

# Topology Reconfiguration in Wi-Fi Home Networks

João Nogueira<sup>1</sup>, Susana Sargento<sup>1</sup>, Peter Steenkiste<sup>2</sup>

<sup>1</sup> Instituto de Telecomunicações, University of Aveiro, Portugal

<sup>2</sup> Computer Science Department, Carnegie Mellon University, Pittsburgh, USA

joanonogueira@ua.pt, susana@ua.pt, prs@cs.cmu.edu

**Abstract**—The use of Wi-Fi is booming in home networks and it is making it harder for the technology to cope with this exponential growth. The high-bandwidth requirement of streaming services, data backups and interactive cloud applications require solutions to improve the performance of the network while simultaneously simplifying its management.

This paper unveils a new Wi-Fi management paradigm relying on dynamic network topology reconfiguration that adjusts the network topology to its traffic matrix, and mitigates the performance pitfalls inherent to Wi-Fi and its fixed topology.

A linear programming formulation relying on cross-layer information is provided to assess the potential gains of such solution, and an evaluation is performed that explores the achievable performance and range extension gains. The simulation results show a significant increase in the wireless network capacity - up to two fold - as well as improvements in the network range.

**Index Terms**—Wireless, Wi-Fi, Home Networks, P2P, Self-Organization, Self-Reconfiguration, Network Topology

## I. INTRODUCTION & MOTIVATION

The current trend for mobility and the increasing demand for high quality multimedia content is pushing the limits of Wi-Fi technology, especially in home environments where the number of Wi-Fi devices keeps on growing. A typical household has a combined Access Point / Router, but because only one device supports multiple wireless devices, the network's QoS drops as the number of devices increases.

Wi-Fi links can run at multi-Gbps bitrates using 802.11ac, but rates are significantly lower in practice, hence, the wireless network can become the bottleneck in home networks such as the ones with heavy usage of the intranet, or served by FTTH / Hybrid-Coax last-mile networks [1]. Because the Wi-Fi network is no longer used just for Internet access, it makes sense to have the peers communicate directly whenever possible [2]. The advantages are many fold: reduced contention and interference, and increased network performance. The increased use of Wi-Fi for communication inside the home is in part motivated the definition of WiFi Direct [2], which allows WiFi devices to communicate directly, without forwarding packets through an access point.

While this problem has some similarities with P2P wireless technologies there are significant differences: those scenarios generally aim for a distributed and peer-independent approach for networking mechanisms in situations where nothing in the environment is taken for granted; in contrast, home networks include an AP that is connected to the wired infrastructure and can naturally act as a coordination agent.

In this assumption lies the key for the incorporation of P2P techniques in home networks. This paper presents an approach for embedding reconfiguration capabilities in home wireless networks that is aware of cross layer information, namely Physical (SNR); MAC; and Network (Traffic matrix). This information is used to establish a network topology that adapts to its nodes' communication requirements. A linear

programming formulation relying on cross-layer information is provided to assess the potential gains of such solution. The results show a significant increase in the wireless network capacity, along with improvements in the network range.

The paper is organized as follows: section II surveys previous work on cognitive networks, self-\* networks and home networks. Section III formulates the problem and the envisioned approach, while section IV specifies the solutions in terms of Linear Programming (LP). The evaluation in section V provides insight on the expected performance improvements, while conclusions are presented in section VI.

## II. RELATED WORK

Self\* networks have been researched extensively in the academia and industry, where the concepts of self-management, self-healing, and self-optimization have been explored initially in the context of 3G and 4G networks [3]. Their main driving force is the fact that they relieve the management and configuration burden away from the user. While on corporate environments this is important to reduce the OPEX, in home environments the key benefit is the reduction in required user expertise. Meshkova et al [4] and Wangt et al [5] present a home network optimization problem, and solve it through a Home Cognitive Resource Manager, which considers goals set by stakeholders, and optimizes them through app-specific utility functions[6]. Although the proposal is complex and complete, it has several drawbacks: requires a 2<sup>nd</sup> radio interface for control; has an app-specific approach; and requires dedicated spectrum sniffers. In addition, by requiring every node in the network to be an autonomous agent, it rules out legacy and low cost wireless nodes, such as Wi-Fi sensors than cannot run the agents.

The need for cooperation between Wi-Fi devices in home networks was also acknowledged by Piamrat et al [7], and a coordination layer on top of Wi-Fi was proposed in order to ensure the quality of multimedia delivery services in scenarios with requirement for wide coverage area and low packet loss. Despite identifying wireless network usage trends and the factors that influence the network performance and stability, the focus on the paper was IPTV, thus being narrowly focused.

The literature in self\* home networks discussed a subset of the requirements and challenges, but failed to address key topics: legacy devices, and generality (service independence).

## III. PROBLEM FORMULATION AND APPROACH

P2P wireless technologies bring complexity to network management and optimization tasks that are unknown to most users. Even for experienced users, the optimal configuration of a wireless network may not be obvious. This section analyses the challenges inherent to the optimization of home wireless networks. After a brief description of the desirable features, the optimization approach and the metrics to optimize, its

main requirements are described: ability to choose between the possible connections to other peers; aware of the traffic-matrix, physical channel and node constraints.

To ensure the best possible performance for the flows between devices on the network, the optimization must go beyond the traditional channel selection problem. As an example, it must be aware of high bandwidth flows and give them priority on the overall solution, leveraging Wi-Fi Direct.

Instead of increasing the global wireless network capacity, we must increase the capacity of the links that are used the most, i.e., lower their link load or usage. In the context of wireless networks this may mean: using a different channel, a different wireless band / interface, and/or a different path (with or without relaying), preferably in an autonomous approach.

It is important to consider the technology constraints for each link: the wireless bands (either 2.4GHz or 5GHz), the Wi-Fi technology supported (802.11a/b/g/n/ac), as well as the physical/environmental conditions of the wireless network. In addition, legacy support must be ensured in order to provide an evolutionary path to new technologies.

The wireless bands supported have an impact on the maximum performance of the wireless links. 802.11g devices can reach 54Mbps link rates, whereas 802.11ac devices can establish link rates in the order of Gbps. As for environmental conditions, because wireless networks operate on shared spectrum, they must be aware of competing networks, and be able to pick the channels that will provide top performance, i.e. that suffer the least from adjacent and co-channel interference. They must also be aware of performance metrics of the wireless nodes participating in the network (usually the SNR).

The challenge is then to decide how the nodes should be connected between each other in a manner that minimizes the wireless network utilization for a specific traffic matrix. The solution has a natural tree shape, given that a cascade of AP-to-Client connections are made to establish network connectivity. This optimization is equivalent to optimizing a Multi-Commodity Minimum-Cost Spanning Tree, where the commodities in question are the network traffic flows, and the goal is to optimize the total load of the network.

As per the previous paragraphs, it is possible to define the inputs of the algorithm as: 1) the network's traffic matrix; 2) information regarding the nodes' hardware; 3) information about the wireless environment. The traffic matrix information is expressed through a demand matrix  $D$ , which contains the requirements, in Kbps, of the source and destination nodes. The use of Kbps as unit of demand has to do with keeping the values of the variables as integers for the LP formulation.

The characteristics of the wireless links between each client in terms of the maximum achievable bitrate, for each available interface, is assumed to be known either directly or indirectly via the SINR between the nodes. Using this information, it is then possible to compute a cost matrix reflecting the performance of each possible link. The cost matrix uses as a base unit the load imposed by a flow of 1Kbps of data: a 54Mbps link will have a load cost of  $1/(54 * 1024)$ , and the maximum link load is 1 (non-linear effects are not considered).

#### IV. LINEAR PROGRAMMING FORMULATION

This section presents a linear programming formulation to the problem. The wireless network is formulated through a graph where the vertices represent the wireless nodes, and the edges represent wireless links. While constraining the solution to a tree shape, the formulation allows for multiple wireless NICs, and accounts for several wireless channels.

1) *Problem Statement:* Given a graph  $G = (V, E)$  and a cost function  $w : E \rightarrow \mathbb{R}^+$ , find the subset  $S$  of  $E$  that minimizes  $\sum_{\{u,v\} \in S} w_{u,v}$  such that: for any two vertices in the ordered pair  $(k, l) \in P$  (subset of source and sink vertices of  $V$ ), there is a single path connecting  $k$  and  $l$  using only edges in  $S$  - tree structure - whose capacity supports the aggregate traffic demand  $d_{kl}$  between the vertices in set  $P$ ; each vertex  $v \in V$  has an associated set of interfaces  $I_v$ , where each interface is limited to operation in a set of channels  $C_i^v : v \in V, i \in I_v$ ; each channel  $c \in C$  has a capacity of  $U_c$ .

2) *Solution:* Define  $E$  as an ordered set of undirected edges, where an edge exists if a node  $v \in V$  is in communication range with another node  $u \in V : u \neq v$ .

Define  $E_D$  as superset of  $E$ , containing 2 directed edges per undirected edge of  $E$ , i.e. if  $u, v \in E$  then  $\{(u, v), (v, u)\} \in E_D$  and  $|E_D| = 2 \cdot |E|$ .

Define  $P$  as a set of ordered pair of vertices which have a positive traffic demand between them, i.e.  $\forall (k, l) \in P, d_{kl} > 0$ .  $d_{kl}$  is the traffic demand, in Kbps, from node  $k$  to  $l$ .

Define  $A$  as an adjacency set where  $A_v$  represents an ordered subset of undirected edges of  $E$ , containing node  $v$ .

Define  $I$  as a set of interfaces such that  $|I|$  is the maximum number of interfaces that a node  $v \in V$  may have.

Define  $C$  as the set of all possible wireless channels, and  $C_i^v$  as the set of channels available for use by node  $v \in V$  through its interface  $i \in I$ . Define  $U_c$  as the total available capacity of the wireless medium on channel  $c$ . A vacant wireless channel has a total capacity of 1 (100% since the load is 0), whereas channels that are being used by neighbor networks will have a  $U_c < 1$ .  $U_c$  is an input parameter of the model.

$T$  is a set of elements defined by  $E_D \times I$ , i.e. its elements are of the type  $(u, v, i) \in T$ , such that  $(u, v) \in E_D, i \in I$ .

$y_{uv}$  is a binary variable, a topology variable, which is 1 if edge  $\{u, v\}$  is in the solution, and 0 otherwise. Note that  $y_{uv}$  and  $y_{vu}$  refers to the same undirected edge  $\{u, v\} \in E$ .

Define  $x_{uv}^{kl}(i, c)$  as another binary variable, a flow variable, which is 1 if the path between nodes  $k$  and  $l$  includes edge  $\{u, v\}$ , uses interface  $i \in I_u$ , and operates on channel  $c \in C_i^u$ ; and is 0 otherwise.

Define  $z_{uv}(i, c)$  as a binary variable, an interface channel use variable, which is 1 if edge  $\{u, v\}$  uses  $i \in I_u$  on channel  $c \in C_i^u$ , and is 0 otherwise.

Define  $q_{uv}^i$  as a load cost. Note that  $q_{uv}^i$  may be different from  $q_{vu}^i$  when the links are asymmetric - which may be the case when the sender and receiver users are subject to different interference. These definitions make it possible to specify the objective function and constraints that model this problem.

*Objective function*

$$\min \left\{ \sum_{(u,v,i) \in T, (k,l) \in P} x_{uv}^{kl}(c,i) \cdot q_{uv}^i \cdot d_{kl} \right\} \quad (1)$$

This objective function minimizes the total time required to transfer the aggregate of the demands across the network.

*Constraints*

$x_{uv}^{kl}(c,i)$ ,  $y_{uv}$ , and  $z_{uv}^{kl}(c,i)$  are binary variables:

$$y_{uv} \in \{0, 1\} \quad \forall (u,v) \in E \quad (2)$$

$$x_{uv}^{kl}(c,i) \in \{0, 1\} \quad \forall (u,v,i) \in T, \forall (k,l) \in P, \forall c \in C_i^u \quad (3)$$

$$z_{uv}^{kl}(c,i) \in \{0, 1\} \quad \forall (u,v,i) \in T, \quad \forall c \in C_i^u \quad (4)$$

Tree-shaped solution and number of edges constraint - a topology with a tree structure must have  $(|V| - 1)$  edges:

$$\sum_{(u,v) \in E} y_{uv} = |V| - 1 \quad (5)$$

Span all vertices constraint - graph must be fully connected:

$$\sum_{(u,v) \in A_v} y_{uv} \geq 1 \quad \forall v \in V \quad (6)$$

Single path constraint and flow conservation at the edges of a path - there is one and only one outgoing flow from source  $k$  between  $(k, l)$ :

$$\sum_{(k,v,i) \in T, c \in C_i^k} x_{kv}^{kl}(c,i) - \sum_{(k,v,i) \in T, c \in C_i^v} x_{vk}^{kl}(c,i) = 1 \quad \forall (k,l) \in P \quad (7)$$

Single path constraint and flow conservation in between the edges of a path - if a vertex is neither a source nor a sink, then for each incoming flow there must be an outgoing flow:

$$\sum_{(u,v,i) \in T, c \in C_i^u} x_{uv}^{kl}(c,i) - \sum_{(u,v,i) \in T, c \in C_i^v} x_{vu}^{kl}(c,i) = 0 \quad (8)$$

$\forall (k,l) \in P, \quad \forall i \in V : k \neq u \neq l$

Channel usage constraints: if a channel is being used by any flow on a directed edge, then it must be part of the channel usage solution, subject to a directional tree-shape constraint, i.e. with a total number of directed edges of  $2 \cdot (|V| - 1)$ .

$$x_{uv}^{kl}(c,i) \leq z_{uv}^{kl}(c,i) \quad (9)$$

$$x_{uv}^{kl}(c,i) \leq z_{vu}^{kl}(c,i) \quad (10)$$

$$\sum_{(u,v,i) \in T, c \in C_i^u} z_{uv}^{kl}(c,i) = 2 \cdot (|V| - 1) \quad (11)$$

$\forall (u,v,i) \in T, \quad \forall (k,l) \in P, \quad \forall c \in C_i^u$

Edge usage constraints: if a flow is using an edge, then the edge must be part of the final solution. The solution is an undirected graph, while the flows are directed.

$$x_{uv}^{kl}(c,i) \leq y_{uv} \quad (12)$$

$$x_{vu}^{kl}(c,i) \leq y_{uv} \quad (13)$$

$$\forall (u,v,i) \in T, \quad \forall (k,l) \in P, \quad \forall c \in C_i^u$$

Capacity constraint: the sum of the load of every flow being

transferred using channel  $c$  must be less than the total capacity of the channel,  $U_c$ .

$$\sum_{(u,v,i) \in T, c \in C_i^u, (k,l) \in P} x_{uv}^{kl}(c,i) \cdot q_{uv}^i \cdot d_{kl} \leq U_c \quad (14)$$

$\forall c \in C$

The output variables  $x$ ,  $y$ , and  $z$  provide complete information about the optimal overall topology ( $y$ ), interfaces and channels used by each node ( $z$ ), and the flows' paths ( $x$ ).

## V. EVALUATION

In order to understand and quantify the benefits achievable, a Matlab simulation is performed under different scenarios. For every scenario, the simulations follow some general steps:

- Generate the network topology with  $N$  nodes;
- Place nodes in an area of  $(400 * \log(N))m^2$  (empirical), log-proportional to the number of nodes (power laws);
- Use a dual slope free space propagation model to estimate the SNR from/to each node on the different interfaces and frequency bands ( $\alpha_1 = 3$ ,  $\alpha_2 = 3.5$ , critical  $d = 5m$ ). Wireless links are considered to be non-existent if the SNR falls below 0dB (distance of  $\sim 20m$  @ 2.4GHz);
- Compute a cost matrix from/to each node, as per III;
- Ensure that a single-AP topology is possible. The most well-connected node is an AP and internet gateway;
- Randomly generate a demand matrix specifying the flows between each node;
- Run the Linear Program Optimization;
- Run the Linear Program Optimization in single-AP mode;

It is assumed that each node has two available interfaces, one in the 2.4GHz band and another on the 5GHz band. The maximum number of channels available for selection is limited to 3 per band for two reasons: making sure that the optimization mechanism does not select too many channels that would suffer from adjacent channel interference because of frequency overlapping; limit the computational requirements, as they scale linearly with the number of possible channels.

Two topology types are set-up in a square 2D area: a random one, where the nodes are spread using a random function with uniform probability; and a star-like topology, with one node in the center of the area and the remaining ones evenly spread in a circle around it - at the maximum possible distance for the square area. The randomly specified flows have a fixed throughput of 128Kbps, and  $N/2$  flows are generated. This low throughput is used to enable low-bitrate connections to be utilized, and avoid overloading the network to the point where any comparison would not be meaningful. The simulations run 100 times per topology and the results are averaged out. The 95% confidence interval is shown.

### A. Cost of the Solutions

In the first 3 scenarios, the generation process ensures that full connectivity exists using a single AP, so that the traditional topology may be compared with the proposed solutions.

The results are evaluated in terms of cost (the value of the objective function for a specific solution) relative to the LP solution cost. Higher costs equate to higher network usages.



The first scenario simulates a network environment with mixed traffic sources, i.e. internet and intranet. Results are presented in figure 1. The second scenario simulates the situation where the AP is used simply to provide internet access. The results are shown on figure 2. The third scenario simulates situations where the traffic is all intranet, such as in surveillance systems, sensor networks, media-streamers/receivers. The results are shown in figure 3.

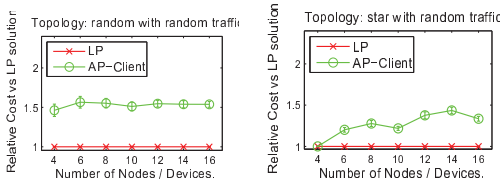


Figure 1. Relative cost of the solutions in a mixed traffic environment.

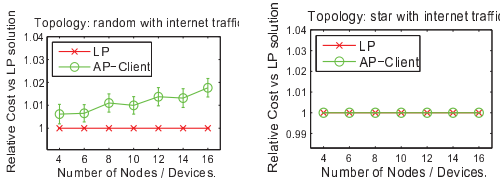


Figure 2. Relative cost of the solutions in an internet traffic environment.

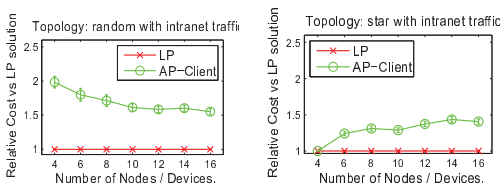


Figure 3. Relative cost of the solutions in an intranet traffic environment.

Regarding scenario 1, on both topologies, the LP solution shows that large performance benefits are possible. On average, a reduction of  $\sim 28\%$  in cost is achievable. The star topology benefits the least, which is to be expected since the nodes are evenly spread out and the AP is widely used as a relay node, particularly in situations with fewer nodes.

The results of scenario 2 are completely different from the ones of the first scenario, because the traffic is all directed to/from the AP, and there is guaranteed connectivity to it (preliminary assumptions), the performance improvements are marginal. There are no performance advantages to be had in the star topology, since no relaying is required. Nevertheless, in the random topology there are some performance gains, mostly due to node relaying, though the cost improvements are marginal (at around 1%). Scenario 3 is the one that takes the most advantage of a topology reconfiguration. The average cost advantage of the LP solution is 31%. This is explained by the reduction in the use of the AP as a central node, the leveraging of direct connections, and the relaying of nodes that are in better position than the AP.

### B. Assessing the Network Range Extension Advantages

A reconfigured topology has an additional advantage besides increased throughput, namely, the potential for range extension of the wireless network. Since node relaying is possible, network nodes that aren't close enough to the AP can still be a part of the network if other device that is connected

to the rest of the network is within range. Such scenario is not possible in current Wi-Fi networks without dedicated devices.

To assess the potential range gains, a simulation is performed. A number of nodes is randomly spread out in an area as previously specified, and 2 tests are performed: the first tests whether a fully connected topology in the typical AP-Client situation is possible; the second tests if there is a possible topology where every node in the network is connected, i.e. node relaying is possible and the graph is 1-connected.

The simulation is run 1000 times for each number of nodes, and the results are presented in figure 4.

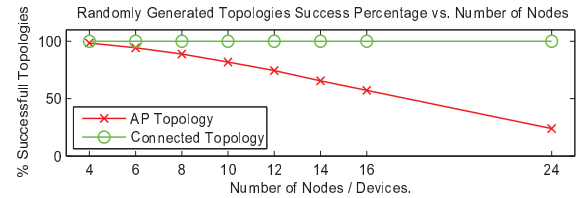


Figure 4. Random Topologies Success Rate vs. Number of Nodes.

As can be assessed through the results, for a small amount of network nodes (up to 6), and proportionally small wireless network area, over 90% of the randomly generated topologies are valid for using a AP-Client topology; as the number of nodes in the network increases so does the network area, and the % of randomly generated topologies valid for an AP-Client configuration starts to diminish. On the other hand, if the topology only needs to be a 1-connected graph to be valid, 100% of the randomly generated topologies are valid. This is an encouraging fact that hints at significant range extension possibilities if the AP-Client topology constraint is removed.

## VI. CONCLUSIONS

Home wireless networks provide non-optimal performance due to deployment constraints and a growing number of Wi-Fi connected devices. In virtue of these performance limitations, self-optimized wireless networks providing automatic topology reconfiguration are shown to have a place in home networks, as they provide tangible performance benefits in terms of wireless network range and performance. These benefits can be exploited through the creation of a management layer taking advantage of the Wi-Fi Direct technology.

## VII. ACKNOWLEDGMENTS

The authors are thankful to the *Fundação para a Ciência e Tecnologia* (FCT) for the Ph.D Grant SFRH/BD/51565/2011.

## REFERENCES

- [1] V. Visoottiviseth, T. Piroonsith, and S. Siwamogsatham, "An empirical study on achievable throughputs of IEEE 802.11n devices," in *7th IEEE WiOpt.* IEEE, Jun. 2009, pp. 1–6.
- [2] Wi-Fi Alliance, "Wi-Fi Direct," *Industry White Paper*, no. October, p. 14, 2010. [Online]. Available: <http://www.wi-fi.org/>
- [3] J. Berg et al., "SOCRATES: Self-Optimisation and self-Configuration in wireless networks." [Online]. Available: <http://www.fp7-socrates.eu/>
- [4] E. Meshkova et al., "Using cognitive radio principles for wireless resource management in home networking," in *IEEE CCNC*, 2011.
- [5] Z. Wang et al., "Self-organizing home networking based on cognitive radio technologies," in *IEEE DySPAN*, 2011.
- [6] M. Petrova et al., "A Common Application Requirement Interface for Cognitive Wireless Networks," in *6th IEEE Sensor, Mesh and Ad Hoc Communications and Networks Workshops (SECON)*, 2009, pp. 1–7.
- [7] K. Piamrat et al., "Coordinated architecture for wireless home networks," *2nd ACM SIGCOMM workshop on Home networks*, p. 49, 2011.