Channel assignment in IEEE 802.11-based substitution networks

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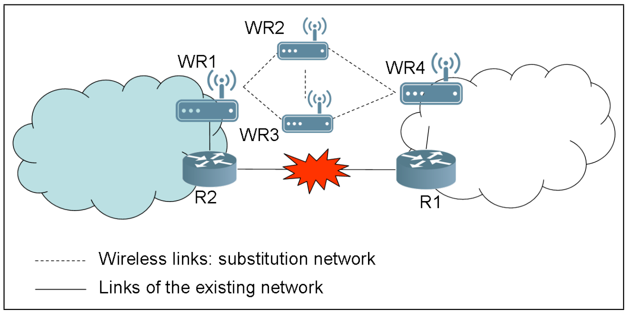


Fig. 1. The connection between two networks has been lost (between R1 and R2). The substitution wireless network, composed of four wireless routers, replace the failing link/network.

***Abstract*—A substitution network is a rapidly deployable wireless network that provides a backup solution to quickly react to failures on an existing network. We consider a substitution network scenario where wireless routers are equipped with several Wi-Fi cards. The problem addressed in this paper deals with the channel assignment of these wireless interfaces. In this particular context, it is possible to derive an objective function that estimates precisely the overall throughput that can be achieved. This problem is formulated through a linear optimization problem for which we propose a heuristics. Solutions give the channel assignments but also the optimal traffic load sharing between the different paths of the substitution network. Simulation results, performed with ns-3, compare our heuristics to the optimum and to classical approaches.**

I. Introduction

A substitution network is a rapidly deployable wireless network that provides a backup solution to quickly react to failures on an existing network [1]. In case of failures, the substitution network is used to carry the traffic in order to ensure the main services. The substitution network has thus to be as efficient as possible to ensure the network availability and to penalize as less as possible the quality of the service. In Figure 1, two domains represented by the two clouds are interconnected through two routers R1 and R2. When the connection between the two domains fails, the substitution network is deployed to ensure the connectivity and the services. The substitution network may rely on Wi-Fi technology. It provides low cost solutions, and transmission rates that offer an efficient solution. But the use of a single channel or a set of aggregated channels, common to all nodes, leads to an important performance reduction in multi-hop wireless networks [2], [3]. An efficient solution to this problem is to equip the wireless routers with multiple wireless network interface cards (NIC). The traffic load carried by the network can then be shared among the different channels significantly increasing the overall throughput. Nevertheless, the availability of these radios and channels raises the problem of the assignment. The channel assignment (CA) problem, that consists in mapping the set of available channels to the radios, must thus be optimized. We base our optimization on an estimation of the overall throughput. Substitution networks imply simple topologies which, very often, have a single source-destination pair. These simple topologies make possible the estimation of the overall throughput (sum of the achieved throughput on the different paths) for a given channel assignment. These estimations give rise to new optimization problems for the channel assignment. To our knowledge, this particular problem has never been addressed. A simpler version, based on the number of conflicting links has been shown NP-hard. Heuristics with a low complexity is thus required even for a small number of nodes/links. A heuristic is then proposed to approach the optimal. The accuracy of our estimations is evaluated through a large set of simulations using the network simulator ns-3 (network simulator version 3 [4]). The simulation results show that our estimations are very close to the obtained throughput. Our solutions also provide the optimal load sharing between the available paths.

We survey in Section II the classical CA algorithms, and the recent contributions. The scenario, notations, as well as the optimization problem, are presented in Section III. Heuristic, used to approximate the optimum of the optimization problem, is described in Section IV. Simulation results are presented in Section V. We conclude in Section VI.

II. Related work

CA in ad hoc networks can lead to the disappearance of some wireless links compared to the topology obtained with a single channel. It may then be more efficient to perform the channel assignments in such a way that the topology is preserved. Consequently, algorithms, considering channel assignments that preserve the topology, try to minimize the overall interferences rather than maximize an estimation of the network throughput. The overall interference is generally estimated as the number of links that interfere with each others, or that cannot be used at the same time according to the CSMA/CA mechanism. The interfering links are then in conflict. In this case, the CA problem consists in finding the channel assignment that minimizes the total number of conflicts while preserving the topology. This problem has been shown NP-hard [5], [6]. The different algorithms that have been proposed are thus heuristics [7], [8], [6]. This formulation of the CA problem has the benefit to require only topological information, but it has several drawbacks. The relationship between achievable throughput and the total number of interfering links is not obvious. If the routing process is not aware of the channel assignment, which will be the case if a classical routing protocol is used, links that will be chosen to carry traffic may experience more conflicts that unused links. Also, the physical transmission rate at which frames are transmitted is not taken into account. A link with a low data rate and with a lot of conflicts can then become the bottleneck and limits the throughput.

Beside, some works join the CA problem to the routing to find the best routing and assignment that maximizes the throughput. This problem, sometimes referred to as the Joined Channel Assignment and Routing (JCAR) problem, has also been shown NP-hard [5], [9]. In most of the papers, the data traffic is assumed to be known in advance [10], [11], [5], or measured in real time [12], [13], [14]. The algorithms are then either practical [12], [15], [13], [5], i.e. algorithms that aim to maximize throughput are given but without explicit formulation, or are heuristics that are related to formal optimization problems that maximize the sum of the end-to-end throughputs [10], [11], [14], [16], [17]. Maximization of the overall throughput may lead to starvation for some flows or at least strong unfairness between flows. Constraints on fairness can thus be added to the optimization problem [11], [16], [17].

The two families of problems are unsuitable to substitution networks. As explained earlier, the classical CA problem may lead to an inaccurate use of resources. Beside, the different JCAR heuristics are very complex and assume the knowledge of the traffic load a priori or measured in real time. But in our context, as wireless routers have been deployed to offer one or several routes, the routes are known in advance but not the traffic. Moreover, as there is a single source-destination pair, only the capacity of the substitution networks has to be maximized without knowledge of the traffic.

III. Scenarios, notations, and optimization problem.

A. Scenario

We consider the scenario shown in Figure 1. The substitution network is composed of two end points (a source and a destination) connected through a set of IEEE 802.11-based wireless routers configured in ad hoc mode. The two end points are also connected to the existing network. Several paths may exist between the source and the destination. Each wireless router is equipped with several interfaces, for which different channels may be assigned. The number of radios may be different from one node to another. We assume that two different channels do not interfere, or equivalently we consider only orthogonal channels.

B. Notations

The initial communication graph $G_I = (V_I, E_I)$ contains all the possible edges, i.e. $e = (v_1, v_2)$ $(v_1, v_2 \in V_I)$ will belong to E_I as soon as a direct wireless communication is possible between the two nodes v_1 and v_2. It may be seen as the communication graph when all the nodes use the same channel. We denote $G = (V, E)$ the communication graph that corresponds to the current channel assignment, with $V = V_I$ and $E \subset E_I$. Some edges present in E_I may not belong to E. It happens when two vertices do not have a common channel assigned to their radios. The n paths are denoted $P = \{p_1, p_2, .., p_n\}$. A path p_i is the set of links/edges $e \in E_I$ that belong to this path. $EC_P(e)$ is the set of edges that are in conflict with edge e in the graph G and that belong to P. The link capacity of an edge e in E_I, is denoted $LC(e)$. It is the maximum throughput of the link without conflict. It is set to 0 if $e \notin E$, i.e. if the two nodes extremity of the edge e do not have a common channel.

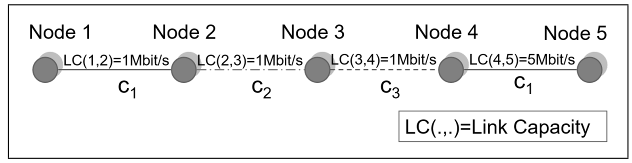


Fig. 2. An example of channel assignment. The represented graph is the communication graph (G_I).

C. Our optimization problems

As mentioned earlier, a classical approach to assign channels, consists in minimizing the number of conflicts. We show through the example presented in Figure 2, that the achievable throughput is related to the number of conflicts, links capacity, but also to links usage. We then present a formal computation of the achievable throughput and our optimization problem.

In Figure 2, the bottleneck is the link $(1, 2)$. The capacity of this link is shared with the link $(4, 5)$ as it uses the same channel (c_1)[1]. But it is not equally shared between these two links, as the link $(4, 5)$ will be used at most 20% of the time (since it will receive at most 1Mbit/s from Node 3). Therefore, the link $(1, 2)$ will approximately keep the remaining 80% of the link capacity. For this example, the maximum throughput can be estimated as the maximum T verifying:

$$\frac{T}{LC(1,2)} + \frac{T}{LC(4,5)} \leq 1 \tag{1}$$

This equation sets that the usage of channel c_1 shared by the links $(1, 2)$ and $(4, 5)$ cannot exceed 1. For $LC(1, 2) = 1$ Mbit/s and $LC(4, 5) = 5$ Mbit/s, we obtain a maximal throughput of $\frac{5}{6}$ Mbit/s.

For the general case, the constraint for a given edge in $P \cap E$, denoted "$edge$", is given by the following equation:

$$\sum_{j=1}^{n} \sum_{e \in EC_P(edge) \cap p_j} \frac{T_j}{LC(e)} \leq 1 \tag{2}$$

As the throughput can be different on each path, we set T_j the throughput on path j. Consequently, we have to sum over all conflicting links for a given path, then over all paths.

[1] We assume that these two links are in conflict with each other.

There is such an equation for all $edge \in E$. Our throughput estimation is then given by:

$$Throughput = \sum_{i=1,..,n} T_i \text{ with } AT \leq 1 \quad (3)$$

$AT \leq 1$ defines the constraints on the usage for each link in P (1 is a vector). $T = (T_1, .., T_n)^\top$ is a vector that represents the throughput for each path. $A = (a_{i,j})$ is a $card(P) \times n$ matrix. By convenience, we associate a unique id i in $\{1, .., card(P)\}$ to each edge in P. The mapping that associates an id to its corresponding edge $e \in E$ is denoted $edge(.)$ ($e = edge(i)$). The coefficients of the matrix A are then formally defined as:

$$a_{i,j} = \sum_{e \in EC_P(edge(i)) \cap p_j} \frac{1}{LC(e)} \quad (4)$$

The optimization problem consists in finding the channel assignment that maximizes the throughput while ensuring that links usage do not exceed 1.

$$\max \sum_{i=1,..,n} T_i \text{subject to } AT \leq 1 \quad (5)$$

IV. Heuristic

Our heuristic is detailed in Algorithm 1. The current assignment consists in a set of global variables R_i^v represented as a matrix $(R_i^v)_{v,i}$. R_i^v represents the i^{th} radio interface of node v. It maps each radio to its assigned channel. When R_i^v equals to -1, the radio is not assigned. Also, we use the matrix A_{best} that is a copy of the matrix $(R_i^v)_{v,i}$, that saves the best assignement. We assume that paths in P are sorted in function of their capacities. p_1 is the path for which $\min_{e \in p_1} LC_I(e)$ is maximum, and so on. We also assume that, for a given path, the edges of the path are sorted in an increasing order according to the link capacity over the number of conflicts in the initial communication graph G_I, i.e. according to $\frac{LC_I(e)}{card(EC_{IP}(e))}$. We start from a null assignment where radio are unassigned. Then, we assign channels to each path, one by one, according to their order. For a given path, the most constrained link is processed first. We assign to the most constrained link the channel that maximizes the throughput. We then consider the second most constrained link, and so on. When a path has been assigned, we keep the value of the total throughput, i.e. the sum of the throughputs on the assigned paths. When assigning channels to a new path, we systematically checked if the total throughput with this path is greater than without this path. Indeed, assignment on a new path may increase conflicts in such a way that the global throughput decreases. In this case, the new path is canceled. In the algorithm, we use four functions that are not described for the sake of clarity:

- `AvailableChannels()` lists the available channels for an edge.
- `Throughput()` computes the throughput for the current assignment. If a route is partially assigned, we do not take into account the non assigned links in the throughput computations.
- `Edge`(p_i, j) returns an edge e that corresponds to the j^{th} most constrained edge (according to the quantity $\frac{LC_I(e)}{card(EC_{IP}(e))}$) on path p_i.
- `AssignTheBestChannel()` assigns the best channel to an edge according to the throughput.

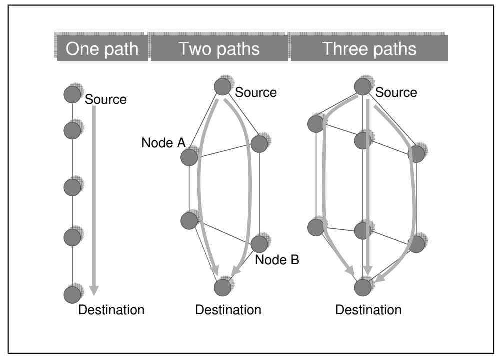


Fig. 3. The simulated topologies. The graphs are the initial communication graphs, i.e. $G_I = (V_I, E_I)$. The arrows show the paths used by the UDP flows.

Algorithm 1: Heuristic

$R_i^v \leftarrow -1 \; \forall v \in V, \forall i \in \{1, .., R^v\}$
$A_{best} \leftarrow (R_i^v)_{v,i}$
$throughput \leftarrow 0$
for $i \leftarrow 1$ ***to*** n **do**
  $C \leftarrow \{c_1\}$
  $j \leftarrow 1$
  while $j \leq card(p_i)$ *and* $C \neq \emptyset$ **do** `//` $\emptyset$ `is the empty set`
    $(v_1, v_2) \leftarrow$ `Edge`(p_i, j)
    $C \leftarrow$ `AvailableChannels`(v_1, v_2)
    if $C \neq \emptyset$ **then**
      `AssignTheBestChannel`(v_1, v_2, C)
    if `Throughput()` $< throughput$ **then**
      $C \leftarrow \emptyset$
    j++
  if $C == \emptyset$ **then**
    $(R_i^v)_{v,i} \leftarrow A_{best}$
  else
    $A_{best} \leftarrow (R_i^v)_{v,i}$

V. Simulations

We perform a set of simulations in order: i) to verify that the heuristic we proposed offers greater overall throughputs than the one based on the number of conflicts, ii) to evaluate the accuracy of our throughput estimation and iii) to evaluate the heuristic's performance in terms of optimality.

1) Simulation settings: Simulations are performed with ns-3. The topology corresponds to a substitution network with a single pair source-destination. One, two, or three disjoint routes are possible as shown in Figure 3. Distances between the nodes are not constant: the location of the points are random but are drawn in order to keep the routes valid. It leads to different link capacities as the Wi-Fi manager adapts its transmission rate to the link quality. The communication graph may be lightly different from one simulation to another: diagonal links (link (A, B) in Figure 3 for instance) may be present or not. The number of nodes belongs to the set $\{4, 6, 8, 10, 12, ...\}$ for two paths, and $\{5, 8, 11, 13, ...\}$ for three paths. The number of radios per node is always equal to 2, except for 3 paths where source and destination have 3 radios. The traffic consists in a set of constant bit rate UDP flows: one flow for each assigned path. The overall throughput is measured as the mean bits per second (expressed in Mbit/s) received at the destination. Each point of the next figures is the average of 25 simulations. The confidence intervals are not shown as there are almost merged with the curves. 4 algorithms are implemented:

- One frequency: the same channel is used by all the nodes.
- Optimal conflict graph: the assignment minimizes the number of conflicts.
- Optimal $Throughput$: the assignment maximizes out throughput estimation (given by Equation (3)). It is based on an exhaustive search that may take several days of computation.
- Heuristic $Throughput$: our heuristic is applied. The linear optimization problem is solved with the simplex algorithm.

2) Simulation results:

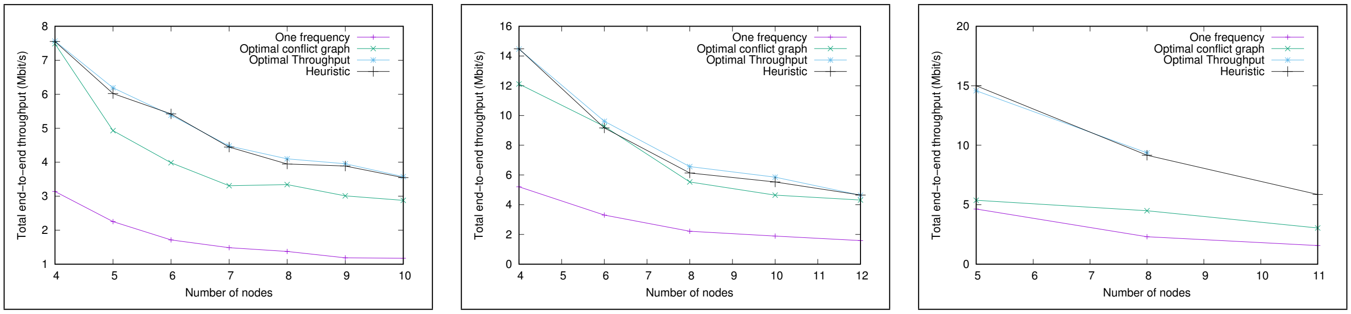
a) 3 channels: We first simulated the substitution network with 3 available channels. It corresponds to the number of non-overlapping channels in the $2.4GHz$ band. Results are shown in Figures 4 for 1, 2 and 3 paths. For three paths, the optimums were not computable for 11 nodes. Several weeks were not sufficient to obtain the result and we had to abort the search. Due to the number of conflicts that increases with the number of nodes, the throughput decreases. The throughput is improved by a factor of at least 2.5 for all algorithms compared to the case with only one radio and one frequency except for the optimal conflict graph with 3 routes. We explain these results below. This improvement highlights the benefit to use several radios. The throughput is multiplied by approximately 2 between 1 and 2 routes, but it is equivalent for two and three paths. It is due to the fact that paths are close (in number of hops) of each other: links of a path are in conflict with most of the links of the two other paths.

The throughput obtained with the conflict based algorithm is equivalent to our heuristic when there are 2 paths, but is definitely lower for 1 and 3 paths. Different causes lead to these differences. Algorithms based on the throughput estimations limit the number of conflicts for links with a low throughput by choosing channels for which the number of conflicts is small. Instead, the algorithm based on the number of conflicts does not distinguish between low and high throughput links. Also, the conflict based algorithm must ensure that the communication graph obtained after assignment is the same as the initial one ($G = G_I$) limiting the use of different channels. Also, it is worth noting that our heuristic is very close to the optimums, and is even almost merged with it.

b) 8 channels: In Figure 5(a), we show the simulation results for 2 paths and 8 channels. The number of nodes varies from 4 to 10. Throughputs corresponding to the heuristic are completely merged with the optimums. The obtained throughput is 5 times greater than for the case with 1 single channel. The throughput remains constant until 8 nodes as the number of links that composes the two paths is lower that the number of available channels. We also observe a significant difference with the conflict based algorithm. Indeed, its constraint on the topology ($G = G_I$) prevents it from benefiting from all the channels. The same remark can be done on Figure 5(b) where we vary the number of channels from 1 to 8 for a fixed number of nodes (8 nodes). It clearly appears that the throughput for the conflict based algorithm stagnates after 3 channels. As in the previous simulations, its constraint on the topology forces the nodes to have common channels with all neighbors (in G_I) and prohibits the use of more than 3 channels for the whole topology. For the other algorithms, the throughput increases more or less linearly with the number of channels. It reaches its maximum for 8 channels: there is then one different channel for each link on the paths. Surprisingly, there is no improvement between 2 and 3 channels. A deeper study on the obtained assignments shows that for 2 frequencies the algorithms assign only one path. The second path is not used because conflicts generated by this path increases the number of conflicts in such a way that the global throughput decreases. With 3 channels the two paths are used. It leads to a higher number of conflicts per link. Nevertheless, the sum of the theoretical throughput for the two paths is only lightly greater than with only one path. There is thus a load sharing on the two paths, but simulations show that it generates a marginal throughput improvement. When the number of channels becomes greater than 3, the number of conflicts decreases on the two paths that benefits to the throughput.

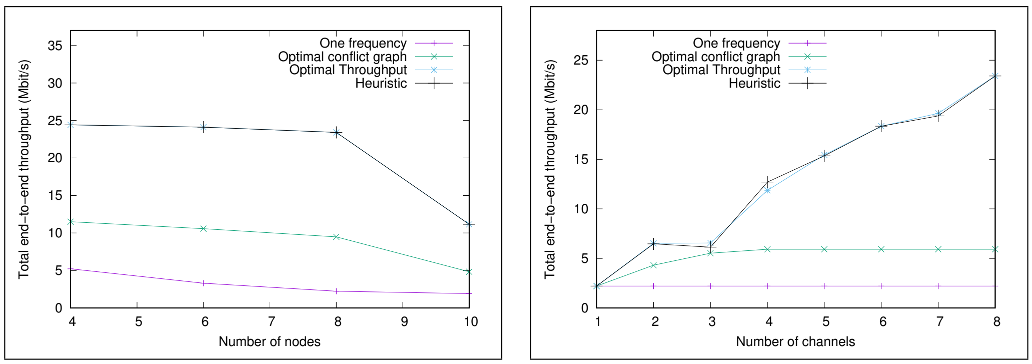
VI. Conclusion

We addressed the problem of channel assignments in substitution networks. With these networks, the topology is simple and interconnects a unique source-destination pair. We have shown that it is then possible to precisely characterize the end-to-end throughput between the source and the destination. The assignment problem is then set as an optimization problem that aims to maximize the throughput. In order to deal with the complexity of the optimization problem, we proposed a heuristic. We show that the results obtained with this heuristic are systematically very close, and even merged, to the optimums. We also observe that the proposed algorithms outperform the classical assignment approach which consists in minimizing the total number of conflicts.



(a) 1 path (b) 2 paths (c) 3 paths

Fig. 4. Overall end-to-end throughput with 1, 2, and 3 paths, when the number of nodes varies. Number of channels = 3, Number of radios = 2.



(a) 8 frequencies - the number of nodes varies. (b) 8 nodes - the number of frequencies varies.

Fig. 5. Overall end-to-end throughput for 8 frequencies and when the number of frequencies varies. Number of radios = 2, Number of paths = 2.

Another advantage of this approach is the fact that the output of the proposed algorithm is the maximum throughput per path allowing the source to optimally share the load on the different available paths.

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