lookup operation is an important part of an overlay network design, we do not consider it here, as for capacity considerations the file download is more important due to the high traffic volume. Therefore, we assume that for each triple *(r,s,f)* an end-to-end path is established via the routing protocol. Routing in this work is done using Dijkstra's algorithm to find the paths with shortest hop count. Multiple shortest paths might be available between a given requester and source. If so, the routing algorithm selects randomly one shortest path from the list. Routing is done before channel assignment and the channel assignment needs to ensure that the nodes along the paths selected share a common channel. We acknowledge that the use of a path with minimum hop count and the independence of routing and channel assignment in this work are simplified assumptions and better strategies might be available (e.g. jointly considering channel assignment and routing, using more advanced routing metrics taking into account channel diversity, etc.). However, we wanted to focus on the impact of peer selection and replica placement, and the model that we develop can be easily extended to more sophisticated routing/channel assignment schemes.

We assume that the channel assignment algorithms maintain the network connectivity by ensuring that two neighbors, which need to communicate (i.e. whose link needs to carry traffic) share a common channel. The channel assignment can take specific objectives into account, such as interference reduction, by e.g. assigning channels that are least used in its neighborhood. By considering such objectives, such as interference reduction [9], schedulable flow rates [3], fair load distribution, etc, the channel assignment is proven to be a NP hard problem. In our study, we apply the channel assignment by having the knowledge of the selected paths chosen by the routing algorithm. However, at this point, we have no knowledge about the flow rates that can be sustained over the selected paths. Two different channel assignments are considered in this work. We also make use of single channel assignment as a baseline approach used to show the advantage of using multi-channel multi-radio in WMN. The two channel assignment schemes are K-Partition proposed by [4] and Breadth First Search applied by [10].

As in [4], the channel assignment need to satisfy four constraints:

1) The number of distinct channels that can be assigned to a wireless mesh network node is limited by the number of NICs on it,
2) Two nodes involved in a link that is expected to carry traffic should be bound to a common channel,
3) The sum of the expected loads on the links that interfere with one another and that are assigned to the same channel cannot exceed the channel's raw capacity, and
4) The total number of available channels is fixed.

Constraints 1, 2 and 4 are captured by the channel assignment. Constraint 3 is ensured by the linear programing model, that will be discussed in Section V. Following [4], the channel assignment problem is divided into *neighbor-to-interface binding* and *interface-to-channel binding*. In neighbor-to-interface binding, for each node we divide all of its neighbours' nodes within its transmission range into k-groups, so that each group can be mapped to one of the *k* interfaces. Each of this neighbors' nodes also partitions its neighbors' nodes into *k*-groups, while maintaining the grouping done by the first node as a constraint. As in [4], this process is repeated until all nodes have partitioned their neighbors. By doing that we ensure that the first constraint is satisfied. Thus, each node has made the decision by which interfaces it is going to communicate with its neighbours. In the interface-to-channel binding, channels are assigned to interfaces. First, the interfaces of nodes are divided into groups to ensure the second constraint. Then, each group is allocated channels making sure that constraint four is not violated.

The K-Partition channel assignment does not take into account the path selected by the routing algorithm. In the first phase, neighbours are bound in a sequential fashion. In the second phase, we start by allocating the groups channels sequentially until the total number of channels is reached and then each group is allocated a channel that is least used in the two hop neighbourhood. However, as in [4], the assignment does not take into consideration the traffic load of the links, and thus assume that the links in the network have similar traffic load.

On the other hand, the BFS channel assignment takes into account the paths selected by the routing algorithm. Thus, the set of paths between requester and source nodes are assumed to be known a priori. Different from the K-Partition that starts the channel assignment from a specific node, in BFS the nodes are traversed in a breadth first search fashion starting at a pseudo node connected to all source nodes holding a file. In the first phase, neighbours are bound to the interface which is supporting the least number of flows. At this point, the actual flow rates are not known, thus the neighbours are bound to the interface just by considering the number of flows. In the second phase, the groups are allocated channels that have the least number of flows in the two hop neighbourhood.

V. PROBLEM FORMULATION

For a given multi-channel multi-radio WMN, with k NICs per node, c channels, a set of requesters R and a set of sources S, the problem formulation is estimate the throughput and fairness for different peer selection and replica placement strategies, given the routing and channel assignment described in Section IV. The peer selection for a given resource (file f) requested by node u represents the selection of a source peer v, responsible for file f given a specific objective, such as fairness and throughput maximization. Replica placement strategies determine at what nodes the resources (files) will be replicated. In general, several replication strategies have been developed, also taking into account the load and the capacity of the node storing the replica. In this work, we consider and compare two simple replication strategies: random replication and replication at gateway nodes. In random replication, we randomly pick the nodes which store replicas of a given resource. In gateway based replication, only gateway nodes which connect the mesh to the internet can store replicas. In the latter case, the replica selection problem translates then to the gateway selection problem. The number of replicas to use will be determined later by the scenario evaluated. In general, more popular content should be replicated more often, while taking into account the availability of content in the network, determined by the cache capacity of the nodes and the node uptime.

The peer selection is represented by the matrix P such that $\forall (u,f) \in R$, p_{uf} of P is the source peer selected by node u to download file f which should ensure that $(p_{uf}, f) \in$ S. The path selected by node u to download file f is given by the set of links $\Re^P_{uf}$. The flow rate x^P_{uf} is used to represent the rate at which node u is downloading the file f. The flow rates of the form x^P_{uf} are the output of the linear programming model. The collision domain of link l is represented by C_l and determined by the channel assignment scheme. The number of links in C_l which are responsible for the flow x^P_{uf} is given by $\delta_{luf} = size(C_l \cap \Re^P_{uf})$. For each peer selection P the linear programming model is used to formulate the collision domain by the following constraints:

$$x^P_{uf} \quad \geq \quad 0 \quad \forall (u,f) \tag{1}$$

$$\sum_{uf} \delta_{luf} \cdot x^P_{uf} \quad \leq \quad B \quad \forall l \in \bigcup_{(u,f)\in R} \Re^P_{uf} \tag{2}$$

Constraint 1 ensures non negative flow rates. Constraint 2 ensures that the total flow in any collision domain does not exceed the nominal capacity. Solving an optimization problem leads then to a rate allocation $X = \{x_1, x_2, ..., x_P\}$, where P is the number of source nodes chosen by the peer selection schemes, that can be feasible scheduled, given the routing and channel assignment strategy.

Four peer selection objectives are studied in this work. As we are going to see, besides the basic constraints (1)-(2), different objectives lead to additional specific constraints.

A. Max Rate Allocation

The Max Rate Allocation (MRA) selects the source peers for which the sum of user's flow rates achieved is maximum. Thus, by MRA we can estimate the maximum throughput achievable. In MRA our objective is

$$Maximize \quad S^P = \sum_{uf} x^P_{uf} \tag{3}$$

subject to constraints (1)-(2). As this approach tries to maximize the aggregated throughput it could result in unfair rate allocations ending up with zero rates for a few requesters.

B. Minimum Guaranteed Maximum Rate Allocation

The Minimum Guaranteed Maximum Rate Allocation (MGMRA) tries to achieve a degree of fairness by finding the maximum aggregated throughput while putting a lower bound x_G on the achievable flow rates. Besides the constraints (2) we need also to satisfy (5). Thus, in MGMRA our objective is

$$Maximize \quad S^P = \textstyle\sum_{uf} x^P_{uf} \tag{4}$$

$$x^P_{uf} \geq x_G \quad \forall (u, f) \tag{5}$$

subject to constraints (2) and (5). Setting $x_G = 0$ translates to MRA. A higher x_G value increases fairness but might result in allocations that may not be schedulable for a given channel assignment and routing.

C. Maximum of Minimum Rate Allocation

The Maximum of Minimum Rate Allocation (MMRA) selects the peers for which the minimum among the flow rates is as high as possible. MMRA is a fair selection scheme as it ensures none of the requesters are deprived. Here, besides the constraints (1)-(2) we need also to satisfy (7). Thus, in MMRA our objective is

$$Maximize \quad x^P_{min} \tag{6}$$

$$x^P_{uf} \geq x^P_{min} \quad \forall (u, f) \tag{7}$$

subject to constraints (1)-(2),(7). The peer selection P for which $x^P_{min}$is the maximum, is the one selected by MMRA.

D. Proportional Fairness

Assuring fairness may involve several layers, since unfairness occurs mainly in MAC (e.g. channel assess and scheduling) and transport layers (e.g. congestion control). Here, we use a simple *proportional fairness* index $\lambda = min(X)/max(X) \in [0, 1]$ proposed by [11], where X is the set of user's flow rates, $X = \{x_1, x_2, ..., x_S\}$, and S is the number of source nodes chosen by the peer selection. When $\lambda = 0$, some user's flow rates are allowed to starve, whereas for $\lambda = 1$ absolute fairness is enforced. In order to verify that absolute fairness is achieved, we make use of the Jain's Fairness Index in the evaluation which is given by $J(x_1, x_2, ..., x_n) = \frac{(\sum x_i)^2}{(n.\sum x_i^2)}$ [12].

The proportional fairness objective is to select peers for which the throughput is maximum with the constraint that λ of the flow rates will not be less than a given value λ_{min}. Proportional fairness ensures fairness in relation with the maximum flow rate by considering constraints (9)-(11). In constraint (9) , (10) the minimum and maximum flow rates are known. Constraint (11) guarantees proportional fairness. Thus, in proportional fairness our objective is to

$$Maximize \quad S^P = \textstyle\sum_{uf} x^P_{uf} \tag{8}$$

$$x^P_{uf} \geq x^P_{min} \quad \forall (u, f) \tag{9}$$

$$x^P_{uf} \leq x^P_{max} \quad \forall (u, f) \tag{10}$$

$$x^P_{min} \geq \lambda_{min}.x^P_{max} \tag{11}$$

subject to constraints (1)-(2),(8)-(11).

VI. EVALUATION

We use Octave [13] and the *glpk* function to solve the linear programming model. We assume nodes are always on and have infinite cache to store the replicas. If nodes would have limited cache, the cache replacement strategy has a major impact on achievable capacity which we did not evaluate in this work. The topology of the WMN is a 7x7 grid of wireless mesh routers. The number of interface per-node used is one, two or four radios. The number of channels is varied from 1 to 12. Channels are bound to radios during the whole download time according to the channel assignment algorithm. The nodes are spaced by 100 meters having also a transmission range of 100 meters. Three nodes are randomly selected to be gateway nodes connecting the mesh to the internet. In the model, wireless link capacity is set to 100 units, and is assumed to be constant. Six requesters, where each pair requests a different file from the given set of files (f_1, f_2, f_3), are randomly picked. The replica placement mandates what source nodes hold which files. We considered two cases: gateway and random. In the gateway based scheme, when no replication is used, there is just one file per gateway. The number of requesters and sources is kept small as the simulation time grows rapidly with their increase. However, such decision still allows us to achieve concise results in order to analyze and compare the selected approaches. For each combination of peer selection, replica placement, routing and channel assignment algorithm, average and stddev. of 5 runs is calculated, if not stated otherwise.

A. Impact of Replication

Figures 1 and 2 show the aggregated throughput of user's flow rates in terms of degree of replication for gateway and random based replication, respectively. Each of the six requesters is looking for three distinct files f_1, f_2 and f_3. In case of degree of replication equal to 1 (x-axis), the three files are located at three different gateways, or three randomly selected nodes. As we increase the amount of replication, additional replicas are spread at the gateways or at additional random nodes. For example, at degree of replication equal to 2.3, we have a total of 7 files in the network (e.g. $3f_1$,

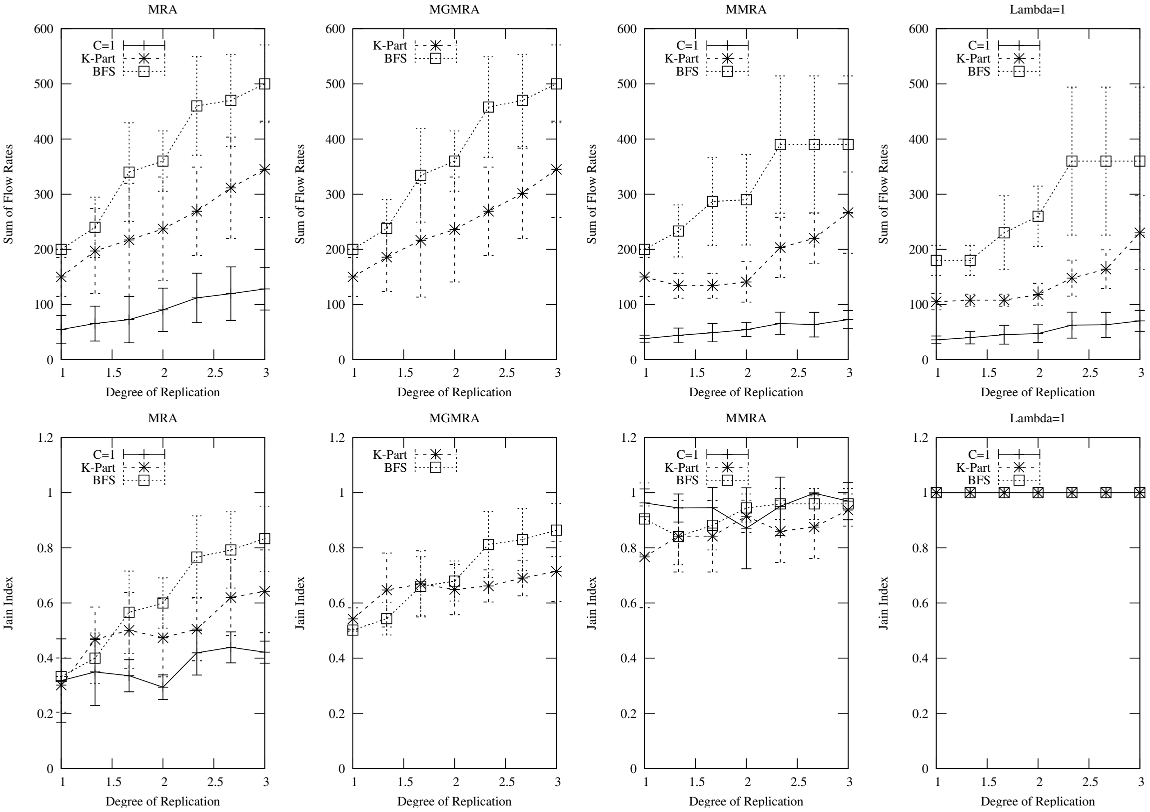


Figure 1: Impact of replication for files located at the gateways

$2f_2$,and $2f_3$), spread over 3 gateways or at 7 different nodes for gateway and random replication, respectively. For a fair comparison, as degree of replication increases, additional sources are added rather than changing the complete set of sources, also maintaining the same set of requesters. At the lower part of Figures 1 and 2 we also present the Jain index for each peer selection scheme. The use of multiple channels and multiple interfaces are presented, while using K-Partition and BFS. For those graphs we make use of two interfaces and 6 channels, if not mentioned otherwise.

Analyzing Figure 1, we can see that for MRA with a single channel the throughput increases with the degree of replication. However, in terms of fairness, we note that single channel remains unfair even at higher degree of replication. This is because when using single channel meshes, capacity is severely limited and the MRA will try to maximize flow rates for a small set of flows leaving not much remaining capacity for the other users, leading to unfairness. Compared to single channel, K-Partition provides better throughput, leading also to fairness among flows. However, BFS provides the highest throughput as it leads to the increase of individual flow rates, which consequently leads to more fairness if compared to K-Partition and single channel cases. This is mainly due to nature of BFS, that gives priority for links that carry traffic while assigning channels.

For MGMRA we set the minimum flow rate to 10% of the maximal achieved rate. MRA and MGMRA look very similar as the minimum guaranteed flow rate of 10% can be achieved without the reduction of other flow rates. What is interesting to note is that for MGMRA, the single channel assignment can not guarantee the minimal flow rate of 10%, therefore no results are plotted. On the other hand, MMRA can guarantee a better degree of fairness among the flow rates, even for single channel and lower degree of replication, if compared to MRA and MGMRA. However, this comes at the expense of slightly smaller aggregated throughput, especially for K-Partition, which is not effective when allocating channels. By comparing the results of MRA with MMRA and proportional fairness for $\lambda = 1$, we can see clearly the trade-off between fairness and maximum achievable throughput.

The same conclusion can be drawn for random replication scenario seen in Figure 2. However, we can note that for all peer selection and channel assignment scheme there is an improvement in throughput if compared to the replication at the gateways. This is because by randomly selecting the replica placements instead of clustering the replicas at the gateways, we increase the probability to find disjoint paths in the network and consequently lowering the collision probability over the wireless links. As throughput increases, more fairness is provided to the flow rates as seen by the Jain index at the bottom of Figures 1 and 2. Note, that for random replication and sufficient number of replicas we can satisfy MGMRA, not possible for gateway replication due to higher load around the gateway nodes. However, for both replication schemes, the maximum theoretical throughput of 600 is never achieved.

B. Impact of number of channels and radios

Figures 4a and 4b show the throughput in terms of the total number of channels for the gateway and random replication, respectively. Due to space limitation, we just plot K-Partition for MRA, however its behaviour is similar to BFS. We have used the same 7x7 grid topology with each node having two NICs and two requesters for each of the three files, and files replicated at three gateways or randomly.

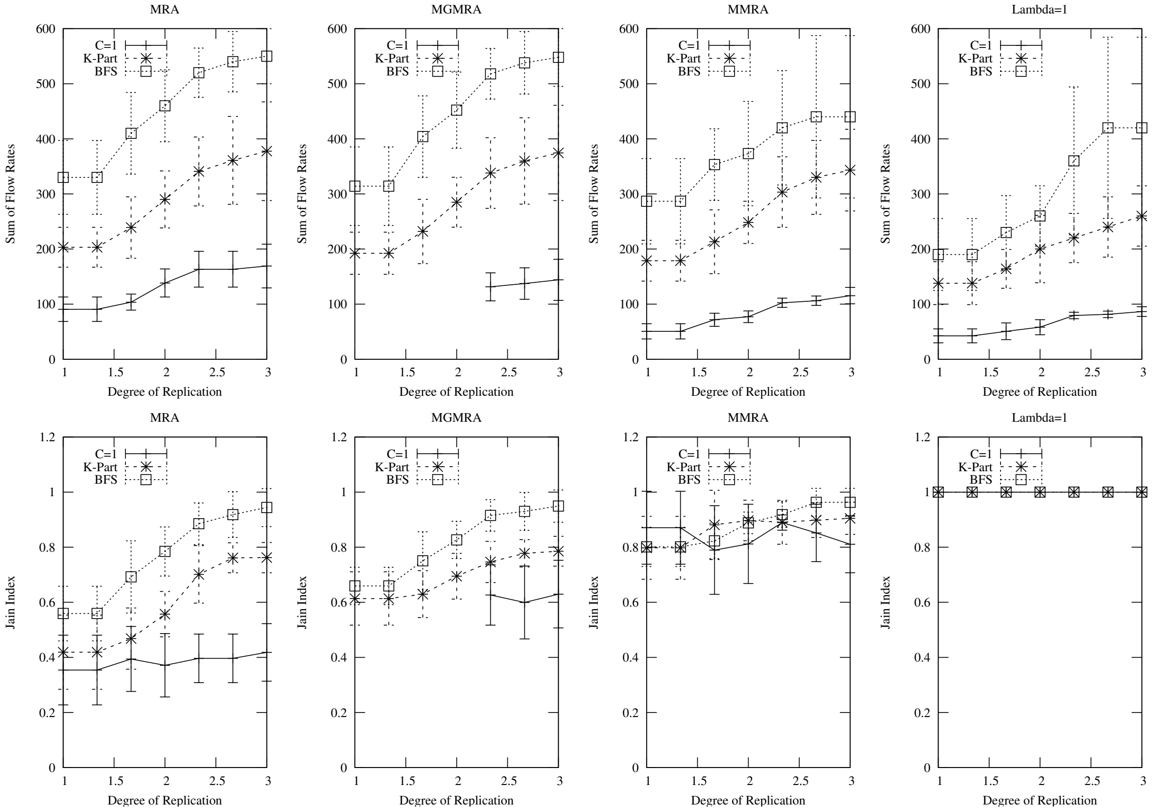


Figure 2: Impact of replication for files located at the random nodes

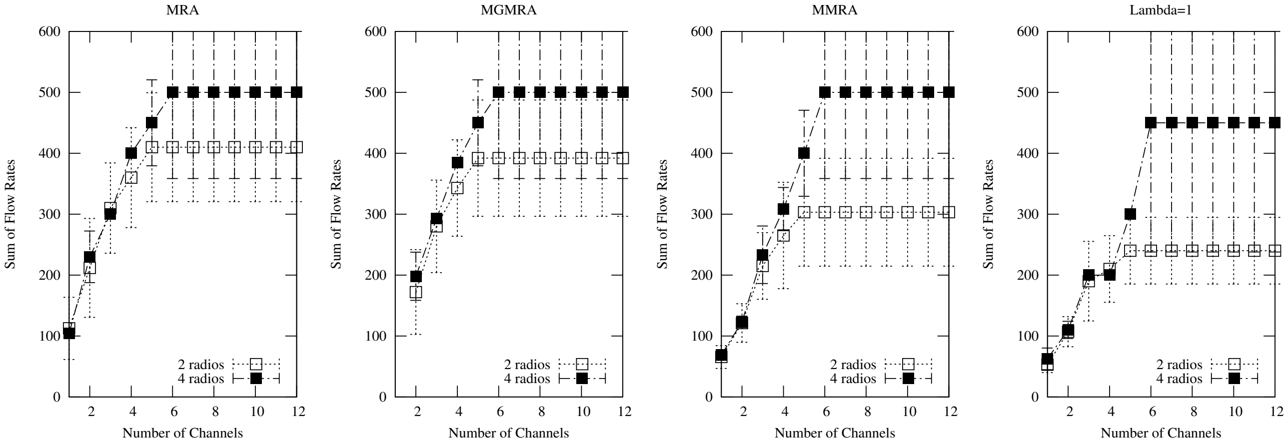
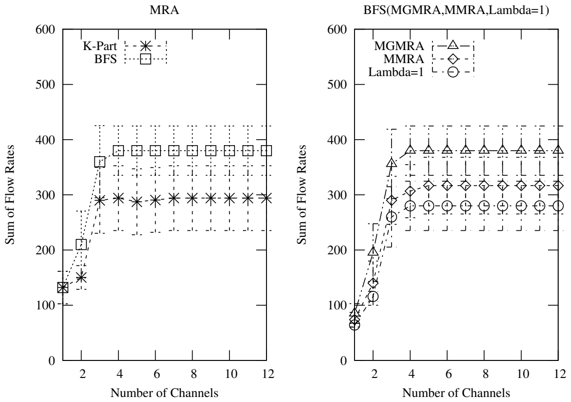
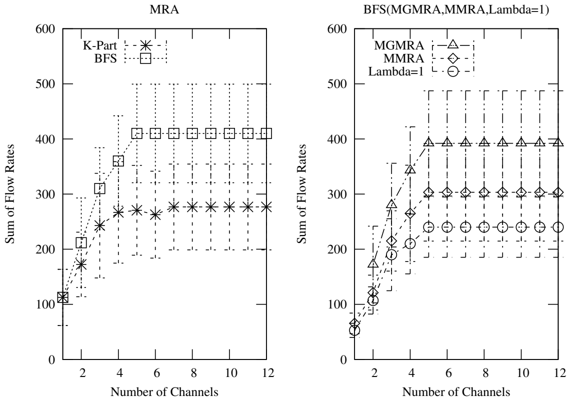


Figure 3: Impact of number of radios for BFS and random replication

We can see that for all peer selection the throughput increases with the total number of channels but only to a certain number of channels after which it remains the same. Adding more channels will not reduce the collisions as the number of interfaces is a limiting factor. The trend is the same for all peer selection schemes, however different maximum throughput can be achieved. For MMRA and proportional fairness (Lambda=1), the maximum achieved throughput is lower compared to MRA and MGMRA as fairness among flow rates needs to be guaranteed. K-Partition always provides lower throughput compared to BFS due to the fact that it can only use the channels which are least assigned rather than the ones that are least used. Therefore, we end up in cases where the amount of load in a given set of least used channels might be very different as the number of active links will be different in this set. It is interesting to see that the optimum number of channels, i.e after which there is no increase in throughput, is higher for BFS than K-Partition in both replication cases. This shows that as more channels are made available, BFS makes better use of them by breaking down the bottleneck collision domain compared to K-Partition that distributes them evenly. What is interesting to note is that for BFS and smaller number of channels (e.g number of channels equal to 2, 3 and 4) it is better to replicate at the gateways compared to random replication. This is due to the fact that the BFS channel assignment starts from a smaller number of nodes (just at the gateways) meaning that better re-use of channels is possible compared to random replication where the assignment starts



(a) Throughput versus number of channels: replication at the gateways



(b) Throughput versus number of channels: random replication

Figure 4: Throughput versus number of channels

at every random source.

Figure 3 presents the impact of number of radios as number of channels increases for BFS and random replication. For all peer selection schemes the total throughput increases with the number of radios. The optimum number of channels increases from 4 channels while using 2 radio interfaces to 6 channels while using 4 radio interfaces. By having more radios and channels, nodes can break the collision domain by assigning different set of channels and interfaces among its neighbors. MMRA and proportional fairness have a much higher gain in throughput compared to MRA and MGMRA, due to the increase in number of radios. Therefore, for the given scenario and using BFS, we can guarantee a higher degree of fairness among users' flow rates if using 6 channels and 4 radio interfaces.

C. Impact of lambda

Finally, in Figure 5 we show the trade off between fairness and throughput by varying the proportional fairness factor λ. The same gateway topology is used while applying a degree of replication of two, two NICs and a total of six channels. As expected, higher λ leads to decrease in throughput for all channel assignment schemes, due to the reduction of some flow rates while enforcing fairness among them. However, when $\lambda = 0.4$ the Jain index is satisfactory and still high throughput can be achieved, especially when using BFS or K-Partition.

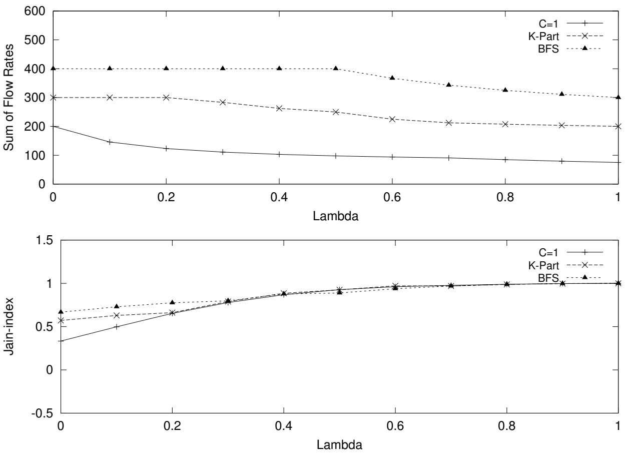


Figure 5: Tradeoff between maximum throughput and fairness

D. Model validation through simulation

To validate our assumptions, we compare the results obtained by the model with ns-2 simulation (ns2.33). For both cases, we used a 5x5 grid wireless mesh topology and the 802.11a MAC layer with and without RTS/CTS in the simulator. Constant bit-rate (CBR) UDP flows are used, as we would like to avoid TCP's congestion control mechanism. The basic data rate is set to 6Mbps and the packet size to 1470 bytes.

For this comparison, we used MRA as the peer selection scheme and every node operates in a single channel environment using replication at the gateways. Figure 6 compares the theoretical with simulation results of the normalized throughput for different degrees of replication. Each point is an average of 10 runs normalized to the highest throughput (degree of replication equals to 3). For each run, three random requesters are selected among the nodes (excluding the three gateways already selected). In order to make this comparison, we feed the simulation with the set of requesters, gateways, and shortest paths as calculated by the model. As we can see in Figure 6, using RTS/CTS at the MAC layer protects senders and receivers from collisions. This results in a close match with the model as the collision domain model assumes that link constraints are symmetric [8]. However, for asymmetric MAC layer (no RTS/CTS), the presented model reasonably matches the simulation results.

VII. CONCLUSION AND FUTURE WORK

In this paper, we have developed a numerical model to calculate capacity and fairness for P2P traffic in multi-channel multi-radio WMN. Based on the collision domain concept we formulated different peer selection strategies, MRA, MGRA, MMRA and proportional fairness as a constrained linear program to derive the user's flow rates. The model is flexible, allowing the evaluation in arbitrary topologies, for different number of NICs and channels. We evaluated the impact of different channel assignment schemes, number of radios and channels. Given the set of routing, channel assignment and peer selection scheme, the model is capable of deriving the users' flow rate and fairness amongst user flows, for resources replicated at gateways or at random nodes.

We have shown that for lower degrees of replication, random replication is better than replication at gateway nodes, if enough channels are available. This is because the traffic can be spread out more effectively. For single channel assignment

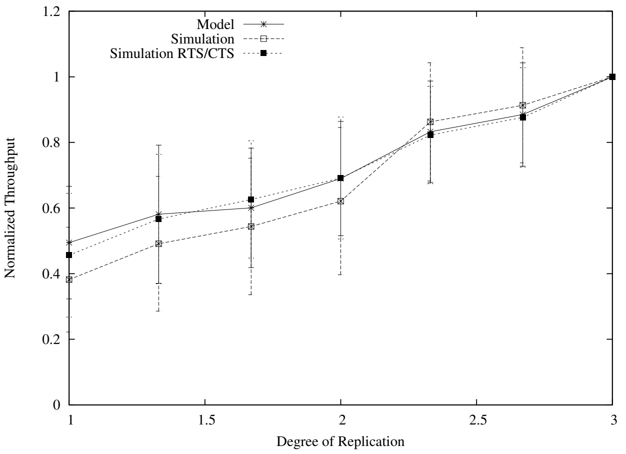


Figure 6: Theoretical and simulation results of the normalized throughput for different degrees of replication

schemes, MMRA might result in infeasible rates due to the limited capacity. While MRA allows to achieve the highest aggregated throughput, it results in limited fairness. On the other hand, MMRA and proportional fairness are more fair but suffer in aggregated throughput. The effect of total number of channels on throughput is also studied. An optimal number of channels can be identified for a given number of radios, beyond which the throughput cannot be increased by adding more channels. Moreover, such optimal number of channels can be different for different channel assignment/topologies.

As a future work, we intend to use the model to develop novel routing, channel assignment and peer selection strategies that are more sophisticated and take into account the interaction among the different layers. Also, a study of degree of replication and throughput for each file rather than the entire network will provide better insights into how replication should be done for files with different popularities.

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