A Framework for Massive Access and Radio Resource Management in Urban WLANs

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***Abstract*—The challenge in future unlicensed wireless networks will be the coordination of spectrum access among wireless LAN (WLAN) nodes in high dense areas. New WLAN standards, such as IEEE 802.11ah, will provide optimized outdoor WLAN coverage with a range of 1 km, thus exceeding the number of associated WLAN nodes. Hence, *massive access* schemes are required in order to coordinate the wireless access among WLAN nodes and to mitigate mutual interference. In addition, various wireless networks will co-exist, such as WLANs and sensor networks, competing for channel access. Hence, a framework in order to coordinate WLANs and sensor networks in dense areas is essential. This paper is intended to outline the challenges of wireless access in urban WLANs and proposes a framework which considers the challenges of dense wireless access and discusses potential solutions. The contributions are twofold. A clustering framework is proposed to deal with the massive access of wireless nodes, in particular of IEEE 802.11ah WLAN nodes. Further, a radio resource monitoring and management (RRMM) is proposed to manage the co-existence among wireless networks. A novel system architecture is proposed and discussed in order to monitor and manage the WLAN access in highly dense urban areas.**

***Index Terms*—WLAN, sensor networks, IEEE 802.11ah, sub-1 GHz, IEEE 802.15.4, massive access, radio resource management, monitoring.**

I. Introduction

The use of unlicensed and cost-efficient wireless LANs (WLANs) attracts cellular operators and service providers to provide ubiquitous wireless access for mobile users. Such networks would allow simple and cheap Internet access (dump pipes), while more effort could be concentrated on creating new services and offering solutions to increase the operator's revenue. In addition there is a prediction that the WLAN traffic initiated by smart phone users would ramping up and would lead to over 10 billion devices worldwide in 2017 [1]. WLAN access in cities will increase and the integration of machine-to-machine (M2M) services and Internet-of-Things (IoT) will further increase the demand for wireless access.

A trend can be observed in which WLAN traffic significantly increases in the access network of cellular providers. It has been reported in [2] that WLAN traffic is increasing, and has already reached a dramatic ratio of over 50% for WLAN traffic for some cellular operators, compared to the cellular initiated traffic volume.

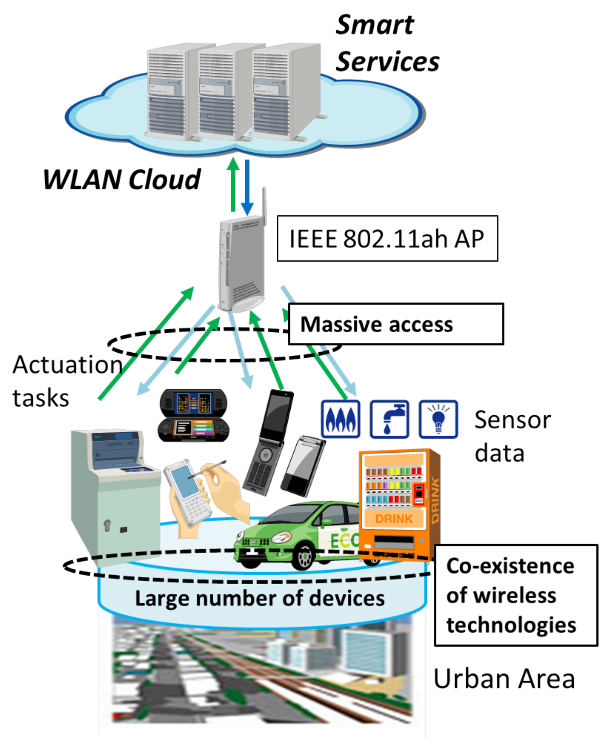

Fig. 1. Massive Access scenario in urban WLANs.

In addition to the massive increase of wireless traffic, there is a challenge in the revenue which a cellular operator can obtain. The problem is that the wireless traffic increase rapidly in parallel to an increase of investment costs for infrastructure, e.g., to offer data pipes. Although, the amount of data traffic outperforms the costs, the network investments decrease the operator's revenue. Further, high speed wireless access is provided by alternative systems, such as IEEE 802.11 WLANs, which provide more than 1 Gbps [3]. Thus, it can be predicted that WLANs will gain more attraction by cellular operators - from those who are ready to invest and want to deploy a next generation wireless system - and local service providers - from those who are looking into wireless transmission systems without licensing radio access - e.g., to setup a wireless Internet service. Fig. 1 illustrates a dense urban

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WLAN scenario in which a huge number of access devices in various wireless networks compete for wireless access,, e.g., to forward sensor/actuator data from/to the service cloud via WLAN access point (AP) with large wireless coverage.

IEEE 802.11ah will be an optimal candidate for sensor networks in urban areas, e.g., to access sensor data via Wi-Fi devices, which are widely used and highly accepted. However, due to the longer range at lower frequencies, there is the challenge that more devices will be accessible in a larger coverage of a single WLAN AP, competing for channel access. The *massive access* of 6000 WLAN nodes within a WLAN AP coverage radius of $r = 1000\,\mathrm{m}$ is such potential challenge, when using long-range Wi-Fi in high dense urban environments, where the number of devices per km^2 can easily reach 2000 nodes [4], [5]. Even thousands of WLAN nodes occur in dense areas, such as airports, as reported in [6]. This paper outlines the problem of massive access in urban WLANs and a new framework is proposed.

Further, the presence of heterogeneous sensor networks, such as IEEE 802.11ah and IEEE 802.15.4 networks, will increase, competing for channel access in the same radio-band. Hence, a solution of *co-existence* is essential, e.g., to monitor and control the media access, in order to mitigate interference and potential packet collisions among wireless systems. In this paper a *radio resource monitoring and management* (RRMM) framework is proposed and discussed.

To the best of our knowledge there has been no reports on a framework for massive access and radio resource management for unlicensed, long-range sub-1 GHz wireless communication systems.

The contributions of our study include:

- an overview of sub-1 GHz WLANs and its developing standard IEEE 802.11ah;
- thorough introduction the problem which arise from massive access and co-existence in long-range wireless networks;
- detailed framework proposal for massive access and RRMM to tackle the challenges which arise in highly dense WLANs;
- a discussion on how to investigate the proposed framework in a wireless platform in real-time.

This study is organized as follows. In Section II we reflect on related work on dense WLANs and massive access, followed by a detailed gap analysis. In Section III we outline the advantages of sub-1 GHz WLANs and refer to the IEEE 802.11ah WLAN standard which is under development and we briefly refer to IEEE 802.15.4 sensor networks. In Section IV we outline the problem of massive access which occur in urban WLANs and proposed a massive access framework. We give statements on the co-existence of IEEE 802.11ah and IEEE 802.15.4 and outline potential threats, such as packet collisions, and propose a radio resource monitoring and management (RRMM) framework. In Section V we discuss a sub-1 GHz platform candidate in order to investigate the effectiveness of the proposed framework. We conclude our study in Section VI.

II. Related Work

Recently, massive access schemes have been proposed in 3GPP networks, as in [7], [8], and [9]. As such, these studies have a limited use for WLANs. Performance studies of large number of WLAN nodes and APs have been presented in [6], and [10]–[15].

First, we found that a helpful definition of massive access was not given by any author. In particular, IEEE 802.11 specifies an *address identifier field* (AID) which allows 2007 associated WLAN nodes [3]. However, authors argue with much less WLAN nodes in coverage of a single AP. In contrast, we will define massive access in Section IV-A.

Some studies do not present any details about the number of expected WLAN nodes or APs within a wireless network, as in [12], [14], and [15]. Thus, it can be concluded that the problem of massive access in dense WLANs has not been tackled thoroughly. Other studies only consider limited simulation setups, e.g., 20 APs, as in [10], or single WLAN/STA communication, as in [11], and [13]. The study in [6] argues that the collision probability increases in dense WLANs - here for a density of 50 WLAN nodes.

Next, a detailed gap analysis is provided in order to identify the requirements on a new system architecture for dense WLANs.

Our findings can be summarized as follows:

- close cellular integration (tight coupling) of unlicensed, long-range outdoor WLANs to support a large number of WLAN nodes is missing in the literature;
- resource management framework for dense WLANs in urban areas has not been proposed in the literature;
- shaping, optimization, and visualization of traffic in dense WLANs is required;
- interconnection among cloud networks, including WLANs, wireless personal area networks (WPANs), and home gateways, is required;
- access automation and service level agreement (SLA) provision are not mentioned for outdoor WLANs;
- access to data centers (DC) and (centralized) policy control is required.

The analysis shows that there are new topics relevant for operators, including parameters for storage capabilities, billing models, policy controlled access, and the visualization of network resources. Monitoring and visualization of WLAN user sessions, CPU loads, and threshold observation are further topics and have not been mentioned in the literature. Instead, we propose a novel framework, that provides tight coupling, monitoring (sensing), management (control), and visualization (data center) for urban, long-range WLANs.

III. Rationale for Sub-1 GHz WLANs

Wireless operators are challenged by the emerging demand in new aspects of future wireless networks. First, as it has been outlined, there is a demand for a *cost-efficient* deployment and maintenance of wireless access systems in order to achieve a *high revenue*. Second, there is a need to reduce the *energy*

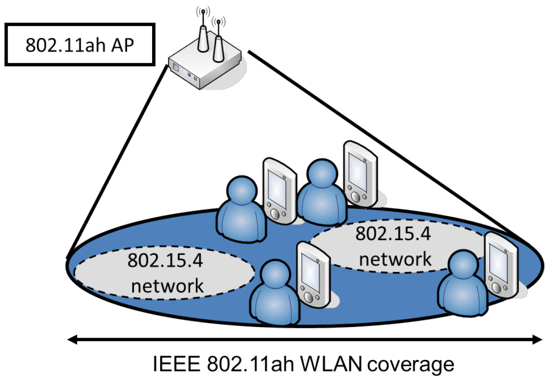

Fig. 2. Long-range IEEE 802.11ah coverage and short-range IEEE 802.15.4 sensor networks.

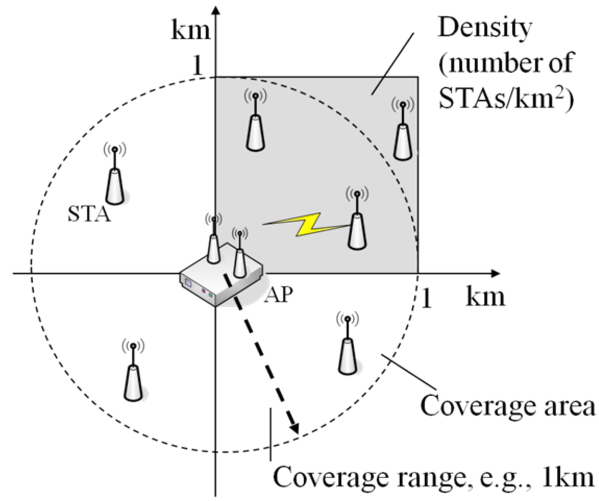

Fig. 3. IEEE 802.11ah WLAN scenario in a dense urban area.

consumption of access technologies. This can be requested in order to reduce electricity costs, thus further increasing the operator's revenue. It can also be initiated by state governments, aiming for energy efficient communication systems. Then, there is a demand for *robust* wireless communication systems, in order to reduce wireless retransmissions and to increase the quality of user experience. Finally, due to recent natural incidents, such as earthquakes and tornadoes, there is a strong demand by governments for *resilient* wireless access systems. The IEEE 802.11 and IEEE 802.15 standards will play an important role in the design of future wireless systems, to accomplish the demands of a cost efficient, low energy consumption, robust, and resilient wireless communication.

WLANs have been deployed during the last two decades, mainly for the use in indoor environments. Recently, there is a demand for optimizing WLANs for the outdoor deployment. There are potential radio-bands worldwide in the sub-1 GHz band available which provide unique wireless features, such as longer range, energy efficiency, and high penetration. The IEEE 802.11 has started a new standardization project, the IEEE 802.11ah [4], which aims to standardize physical layer (PHY) and media access control (MAC) for unlicensed access in the industrial, scientific, and medical (ISM) sub-1 GHz band. Fig. 2 depicts the large coverage area by IEEE 802.11ah WLAN covering IEEE 802.15.4 sensor networks.

A. Sub-1 GHz WLAN Propagation Characteristics

The excellent propagation characteristic of ultra-high frequencies (UHF) below 1 GHz motivates the design of sub-1 GHz wireless communication systems, due to longer range and better propagation performance. Studies have shown that sub-1 GHz frequencies have higher reach, e.g., behind vehicles and buildings, where 2.4 GHz WLAN lead to many gray zones [16]. There are already frequencies assigned in different countries allowing the license-free use in the sub-1 GHz ISM (industrial, scientific, medical) radio band, e.g., USA, China, Europe, and Japan. For instance, in Japan the 915-930 MHz band is available for wireless transmissions and allows up to 1 MHz channel bandwidth [17].

The IEEE 802.11ah Task Group aims to standardize a long-range WLAN system that will allow up to 1 km coverage range. The modulation scheme proposed will have to support multi-antenna systems and path loss models for longer range, robustness and power efficiency. For example, the *urban macro* sub-1 GHz WLAN path loss model is given by [5],

$$L(dB) = 8 + 37.6 \cdot \log_{10}(d), \tag{1}$$

with d as the distance between wireless sender and receiver in [m].

The *urban pico/hotzone* sub-1 GHz WLAN path loss model is given by [5],

$$L(dB) = 23.3 + 36.7 \cdot \log_{10}(d). \tag{2}$$

Fig. 3 illustrates a single IEEE 802.11ah WLAN AP, which is surrounded by multiple IEEE 802.11ah WLAN stations (STAs). Due to the large coverage of a single AP, thousands of WLAN STAs could be in coverage in dense urban areas, thus competing for channel access.

B. Potential Smart City Use Cases

In the following two potential use cases are outlined when using IEEE 802.11ah. The first use case is a typical city guide scenario in which a mobile user wants to get access to local information, e.g., to find the nearest convenience store. The user may activate his smart phone which uses IEEE 802.11ah long-range WLAN to receive local advertisements. This can be in form of beaconing/advertising the presence of such services. Fig. 4 shows a typical long-range urban WLAN scenario.

Second, a use case is presented in which long-range outdoor WLAN is used in order to get access to other users in an urban environment. Long-range WLAN can be used in order to socialize with other users. It can also be used, e.g., for object localization or person observation, e.g., parents want to observe their kids on their way from/to school. Fig. 5 shows a typical long-range outdoor person observation scenario.

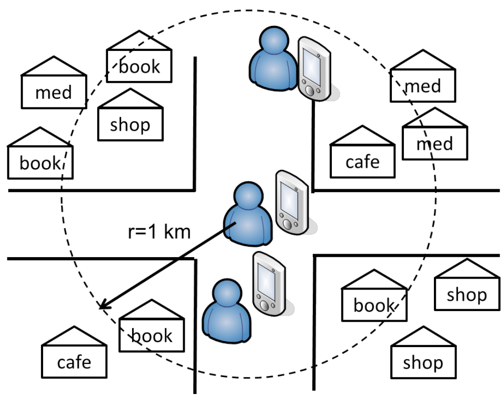

Fig. 4. Smart city scenario: long-range ($r = 1$ km) service discovery with IEEE 802.11ah WLAN.

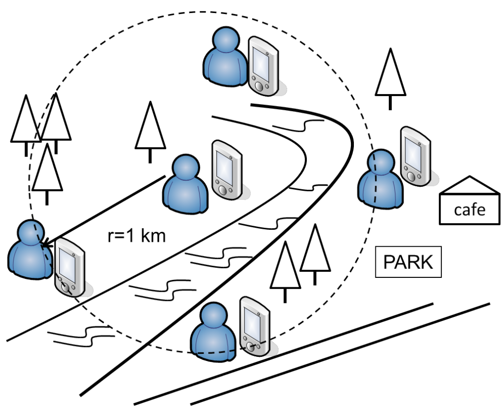

Fig. 5. Smart city scenario: long-range ($r = 1$ km) person surveillance with IEEE 802.11ah WLAN.

C. IEEE 802.15.4 Sensor Networks

There will be a huge deployment of IEEE 802.15.4 M2M and IoT networks in the near future. IEEE 802.15.4 offers energy-efficient, low-cost and low-data rate which is optimized for short range communication at various carrier frequencies, including 900 MHz and 2.4 GHz ISM-band [18]. IEEE 802.15.4 offers a limited coverage area, large number of nodes and low data rate, e.g., for meter or sensor data. Gaussian Frequency Minimum Shift Keying (GFSK) is used as a modulation scheme. Low sending power is typical for IEEE 802.15.4 sensor nodes. We compare the parameters of IEEE 802.11ah and IEEE 802.15.4 in Table I.

TABLE I
CHARACTERISTICS OF URBAN WLAN AND SENSOR NODES

Parameter	IEEE 802.11ah	IEEE 802.15.4g
Throughput [kbps]	< 1000	< 100
Coverage [m]	< 1000	< 1000
Scalability [nodes]	thousands	hundreds
Tx power [mW]	1 to 1000	1 to 20
Media access	CSMA/CA	LBT, CSMA
Battery lifetime [years]	> 2	< 2
Modulation	(MIMO-) OFDM	FSK, GFSK, (OFDM)

IV. Proposed Framework for Massive Access and Radio Resource Management

A. Definition of Massive Access in WLANs

We define massive access in WLANs, *as a new communication type in which hundreds or thousands of WLAN STAs compete for contention-free access in a single WLAN*. Potential solutions include the *grouping*, *prioritizing*, and *synchronizing* of wireless media access. Fig. 6 illustrates the stable region of a general system, here a WLAN system. System parameters are the system limits of active WLAN stations $L1$ and number of WLAN APs $L2$. If the number exceeds, the system is in an unstable state, thus leading to unwanted communication failures, e.g., retransmissions due to wireless data packet collisions of control frames.

B. Sub-1 GHz System Model

Let us consider a sub-1 GHz IEEE 802.11ah WLAN coverage area with N channels, indexed by $N = \{n|n = 1, 2, ..., N\}$, provided by an WLAN AP. Assume OFDM as uplink and downlink with a time duration T. There are M WLAN nodes, equipped with IEEE 802.11ah devices, distributed within the WLAN AP coverage. Let $F = \{m_i|i = 1, 2, ..., M\}$ the indexed i WLAN nodes. Wireless links and location of the WLAN STAs are stationary. The WLAN STAs periodically transmit sensor data to the WLAN AP. We assume each WLAN node has a 1-hop transmission link between WLAN node and AP. The achievable rate for any link denoted as r_c for spectral bandwidth B_c and noise power N_0, can be written as:

$$r_c = B_c \cdot log_2(1 + p_c|h_c|^2/N_0B_c) \quad (3)$$

with h_c as the channel gain and p_c as the transmitting power.

Scalability is critical in dense WLANs. Current media access schemes, such as *carrier sense multiple access/collision avoidance* (CSMA/CA) show significant limitations in the presence of a high number of WLAN nodes. CSMA/CA has

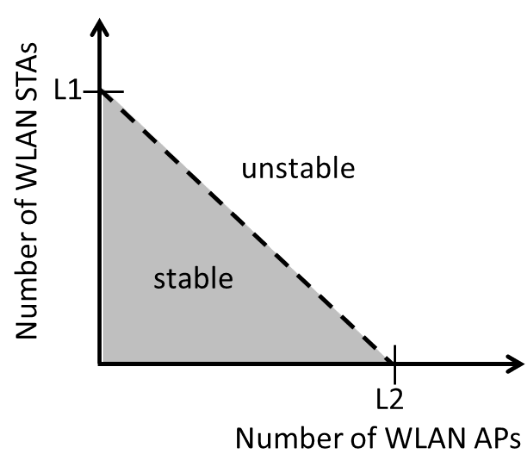

Fig. 6. Stable region of a system, here a WLAN system.

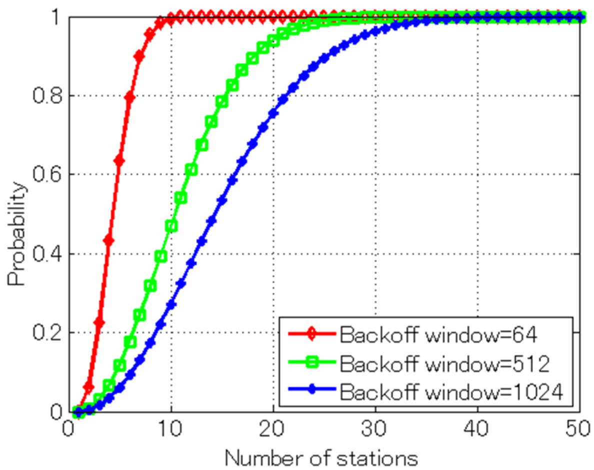

Fig. 7. Increased collision probability of collisions in dense WLANs.

been found to work in an optimal regime when the number of WLAN nodes is low, e.g., few nodes. If the number of WLANs nodes increases, *virtual carrier sensing* which uses *request to send/clear to send* (RTS/CTS) schemes can further improve the co-existence among multiple WLAN nodes. However, if the number of WLAN nodes increases, e.g., more than 30 nodes, new problems occur. The RTS/CTS scheme, which utilizes small messages (RTS frames) in order to reserve the media among WLAN nodes, lead to the collision of RTS frames. In distributed coordinated WLANs, the collision probability P_{col} of n WLAN STAs with access probability τ is given by

$$P_{col} = 1 - (1 - \tau)^{n-1}. \quad (4)$$

Fig. 7 show the probability of frame collisions related to the number of terminals. It can be observed in Fig. 7 that the probability of collisions immediately increases when the number of terminals increases. For larger *backoff window* the collision probability can be relaxed. However, for larger than 30 WLAN nodes, the collision probability increases significantly. Thus, new access schemes are necessary to develop.

C. Proposed Framework

Network management and provisioning of devices have been addressed within many standard organizations, e.g., *Open Mobile Alliance* (OMA) [19] and the *Broadband Forum* (BBF) [20]. For instance, in BBF MR-235, a broadband access framework is given, that interconnects cellular and WLAN for broadband in-house use. However, such networks are designed for indoor applications and for limited coverage and focused on high throughput and Wi-Fi offloading features. In OMA DM v2.0 a hierarchical architecture is presented to organize a large number of wireless access terminals (framework architectures are not shown here due to the brevity of the paper). The new standard organization OneM2M [21] is underway to propose a framework for massive number of M2M terminals in the near future.

Scalability can be achieved through hierarchical structures of WLAN APs, e.g., such in OMA [19]. Instead of a hierarchical structure, which needs further deployment of APs, we propose to scale the WLAN through physical schemes. In particular, we propose a sectorized beamforming for the access in dense WLANs.

In the following, a new framework for massive access in dense WLANs is proposed that can be summarized as follows:

- support of large number of access terminals, thousands of stations;
- support of short burst data, medium data;
- co-existence and self-organization among wireless networks;
- sectorization and clustering of WLANs.

The challenges regarding the number of wireless devices and the interference among different device classes require the design of new architectural framework for spectrum access. Spectrum access coordination among the devices is required in order to achieve a robust data rate for each link which would beneficial for the reliability and resilience of wireless communication in a dense WLAN, e.g., in an highly dense urban WLAN. In this framework, a coordination between the devices and services is proposed. It requires the frequent sensing and monitoring of network activities in order to detect anomalies and performance outages. In addition, the coordination between different device classes is proposed. In the future it is expected that heterogeneous wireless network will co-exist. Here, a radio resource monitoring and management (RRMM) is in the focus of a potential solution to manage the access among wireless networks. In the following two subsections, the two proposed schemes are described in detail.

1) Massive Access Framework: Massive Access framework is targeting the coordination within a wireless network. The proposed scheme is to *cluster* the devices into groups when a certain number of wireless nodes n in network i reaches a threshold Λ. If $n_i > \Lambda$ the massive access scheme is initiated. Without loss of generality, for $\Lambda = 100$ nodes, sectorization of the WLAN is proposed. The cluster can be in form of device classes, e.g., electrical power consumption, same QoS, or access priority. The cluster can be physical realized in form of partitioning the wireless coverage, e.g., using beamforming, where WLANs in a certain location of the network are allowed to access the media. Both schemes organize the networks in clusters, in order to minimize the number of active devices within a time frame t_s. At $t_s + 1$ the massive access scheme selects a new cluster and continues with the communication while other clusters remain silent in order to avoid interference during ongoing transmissions. Fig. 8 illustrates the sectorization of a WLAN cell. It shows the WLAN AP with 3 sectors in which WLAN nodes are organized in clusters. Media access of the clusters is controlled by the WLAN AP, e.g., through time synchronization mechanisms [3].

2) Radio Resource Monitoring and Management (RRMM) Framework: RRMM is targeting the coordination among wireless networks. In the RRMM framework, data from the wireless networks are collected via APs and spectrum sensor

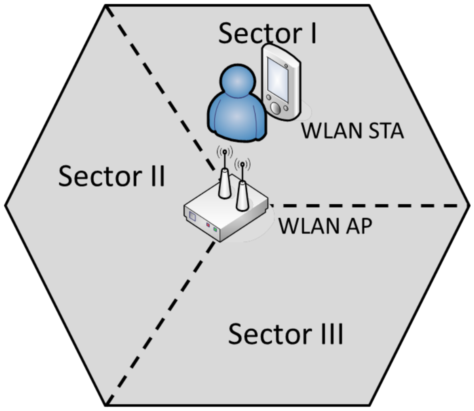

Fig. 8. Proposed sectorization for massive access in urban WLANs.

devices, e.g., to detect transmission failures. Sensing data is forwarded via a common interface. A central/distributed RRMM entity receives the data, which can be stored in data bases (DB). The RRMM decides which network gains access and sends the decision via a common interface.

The RRMM executes the following actions:

- Clustering [7], e.g. in regard of the density, access priority and distribution of WLAN nodes;
- Synchronization of sleep and wake-up periods to increase electrical power efficiency [22];
- Antenna array switching [23], horizontal beamforming [24], vertical beamforming [25], 3D-beamforming [26], pencil beamforming [27];
- Interference alignment [28] and avoidance [29].

Fig. 9 illustrates the proposed framework. Each WLAN AP is linked to a RRMM unit via a common interface. In addition, sensor nodes are connected to the RRMM. This allows monitoring the wireless system performance and spectrum information. Data are stored in additional data bases, e.g., for decision making in the RRMM. Feedback information in form of control data, e.g., to synchronize media access, is transmitted via a common interface. A sequence description of the proposed RRMM framework is given in Table II.

TABLE II
SEQUENCE DESCRIPTION OF THE PROPOSED RRMM FRAMEWORK.

Proposed RRMM Framework
Step1: Sectorization, access prioritization among WLAN nodes.
Step2: Monitor of wireless network anomalies and failures.
Step3: Calculate media access and decision making.
Step4: Time synchronization among wireless networks.
Step5: Execute media access, monitor, and control.

V. PROPOSED SUB-1 GHZ WLAN PLATFORM

Finally, we outline how to evaluate the proposed framework. A low-cost solution has been proposed in [30] that allows a simple operation of MIMO-OFDM functions in a configurable software radio platform. For the sub-1 GHz platform

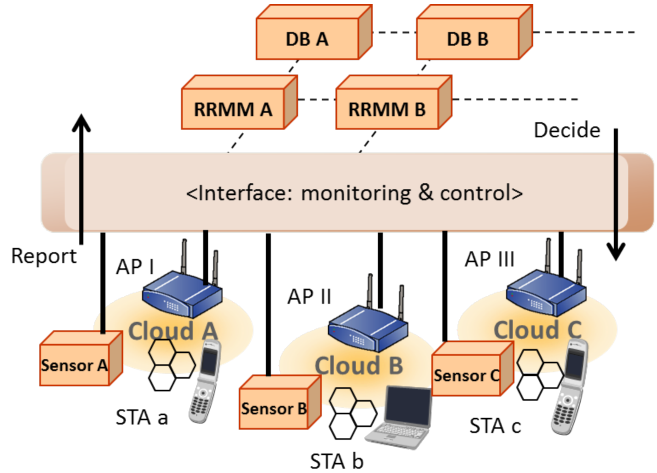

Fig. 9. Proposed RRMM framework for dense WLANs.

open-source software is applied in order to design a generic platform, that is independent from the carrier frequency f_c and allows MIMO-OFDM operation in narrow-band wireless systems, e.g., 1 MHz channel bandwidth.

In addition, IEEE 802.15.4 sensor nodes are part of the platform to emulate a smart meter sensor network, e.g., to transmit short burst sensor data (10 byte) in short range. First results of concurrent use of IEEE 802.11ah and IEEE 802.15.4 networks show that there is a demand for access control in order to reduce the number of packet collisions, which occur when wireless carrier sense levels - here WLAN and WPANs - are not synchronized, and as such, lead to unstable system operations. We are planning a thorough evaluation of the co-existence in real wireless networks as future work, including the implementation of the proposed RRMM framework.

VI. CONCLUSIONS

In this paper, the challenges of wireless access in high dense networks, such as in urban WLANs, are described. Such challenges are imminent when a large number of WLAN nodes - here 6000 WLAN nodes - compete for wireless access in long-range outdoor WLANs. Further, the problems of heterogeneous access are outlined, which require an intelligent management framework to manage the co-existence among wireless networks - here IEEE 802.11ah and IEEE 802.15.4 networks - to mitigate the interference among the networks. The proposed RRMM framework aims to support a large number of WLAN nodes in dense urban areas. There are some topics in this area that need more investigation. In particular, the effectiveness and practical implementation of the proposed framework need further investigation. Therefore, an IEEE 802.11ah prototype has been implemented in [30] which allows the implementation of the proposed framework, including massive access and RRMM scheme, and to evaluate the performance boundaries in dense WLANs and co-existence strategies among IEEE 802.11ah and IEEE 802.15.4 networks.

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