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Тема / Topic	**Проектирование и реализация алгоритма адаптивного управления радиоресурсами в беспроводных сетях стандарта IEEE 802.11 с несколькими точками доступа / Design and Implementation of Adaptive Radio Resource Management algorithm in IEEE 802.11 multi-AP WLANs**

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Abstract

As IEEE 802.11-compatible ("Wi-Fi") Wireless Local Area Networks (WLAN) become ubiquitous, the rising density of WLAN deployments leads to congestion of frequency bands and performance degradation due to interference. Thus, Radio Resource Management (RRM) algorithms for mitigating those problems become in demand, especially for large WLAN deployments. While several commercial RRM solutions exist, their implementation details remain undisclosed. At the same time, proposals from previous research have considerable obstacles for production usage. This thesis presents a novel super-cell RRM algorithm. This algorithm adjusts frequency and transmission power parameters based on physical-layer and link-layer metrics, and employs usage of a WLAN Controller (WLC) as a central entity able to gather data for overall WLAN. Integrated into the Wimark WLC RRM module, our approach achieves up to 67% faster convergence without requiring changes to the 802.11 standard. With enhanced spectrum management, our algorithm delivers 31% increase in Signal-to-Interference-Plus-Noise Ratio (SINR) on Access Points (APs) and up to 29% bandwidth improvement compared to legacy algorithms, demonstrating its readiness for production usage and integration into existing enterprise infrastructure.

Chapter 1

Introduction

I Part 1. Introduction

A. Importance of the topic

Nowadays, wireless local area networks (WLAN) implementing IEEE 802.11 standards,commonly known under "Wi-Fi" brand, become an increasingly popular solution for last-mile internet access with a diverse population of users, starting from home Wi-Fi routers up to large campus- and city-scale WLANs with coverage areas reaching several square kilometers. As a result, the density of Wi-Fi network increases, so the frequency band allocated for 802.11 networks becomes more congested, which leads to interference and signal cancellation between different WLANs, resulting in network performance degradation. Moreover, other appliances operating on frequencies that overlap with Wi-Fi band, undermining the performance of WLANs. To meet current bandwidth and latency expectations of modern network applications, such as video streaming, cloud computing, and video conferencing, the wireless network must be able to provide sufficient capacity to all clients. In this light, proper radio resource management becomes crucial for operating wireless networks.

B. What is already known about the topic

The problem of managing radio resources is studied extensively in the context of cellular networks, which are characterized by extensive frequencies reuse, large number of clients and large coverage areas spanning multiple kilometers, so the proper spectrum management is vital for operation of cells. This problem breaks down to the following: given a set of access points $\boldsymbol{B}$, which can communicate over a set of channels $\boldsymbol{C}$, with a maximum transmit power of P_{max}, establish a radio link between a client device and an access point by assigning it a triplet (b, c, p), where $b \in \boldsymbol{B}$, $c \in \boldsymbol{C}$, $p \leq P_{max}$. Essentially, RRM algorithms aim to provide such assignments that maximize the overall network performance.

C. Limitations of existing approaches

A growing demand for Radio Resource Management (RRM) solutions, especially for large enterprise-grade multi-AP WLAN deployments, has led to the development of multiple commercial solutions, such as Cisco Radio Resource Management (RRM) **ciscoCiscoRadioResource**, Aruba Adaptive Radio Management (ARM) **arubaAdaptiveRadioManagement**, and others. However, existing solutions offered by major vendors are proprietary, so their source code, used algorithms and details of operation are not disclosed. In the same time, most studies on RRM have only focused on cellular networks, while RRM in 802.11 networks received much le. Existing works on RRM in 802.11 networks have problems in applicability, since real-world hardware poses constraints on what metrics can be retrieved from the WLAN and which physical and link-level parameters can be adjusted.

D. Contribution and signiicance of the thesis

This thesis aims to fill this gap by proposing a new RRM algorithm that, unlike existing market solutions, is publicly available, and at least as effective, while being practical and applicable to real-world WLAN deployments. By analyzing theoretical works on 802.11 RRM, we come up with suitable optimization approach that combines both Adaptive Channel Selection (ACS) and Transmit Power Control (TPC) techniques to improve RF spectrum situation EM compatibility and channel reuse, which in turn leads to improved capacity of a wireless network. Our approach benefits from the employment of Wireless LAN Controller (WLC) a central entity in the WLAN architecture that is able to control and collect telemetry from all access points within a WLAN.

Nowadays, wireless local area networks (WLAN) implementing IEEE 802.11 standards, which are commonly known under "Wi-Fi" brand, become an increasingly popular solution for last-mile internet access with a diverse population of users, starting from home Wi-Fi routers up to large campus- and city-scale WLANs with coverage areas reaching several square kilometers. As a result, the density of Wi-Fi network increases, so the frequency band allocated for 802.11 networks becomes more congested, which leads to interference and signal cancellation between different WLANs, resulting in network performance degradation. Moreover, other appliances operating on frequencies that overlap with Wi-Fi band, undermining the performance of WLANs. This situation has led to a growing demand for Radio Resource Management (RRM) solutions, especially for large enterprise-grade multi-AP WLAN deployments. However, existing solutions offered by major vendors are proprietary, so their source code, used algorithms and details of operation are not disclosed. In the same time, academic papers on RRM are mostly focused on cellular networks, which are different, so their solutions are not directly applicable to WLANs. Existing works on RRM in 802.11 networks have problems in applicability, since real-world hardware poses constraints on what metrics can be retrieved from the WLAN and which physical and link-level parameters can be adjusted. This thesis aims to fill this gap by proposing a new RRM algorithm that, unlike existing market solutions, is publicly available, and at least as effective, while being practical and applicable to real-world WLAN deployments. By analyzing theoretical works on 802.11 RRM, we come up with suitable optimization approach that combines both Adaptive Channel Selection (ACS) and Transmit Power Control (TPC) techniques to improve RF spectrum situation EM compatibility and channel reuse, which in turn leads to improved capacity of a wireless network. Our approach benefits from the employment of Wireless LAN Controller (WLC) a central entity in the WLAN architecture that is able to control and collect telemetry from all access points within a WLAN.

Integrated into the Wimark WLC RRM module, our approach achieves up to 67% faster convergence. The enhanced spectrum management provided by our algorithm delivers 31% increase in Signal-to-Interference-Plus-Noise Ratio (SINR) on Access Points (APs) and up to 29% bandwidth improvement compared to legacy algorithms, demonstrating its readiness for production usage and integration into existing enterprise infrastructure.

The rest of this Thesis is structured as follows: Chapter 2 reviews existing academic research on managing radio resources and publicly available information about proprietary RRM solutions; in Chapter 3, we formulate the mathematical model of transmission in a wireless network, review the existing RRM algorithm at Wimark Systems, identify its weaknesses and derive a new algorithm; in Chapter 4, we describe implementation details for the algorithm in NS-3 simulator and Wimark products; in Chapter 5, we evaluate the performance of our algorithm; Chapter 6 contains the results and discussion.

Below in this chapter, we briefly review the fundamentals of Radio Frequency (RF) communications, and IEEE 802.11 standard for wireless LAN.

II Overview of IEEE 802.11 standard

Throughout this Thesis, we will refer to field-specific terms, whose definitions are given in Table 1.2:

A. Transmission medium

The primary medium for communications in IEEE 802.11 are electromagnetic (EM) radio-frequency (RF) waves operating within the microwave range [2]. Infrared radiation (IR) as a transmissions medium was defined in the legacy 802.11 standard and then had been deprecated; 802.11bb amendment, introducing communications through visible light, is yet to be finalized and become commercially mature technology.

B. Frequency band

Most of the 802.11 amendments, including b,g,n, and partially ax, operate at the unlicensed 2.4 GHz ISM (Industrial, Scientific, Medical) RF band [2], [4]. Using an unlicensed frequency band, however, introduces multiple challenges: the radio spectrum becomes congested with non-802.11 sources, such as microwave ovens, Bluetooth Personal Area Networks (PAN), cordless phones etc. [2], [4]. Moreover, 2.4 GHz signals can propagate through solid obstructions like walls, doors, and windows better than signals operating on higher-frequency ones [4]. This property can provide better coverage and signal quality for clients, although can cause interference for neighboring WLANs, which will in turn lead to degradation of signal quality.

2.4 GHz band is split into 14 channels, each 22 MHz wide [1]. Each channel is characterized by its *center frequency*, +- 11 MHz, with 5 MHz width between two adjacent centers, i.e, the channels *overlap*. Channel 1 has central frequency 2.412 GHz, Channel 14 2.484 GHz. Thus, for channels to be non-overlapping, they must have at least 5 channels in between. Such non-overlapping channels are 1, 6, 11, with central frequencies 2.412, 2.437, and 2.462 MHz, respectively.

Another frequency band is used by 802.11a/ac/ax radios is 5 GHz U-NII.

C. Signal quality and its metrics

Thus, the presence of physical obstructions, background noise and interference from other access points urges us to explore possible measurements and metrics for a wireless signal quality. Below, we will briefly describe the most widely used quantities:

A measure widely used in RF engineering and employed by Wi-Fi vendors is **Signal-to-Noise Ratio (SNR)**, which is defined as a ratio between the received signal power and the power of background noise [2]:

$$SNR = \frac{P_{signal}}{P_{noise}} \tag{1.1}$$

Since SNR is essentially a difference in power, which is measured in Watts, in practice it is measured in a relative unit on a logarithmic scale called **decibel (dB)** [1,2]:

$$SNR_{dB} = 10 \log_{10} \frac{P_{signal}}{P_{noise}} \tag{1.2}$$

In recent years, **Signal-to-Interference-Plus-Noise ratio (SINR)** measurement have become a more widespread measurement of wireless networksśignal quality. Similarly, it is defined as:

$$SINR = \frac{P_{signal}}{P_{noise} + P_{interf}} \tag{1.3}$$

where P_{signal} is the power of the signal of interest, and P_{interf} is the power of interfering signals. By considering interference from other 802.11 devices, which is typically a dynamic quantity that changes rapidly over time unlike background noise, SINR describes EM spectrum situation more accurately.

Received Signal Strength Indicator (RSSI) relative measure of signal strength in range from 0 to 255, where 0 is the weakest signal a receiver is able to sense. The exact correspondence between RSSI and received signal power is implementation-specific and is left on behalf of hardware manufacturers [1].

D. Radio Resource Management

The scarcity of available frequency bands in the time of growing demand for wireless connectivity has led to the development of methods called *spectrum management* or *radio resource management (RRM)*. Most of research on RRM is focused on cellular networks, where coverage area of base stations spans across multiple kilometers, and the number of clients for one station can reach several thousands, so proper spectrum management is vital for operation of cells. However, from the physical layer perspective, the radio situation in 802.11 networks is similar. As described in [5], given a wireless network with a set of access points $\boldsymbol{B}$, which can communicate over a set of channels $\boldsymbol{C}$, with a maximum transmit power of P_{max}, establishing a radio link between a client device and an access point requires from the wireless infrastructure to assign:

1. An access point $b \in \boldsymbol{B}$;
2. A frequency channel $c \in \boldsymbol{C}$;
3. A transmission power level $p \leq P_{max}$.

Obviously, channel and transmission power are *global* for a given access point in a sense that all its other clients will have to adjust their parameters correspondingly: switch the operating channel and deal with the new received signal strength from their AP. In Wi-Fi, the first requirement is usually decided by the client itself: user chooses SSID they wish to use, and in case if multiple APs serve the same SSID, a client device associates with AP having the strongest signal available. Later, a client can switch to another access point within the same extended service set via *roaming* methods, such as *Fast Basic Service Set (BSS) Transition* defined in 802.11r [6]. The roaming decision is ultimately made by a client device, which sends a reassociation request to start the roaming process [4]. The access point, however, can force a client to find another access point by sending a deauthentication frame, or moving to another channel without notifying. The second and third requirements are a part of current AP configration and a subject to change. A client discovers current operating channel of APs by tuning on each available channel in a succession, while transmission power only can be estimated by measuring received signal strength. Thus, **the goal of a radio resource allocation algorithm is to optimize spectrum usage within a WLAN via assigning an operating channel and a transmission power level to each access point in a way that maximizes the overall network performance.**

As it will be shown in Section 2.1, the 802.11 standard does not provide any algorithms for channel and transmission power assignment, however, some amendments introduce methods for measurement, signaling and radio adjustment that can be used for RRM purposes.

Note that related researches and commercial solutions introduce many different terms for the same procedure of channel change that can use different algorithms and slightly vary according to specifics of their application: *Frequency Selection*, *Frequency Planning*, *Channel Selection*, *Channel Planning*, *Channel Assignment*, etc. Adjustment of transmission power is usually In this Thesis, we consider those terms to be synonyms.

Term	**Definition**
Signal	Airborne RF energy
Channel	A band of frequencies that 802.11 devices can use for communications [1]
Inteference	Destructive influence of another signal leading to degradation of signal quality and loss of frames
Noise	Signal that cannot be demodulated as 802.11 signal
SNR (Signal-to-Noise Ratio)	Signal quality metric, defined as ratio of signal power to the noise
SINR (Signal-to-Interference-plus-Noise Ratio)	Signal quality metric, defined as ratio of signal power to the sum of noise power and power of interefering signals
RSSI (Received Signal Strength Indicator)	A metric of a wireless signal quality defined in 802.11, varying from 0 to 255, where exact mappings to Rx signal power are vendor-specific.
Radio cell	A geographical area covered by a radio transmitter [2]
Basic Service Set (BSS)	A set of stations belonging to the same radio cell and exchanging information [3]
Distribution System (DS)	A network that interconnects multiple BSSs and provides connectivity to a wired network [3]
Extended Service Set (ESS)	A set of BSSs interconnected by a DS [3]
Infrastructure mode	A centralized mode of a 802.11 WLAN operation using a star topology, where AP serves as a central entity for managing WLAN and switching traffic
Station (STA)	A client device that can connect to a WLAN
Access Point (AP)	A device that provides wireless access to a wired network
Network capacity	Maximum transmission rate that any station can achieve in a given WLAN

TABLE I
Used terms and definitions

Chapter 2

Literature Review

The purpose of this chapter is to explore existing approaches on Radio Resource Management in IEEE 802.11 networks, including surveying what is proposed as a part of the 802.11 standard itself, what research has been done and what is offered by existing commercial solutions. This chapter is organized as follows:

- Section 2.1 provides an overview how radio resource management is facilitated within the IEEE 802.11 standard;

- Section 2.2 provides a synthesis on previous research in radio resource management;

- Section 2.3 provides an overview of proprietary RRM solutions from major vendors;

- Section 2.4 summarizes the chapter.

Table 1.2 contains the list of definitions used in this chapter.

I Radio Resource Management in IEEE 802.11

As discussed in Section 1.2.4, a radio resource allocation algorithm aims to optimize network capacity through optimizing spectrum usage by adjusting two parameters: frequency and transmission power of each access point. In this section, we provide an overview of how radio resource management is facilitated within the IEEE 802.11 standard.

A. *IEEE 802.11h*

To comply with legal requirements on transmissions in 5 GHz, 802.11h-2003 [7] amendment (*Spectrum and Transmit Power Management Extensions*) was introduced. Since the goal of this amendment is to prevent legacy 802.11a 5GHz APs from interference with radars, 802.11h is not oriented for optimizing capacity of a wireless network. However, 802.11h introduces [3] spectrum management methods, namely, *Dynamic Frequency Selection (DFS)*, facilitating automatic change of AP's operating frequency, and *Transmit Power Control (TPC)*, adjusting the power of AP's transmitter. Those methods can be further used in implementation of radio resource management algorithms.

II Previous Works

Interference from other Access Points poses a serious obstacle [8] for delivering acceptable quality of service in large 802.11 WLAN deployments. Although the 802.11 carrier-sense MAC protocol is designed to be resilient to interference, improper placement of APs leads to considerable degradation of WLAN performance due to co-channel interference [9]. However, for interference between cells within a WLAN, such problem in principle can be solved by proper **site surveying**, i.e. planning of geographical placement of cells. Another major source of interference is rogue APs, which are operated by third parties and in general are not under control of WLAN administrators. Note that rogue APs are not assumed to be malicious and not posing threats other than congesting channels and occuping airtime. According to [8], interference from rogue APs can introduce up to 50% delays in a WLAN. Moreover, the prevalent amount (more than 70%) of rogue APs are stationary [8], so their radio presence can be considered as a constant factor in the WLAN. In this light, attempts to improve spectrum management via channel assignment and transmit power control adjustment algorithms encompass research on Radio Resource Management algorithms. As shown in Section 2.1, the IEEE 802.11 standard provides a limited set of tools for radio resource managemens, leaving assignment algorithms and policies on behalf of WLAN equipment vendors. As reported in [8], Cisco's RRM software, shipped with Cisco Aironet APs and Cisco WLAN Controller, was able to improve network performance using Dynamic Channel Selection (DFS) and Transmit Power Control (TPC) so that carrier sense interference was responsible for only 5% of network delays. RRM solutions from Cisco and other vendors will be surveyed in Section 2.3. However, since this technology is proprietary, implementation details are not disclosed, while there probably could be vast space for improvement of algorithms. Moreover, such solutions do not possess interoperability with networking products from other vendors, which is a major obstacle for large-scale WLAN deployments and leads to vendor lock-in situations. Thus, research on radio resource management algorithms, especially ones is of great importance for the industry.

A. Radio Resource Management Approaches

As RRM is a broad topic which doesn't imply a single methodology, approach, or optimization goal, classification of RRM algorithms is a challenging task. Most of papers with the "Radio Resource Management" keyword are focused on problems of cellular networks, such as LTE or 5G. While the problem formalization, some optimization objective and algorithms can be used for research in 802.11 networks, band usage, deployment and operation specifics make most of the proposals inapplicable for 802.11 networks. To the best of our knowledge, no comprehensive survey on RRM in 802.11 WLAN exist. However, we will refer to [10], which provides detailed overview of previous research. In [10], authors classify RRM algorithms into three categories:

- *per-cell* approaches seek to optimize the RF situation within the AP's cell coverage. This means that adjustments of radio parameters applied on a cell scale and will be in effect for all stations within the cell. Such classification can be further divided into:
  - *localized (uncoordinated) per-cell*, where each AP performs RRM decisions independently;
  - *centralized per-cell*, where a central entity, such as WLAN Controller, performs RRM decisions for all APs within a WLAN. Some authors refer to this approach as *super-cell* approach [9];
  - *coordinated per-cell*, employing cooperation between APs for making coordinated RRM decisions.
- *per-link* approaches, which optimize the transmission power for a given station;

- *per-flow* approaches, which employ frequency and AP Tx power adjusting to optimize the QoS to the granularity of a given traffic flow within a station, for example, to the flow of a VoIP application.

In fact, a simple localized per-cell RRM is already widely implemented: almost every home Wi-Fi router is able to select channel automatically, and the method of least-congested channel scan is known and applied [11]. However, limitations of such approach are clear: uncoordinated localized decision-making is prone to yield suboptimal results. We can imagine a bit exaggerated extreme case, where a number of APs can sense that channel C_i is not congested and make a decision to switch to that channel. As a result, C_i becomes congested, so APs will seek to switch to another channel C_j, where the problem will reoccur. This displays that RRM algorithms need a certain degree of coordination between APs using an algorithm aiming to improve overall WLAN capacity and thus achieve a global optimum. Simple per-cell TPC methods with P_{Tx} adjustment with respect to keeping a tolerable SINR (Signal-to-Noise-plus-Interference Ratio) has shown [12], [13] the potential to improve overall bandwidth, although methodological issues such model oversimplification, unrealistic experiment conditions, statistically insignificant results imply the need for the further investigation. Another aspect overlooked is the impact of 802.11 roaming on TPC, since [12], [13] only consider the case of independent access points providing distinct extended service sets, which is not the case for enterprise WLANs. As shown in [14], per-link TPC considerably improves WLAN performance, achieves more spatial reuse, increases throughput, and able to avoid channel access asymmetry and receiver-side interference (also known as hidden-node problem). However, such approach has certain hardware requirements, namely, *per-packet transmit power control*, a feature available only for a small number of 802.11 chipsets from Atheros, which limits the applicability of this approach. It is challenging to implement per-flow RRM for vanilla 802.11, since it requires an extension framework over the 802.11 standard that allows (1) distinguishing particular traffic flows between STA and AP (2) QoS requirements detection [10]. Thus, such approach remains of little interest for the purpose of this thesis.

B. Mathematical Models for Radio Resource Management

Most of works on RRM consider [9], [10] network planning as optimization problem, with the goal of minimizing or maximizing some metrics. To reduce search space while brute-forcing optimal channel parameters for each AP within a WLAN, [9] propose heuristics to reuse channels for non-overlapping cells. Other approaches aim to keep some pre-defined target metric, such as SINR, within pre-defined acceptable boundaries [12].

III Proprietary RRM Solutions

This section is dedicated to surveying proprietary RRM solutions from major vendors. We will consider Cisco, Juniper Networks, and Ruckus Networks, since they are the most popular vendors in enterprise WLAN market [15]. To the best of our knowledge, there are no peer-reviewed evaluations of Juniper Networks RRM efficiency, so we can only rely on vendor's claims.

A. Cisco

Cisco offers several RRM solutions. First, Cisco CleanAir is a flagship technology from Cisco [16] to optimize network performance, avoid jamming, and detect interference sources, including non-802.11 ones. Cisco states that it outperforms competitors by:

- using dedicated hardware for RF analytics: Cisco Catalyst 9100 Series Access Points are equipped with *scanning radio* that performs background RF scanning without occupying main APs radio transcievers, which allows to avoid interruptions in providing services to clients, and Cisco RF ASIC, a chip capable of performing wireless network analytics;
- classifying and visualizing interferers;
- managing radio resources on a WLAN-wide scale, providing real-time and historical information with different granularity;
- CleanAir is event-driven, that means it can adapt to changing RF environment and adjust radio parameters in a matter of few minutes, drastically reducing downtime.

However, CleanAir is only available for the most expensive models in the Cisco product line, which makes it inapplicable for large-scale deployments. Also, lack of compatible radio analytics hardware from other vendors and implementation details render this technology fundamentally unusable for non-Cisco equipment. On the other hand, Cisco Catalyst product line of WLAN Controllers provide "regular" RRM functionality that only requires regular Wi-Fi chipset and can be used with all Cisco APs [17].

B. Juniper Networks

Juniper Networks offers Mist AI RRM technology to improve network performance. The notable features are [18], [19]:

- *automatic dual-band radio management* if RRM system finds 2.4-GHz radio transmitter to be unused on a given AP, it disables the radio to free airspace for other access points;
- Juniper Mist APs are equipped with so-called Predictive Analytics and Correlation Engine (PACE) "to monitor conditions and make out-of-band adjustments" [19];
- Telemetry is sent to the Juniper Mist Cloud, so that the cloud can make regular adjustments to APs based on historical data and usage statistics;
- According to [18], a Reinforcement Learning (RL) approach is taken for channel and power planning of APs within a WLAN.

C. Ruckus Networks

Ruckus Networks offers [20] ChannelFly RRM technology that provides automatic channel selection, so power planning is not featured. As Ruckus describes, "ChannelFly constantly learns about each channel's capacity using actual activity on across all channels within the 2.4 and 5GHz bands. With this information, ChannelFly builds a statistical model over time to determine what channel will yield the greatest capacity for clients". Ruckus states that ChannelFly has no "dead time", as Ruckus calls the time period when an AP performs background scanning on different channels and is unable to communicate with its clients, which implies that Ruckus APs are also equipment with dedicated scanning radio. Another feature from Ruckus is "smart adaptive antenna array", which makes signal from Ruckus APs more directed to improve SNR.

D. Aruba Networks

Earlier RRM technology by Aruba is called ARM (Adaptive Radio Management) **arubaARM**. It utilizes ACS and TPC features to improve RF situation in WLAN. While utilizing simple algorithmic techniques, it is notable for its comprehensive description by Aruba documentation, unlike solutions by other vendors. Let us note its main features [21]:

- **Application Awareness**: since background scanning of channels required for gathering RRM statistics requires AP to go off-channel and stop serving clients as it hops over other channels for a certain time period ("dead time" in Ruckus terminology), Aruba allows to throttle background scanning based on traffic load. That is, in case of heavy traffic load, APs will reduce the frequency of background scanning, while resuming the normal frequency of background scanning when the traffic load is back to normal [22];

- **Mode Awareness**: in case of too dense AP installation, excessive APs causing interference can be turned into Air Monitor mode, continuously sending RRM telemetry to a controller;

- **Band Steering**: dual-band capable clients are encouraged to use 5GHz band;

- **802.11n HT Mode Support**: ARM is able to use 40 MHz channel pair, automatically selecting primary and secondary operaing channels.

- **Noise and Error Monitoring**: ARM is advertised to distinguish 802.11 and non-802.11 sources of noise.

- **Spectrum Load Balancing**: by analyzing the number of clients for each of the neighboring access point, controller can identify APs with the higher client load and make them reject association request in favor of less loaded APs; However, a client can attempt to re-connect to the same APs on the second try and be admitted.

- **Noise Interference Immunity**: essentially adjusts Rx sensitivity threshold, reducing time wasted on attempts of decoding weak and non-802.11 signals.

Reports from system administrators, though, suggest that RRM decisions in Aruba ARM are made by APs rather than controller. Among other user complains are unnecessary disabling of 2.4GHz radios, errorneous TPC leading to coverage holes [23].

However, ARM is a legacy technology. Its successor, Aruba AirMatch, introduced in recent ArubaOS versions, is a more sophisticated RRM technology, which is based on AI and machine learning and is able to perform channel and power planning on a WLAN-wide scale, suggesting ARM was implemented in a per-cell way and AirMatch is a super-cell solution.

Notable AirMatch features:

- Channel width adjustment based on device density - the more devices are connected to an AP, the narrower channel width is used to allow channel reuse and reduce interference;

- APs measure RF environment for 5 minutes every 30 minutes;

- Decisions based on a 24-hour period analytics unlike instant RF situation snapshots in ARM;

- Elimination of coverage holes based on TPC.
- Configurable thresholds in channel quality improvements to trigger channel and EIRP planning, default threshold is 15%.
- ClientMatch technology that manages clients: performs load balancing between APs, encourages clients to switch to APs providing better signal strength and using higher bands (5 GHz or event 6 GHz in 802.11ax)

Similarly to ARM, Aruba provides more information about AirMatch operating logic than other vendors about their RRM solutions.

According to [24], AirMatch blacklists channel for channel selection if a radar was detected on it (in 5 GHz case) or in case if high noise level was detected on it (for all bands). In those cases, AirMatch will select channel with a manimum interference index.

It is not clear if AirMatch uses the same metrics as ARM, but only ARM metrics are described in the documentation. To make RRM decisions, ARM uses two metrics:

- **Coverage Index** - calculated as a ratio $\frac{x}{y}$, where x is the AP's weighted calculation of SNR on all valid APs on a specified 802.11 channel, and y is the weighted calculation of the AP's SNR the neighboring APs see on that channel.
- **Interference Index** - metric to measure co-channel and adjacent-channel interference, calculated as a sum of four quantities a, b, c, d:
  - a is the channel interference the AP sees on its selected channel.
  - b is the interference the AP sees on the adjacent channel.

- c is the channel interference the AP neighbors see on the selected channel.
- d is the interference the AP neighbors see on the adjacent channel.

Additionally, Aruba APs collect several other metrics, including L2 metrics:

- Amount of Retry frames (measured in %)
- Amount of Low-speed frames (measured in %)
- Amount of Non-unicast frames (measured in %)
- Amount of Fragmented frames (measured in %)
- Amount of Bandwidth seen on the channel (measured in kbps)
- Amount of PHY errors seen on the channel (measured in %)
- Amount of MAC errors seen on the channel (measured in %)
- Noise floor value for the specified AP

As per Aruba documentation, those metrics "provide a snapshot of the current RF health state" [25], which implies they are only used for network administator's reference and are not employed in RRM decision-making.

IV Conclusion

Summarizing from the previous sections, we can conclude that the problem of radio resource management in 802.11 WLANs is still relevant, since the IEEE

802.11 standard provides only limited tools for RRM, while existing commercial solutions are proprietary and lack interoperability. Thus, there is a need for a novel RRM algorithm that can be implemented in existing enterprise WLAN infrastructure and improve overall network performance. After analyzing previous research, we consider super-cell approach as the most applicable to our work, since the presence of WLC as a centralized entity with orders of magnitude higher computation power and ability to collect and store statistics from all APs all over the WLAN in the long term can release the burden of RRM from Access Points and potentially improve the overall network efficiency.

Chapter 3

Problem statement and baseline solution analysis

The purpose of this chapter is to lay a foundation for the further work in this Thesis via formal definition of RRM problem and analysis of existing RRM algorithm from Wimark Systems. The chapter is organized as follows. Section 3.1 defines the problem of RRM and its goals. Section 3.2 describes the baseline RRM algorithm from Wimark Systems and considerations that led to such solution.

I Problem statement

II Baseline solution analysis — RRMGreedy

The greedy RRM algorithm from Wimark Systems that we will refer to as *RRMGreedy* is based on background scanning by access points. The goal of this thesis is to create a new RRM algorithm that is overall better in managing radio resources and at least not worse than *RRMGreedy* in corner cases.

A. RRMGreedy description

Here, we describe algorithm *RRMGreedy*. As the name suggests, it tries to achieve optimal radio resource allocation in a greedy way, taking the local optimum for each device in a RRM group. The algorithm operates on the granularity of interfaces rather than access points.

In other words, we consider **RRM group** G as a set of **wireless interfaces** w (that we will further refer to as simply **interfaces**), where several interfaces can belong to a single access point. On a high level, the algorithm consists of two main steps — **Channel Selection** and **Transmit Power Adjustment**:

1. **Channel Selection**:

   (a) compute **group interference** I — sum of interference scores for each interface in group:

   $$I = \sum_{i=0}^{|G|} OnIfaceInterference(w_i) \tag{3.1}$$

   We denote initial group interference score as I_0.

   (b) for each w_i, compute its updated interference score for every channel possible for that interface c_i^k:

   $$interf_i = OnIfaceInterference(w_i, c_i^k) \tag{3.2}$$

   If there is a channel c_i^k which reduced $interf_i$, update interface settings to issue change to that channel later.

   (c) **continue while there is an improvement**, i.e., previous group interference score is larger than the latest one: $I_{j-1} > I_j$ for $j > 1$

2. **Transmit Power Adjustment**:

   (a) Compute group interference as in step 1a

   (b) Identify the *worst interface* interface w_m experiencing *worst interference* (i.e. whose interference score is the largest):

$$w_m = \arg\max_i FromIfaceInterference(w_i) \tag{3.3}$$

   (c) Gradually reduce transmit power of w_m with exponential backoff until it stops being the worst interface or reaches minimum Tx power.

Listing 3.1 shows pseudocode for *RRMGreedy*:

```
Algorithm RRMAlgoGreedy
Input:
    data: RRMInitData
Output:
    GroupDataWithEvent: final configuration and event data for CPEs
Begin
    // Step 0: Prepare raw scanning data received from APs
    scandata := ProcessScanDataForGroup(data.CPEs, data.ScanData)

    // Step 1: Set Maximum Transmission Power
    For each cpe in data.CPEs
        For each iface in cpe.State.Wifi
            MaxIfaceTxPower := Max Tx power for given hardware
            scandata[iface].TxDiff := MaxIfaceTxPower - iface.TxPower

    // Step 2: Optimize Channel Selection
    // calculate initial group interference
    groupInterference := GroupInterference(scandata)
    Repeat until no improvement in groupInterference
        For each cpe in data.CPEs
            For each iface in cpe.State.Wifi
```

```
                bestChannel := choose channel that yields minimal InterferenceOnCPE(scandata, channel, width) for this iface
                scandata[iface].channel := bestChannel
        Recalculate groupInterference := GroupInterference(scandata)

    // Step 3: Adjust Transmission Power (if enabled)
    If TPC enabled
        Repeat until no improvement in groupInterference
            Identify worst-performing interface using InterferenceFromCPE
            Calculate needpower and bestpower for worst interface
            Update scandata with new Tx power settings
            Evaluate total interference using GroupInterference

    // Step 4: Final Data Assembly and Event Generation
    finaldata, eventsData := Assemble final configuration and events
    If no significant improvement in interference
        Return error "No significant changes made"

    Return finaldata and eventsData
End Algorithm
```

Listing 3.1: greedy RRM algorithm

Listing 3.2 shows pseudocode for *ProcessScanDataForGroup()* that splits measurement data from each interface.

```
For each scan from interface in RRM group
    For bssid, signaldata in scan
        channel := signaldata.channel
        If bssid in RRMGroup
            interface.Inner[channel].append(signaldata)
        Else
            interface.Outer[channel].append(signaldata)
```

Listing 3.2: ProcessScanDataForGroup pseuodocode

Listing 3.4 shows pseudocode for *OnIfaceInterference()* function that calculates interference experienced by given wireless interface from outer and inner sources. Essentially, it breaks down to calculating

$$interf_i = OnIfaceInterference(w_i, channel, width) = interf_i^{outer} + interf_i^{inner} \quad (3.4)$$

$$interf_i^{outer} = \sum_{j=0}^{|S_i^{outer}|} ChannelInterference(w_i, s_i^j) \cdot scale(s_i^j) \quad (3.5)$$

$$interf_i^{inner} = \sum_{j=0}^{|S_i^{inner}|} ChannelInterference(w_i, s_i^j) \cdot scale(s_i^j + w_i.TxDiff) \quad (3.6)$$

where:

- S_i^{outer} is a set of signals sensed by w_i on from stations not in G
- S_i^{inner} is a set of signals sensed by w_i from stations in G, s_i^j is j-th signal in S_i^{outer} or S_i^{inner}
- $scale(x)$ is a min-max normalization function that normalizes x to [0, 1] scale with given $maxSignal$ and $minSignal$:

$$scale(x) = \frac{x - minSignal}{maxSignal - minSignal} \quad (3.7)$$

- $w_i.TxDiff$ is a transmit power adjustment for w_i

as follows:

1. **Calculate outer interference**: recall that **outer interference** is interference originating from access points not in the RRM group G. Based on earlier measurements sent by w_i, for each sensed signal $s \in S_i = S_i^{inner} \cap S_i^{outer}$ we calculate adjacent-channel/co-channel interference score with *ChannelInterference()* (Listing 3.3). Then, for each signal on given channel, we

calculate interference score as a product of *ChannelInterference()* and signal power normalized to [0, 1] scale. Finally, we sum up interference scores for all signals on this channel.

$$interf_i^{outer} = \sum_{j=0}^{|S_i^{outer}|} ChannelInterference(w_i, s_i^j) \cdot \frac{signal_i^j - minSignal}{maxSignal - minSignal} \tag{3.8}$$

where S_i^{outer} is a set of signals sensed by w_i on channels not in $\mathbf{G}$, s_i^j is j-th signal in S_i^{outer}, $signal_i^j$ is power of s_i^j normalized to [0, 1] scale, and *maxSignal* is the maximum signal power in S_i^{outer}.

2. **Calculate inner interference**: recall that **inner interference** is interference originating from access points in the RRM group G. In the same way as for outer interference, we calculate interference score for each signal on given channel as a product of *ChannelInterference()* and signal power normalized to [0, 1] scale. One difference is that TxDiff is taken into account for Tx power adjustment. Finally, we sum up interference scores for all signals on this channel.

$$interf_i^{inner} = \sum_{j=0}^{|S_i^{inner}|} ChannelInterference(w_i, s_i^j) \cdot \frac{signal_i^j + w_i.TxDiff}{maxSignal} \tag{3.9}$$

where S_i^{inner} is a set of signals sensed by w_i on channels in G, s_i^j is j-th signal in S_i^{inner}, $signal_i^j$ is power of s_i^j normalized to [0, 1] scale, and *maxSignal* is the maximum signal power in S_i^{inner}.

```
Function ChannelInterference(ch1, ch2, width)
    add := 0
    If ch1 < 36 // channels less than 36 belong to 2.4 GHz band
```

```
        add := 1
    If abs(ch1 - ch2) >= width / 5 + add
        Return 0  // No significant interference
    Else
        Return 1  // Significant interference
```

Listing 3.3: ChannelInterference() function

In *ChannelInterference()*, the threshold for determining interference $width/5+add$ is a heuristic. It divides the channel width by 5, which suggests a rule of thumb about how close channels can be before they start to interfere significantly. The addition of add for lower 2.4 GHz channels suggests a more conservative threshold for these channels.

```
Function InterferenceOnCPE(scandata, interface, interfaceChannel,
   interfaceChannelWidth)
    ifData := scandata[interface]

    // Calculate interference from outer APs
    outerInterf := 0
    For each otherChannel, signalData in ifData.Outer
        inteferenceScore := ChannelInterference(otherChannel,
   interfaceChannel, interfaceChannelWidth)
        If ci == 0 // channels are orthogonal
            Continue
        // calculate cumulative interference score for all signals on this
   channel
        chsum := 0.0
        For each signal in signalData // every signal sensed on otherChannel
            sigRating := signal power (in dBm) normalized to [0, 1] scale
            chsum += interferenceScore * sigRating
        outerInterf += chsum

    // Calculate interference from inner APs
    innerInterf := 0
    For each otherChannel, signalData in ifData.Inner
```

```
        oth, ok := data[othKey]
        If not ok
            Continue
        ci := ChannelInterference(oth.Settings.Central, ch, width)
        If ci == 0
            Continue
        chsum := 0.0
        For each signal in signalData
            sourceInterface := interface from where signal origins
            adjustedSignal := signal + sourceInterface.TxDiff
            sigRating := adjustedSignal power (in dBm) normalized to [0, 1] scale
            chsum += ci * sigRating
        innerInterf += chsum

    Return outerInterf + innerInterf
```

Listing 3.4: OnIfaceInterference() function

After the channel selection is completed, transmit power adjustment is performed. The goal of this step is to reduce transmit power of the interface that experiences the most interference from other interfaces in the group.

Check all interfaces $w_i \in G$. If w_i interferes with currently considered interface $w, w \neq w_i$,

```
Function FromIfaceInterference(scandata, iface)
    sum := 0.0
    maxsignal := MinSignal
    thisdata := scandata[iface]

    For each otherIface in data
        if otherIface == iface
            Continue
        // Get all measurements of signals from iface that otherIface received
        thisIface := othCpe.InnerMeasurements[iface]
```

```
     If thisIface == nil // no measurements for this interface from otherIface
         Continue
     ci := ChannelInterference(thisdata.Settings.Central, otherIface.Settings.Central, otherIface.Settings.Width)
     If ci == 0 // channels are orthogonal
         Continue
     chsum := 0.0
     For each sig in thisIface
         signal := sig.Signal + thisdata.TxDiff
         sigRating := signal power (in dBm) normalized to [0, 1] scale
         chsum += ci * sigRating
         maxsignal = max(signal, maxsignal)
     sum += chsum

 Return sum, maxsignal
```

Listing 3.5: FromIfaceInterference() function

B. Evaluating asympotic complexity

We will now evaluate asymptotic complexity of *RRMGreedy* algorithm. First, let us consider the complexity of auxiliary functions that are used:

1. $ChannelInterference(ch_1, ch_2, width)$ has constant complexity $O(1)$.

2. $OnIfaceInterference(G, w_i)$ has complexity linear w.r.t. the number of signals sensed by w_i, i.e., $O(|S_i|) = O(|S_i^{outer}| + |S_i^{inner}|)$

3. $FromIfaceInterference(G, w_i)$ has complexity proportional to the product of number of interfaces in G and amount of signal samples from w_i heard by other interfaces, which is limited by some constant C, reasonably small in practice ($C < 10$), i.e., $O(|G| \cdot C) = O(|G|)$

Let's consider time complexity of the main phases of the algorithm:

1. **ProcessScanDataForGroup** has complexity $O(|G| \cdot |S|)$, where $|S|$ is the total number of signals in all scans from all interfaces in G.

2. **Set Maximum Transmission Power** has complexity $O(|G|)$

3. **Optimize Channel Selection** is an iterative algorithm, going for each $w_i \in G$ and for each channel $c \in w_i.channels$ running $OnIfaceInterference(G, w_i)$ until there is no improvement, so its worst-case time complexity can be estimated as $O(|G| \cdot C \cdot K \cdot |S_i|)$, where C is the number of channels and K is the number of iterations.

4. **Adjust Transmission Power** is an iterative algorithm, going for each $w_i \in G$ until there is no improvement yielded by $FromIfaceInterference()$, so its worst-case time complexity can be estimated as $O(|G| \cdot K \cdot |G|) = O(|G|^2 \cdot K)$, where K is the number of iterations.

5. **Final Data Assembly and Event Generation** has complexity $O(|G|)$

C. RRMGreedy flaws

D. Evaluation on real-world data

E. Simulation

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