Автономная некоммерческая организация высшего образования «Университет Иннополис»

ВЫПУСКНАЯ КВАЛИФИКАЦИОННАЯ РАБОТА (БАКАЛАВРСКАЯ РАБОТА)
по направлению подготовки
09.03.01 - «Информатика и вычислительная техника»

GRADUATION THESIS
(BACHELOR'S GRADUATION THESIS)
Field of Study
09.03.01 – «Computer Science»

Направленность (профиль) образовательной программы «Информатика и вычислительная техника»
Area of Specialization / Academic Program Title:
«Computer Science»

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**

Работу выполнил / Thesis is executed by	**Булгаков Артем Владиславович / Artem Bulgakov**	подпись / signature
Руководитель выпускной квалификационной работы / Supervisor of Graduation Thesis	**Сейтназаров Шынназар Оралбаевич / Shinnazar Seytnazarov**	подпись / signature
Консультанты / Consultants		подпись / signature

Иннополис, Innopolis, 2023

Contents

List of Tables

List of Figures

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, most of the previous studies only evaluate performance in simulators and have considerable obstacles for production usage. In this study, I present a novel centralized RRM algorithm for multi-AP WLAN deployments. This algorithm adjusts frequency and transmission power parameters of access points based on physical-layer metrics, and uses WLAN Controller (WLC) as a central entity to gather data and perform computations. Integrated into the Wimark WLC RRM module, my approach achieves up to 67% faster convergence on 2.4 GHz IEEE 802.11n-compatible WLAN. With enhanced spectrum management, my 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 Wimark Systems algorithm, demonstrating that the algorithm is production-ready and can be easily integrated into existing enterprise WLAN infrastructures.

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 suf-

ficient capacity to all clients. In this light, proper radio resource management becomes crucial for operating wireless networks.

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 (or base stations in cellular terminology) $\boldsymbol{B}$, 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.

B. *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) [1], Aruba Adaptive Radio Management (ARM) [2], 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 less attention. Many existing works on RRM in 802.11 networks have applicability problems, since real-world hardware poses constraints on what metrics can be retrieved from the wireless interface and which physical and link-level parameters can be adjusted.

C.   Contribution and significance of the thesis

This study 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 RRM approach is encompassed within the centralized architecture, introduced by Cisco as Unified Wireless Network (UWN) [3], a highly centralized wired-wireless architecture controlled by a Wireless LAN Controller (WLC). This approach allows for a more efficient spectrum management, as the WLC can collect data from all access points and make decisions based on the global view of the network, which is not possible in a distributed architecture, where each access point makes decisions independently.

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 limitations 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 Fre-

quency (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 [7].

B.   Frequency band

Main frequency bands are: 2.4 GHz band introduced by 802.11b, 5 GHz band introduced by 802.11a and 6 GHz, introduced by 802.11ax. This study focuses on first two bands as used the most frequently. Below I describe those bands in more details.

Most of the 802.11 amendments, including b,g,n, and partially ax, operate at unlicensed 2.4 GHz ISM (Industrial, Scientific, Medical) RF band [5], [7]. 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. [5], [7]. Moreover, 2.4 GHz signals can propagate through solid obstructions like walls, doors, and windows better than signals operating on higher-frequency ones [7]. 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.

The 2.4 GHz ISM band is split into 14 channels. Depending on local regulations, number of possible channels can vary, but in general channels 1-11 are available at every region. Assuming 20 MHz channel width, each channel is characterized by its *center frequency*, ± 10 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 or 25 MHz in between. Such non-overlapping channels are 1, 6, 11, with central frequencies 2.412, 2.437, and 2.462 MHz, respectively.

The 5 GHz U-NII (Unlicensed National Information Infrastructure) series of bands is used by 802.11a/802.11ac/802.11ax amendments. Unlike the 2.4 GHz band, channels do not overlap. On the end of each band *guard band* as an additional measure to avoid interference. Combined, bands U-NII-1, U-NII-1, U-NII-2A, U-NII-2C, U-NII-3 provide twenty-five 20 MHz or twelve 40 MHz non-overlapping channels [7]. However, some channels may not be available in different regions, since this band can also be used by military and weather radars. The first channel from U-NII-1 band has number 36.

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:

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

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 networkśignal 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 [7].

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 [8], given a wireless network with a set of access points B, which can communicate over a set of channels 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 $b \in B$;

2. A frequency channel $c \in C$;

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 managed 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 [9]. The roaming decision is ultimately made by a client device, which sends a reassociation request to start the roaming process [7]. 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 configuration 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 similar 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 study, we use those terms interchangeably.

Term	Definition
Signal	Airborne RF energy
Channel	A band of frequencies that 802.11 devices can use for communications [4]
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 [5]
Basic Service Set (BSS)	A set of stations belonging to the same radio cell and exchanging information [6]
Distribution System (DS)	A network that interconnects multiple BSSs and provides connectivity to a wired network [6]
Extended Service Set (ESS)	A set of BSSs interconnected by a DS [6]
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 (RRM) 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. The very need for an RRM algorithm comes from situation called *Overlapping Basic Service Sets* in the IEEE 802.11 standard, when there are two basic service sets operating on the same channel within reach of each other. This situation leads to co-channel interference, which degrades network performance. In this section, I provide an overview of methods and techniques provided by IEEE 802.11 standard that can assist in radio resource management.

A. IEEE 802.11h

To comply with legal requirements on transmissions in 5 GHz, 802.11h-2003 **80211h** 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 [6] 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, however, do not implement RRM in the sense of optimizing network capacity, but rather are aimed at preventing interference with radars operating on the 5 GHz band. 802.11h describes procedures for: quieting the channel to detect presence of a radar, switching to another channel if a radar detecting, advertising the channel switch to client

stations (STAs). Radar detection itself, though, is beyond the scope of 802.11 standard **80211h**. However, the methods introduced in 802.11h can be considered as a foundation for further research on RRM algorithms.

B. IEEE 802.11k

The amendment 802.11k-2008 **80211k** (*Radio Resource Measurement*, not to be confused with *Radio Resource Management*) improves the performance of roaming. Roaming is a process of station moving from one access point to another [7]. The amendment 802.11k improves roaming by allowing stations to request from access points various reports, such as *neighbor reports* for discovering possible access points that STA can roam to, *link measurements* to estimate how well AP can hear the station etc. This allows stations to reduce power consumption, speed up roaming and decrease power consumption and airtime usage spent on sending probe requests to each channel when trying to find another AP to roam. However, this amendment is also not aimed at optimizing network capacity, but rather at improving roaming performance.

C. IEEE 802.11ax

The amendment 802.11ax **80211ax** (*High Efficiency WLAN*) introduces means to address OBSS problem. The amendment introduces *Basic Service Set (BSS) Coloring*, a method to distinguish between different BSSs operating on the same channel. It works as following: each BSS is assigned with *color*, a 6-bit value spanning from 1 to 63, that resides in the PHY header. Devices belonging to the same BSS check this color when demodulating transmissions (i.e., check if this frame is an *intra-BSS*). If it contains the wrong color (*inter-BSS* frame),

further demodulation is not performed, thus saving processing time [10]. If an intra-BSS frame is found to use the same color, AP switches to another color. This technique, however, does not solve the problem of co-channel interference and does not attempt to switch channels in case of interference, so this cannot be considered as a complete RRM solution.

II Previous Works

Interference from other Access Points poses a serious obstacle [11] 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, interference reduces the available airtime and causes loss of frames already sent. Thus, network capacity and performance tend to degrade drastically [12]. For interference between cells within a single WLAN, such problem in principle can be solved by proper **site surveying**, i.e., planning of geographical placement of cells. However, another and the major source of interference are rogue access points (RAPs), which are operated by third parties and in general are not under control of WLAN administrators. According to [11], 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 [11], so their radio presence can be considered as a constant factor in the WLAN. Note that *rogue* does not imply that those APs are malicious or posing threats other than congesting channels and occuping airtime as a result of their legitimate operation. 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 [11], 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 those technologies are proprietary, their implementation details are not disclosed, so they cannot be properly evaluated in an independent research or adopted by third-party vendors. Moreover, such solutions lack interoperability, so it is difficult to use them 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 is important for the industry.

A. *Radio Resource Management Approaches*

As RRM is a broad topic which does not imply a single methodology or approach, classification of RRM algorithms is a challenging task. Most of the papers with the "Radio Resource Management" keyword are focused on problems of cellular networks, such as LTE or 5G. At the same time, the problem formalization, some optimization objective and algorithms can also be used for research in 802.11 networks, but band usage, client management, deployment and operation specifics make most of the proposals inapplicable for 802.11 networks. To the best of my knowledge, no comprehensive survey on RRM in 802.11 WLAN exist. I will refer to [13], which provides detailed overview of previous research, and [14], describing state-of-the-art on RRM. In [13], authors classify RRM al-

gorithms 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 [12];

  - *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 has the option to select channel automatically. Typically, in this case access point surveys each channel, makes an estimation how congested it is, then switches to the least congested one. This technique is called *least-congested channel scan*, or *least-congested channel search* (LCCS), and the original design uses the number of associated clients as estimation of channel congestion [15]. As analyzed in [16], LCCS has several limitations:

1. LCCS is unable to accurately identify interference scenarios where clients connected to different Access Points (APs) interfere with each other without the APs themselves causing interference. This issue is particularly prevalent in real-world setups where APs are strategically placed to ensure wide coverage while overlapping minimally to avoid coverage gaps;

2. LCCS also falls short in optimizing channel reuse based on the distribution of clients. It fails to account for the interference experienced by clients, thus missing the opportunity for channel reuse strategies based on client locations and densities.

In general, uncoordinated decision-making like LCCS tends to yield suboptimal results. Consider an 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 situation 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.

Research on Transmit Power Control (TPC) methods, which adjust transmission power P_{Tx} to maintain an acceptable Signal-to-Noise-plus-Interference Ratio (SINR), shows potential for enhancing bandwidth. However, criticisms regarding these studies' simplified models, unrealistic experimental setups, and statistically uncertain outcomes suggest the need for further investigation [17], [18]. The effect of IEEE 802.11 roaming on TPC is underexplored, especially in scenarios where APs are part of the same extended service set (ESS), which is more common in enterprise WLANs.

As shown in [19], 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 selection of 802.11 chipsets. In turn, implementing per-flow RRM in standard 802.11 networks requires an advanced framework for identifying specific traffic flows and assessing their Quality of Service (QoS) demands [13]. Therefore, this thesis will concentrate on solutions that are more practical and applicable to the hardware and software currently available on the market.

B.   Mathematical Models for Radio Resource Management

Building on the definition of the Radio Resource Management (RRM) problem introduced in 1, we consider a network composed of a set of base stations (access points) denoted as $\boldsymbol{B}$, capable of operating over a collection of channels $\boldsymbol{C}$, each with a maximum transmission power limit P_{max}. The core objective of RRM is to establish a radio link between a client device and an access point by assigning a triplet (b, c, p), where $b \in \boldsymbol{B}$ signifies the base station, $c \in \boldsymbol{C}$ the channel, and $p \leq P_{max}$ the transmission power, so that network capacity is maximized.

The RRM problem, thus, decomposes into three crucial tasks:

- *Client Assignment* — allocating a base station (access point) to a client;

- *Adaptive Channel Selection* — determining the optimal frequency (channel) for client communication;

- *Transmit Power Control* — setting the appropriate transmission power for client communication.

Client Assignment is typically handled by the 802.11 client through roaming decisions, with amendments like 802.11k/r/v designed to enhance and expedite the process of switching to an access point that offers superior service quality. This aspect, therefore, lies beyond the scope of this study.

Channel allocation and transmit power selection, though extensively studied, are often addressed as separate entities in the literature. Combining these factors introduces complexity, as their objectives can conflict. For example, if the objective is to minimize interference, it can be achieved with minimizing the transmission power. However, such outcome probably does not satisfy coverage and quality of service requirements. On the other hand, considering channel and transmit power together can also be troublesome, since change in one variable would change the overall RF situation, and the algorithm would not converge.

Another aspect is metric selection. Although the most intuitive and desired metrics are high-level ones like network throughput and capacity, actual values of such metrics cannot be used at the time of RRM computations: a significant time of monitoring is required to estimate how throughput changed, so only past records can be used. Another, simpler approach, followed by many works, is to assume that network throughput or capacity is a function of one or more physical layer metrics, such as interference, Received Signal Strength Indicator (RSSI), Rx signal power etc. Indeed, low interference level and low power signal from other APs implies that less transmission errors tend to happen, and more frames can be transmitted with CSMA/CA MAC mechanism. This reliance on physical layer metrics allows for more immediate adjustments in RF (Radio Frequency) configuration of a WLAN, ensuring the adaptability of the network to immediate environmental changes. However, RRM adjustments in practice can lead to disruptions. Most client devices lack support for the Channel Switch Announce-

ment feature from 802.11h, interpreting a channel switch as if the AP has become unavailable. Therefore, utilizing historical data becomes instrumental in making informed, albeit infrequent and periodic, RRM decisions.

Thus, channel and transmit power settings for each AP should yield optimal value of some given metric for the whole WLAN, such as: interference level, WLAN throughput, WLAN capacity, etc. Thus, most of the works consider RRM as an optimization problem, such as integer linear programming (ILP) [20] [21] or binary quadratic programming (BQP) [14]. Since both ILP and BQP are proven to be NP-hard problems, researchers propose heuristics to reduce search space [12], or apply meta-heuristic methods such as genetic algorithms [22] or deep neural networks [14]. Other approaches, while not solving optimization problem explicitly, aim to keep some target metric, such as SINR (Signal-to-Interference-plus-Noise Ratio), within pre-defined acceptable boundaries [17]. In [16], authors employ a graph model, where APs are represented as nodes and edges connect APs which can potentially interfere. Using such model, each node can be assigned a color representing its channel.

It is important to emphasize that in 802.11 WLANs, all clients connected to a specific Access Point (AP) utilize the same frequency and transmission power settings. Given the limited applicability of per-link (per-client) Transmit Power Control (TPC), as previously discussed, it is assumed that both frequency and transmission power are configured for the entire cell. This means that all clients of a given AP operate on the same frequency, and the AP maintains a consistent transmit power level for communication with all its clients.

III Proprietary RRM Solutions

This section surveys proprietary RRM solutions offered by leading vendors in the enterprise WLAN market. I focus on Cisco, Juniper Networks, and Ruckus Networks, since they are the most popular vendors in enterprise WLAN market [23]. To the best of my knowledge, peer-reviewed evaluations of those proprietary RRM efficiency are very limited and scarce, so one could only rely on the claims made by vendor themselves.

A. Cisco

Cisco's RRM strategy is integral to its Cisco Centralized Architecture, known as the Unified Wireless Network (UWN) [3]. In the UWN framework, a single or multiple Wireless LAN Controllers (WLCs) manage up to several thousand Access Points (APs). These WLCs act as the core of the WLAN architecture, enabling centralized control and the collection of telemetry from all APs within the network. A WLC can be either specialized hardware or a virtual machine hosted in the cloud [24]. Effectively, in UWN, access points can be thought of as Wi-Fi network interface cards for the WLC, providing minimal real-time functionality from 802.11 standard that cannot be carried out to WLC due to propagation and transmission delays. This architectural model has become the de facto standard for large-scale enterprise WLANs and is employed by most major vendors in the industry.

Cisco offers several RRM solutions. First, CleanAir is a flagship technology from Cisco [25] to optimize network performance, avoid jamming, and detect interference sources, including non-802.11 ones. Cisco states that it outperforms

competitors through several features:

- It utilizes specialized hardware for RF analytics. For instance, the Cisco Catalyst 9100 Series Access Points contain a scanning radio for background RF scanning. This functionality allows for continuous service provision to clients without disrupting the main AP radio transceivers. Additionally, the Cisco RF ASIC, a dedicated chip, enables advanced wireless network analytics and spectrum analysis unavailable to conventional Wi-Fi modules;

- Classifying and visualizing interference sources thanks to dedicated RF hardware;

- Comprehensive WLAN-wide radio resource management, supplying both real-time and historical data at varying levels of 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 higher-end models in the Cisco product line, posing limitations for its large-scale deployment. Furthermore, lack of compatible radio analytics hardware from other vendors and undisclosed implementation details restrict the utility of this technology for integration with non-Cisco equipment. On the other hand, Cisco Catalyst product line of WLAN Controllers also provide "regular" RRM functionality that only requires regular Wi-Fi chipset and can be used with all Cisco APs [1]. The trade-off for this convenience is access to less detailed information about the RF environment and the necessity for Access Points to temporarily switch off their current channel to conduct scanning. In this case, APs collect statistics on their current channel any time they

are not transmitting data. Additionally, periodically APs scan other channels to gather statistics. [24]. At that time, AP is not available to clients, so, scanning introduces latencies for the clients connected to the AP.

Cisco RRM employs a super-cell concept, wherein a designated WLAN Controller aggregates neighbor and channel data for each AP within an "RF Neighborhood", which includes APs within mutual detection range, enhancing the efficiency of RRM across the network [24].

B.   Juniper Networks

Juniper Networks offers Mist AI RRM technology to improve network performance. The notable features are [26], [27]:

- 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 incorporate the Predictive Analytics and Correlation Engine (PACE) "to monitor conditions and make out-of-band adjustments" [27];

- Telemetry is sent to the Juniper Mist Cloud, so that the cloud can periodically fine-tune APs based on historical data and usage statistics;

- Employing a Reinforcement Learning (RL) methodology for the strategic planning of channel selection and power settings across APs in a WLAN, aiming for optimal network performance [26].

C. Ruckus Networks

Ruckus Networks offers ChannelFly RRM technology, which provides automatic channel selection. ChannelFly estimates capacity of each channel by continuously monitoring the activity of each channel across the 2.4 and 5GHz bands. Based on this information, ChannelFly develops a statistical model to predict which channel will offer the highest capacity for clients, as detailed by [28]. A key benefit of ChannelFly is its ability to avoid "dead time", defined as the period an AP spends scanning different channels, during which it cannot communicate with clients. This capability implies the inclusion of dedicated scanning radios in Ruckus APs, allowing continuous communication with clients while performing channel assessments.

Additionally, Ruckus offers a "smart adaptive antenna array" technology. This feature enhances the directionality of signals from Ruckus APs, focusing the transmission towards clients to improve the Signal-to-Noise Ratio (SNR).

D. Aruba Networks

The Adaptive Radio Management (ARM) technology by Aruba represents an earlier approach to Radio Resource Management (RRM), utilizing Adaptive Channel Selection and Transmit Power Control to enhance the RF environment in WLANs. ARM stands out for its algorithmic simplicity and the thoroughness of its documentation provided by Aruba, in contrast with other vendors [29].

Key features of ARM include [30]:

- **Application Awareness**: Addressing the "dead time" caused by APs during channel scanning, ARM throttles the frequency of background scans based on current traffic load, reducing scans under heavy traffic and resuming

normal scanning rates when traffic diminishes [2].

- **Mode Awareness**: To mitigate interference in environments with densely installed APs, ARM can switch excessive APs to Air Monitor mode, where they continuously collect and send RRM telemetry to the controller.

- **Band Steering**: Encourages dual-band capable clients to prefer the 5GHz band to alleviate congestion on the 2.4GHz band.

- **802.11n HT Mode Support**: ARM can utilize a 40 MHz channel pair for 802.11n networks, selecting the best primary and secondary operating channels automatically.

- **Noise and Error Monitoring**: Distinguishes between 802.11 and non-802.11 noise sources, improving network reliability.

- **Spectrum Load Balancing**: Analyzes client distribution across neighboring APs to direct new connections to less burdened APs, though clients may reconnect to their original choice upon a subsequent attempt.

- **Noise Interference Immunity**: Adjusts the receiver sensitivity threshold to ignore weak and non-802.11 signals, reducing unnecessary decoding efforts and improving network performance.

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, erroneous TPC leading to coverage holes [31].

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 [29], 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 minimum 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 a $\frac{x}{y}$, 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:

  - 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

Aruba documentation indicates that these metrics offer a "snapshot of the current RF health state" [32], suggesting they are informational tools for network administrators rather than being actively used in RRM decision-making.

IV   Conclusion

Summarizing the insights from prior sections, I 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.

I find super-cell approach most fitting for a modern RRM algorithm that can be applied in real-world WLAN deployments. Super-cell algorithms, while being practical and having less obstacles in hardware and current device drivers compared to other approaches, still have the potential to vastly improve RF situation and, thus, WLAN performance.

Centralized management that is typically utilized in super-cell RRM is the standard approach when building modern WLANs, allowing to gather more information about RF environment and come up with more optimal allocations compared with local RRM decision-making. Moreover, presence of WLC as 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 releases the burden of RRM from Access Points and potentially improves the overall network efficiency.

Despite the promising capabilities of per-link and per-flow radio resource

management approaches for optimizing wireless networks in a more fine-grained and application-aware manner, they have considerable limitations that currently prevent from implementing them in production wireless networking solutions.

As a summary of this survey, we can identify the research gap: the problem of radio resource management in 802.11 WLANs is still relevant, since IEEE 802.11 standard does not provide fully-fledged RRM, while existing commercial solutions are proprietary and lack interoperability. Thus, there is a need for a novel RRM algorithm addressing key issues, including:

- Design for centralized management of enterprise WLAN, working as a part of Wireless LAN Controller;

- Applicability with current hardware and software, namely:

  - Effortless integration with OpenWRT-based access points;

  - Requires data like physical and link-layer statistics that can be obtained using only regular Linux Wi-Fi drivers like `nl80211` and standard Linux networking tools;

- Performing not worse than existing RRM algorithm from Wimark Systems that will be analyzed in Chapter 3.2;

- Able to combine both channel selection and transmit power adjustment to improve RF environment and network performance.

The following chapters will focus on analyzing the limitations of current algorithms and developing a new one.

Chapter 3

Problem statement and baseline solution analysis

The purpose of this chapter is to lay a foundation for the further work in this study via formal definition of RRM (Radio Resource Management) 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, which will be further referred to as *RRMGreedy*, is based on background scanning by access points. The goal of this study 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*

This section describes *RRMGreedy* algorithm. As the name suggests, the algorithm 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, I consider **RRM group** G as a set of **wireless interfaces** w (that will be further referred 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:

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

   Initial group interference score is denoted as I_0.

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

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

   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 inter-ference 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 w_m* causing the *worst interference* (i.e. whose from-interference score is the largest):

   $$w_m = \arg\max_i FromIfaceInterference(w_i) \qquad (3.3)$$

   (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*:

```
1  Algorithm RRMAlgoGreedy
2  Input:
3      data: RRMInitData
4  Output:
5      GroupDataWithEvent: final configuration and event data for CPEs
6  Begin
7      // Step 0: Prepare raw scanning data received from APs
8      scandata := ProcessScanDataForGroup(data.CPEs, data.ScanData)
9
10     // Step 1: Set Maximum Transmission Power
11     For each cpe in data.CPEs
12         For each iface in cpe.State.Wifi
13             MaxIfaceTxPower := Max Tx power for given hardware
14             scandata[iface].TxDiff := MaxIfaceTxPower - iface.TxPower
15
16     // Step 2: Optimize Channel Selection
17     // calculate initial group interference
18     groupInterference := GroupInterference(scandata)
```

```
19    Repeat until no improvement in groupInterference
20        For each cpe in data.CPEs
21            For each iface in cpe.State.Wifi
22                bestChannel := choose channel that yields minimal
    InterferenceOnCPE(scandata, channel, width) for this iface
23                scandata[iface].channel := bestChannel
24        Recalculate groupInterference := GroupInterference(scandata)
25
26    // Step 3: Adjust Transmission Power (if enabled)
27    If TPC enabled
28        Repeat until no improvement in groupInterference
29            Identify worst-performing interface using InterferenceFromCPE
30            Calculate needpower and bestpower for worst interface
31            Update scandata with new Tx power settings
32            Evaluate total interference using GroupInterference
33
34    // Step 4: Final Data Assembly and Event Generation
35    finaldata, eventsData := Assemble final configuration and events
36    If no significant improvement in interference
37        Return error "No significant changes made"
38
39    Return finaldata and eventsData
40 End Algorithm
```

Listing 3.1: greedy RRM algorithm.

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

```
1 For each scan from interface in RRM group
2    For bssid, signaldata in scan
3        channel := signaldata.channel
4        If bssid in RRMGroup
5            interface.Inner[channel].append(signaldata)
6        Else
7            interface.Outer[channel].append(signaldata)
```

Listing 3.2: ProcessScanDataForGroup pseudocode.

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

In other words, the algorithm is as follows:

1. **Calculate outer interference**: as defined earlier in this chapter, **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

$s \in S_i = S_i^{inner} \cap S_i^{outer}$, calculate adjacent-channel/co-channel interference score with *ChannelInterference()*. This function, given current interface channel, its channel width, and some other channel, returns an estimation of interference between these channels using a simple heuristic (Listing 3.3). Then, for each signal on a given channel, calculate interference score as a product of *ChannelInterference()* and signal power normalized to [0, 1] scale. Finally, sum up interference scores for all signals on this channel.

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

$$(3.8)$$

where S_i^{outer} is a set of signals sensed by w_i on channels not in **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**: as defined earlier in this chapter, **inner interference** is interference originating from access points in the RRM group *G*. In the same way as for outer interference, 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, sum up interference scores for all signals on this channel.

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

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}.

```
1  Function ChannelInterference(ch1, ch2, width)
2      add := 0
3      If ch1 < 36 // channels less than 36 belong to 2.4 GHz band
4          add := 1
5      If abs(ch1 - ch2) >= width / 5 + add
6          Return 0  // No significant interference
7      Else
8          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.

```
1  Function InterferenceOnCPE(scandata, interface, interfaceChannel,
       interfaceChannelWidth)
2      ifData := scandata[interface]
3
4      // Calculate interference from outer APs
5      outerInterf := 0
6      For each otherChannel, signalData in ifData.Outer
7          inteferenceScore := ChannelInterference(otherChannel,
       interfaceChannel, interfaceChannelWidth)
8          If ci == 0 // channels are orthogonal
9              Continue
10         // calculate cumulative interference score for all signals on this
       channel
11         chsum := 0.0
12         For each signal in signalData // every signal sensed on otherChannel
```

```
13              sigRating := signal power (in dBm) normalized to [0, 1] scale
14              chsum += interferenceScore * sigRating
15          outerInterf += chsum
16
17      // Calculate interference from inner APs
18      innerInterf := 0
19      For each otherChannel, signalData in ifData.Inner
20          oth, ok := data[othKey]
21          If not ok
22              Continue
23          ci := ChannelInterference(oth.Settings.Central, ch, width)
24          If ci == 0
25              Continue
26          chsum := 0.0
27          For each signal in signalData
28              sourceInterface := interface from where signal origins
29              adjustedSignal := signal + sourceInterface.TxDiff
30              sigRating := adjustedSignal power (in dBm) normalized to [0, 1]
    scale
31              chsum += ci * sigRating
32          innerInterf += chsum
33
34      Return outerInterf + innerInterf
```

Listing 3.4: OnIfaceInterference() function.

After the channel selection is completed, algorithm performs transmit power adjustment. 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, $w \neq w_i$,

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

```
5
6    For each otherIface in data
7        if otherIface == iface
8            Continue
9        // Get all measurements of signals from iface that otherIface
     received
10       thisIface := othCpe.InnerMeasurements[iface]
11       If thisIface == nil // no measurements for this interface from
     otherIface
12           Continue
13       ci := ChannelInterference(thisdata.Settings.Central, otherIface.
     Settings.Central, otherIface.Settings.Width)
14       If ci == 0 // channels are orthogonal
15           Continue
16       chsum := 0.0
17       For each sig in thisIface
18           signal := sig.Signal + thisdata.TxDiff
19           sigRating := signal power (in dBm) normalized to [0, 1] scale
20           chsum += ci * sigRating
21           maxsignal = max(signal, maxsignal)
22       sum += chsum
23
24   Return sum, maxsignal
```

Listing 3.5: FromIfaceInterference() function.

B. *Evaluating asympotic complexity*

In this section, I evaluate asymptotic complexity of *RRMGreedy* algorithm. First, I consider the complexity of used auxiliary functions:

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., $O(|G| \cdot C) = O(|G|)$.

Next, I analyze 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*

Bibliography cited

[1] Cisco. "Radio Resource Management White Paper," Cisco. (), [Online]. Available: `https://www.cisco.com/c/en/us/td/docs/ wireless/controller/technotes/8-3/b_RRM_White_ Paper.html` (visited on 09/23/2023).

[2] "Understanding ARM." (), [Online]. Available: `https://www. arubanetworks.com/techdocs/ArubaOS_62_Web_Help/ Content/ArubaFrameStyles/ARM/ARM_Overview.htm` (visited on 01/16/2024).

[3] "Cisco Unified Wireless Network Solution Overview [Design Zone for Mobility]," Cisco. (), [Online]. Available: `http://www.cisco. com/en/US/docs/solutions/Enterprise/Mobility/ emob30dg/Overview.html` (visited on 03/19/2024).

[4] "The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition," *IEEE Std 100-2000*, pp. 1–1362, Dec. 2000. DOI: `10.1109/IEEESTD. 2000.322230`.

[5] A. S. Tanenbaum, *Computer Networks*, 6th edition. Pearson, Apr. 24, 2020, 0 pp., ISBN: 978-0-13-676405-2.

[6] A. Könsgen, "Spectrum Management Algorithms," in *Design and Simulation of Spectrum Management Methods for Wireless Local Area Networks*, A. Könsgen, Ed., Wiesbaden: Vieweg+Teubner Verlag, 2010, pp. 103–132, ISBN: 978-3-8348-9738-1. DOI: `10.1007/978-3-8348-9738-1_4`.

[7] D. D. Coleman and D. A. Westcott, *CWNA Certified Wireless Network Administrator Study Guide: Exam CWNA-108*, 6th edition. Sybex, Mar. 9, 2021, 1088 pp., ISBN: 978-1-119-73450-5.

[8] J. Zander, "Radio resource management in future wireless networks: Requirements and limitations," *IEEE Communications Magazine*, vol. 35, no. 8, pp. 30–36, Aug. 1997, ISSN: 1558-1896. DOI: `10.1109/35.606024`.

[9] "802.11r-2008 - IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Fast Basic Service Set (BSS) Transition | IEEE Standard | IEEE Xplore." (), [Online]. Available: `https://ieeexplore.ieee.org/document/4573292` (visited on 03/19/2024).

[10] "Cisco Catalyst 9800 Series Wireless Controller Software Configuration Guide, Cisco IOS XE Bengaluru 17.4.x - BSS Coloring [Cisco Catalyst 9800 Series Wireless Controllers]," Cisco. (), [Online]. Available: `https://www.cisco.com/c/en/us/td/docs/wireless/controller/9800/17-4/config-guide/b_wl_17_4_cg/m_bss_coloring_ewlc.html` (visited on 03/20/2024).

[11] K. Sui, Y. Zhao, D. Pei, and L. Zimu, "How bad are the rogues' impact on enterprise 802.11 network performance?" *2015 IEEE Conference on Computer Communications (INFOCOM)*, pp. 361–369, Apr. 2015. DOI: `10.1109/INFOCOM.2015.7218401`.

[12] A. Levanti, F. Giordano, and I. Tinnirello, "A CAPWAP-Compliant Solution for Radio Resource Management in Large-Scale 802.11 WLAN," in *IEEE GLOBECOM 2007-2007 IEEE Global Telecommunications Conference*, Washington, DC, USA: IEEE, Nov. 2007, pp. 3645–3650, ISBN: 978-1-4244-1042-2 978-1-4244-1043-9. DOI: `10.1109/GLOCOM.2007.692`.

[13] F. Bouhafs, M. Seyedebrahimi, A. Raschella, M. Mackay, and Q. Shi, "Per-Flow Radio Resource Management to Mitigate Interference in Dense IEEE 802.11 Wireless LANs," *IEEE Trans. on Mobile Comput.*, vol. 19, no. 5, pp. 1170–1183, May 1, 2020, ISSN: 1536-1233, 1558-0660, 2161-9875. DOI: `10.1109/TMC.2019.2903465`.

[14] W. Lee and J.-B. Seo, "Deep Learning-Aided Channel Allocation Scheme for WLAN," *IEEE Wireless Commun. Lett.*, vol. 12, no. 6, pp. 1007–1011, Jun. 2023, ISSN: 2162-2337, 2162-2345. DOI: `10.1109/LWC.2023.3257128`.

[15] M. Achanta, "Method and apparatus for least congested channel scan for wireless access points," U.S. Patent 20060072602A1, Apr. 6, 2006. [Online]. Available: `https://patents.google.com/patent/US20060072602A1/en` (visited on 11/16/2023).

[16] Arunesh Mishra, A. Mishra, Suman Banerjee, *et al.*, "Weighted coloring based channel assignment for WLANs," *Mobile Computing and Commu-*

nications Review, vol. 9, no. 3, pp. 19–31, Jul. 1, 2005. DOI: `10.1145/1094549.1094554`.

[17] M. Michalski and K. Staniec, "A simple performance-boosting algorithm for transmit power control in WLAN access points," *2016 21st International Conference on Microwave, Radar and Wireless Communications (MIKON)*, pp. 1–4, May 9, 2016. DOI: `10.1109/mikon.2016.7492075`.

[18] .. and.., "," vol. 7, no. 3, pp. 25–37, 2021, ISSN: 1813-324X, 2712-8830. DOI: `10.31854/1813-324X-2021-7-3-25-37`.

[19] K. Ramachandran, R. Kokku, H. Zhang, and M. Gruteser, "Symphony: Synchronous two-phase rate and power control in 802.11 wlans," *IEEE/ACM Transactions on Networking*, pp. 132–145, Jun. 17, 2008. DOI: `10.1145/1378600.1378616`.

[20] Y. Lee, K. Kim, and Y. Choi, "Optimization of AP placement and channel assignment in wireless LANs," in *27th Annual IEEE Conference on Local Computer Networks, 2002. Proceedings. LCN 2002.*, Nov. 2002, pp. 831–836. DOI: `10.1109/LCN.2002.1181869`.

[21] R. Rodrigues, G. Mateus, and A. Loureiro, "On the design and capacity planning of a wireless local area network," in *NOMS 2000. 2000 IEEE/IFIP Network Operations and Management Symposium 'The Networked Planet: Management Beyond 2000' (Cat. No.00CB37074)*, Apr. 2000, pp. 335–348. DOI: `10.1109/NOMS.2000.830394`.

[22] A. Raschellà, M. Mackay, F. Bouhafs, and B. I. Teigen, "Evaluation of Channel Assignment Algorithms in a Dense Real World WLAN," in *2019*

4th International Conference on Computing, Communications and Security (ICCCS), Oct. 2019, pp. 1–5. DOI: `10.1109/CCCS.2019.8888082`.

[23] "WiFi Market - Size, Share & Trends." (), [Online]. Available: `https://www.mordorintelligence.com/industry-reports/wi-fi-market` (visited on 11/16/2023).

[24] S. Arena, F. S. Crippa, N. Darchis, and S. Katgeri, *Understanding and Troubleshooting Cisco Catalyst 9800 Series Wireless Controllers*, 1st edition. Cisco Press, Jul. 25, 2022, 656 pp., ISBN: 978-0-13-749232-9.

[25] "Cisco CleanAir Technology At-a-Glance," 2014.

[26] JuniperNetworks, director, *Understanding Radio Resource Management RRM*, Jul. 19, 2023. [Online]. Available: `https://www.youtube.com/watch?v=BUmhVytJfXI` (visited on 10/31/2023).

[27] "Radio Management (technology) | Mist | Juniper Networks." (), [Online]. Available: `https://www.juniper.net/documentation/us/en/software/mist/mist-wireless/topics/concept/wireless-rrm.html` (visited on 11/16/2023).

[28] "Ruckus ChannelFly Feature Sheet." (Jan. 24, 2023), [Online]. Available: `https://web.archive.org/web/20230124150501/https://webresources.ruckuswireless.com/pdf/feature-sheets/fs-channelfly.pdf` (visited on 11/16/2023).

[29] "ArubaOS 8.6.0.0 User Guide," PSNow. (), [Online]. Available: `https://www.hpe.com/psnow/doc/a00092459en_us` (visited on 01/16/2024).

[30] "ARM Overview." (), [Online]. Available: `https : / / www . arubanetworks.com/techdocs/ArubaOS_60/UserGuide/ ARM.php` (visited on 01/16/2024).

[31] "Taming Aruba ARM | Wifizoo." (Nov. 9, 2012), [Online]. Available: `https://wifizoo.org/2018/01/11/taming-aruba-arm/` (visited on 01/16/2024).

[32] "ARM Metrics." (), [Online]. Available: `https : / / www . arubanetworks.com/techdocs/ArubaOS_62_Web_Help/ Content/ArubaFrameStyles/ARM/ARM_Metrics.htm` (visited on 11/01/2023).