This article has been accepted for publication on the 18th International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM) Demo Session (WoWMoM 2017 Demo Session), but has not been fully edited. Content may change prior to final publication.

Practical Distributed Channel Assignment in Home Wi-Fi Networks

Sven Zehl, Anatolij Zubow and Adam Wolisz
{zehl, zubow, wolisz}@tkn.tu-berlin.de
Telecommunication Networks Group, Technische Universität Berlin, Germany

***Abstract*—The efficient management of radio resources in today's home or residential Wi-Fi networks is still an open research question. Due to the chaotic and unplanned deployment of Wi-Fi Access Points (APs) and the fact that all APs are managed individually by their owners, home Wi-Fi networks suffer from performance degradation due to contention and interference.**

In this paper we present and showcase a distributed radio channel assignment scheme, implemented using the ResFi platform, in which neighboring home Wi-Fi APs cooperate with each other in order to negotiate radio channel selection by taking into account the instantaneous network load of neighboring APs (two hop neighborhood). While the information about the network load can be directly exchanged between ResFi-enabled APs using the ResFi out-of-band Internet control channel, the information about the network load of co-located non-ResFi APs first needs to be estimated passively by monitoring the data traffic on the radio channel.

The presented demonstrator of the approach is implemented using commodity hardware and enables the audience to observe the distributed channel adaptation in real-time.

Index terms— Wi-Fi, Cooperative Networks, Self-Organizing Networks, Home Wi-Fi, Smart Cities, ResFi

I. Introduction

In the last years the popularity of IEEE 802.11 (Wi-Fi) networks has increased significantly because of their ability to provide a comfortable way to connect a multitude of devices. As most recent applications like virtual reality or 4K video streaming require high QoS, the dense deployments of Wi-Fi Access Points (APs) observed nowadays cause performance issues due to high contention and interference within the limited set of radio frequencies.

In enterprise networks, remaining within a single administrative domain, this issue is commonly solved by installing a centralized controller which manages the channel assignment of all APs with respect to the load they carry and in order to avoid overlapping channels. But in contrast, residential or home Wi-Fi deployments usually consist of multiple autonomous APs remaining under administration of their individual users, who due to lack of technical skills attempt to minimize the configuration effort. While in the past this led to the well-known phenomenon of using mostly the same pre-configured channel, manufacturers started increasing the scope of self-optimization functions provided. This self-optimization, which is mostly only activated during the set-up or reset of an AP, is, however, still limited to functions depending

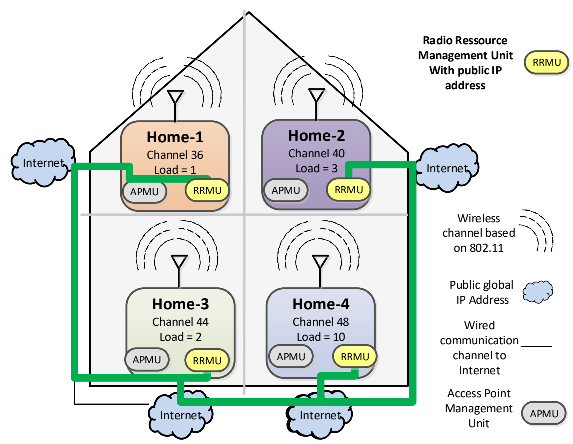

Fig. 1. Illustration of a residential apartment building with ResFi enabled APs - neighboring APs detect each other over the air and establish encrypted control channels over the Internet which are then used by distributed radio resource management applications.

exclusively on local observations within the AP and local controls. In the residential deployment the individual APs - even located in close proximity - do not have a direct way to enter an organized information exchange and negotiations.

In this paper, we demonstrate the ResFi framework [1] which enables residential Wi-Fi APs to detect their neighboring APs and to build up secured side-channels over the Internet to them, cf. Fig. 1. These control channels are then used to perform distributed radio resource management (RRM) such as radio channel assignment with the N-hop neighborhood.

Moreover, we showcase a distributed channel assignment application which enables neighboring APs to negotiate radio channel assignments by taking into account their current network load and the network load of their N-hop neighbors.

Contributions:

a) Demonstrator: The demo setup consists of four home APs, each running the ResFi framework together with the proposed channel assignment application. A Wi-Fi spectrum analyzer allows the audience to observe the channel adaptation in real-time. During the course of the demonstration the channel assignment application can be turned on and off to show the benefits of the proposed cooperative channel assignment approach.

b) Channel assignment approach: Every ResFi enabled AP shares the gathered load information about its own load

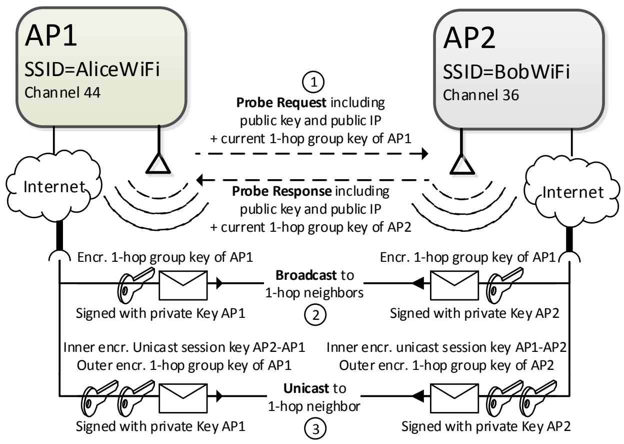

Fig. 2. Overview of the system architecture of ResFi: the wireless channel is used for the exchange of configuration parameters (global IP of the RRM unit, transient group encryption key and public RSA key) which are afterwards used for setting up secure P2P out-of-band control channels over the Internet.

and about the load of co-located non-ResFi APs operating on the same radio channel with all two hop neighbors in real-time. This gives all participating APs the complete knowledge about the load of all used radio channels without the necessity to perform periodic channel scanning (which would either require an additional radio interface or would cause inconvenient network outages observed by the client STAs due to radio channel switching). Our approach enables the participating APs to perform adaptive channel assignment with real-time load information incorporating all two hop neighbor APs which in addition to reducing contention also enables to mitigate co-channel interference due to possible hidden node problems.

II. The ResFi approach in a nutshell

ResFi enables distributed Radio Resource Management (RRM) functionality in home Wi-Fi deployments. The radio interfaces of participating APs are used for efficient discovery of adjacent APs and to create a side-channel for the exchange of connection parameters (like the public IP address of AP's RRM unit) and security credentials. Those data enable in turn the setting up of secured communication tunnels between adjacent APs via the (wired) Internet, cf. Fig. 1.

The ResFi connection procedure, which is fully compliant to the IEEE 802.11 standard, depicted in Fig. 2, can be presented in a nutshell as follows: During the boot-up phase of any AP a broadcast probe request frame including a special ResFi vendor specific information element (IEV) containing so-called "contact data" is triggered sequentially on each of the supported channels (standard active scanning procedure of 802.11). Any AP within the coverage of this scan request is expected to answer with the respective "contact data" of the responder, cf. Fig. 2 tag (1). The contact data, embedded in a IEV of both the active scan probe request and response consists of the globally-routable IP address and port number of the AP's RRM unit (RRMU) (on the fixed internet) as well as of a transient one-hop group encryption key and a public cryptography key individual to this RRMU. After having completed the active scan and having received the answers, the RRMU of the newly booted AP can establish a secure, point-to-point control channel to the RRMUs of all the "discovered" APs over the wired backbone Internet, cf. Fig. 2 tag (2). In addition, the discovered APs will do the same in the reverse direction.

It is, however, well known that RRM (e.g. channel selection) can achieve better efficiency if performed over a cluster of APs larger than one hop neighborhood. Therefore, ResFi provides the functionality that each RRMU is able to act as a forwarder enabling to extend secure connectivity towards up to N hops (N can be set individually for every message sent via ResFi's northbound framework API). ResFi does not define the precise policy to create an RRM cluster within the scope of the connectivity borders mentioned above; neither does it feature a specific RRM approach. Both of these decisions are delegated to an RRM application which is not a part of the platform itself.

The security of the control channel is not constrained to the establishment with the use of proper cryptography keys; in addition the keys are occasionally changed. Further, as the exchanged symmetric group encryption keys are known to the full group, ResFi applications can, to enable confidentiality between two APs, request uni-cast encryption with a distinct peer by utilizing the asymmetric keys exchanged during the discovery phase, cf. Fig. 2 tag (3).

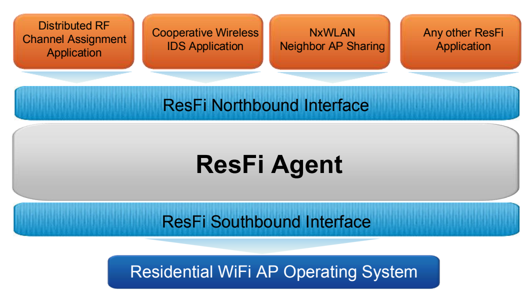

Fig. 3. ResFi northbound and southbound API, while the south-bound API enables vendors to connect their AP solution with ResFi, the extensible northbound API is used by ResFi applications which can run concurrently on top of ResFi.

ResFi provides a well-defined north-bound and south-bound API, cf. Fig. 3. While the south-bound API enables vendors and researchers easily to connect their current AP solution with the ResFi framework, the extensible northbound API is used by ResFi application developers to implement their own RRM solution, e.g. as shown in [2].

Multiple ResFi applications can be executed concurrently and independently from each other on top of the ResFi framework which takes care about the correct message passing and security of the Internet side-channel.

For more details about the ResFi framework, please refer to our full paper [1].

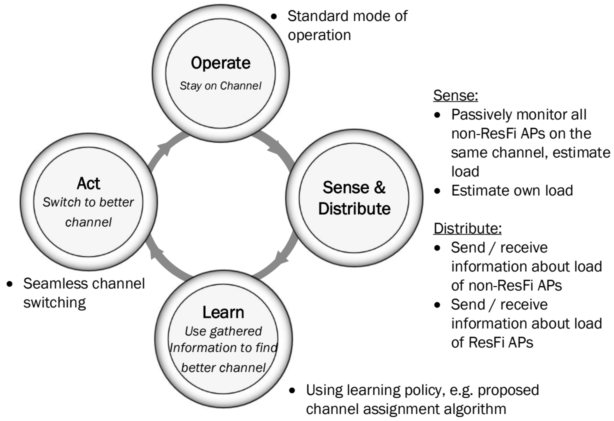

Fig. 4. ResFi channel assignment application represented as cognitive loop.

III. Distributed Channel Assignment Application for Home Wi-Fi Networks

The demonstrated distributed channel assignment application running on top of the ResFi framework can be illustrated as a cognitive loop shown in Fig. 4. In a first step, the required information for decision making is gathered. For this reason, the state ***Sense & Distribute***, is used on the one hand for local sensing of the network load, e.g. number of active STAs, of non-cooperative, i.e. non-ResFi, APs, and on the other hand for local estimation of the own network load within the AP. Every time new information was collected it is shared among all participants running the channel assignment application. Retroactively, all other cooperating APs share their collected information about their own network load as well as the load of non-cooperating APs on their radio channel. The ***Learn*** state enables to analyze the network load information to find a better radio channel adaptation. In the next step, ***Act***, the AP together with all associated client stations (STAs) switch to the channel given in the newly estimated channel allocation. Finally, ***Operate*** represents the standard mode of operation.

For the purpose of the demo the following specific approach was selected:

A. Sensing & Distributing Phase

1) Estimating own load: As an estimate of the network load of a home AP we selected the number of active client stations as metric. In particular we define a STA as being active if it has transmitted or received more than `thr_threshold` bytes during the last sample interval `sample_inter`. In the current setup we used a sample interval of 5 s and a threshold of 500 Kbyte. In addition, all APs send their current load to all of their ***two-hop neighbors*** in the interval `sample_inter`. Taking the two hop neighborhood into account enables the channel assignment application to mitigate also interference situations that occur when two different APs are out of carrier sensing range, e.g. hidden node situations. Moreover, it also incorporates the situation in which clients associated to two different APs interfere with each other while the corresponding APs are not interfering.

Algorithm 1 Channel Assignment Algorithm (pseudo code)

```
procedure DIST_CHAN_RESFI
    lmax ← 0
    for all resfi_neighbors do  ▷ Receive load information from two hop
    neighboring ResFi APs about their own load and about estimated load of
    all non ResFi APs operating on their radio channel
        lneigh_rf ← receive_rf_load()
        lneigh_nrf ← receive_nrf_load()
        data_fusion(lneigh_rf, lneigh_nrf)
    for all channels x from [1...N] do  ▷ Calculate overall load for each
    available radio channel
        lsumcha[x] ← 0
        for all neighbors with channel x do
            lsumcha[x] ← lsumcha[x] + lneigh
        lsumcha[x] ← lsumcha[x] + lself
    bestcha ← 0
    leastload ← 1e9
    for all channels x from [1...N] do ▷ Choose radio channel with least
    load
        if lsumcha[x] < leastload then
            bestcha ← x
            leastload ← lsumcha[x]
    return bestcha
```

2) Identifying non-cooperative APs: As cooperative ResFi APs are embedding their connection credentials within the special ResFi IEV; all Probe Requests sent by neighboring APs which do not contain the ResFi IEV are classified as non-cooperative APs. In this initial detection step, all non-ResFi APs are then classified as low load APs to enable load detection in the second step.

3) Load Detection of non-cooperative APs: As a result of our utilized distributed channel assignment algorithm, cf. Sec. III-B, APs with low load will be placed together on the same radio channel if the number of available radio channels is not sufficient.
Non-ResFi APs with currently undetermined load will be as described in the last paragraph classified as low load APs and will therefore share their radio channel with a ResFi AP with low load.
As on the one hand, this minimizes the risk of high interference to the ResFi AP , it allows on the other hand to passively monitor the traffic on the radio channel to estimate the load (number of active client STAs) of the non-ResFi AP (we currently use the same threshold and interval for active STA classification as we defined for the own load estimation, cf. Sec. III-A1).
Once the load of the non-ResFi AP(s) was detected, the information is shared with all two-hop neighbors. Moreover, as also legacy APs change their radio channel or may change their load, all ResFi APs permanently and passively monitor their currently used radio channel in order to update the load of non-ResFi APs and in order to report it to all two-hop neighbors.

4) Information Sharing: Reception of messages from neighboring APs is done automatically by the ResFi framework; callbacks can be registered to enable the processing of incoming messages. For sending information to two hop neighbors, the ResFi northbound API enables comfortable ways to send messages to N-hop neighbors.

B. Learning Phase

In the demo we use a simplified version of the weighted coloring channel assignment algorithm *Hsum* proposed by Mishra et al. [3]. We adapted the approach to full-fill the demands of real-world residential Wi-Fi deployments, e.g. data fusion with non-cooperative APs, cf. Sec. III-A3.The part of the algorithm which is executed on every participating AP (ResFi enabled AP) is given as pseudo code in Listing Alg.1. The algorithm takes as input the load (number of active client STAs, cf. Sec. III-A1 and III-A3) of all neighboring ResFi APs (`lneigh_rf`) and all non-ResFi APs (`lneigh_nrf`) whose load was determined passively by the neighboring ResFi APs, cf. Sec. III-A. Afterwards ResFi and non-ResFi APs are treated equally by the algorithm (treated as *neighbors*). The algorithm then chooses a channel with the minimum load.
As we currently not incorporate the adjacent channel interference present in the 2.4 GHz band, we only utilize non-overlapping channels, e.g. channel 1, 6 and 11 plus all available channels of the 5 GHz ISM band.

C. Acting Phase

Fortunately, starting with the definition of the IEEE 802.11n standard, the IEEE defined a method for near seamless channel switching. This method is part of the dynamic frequency selection functionality (DFS), originally defined to enable APs upon the detection of a radar system to perform a channel switch together with their associated client STAs. To this end, the AP announces the imminent channel switch using an additional IE named Channel Switch Announcement (CSA-IE) within its beacon frames including the number of beacon intervals till the channel switch will happen plus the new target channel. Upon reception of the CSA-IE, all client STAs simultaneously perform a channel switch to the new channel. This functionality can be exploited to perform seamless infrastructure initiated channel switches of the client STAs, e.g. as described in [4] and also demonstrated in [5].

As this functionality must be supported by all client STAs which support DFS (most STAs supporting 802.11n and upwards) we rely on this functionality which enables us to perform channel switching whenever a better channel was found by the channel assignment application.

IV. Demonstrator Setup

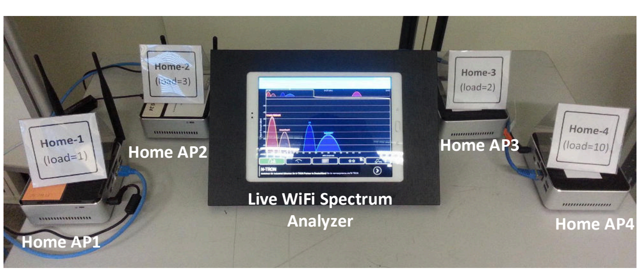

Fig. 5. Demonstrator Setup consisting of four home APs and a real-time spectrum analyzer showing the current channel allocation.

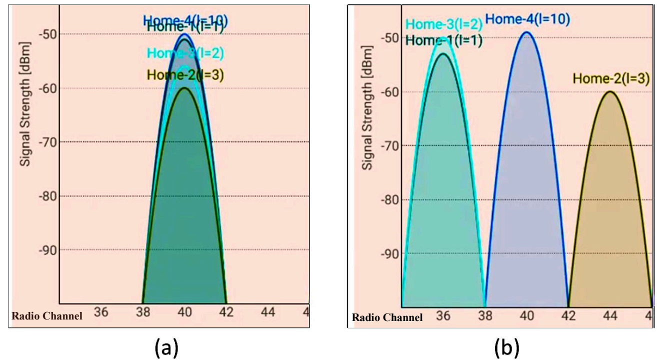

Fig. 6. Screenshots of the Wi-Fi spectrum analyzer (Android Tablet): (a) **baseline** - all home APs are operating on the same pre-configured channel, (b) **proposed** - channels are assigned according to proposed distributed algorithm to home APs taking into account their network loads, i.e. APs with load 10 and 3 respectively are assigned to distinct channels, whereas the APs with less load (1 and 2) are sharing a channel. Note: the number of available radio channels was artificially shortened to three.

The demo setup consists of four home APs, each running the ResFi framework together with the aforementioned distributed channel assignment algorithm, cf. Fig. 5. The APs are small-form-factor-PCs based on Intel NUC and Linux. To enable seamless channel switching, cf. Sec. III-C, we utilize the DFS channel switch functionality present in the Linux software AP solution *hostapd*. Moreover, an Android Tablet running a Wi-Fi spectrum analyzer application allows the audience to observe the channel adaptation in real-time.

During the course of the demonstration we disable the channel assignment application resulting in a configuration where all APs switch to the same radio channel, cf. Fig. 6(a), which mimics the worst case scenario in which all APs use the same static (pre)configured channel. Consequently, we enable the channel assignment application allowing the audience to observe the reassignment of the radio channels to APs depending on their instantaneous network load, cf. Fig. 6(b). Moreover, during the demonstration we vary the number of available channels and change the network load of the APs in order to demonstrate the fast adaptability of the proposed solution.

Acknowledgment

This work has been supported by the EU's H2020 program grant agreement No. 645274 (WiSHFUL project) and the SDN Wi-Fi Community project funded by Deutsche Telekom.

References

[1] S. Zehl, A. Zubow, M. Döring, and A. Wolisz, "Resfi: A secure framework for self organized radio resource management in residential wifi networks," in *IEEE WoWMoM 2016*, June 2016.

[2] P. Gawlowicz, S. Zehl, A. Zubow, and A. Wolisz, "Nxwlan: Neighborhood extensible wlan," *arXiv preprint arXiv:1607.03254*, 2016.

[3] A. Mishra, S. Banerjee, and W. Arbaugh, "Weighted coloring based channel assignment for wlans," *Mob. Comput. Commun. Rev.*, Jul. 2005.

[4] A. Zubow, S. Zehl, and A. Wolisz, "BIG AP – Seamless Handover in High Performance Enterprise IEEE 802.11 Networks," in *NOMS, 2016 IEEE*, April 2016.

[5] S. Zehl, A. Zubow, and A. Wolisz, "BIG AP - A Seamless Handover Scheme for High Performance Enterprise IEEE 802.11 Networks," in *IEEE NOMS Demos 2016*, April 2016.