A Survey on High Efficiency Wireless Local Area Networks: Next Generation WiFi

Hassan Aboubakr Omar*†, Khadige Abboud*,
Nan Cheng*, *Student Member, IEEE*, Kamal Rahimi Malekshan*, *Student Member, IEEE*,
Amila Tharaperiya Gamage*, *Member, IEEE*, and Weihua Zhuang*, *Fellow, IEEE*
*Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1
†Engineering Mathematics and Physics Department, Cairo University, Giza, Egypt
{h3omar, khabboud, n5cheng, krahimim, aptharap, wzhuang}@uwaterloo.ca

***Abstract*—The emerging paradigm of the Internet of Everything (IoE), along with the increasing demand of Internet services everywhere, results in a remarkable and continuous growth of the global Internet traffic. As a cost-effective Internet access solution, WiFi networks currently generate a major portion of the global Internet traffic. Furthermore, the number of WiFi public hotspots worldwide is expected to increase by more than sevenfold by 2018 [1]. To face this huge increase in the number of densely deployed WiFi networks, and the massive amount of data to be supported by these networks in indoor and outdoor environments, it is necessary to improve the current WiFi standard and define specifications for high efficiency wireless local area networks (HEWs). This paper presents potential techniques that can be applied for HEWs, in order to achieve the required performance in dense HEW deployment scenarios, as expected in the near future. The HEW solutions under consideration includes physical layer techniques, medium access control layer strategies, spatial frequency reuse schemes, and power saving mechanisms. To accurately assess a newly proposed HEW scheme, we discuss suitable evaluation methodologies, by defining simulation scenarios that represent future HEW usage models, performance metrics that reflect HEW user experience, traffic models for dominant HEW applications, and channel models for indoor and outdoor HEW deployments. Finally, we highlight open issues for future HEW research and development.**

I. Introduction

The global Internet traffic is expected to experience a manyfold rapid increase in the next few years. As predicted by Cicso, the global Internet Protocol (IP) traffic will grow at a compound annual growth rate (CAGR) of 23 percent from 2014 to 2019, reaching 2 zettabytes/year by 2019 [2]. This predicted growth of IP traffic is driven by many factors. First, the large number of new devices introduced to the market, with high intelligence and capabilities, increases the average number of Internet connections per user. Today, the devices that connect to the Internet are not restricted to portable computers, mobile phones, or tablets, but also include smart appliances, wearing devices, motor vehicles, and so forth. The interconnection of such diverse devices creates the concept of the Internet of Everything (IoE). Another aspect directly contributing to the emergence of the IoE is the fast adoption of IPv6 by device manufacturers and network operators, which is particularly important since some continents (e.g., Asia and Europe) have already exhausted their allocated IPv4 address spaces [2]. Furthermore, the advanced features of the Internet-capable devices, together with the increase in Internet connection speeds, lead to a noticeable growth in the adoption of various 'data-hungry' Internet services in residential, mobile, and business environments. For instance, the Internet services for residential online video, mobile localization, and business video-conferencing respectively increased by 18%, 47%, and 30% between 2013 and 2014 [2]. Specifically, IP video services (including online video, video-on-demand, video file sharing, etc.) represent a major percentage of the global IP traffic, and is expected to at least maintain the same percentage, especially after the development of ultra-high-definition TV technologies, and with the trend of people substituting their traditional TV subscription with online video watching through the Internet. Other trends that can significantly increase the IP traffic in the future are the transition of some applications from offline to online (e.g., gaming) and some services from broadcast to unicast (e.g., line TV) [2].

In the IoE era, the traffic generated from wireless local area networks (WLANs), i.e., WiFi[1] devices, is expected to constitute a considerable portion of the total traffic. In 2014, WiFi traffic represented 42% of the global IP traffic, while cellular network traffic accounted for only 4% (the rest is from wired networks) [2]. This high dependance on WiFi technology for Internet access will continue to increase, mainly due to customer demands (individuals and enterprises) for having cost-effective wireless Internet connections, as well as the reliance of cellular companies on WiFi hotspots for cellular network offloading. Hence, it is estimated that the number of public WiFi hotspots worldwide will significantly increase from around 48 million in 2014 to over 340 million in 2018, i.e., a more than 7x increase [1]. Therefore, in order to cope with the expected growth in the number and density of WiFi networks and the anticipated explosion in the amount of wireless traffic that should be supported by these networks, it is necessary to enhance the current WiFi standard to provide specifications for high efficiency WLANs (HEWs).

The first WiFi standard, also known as the legacy IEEE 802.11 standard, was released in 1997, and was modified by several IEEE 802.11 amendments, as shown in Fig. 1.

[1]The term WiFi is used to refer to the WLAN technology based on the IEEE 802.11 standard [3], including all its amendments.

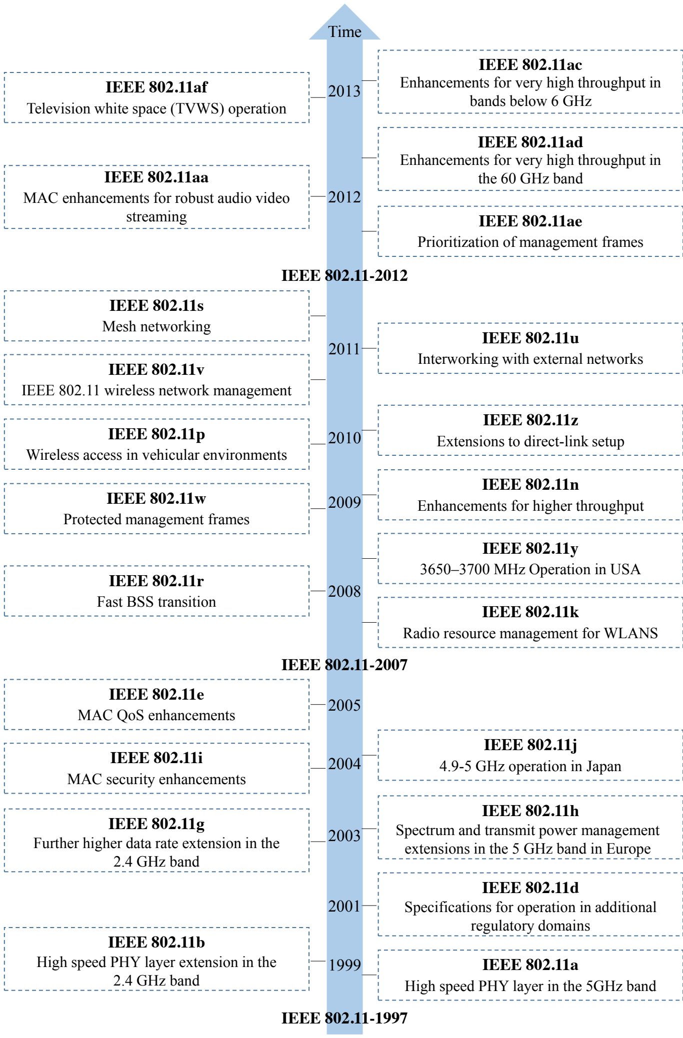


Fig. 1: Evolution of the IEEE 802.11 standard

The legacy IEEE 802.11-1997 standard did not provide a mechanism to achieve a high level of quality-of-service (QoS) provisioning. However, the QoS support was improved in the subsequent IEEE 802.11e amendment, via an enhanced distributed channel access (EDCA) scheme [4]–[11]. To further enhance the QoS provisioning, there has been a lot of research that focuses on new advanced techniques to meet the QoS requirements in WiFi networks [12]–[16]. In 2013, the IEEE 802.11af amendment was released to support operation in the television white spaces (TVWS), i.e., the available frequency bands between television channels [17]. Different from other WiFi amendments, the IEEE 802.11af operates at lower frequency bands, e.g., 54 MHz to 698 MHz in the Unites States and Canada [18], thus allowing for a long communication range, good signal penetration ability, and relatively high throughput – a technology referred to as Super-WiFi. For instance, it is shown that the IEEE 802.11af can provide a throughput of 80 Mbps for a 1200 m communication range, with 6 MHz TVWS channel width and 4 W transmit power level [19]. In order to access the (unlicensed) TVWS without

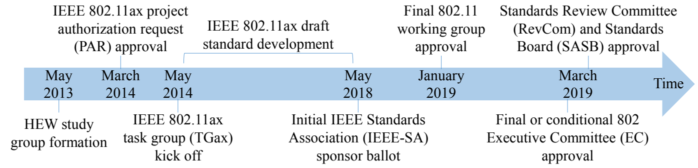


Fig. 2: Timeline of the development of the IEEE 802.11ax standard for HEWs

interfering with the primary (licensed) users of the television broadcast band, cognitive radio techniques can be employed for spectrum sensing and smart utilization of the TVWS [20]–[22]. Also, since the spectrum usage of the television broadcast system is highly stable and predictable, the availability of the TVWS channels does not change frequently and can be obtained before transmission (together with the transmit power limit) from a geolocation database, as described in the IEEE 802.11af amendment [18].

Since May 2014, the IEEE 802.11ax task group has started the development of a new standard for HEWs. Based on the IEEE standardization process [23], the development of the IEEE 802.11ax standard follows the timeline shown in Fig. 2 [24]. Unlike previous IEEE 802.11 amendments, such as IEEE 802.11n/ac, the IEEE 802.11ax task group aims at dealing with future HEW challenges, mainly in terms of the highly dense HEW deployment (indoor and outdoor) in an unmanaged way, and the large volume of traffic that needs to be supported, while preserving a satisfactory level of QoS provisioning for HEW users. Specifically, the focus is placed on achieving high network performance in scenarios with densely deployed access points (APs) and a large number of stations (STAs) associated with each AP, resulting in the formation of closely adjacent basic service sets (BSSs) and a high likelihood of overlapping BSSs (OBSSs)[2], as illustrated in Fig. 3. These dense scenarios are very likely to appear when HEWs are deployed in various environments such as transportation hubs, shopping malls, and outdoor public hotspots, where STAs rely on HEWs for supporting new and enhanced applications for multimedia distribution, localization, cloud access, etc. In these environments, to support various STA applications with the desired QoS requirements, HEWs should achieve efficient channel utilization in a BSS, enhanced spatial frequency reuse among BSSs, high power efficiency for battery-operated STAs, and robust performance in both indoor and outdoor scenarios. These enhancements should be developed for HEWs while preserving economic feasibility, as well as backward compatibility and coexistence with the legacy IEEE 802.11 WLANs that operate on the same radio frequency band.

Achieving the aforementioned objectives for HEWs represents a major challenge that likely cannot be overcome based on a single technology. Hence, the specifications of a future HEW should combine multiple new technologies, including advanced physical (PHY) layer techniques, enhanced medium

[2]The definitions of the terms AP, STA, BSS, OBSS, extended service set (ESS), and BSS area (BSA) are as specified in the IEEE 802.11 standard [3].

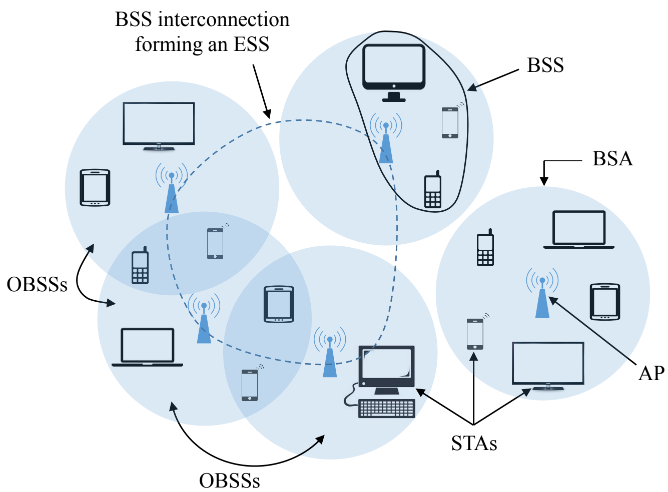


Fig. 3: Illustration of main HEW components

access control (MAC) layer strategies, improved spatial frequency reuse schemes, and efficient power saving mechanisms. Furthermore, to evaluate a newly proposed technology for HEWs, improved performance metrics that reflect HEW user experience should be employed, and suitable simulation scenarios that represent realistic HEW use cases should be considered, covering scenarios with different AP and STA densities, single and multiple management domains, and indoor/outdoor deployment. In this paper, we survey the potential techniques that can be applied for HEWs, present the evaluation methodology for a new HEW technique, and discuss some open issues for future HEW research and development. First, we discuss PHY layer techniques to achieve higher STA-to-STA throughput and enable simultaneous communications among multiple STAs in a BSS. Then, we present cutting-edge research activities on the MAC layer, which allows for efficient channel utilization by BSS members, thus maximizing the gain that is obtained from the underlying PHY layer techniques. Also, to manage interference among adjacent BSSs and efficiently utilize the available radio resources, we provide an overview of spatial frequency reuse schemes, which are particularly needed to improve the system level performance in dense HEW deployment scenarios. Further, suitable power saving mechanisms are discussed for infrastructure-based and ad hoc HEW modes, in order to increase the power efficiency, as a crucial performance metric for HEW STAs. After surveying the potential HEW technologies, we present performance evaluation methodologies, including simulation scenarios, performance metrics, traffic models, and channel models, to assess a new technology proposed to improve the performance of HEWs on the STA, BSS, and system levels. Finally, we discuss open issues related to future HEW research in the PHY/MAC layers, spatial frequency reuse, and STA power efficiency. Table I shows the scope and organization of this paper and Table II lists all the abbreviations used. References to other WLAN topics that are out of scope of this paper are also given in Table I.

II. PHY Techniques

In order to cater for the new requirements, the IEEE 802.11ax standard for HEWs needs an improved PHY layer. The existing WLAN PHY layers are mainly designed for indoor deployment, and thus cannot perform well in outdoor environments with the existence of high multipath delay spread, large Doppler shift, and fast channel variations. Additionally, in a dense HEW deployment scenario, efficient PHY/MAC cross-layer design along with interference cancelation/management techniques should meet strict QoS requirements of HEW applications. In the following, we present potential PHY layer enhancements which are currently being considered by the IEEE 802.11ax task group. These enhancements include adopting orthogonal frequency division multiple access (OFDMA) and deploying technologies such as multiuser multiple-input multiple-output (MU-MIMO) and in-band full-duplex (IBFD) communications. A summary of the PHY layer techniques discussed in this section is provided in Table III.

A. OFDMA

The PHY layer of existing WLANs are mainly based on orthogonal frequency division multiplexing (OFDM). OFDM is a multi-carrier modulation method, in which information bits are carried by sub-carrier signals that are closely spaced

TABLE I: Paper scope and organization

HEW aspect \ Paper scope	Covered topics					Out-of-scope topics	
PHY **Section II**	OFDMA Subsection II-A		MU-MIMO Subsection II-B	IBFD communications Subsection II-C		Hardware design [25]–[27]	Synchronization [28]–[30]
MAC **Section III**	IEEE 802.11 MAC improvements Subsection III-A		Multiuser MAC Subsection III-B	IBFD MAC Subsection III-C		Cooperative MAC [31], [32]	Development platforms [33], [34]
Spatial frequency reuse **Section IV**	Enhanced CCA Subsection IV-A			FFR Subsection IV-B		AP deployment [35]–[39]	Channel selection [40]–[43]
Power efficiency **Section V**	Sleep scheduling in infrastructure-based mode Subsection V-A			Sleep scheduling in ad hoc mode Subsection V-B		Power amplifier [44]–[47]	Network coding [48]–[50]
Evaluation methodology **Section VI**	Simulation methods Subsection VI-A	Performance metrics Subsection VI-B	Simulation scenarios Subsection VI-C	Traffic models Subsection VI-D	Channel models Subsection VI-E	Mathematical analysis [51]–[54]	Experimental evaluation [55]–[57]

TABLE II: List of abbreviations

Acronym	Definition	Acronym	Definition
ACK	Acknowledgement	MCS	Modulation and coding scheme
AC-MAC	AP-client initiated MAC	MIESM	Mutual information ESM
ADC	Analog-to-digital converter	MIMO	Multiple-input multiple-output
AMuSe	Adaptive multicast services	MIMO-BC	MIMO broadcast channels
AP	Access point	MIMO-MAC	MIMO multiple access chandelles
APSD	Automatic power save delivery and notification	MMIB	Mean mutual information per bit
ATIM	Ad hoc TIM	MMO	Massively multiplayer online
AWGN	Additive white Gaussian noise	MPDU	MAC layer protocol data unit
BSA	BSS area	MSDU	MAC layer service data unit
BSS	Basic service set	MU-MIMO	Multiuser MIMO
CAGR	Compound annual growth rate	OBSS	Overlapping BSS
CC	Constrained capacity	OFDM	Orthogonal frequency division multiplexing
CCA	Clear channel assessment	OFDMA	Orthogonal frequency division multiple access
CCA-CS	CCA carrier sensing	ORBIT	Open access research testbed for next-generation wireless networks
CCA-ED	CCA energy detection	P2P	Point-to-point
CCAT	CCA threshold	PER	Packet error rate
CP	Cyclic prefix	PFR	Partial frequency reuse
CSI	Channel state information	PHY	Physical
CSMA/CA	Carrier sense multiple access with collision avoidance	PLCP	PHY layer convergence procedure
CTS	Clear-to-send	PPDU	PLCP protocol data unit
DCF	Distributed coordination function	PSM	Power saving mechanism
DCW	Dynamic contention window	QoS	Quality-of-service
DIFS	DCF inter-frame spacing	QAM	Quadrature amplitude modulation
DSC	Dynamic sensitivity control	RBIR	Received bit mutual rate
EDCA	Enhanced distributed channel access	RTS	Request-to-send
EFFR	Enhanced fractional frequency reuse	S-APSD	Scheduled APSD
EIFS	Extended inter-frame spacing	SFR	Soft frequency reuse
ESM	Effective SINR mapping	SIC	Self-interference cancelation
ESS	Extended service set	SINR	Signal-to-interference-plus-noise ratio
FFR	Fractional frequency reuse	SISO	Single-input single-output
FFT	Fast Fourier transform	STA	Station
FRF	Frequency reuse factor	SU-MIMO	Single-user MIMO
FTP	File transfer protocol	TCP	Transmission control protocol
HCF	Hybrid coordination function	TD-uCSMA	Time-division unbalanced CSMA
HEW	High efficiency WLAN	TGac	IEEE 802.11ac task group
IBFD	In-band full-duplex	TGn	IEEE 802.11n task group
IBSS	Independent BSS	TIM	Traffic indication message
ICI	Inter-cell interference	TVWS	Television white spaces
IFR	incremental frequency reuse	U-APSD	Unscheduled APSD
IoE	Internet of everything	UMa	Urban macro
IP	Internet protocol	UMi	Urban micro
ITU-R	International Telecommunication Union Radio Communication Sector	WARP	Wireless open-access research platform
LoS	Line-of-sight	WiMAX	Worldwide interoperability for microwave access
LTE	Long term evolution	WINNER II	Wireless world initiative new radio consortium II
MAC	Medium access control	WLAN	Wireless local area network
MCF	Mesh coordination function		

(in frequency) and orthogonal to each other. Due to many OFDM advantages, including the efficient OFDM implementation based on Fast Fourier Transform (FFT) algorithms, OFDM is deployed by current WLAN standards, such as IEEE 802.11n/ac, for downlink and uplink communications, i.e., for transmissions from an AP to a non-AP STA and vice versa. Unlike OFDM, where a single STA always transmits and receives signals over all the OFDM sub-carriers, OFDMA allocates different subsets of sub-carriers for different STAs at a given time, allowing for simultaneous uplink transmissions from multiple STAs to an AP, and simultaneous downlink transmissions from an AP to multiple STAs, as illustrated in Fig. 4. By adopting OFDMA for HEWs, interference management among adjacent BSSs can be achieved through fractional frequency reuse (FFR) [58], an advantage that is

TABLE III: Classification of potential HEW PHY techniques

HEW PHY Techniques	**OFDMA**	[58]–[60]
	MU-MIMO	[61]–[68]
	IBFD	[69]–[79]

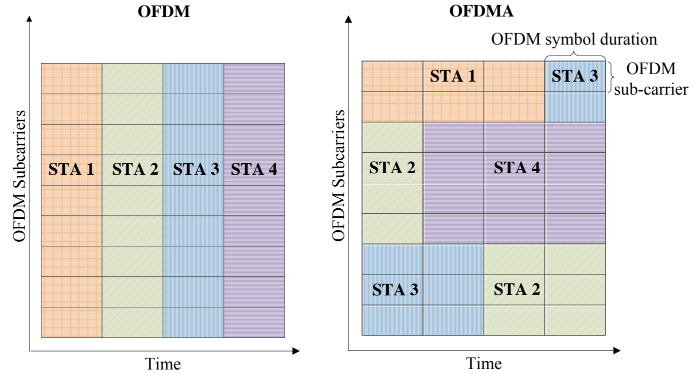


Fig. 4: An example of uplink sub-carrier allocation for STAs in OFDM and OFDMA

particularly useful in a dense HEW deployment scenario, as discussed in Subsection IV-B.

As mentioned, to apply OFDMA in HEWs, different sub-carriers should be allocated to different STA members of a BSS. In this case, an efficient sub-carrier allocation scheme is required to provide a high BSS throughput performance. Specifically, in an outdoor environment, the channel gain between two STAs may considerably vary from one sub-carrier to another, due to a small channel coherence bandwidth. Furthermore, for each sub-carrier, the channel gains from different STAs to an AP differ, due to different multipath signal propagation between each STA and the AP. The variance of the channel gain between two STAs over different sub-carriers is referred to as frequency diversity, while the variance of the channel gain between the AP and different STAs (over the same sub-carrier) is referred to as multiuser diversity. By exploiting frequency and multiuser diversities, sub-carriers can be efficiently allocated to STAs, in order to maximize the throughput achieved over each sub-carrier [59], [80]. That is, if the channel gain between the AP and a STA is low over a sub-carrier, the sub-carrier can be allocated to another STA that has a higher channel gain. This flexibility represents an advantage of OFDMA as compared to OFDM, in which many sub-carriers may be left unused due to poor channel conditions, e.g., when a water-filling algorithm is deployed for OFDM sub-carrier power allocation.

Another advantage of deploying OFDMA for HEWs is the efficient utilization of frequency resources and the backward compatibility with previous IEEE 802.11 amendments that are based on OFDM, such as IEEE 802.11n/ac. For example, if the total available bandwidth is 80 MHz, an IEEE 802.11n AP can utilize the maximum allowed of 40 MHz, while an IEEE 802.11ac or an HEW AP can operate over the entire 80 MHz [60]. When a STA that uses a previous IEEE 802.11 amendment joins an HEW, the STA can be allocated a set of sub-carriers in the frequency band that is supported by the previous amendment. For instance, if an IEEE 802.11n STA is connected to an HEW AP, the STA will be allocated sub-carriers in a contiguous bandwidth of 40 MHz. On the

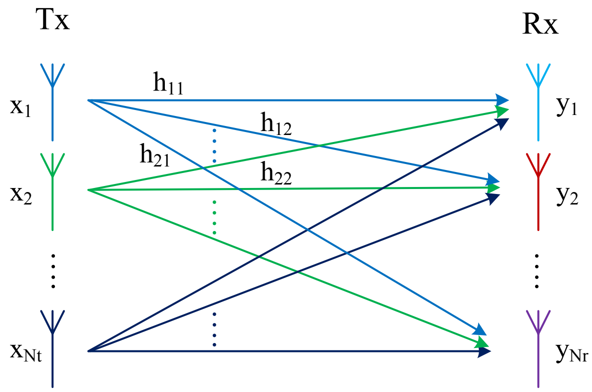


Fig. 5: MIMO channel model with N_t transmit antennas, N_r receive antennas, and channel gain h_{ij} between the i^{th} transmit antenna and the j^{th} receive antenna

other hand, when an HEW STA (supporting OFDMA) joins an AP that uses a previous IEEE 802.11 amendment (supporting OFDM), the STA communicates with the AP as if the STA is allocated all the sub-carriers available in the frequency channel over which the AP is operating. Furthermore, different modulation orders can be used over different sub-carriers, according to the standard supported by each communicating STA [60]. Hence, IEEE 802.11n and IEEE 802.11ac STAs can use the highest supported modulation orders, i.e., 64-quadrature amplitude modulation (QAM) and 256-QAM, respectively, to simultaneously communicate with an HEW AP. However, to adapt OFDMA for HEWs, many issues still need investigation, especially for uplink communications, as discussed in Section VII-A.

B. MU-MIMO

Multiple-input multiple-output (MIMO) is a technique to increase the wireless link capacity by exploiting multipath signal propagation using multiple transmit and receive antennas. When the transmit and receive antenna arrays are spaced apart far enough, the multipath fading that a transmitted signal encounters differs from one transmit-receive antenna pair to another. As illustrated in Fig. 5, for a MIMO channel with N_t transmit antennas and N_r receive antennas, the input and output relationship can be described by $y = H^T x + n$, where $x = [x_1, ..., x_{N_t}]^T$ is the vector of symbols transmitted by the N_t transmit antennas, $y = [y_1, ..., y_{N_r}]^T$ is the vector of symbols received by the N_r receive antennas, $n = [n_1, ..., n_{N_r}]^T$ is the noise vector, and H is an $N_t \times N_r$ matrix of channel gains. The difference in channel quality between pairs of transmit-receive antennas is utilized either to improve the reliability of signal transmission (thanks to the existence of different signal propagation paths, i.e., spatial diversity) or to simultaneously transmit independent data streams from different transmit antennas, also known as spatial multiplexing. In spatial multiplexing, if the transmitter has N_t transmit antennas and the receiver has N_r receive antennas, the maximum number of data streams is $N_s = \min(N_t, N_r)$. Therefore, the data rate will increase by a factor of N_s, as compared to using a single antenna at the transmitter and a single antenna at the receiver, i.e., single-input single-output (SISO). The advantages of MIMO comes at the cost of requiring more complex signal processing and channel state information (CSI) at the transmitter and/or receiver. In an open-loop MIMO system, the CSI (i.e., the H matrix) is not available at the transmitter, and the receiver uses the CSI to decode the transmitted vector, x, based on the received vector, y. On the other hand, in a closed-loop MIMO system, the CSI is available at the transmitter (through feedback from the receiver) and is used to pre-code the transmitted symbols. The capacity gains of different open-loop and closed-loop MIMO systems are analyzed in [61].

In a single-user MIMO (SU-MIMO) system, the transmission is between a single transmitter and a single receiver that have multiple transmit and receive antennas. On the other hand, in a MU-MIMO system, the available antennas are spread over multiple independent transmitters and receivers. MU-MIMO leverages the spatially distributed user locations to achieve a spatial multiple access gain, which is useful when the number of STAs is large and the number of antennas at the AP is more than the number of antennas at each STA. In addition, MU-MIMO is more immune to signal propagation issues that degrade the SU-MIMO performance, such as antenna correlations or channel rank loss. MU-MIMO can be categorized into MIMO broadcast channels (MIMO-BC) and MIMO multiple access chandelles (MIMO-MAC). MIMO-BC refers to simultaneous transmission from a single AP to multiple STAs using spatially multiplexed downlink streams, while MIMO-MAC refers to simultaneous transmission from multiple STAs to a single AP using spatially multiplexed uplink streams. Unlike SU-MIMO systems, most of the MIMO-BC schemes require CSI to be available at the transmitter AP. Obtaining CSI at the transmitter side is generally more costly than at the receiver side, due to the requirements of feedback messages from the receiver. However, MIMO-MAC requires CSI only at the receiver AP, which costs less in signaling overhead, as compared to MIMO BC. The performance of MU-MIMO systems, including MIMO-BC and MIMO-MAC, has been extensively studied [61]–[66].

In the IEEE 802.11n amendment, a limit of up to four downlink SU-MIMO data streams is allowed between an AP and a STA [3]. The maximum number of simultaneous downlink streams of SU-MIMO is increased to eight in the IEEE 802.11ac amendment [81]. Also, the IEEE 802.11ac provides simultaneous data streams for up to four downlink MU-MIMO STAs (i.e., MIMO-BC). For HEWs, adopting uplink MU-MIMO (i.e., MIMO-MAC) [67] and employing a large number of antennas (Massive-MIMO) [68] are currently proposed by the IEEE 802.11ax task group.

C. IBFD Communications

IBFD communications is a technology that allows a transceiver to simultaneously transmit and receive signals on the same frequency band [69], thus providing an oppor-

TABLE IV: Comparison of four well known IBFD designs

Reference	Year	# antennas		SIC				Bandwidth	Frequency band
		TX	RX	Analog	Digital	Antenna	Total		
[71]	2010	2	1	20 dB	10 dB	30 dB	60 dB	5 MHz	2.4 GHz
[70]	2011	1	1	45 dB	28 dB	-	73 dB	10 MHz	2.4 GHz
[74][3]	2014	2	1	2 dB	18 dB	65 dB	85 dB	20 MHz	2.4 GHz
[75]	2013	1		47 dB	48 dB	15 dB	110 dB	80 MHz	2.4 GHz

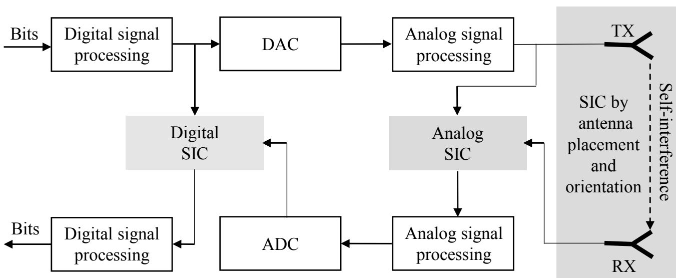


Fig. 6: A generic block diagram of an IBFD transceiver showing the SIC in the digital, analog, and signal propagation domains

tunity to (theoretically) double the spectral efficiency of a communication system. The main challenge to realize IBFD communications is how to cancel self-interference from the transceiver's own transmitted signal, which has much higher power (up to 10^9x [70]) as compared to the desired signal that is being simultaneously received. Self-interference cancelation (SIC) can be achieved after the received signal is digitized by an analog-to-digital converter (ADC) at the receiver (i.e., in the digital domain), before the received signal is digitized by the ADC (i.e., in the analog domain), or by proper antenna placement and orientation, as shown in Fig. 6. By using analog and digital SIC techniques, the IBFD design in [70] can achieve up to 73 dB of SIC for a WiFi signal having 10 MHz bandwidth. This design represents an improvement to the IBFD technique in [71] that achieves 60 dB of SIC for an IEEE 802.15.4 system operating on a channel bandwidth of 2 MHz, with lower transmit power as compared to WiFi. Also, the SIC realized in [70] is expected to increase by around 40 dB, resulting in a total of 113 dB SIC, if the transmit and receive antennas are physically separated (in [70], the two antennas are connected by a low loss wire). Proper separation and orientation of the transmit and receive antennas, together with the existence of the mobile device (e.g., laptop) in between, can achieve significant SIC [72]. By using antenna separation, together with analog and digital SIC, IBFD designs can achieve 80 dB of SIC for a narrowband signal with bandwidth of 625 KHz [73] and a median of 85 dB of SIC for an OFDM signal with bandwidth of 20 MHz [74]. Further, a 110 dB of SIC can be realized for an 80 MHZ WiFi signal (which is the largest WiFi channel bandwidth as defined in the IEEE 802.11ac amendment), by using only one antenna and a circulator to simultaneously transmit and receive signals [75]. This significant SIC of 110 dB results in a throughput gain that is close to two times, as expected from IBFD communications [75]. While most of the existing IFBD designs are based on omni-directional antennas, directional antennas are also introduced for IBFD communications [76], by using the same analog and digital SIC techniques as proposed in [70]. Four of the most well known IBFD designs that are considered by the IEEE 802.11ax task group [77] [78] are summarized in Table IV, and a wide range of other IBFD techniques can be found in [69] and [79].

In summary, this section discusses three potential PHY layer technologies for HEWs, which are OFDMA, MU-MIMO, and IBFD. The main characteristics and advantages of OFDMA are highlighted in comparison with the currently adopted PHY method in WLAN standards, OFDM. Utilizing OFDMA in HEWs poses interference issues, which can be mitigated by efficient sub-carrier allocation schemes that exploit frequency and multiuser diversities. Although deploying different MIMO systems can be advantageous for HEWs, it is associated with the cost of signalling overhead, especially when CSI is required at the transmitter side. When considering IBFD communications for HEWs, SIC is a major design issue which should be tackled by proper antenna placement and orientation along with analog and digital SIC techniques. In order to maximize the throughput gain achieved in HEWs by applying an improved PHY layer, either based on IBFD communications, or via OFDMA and MU-MIMO techniques (Subsections II-A and II-B), suitable MAC strategies should be developed for HEWs, as discussed in the following.

III. MAC Strategies

In many HEW deployment scenarios, such as in a stadium, airport, or concert hall, it is likely that a considerably large number of STAs will exist in proximity of each other, resulting in the formation of a BSS with a high number of STAs associated with the same AP. In such a highly dense BSS scenario, the intensity of channel contention among the BSS members (i.e., the AP and its associated STAs) increases significantly and may result in a severe degradation of the HEW performance, due to a large channel access delay and a high transmission collision rate. Hence, in order to improve the channel utilization and the BSS throughput, it is crucial to develop an efficient MAC scheme, which can effectively reduce the probability of a transmission collision among different STAs, allow for simultaneous transmissions in the same BSS, and decrease the channel time for transmission of control information. To achieve these objectives, there are many

[3]The indicated values of SIC in this row are approximate median values, based on the cumulative density functions of the SIC in the analog, digital, and signal propagation domains [74].

TABLE V: Classification of potential HEW MAC strategies

HEW MAC Strategies	**IEEE 802.11 MAC Improvements**	Enhanced back-off schemes	[82]–[89]
		Efficient handshaking	[90]–[94]
		Frame aggregation mechanisms	[95]–[98]
		TDMA-like CSMA	[99]–[105]
		Efficient multicast/broadcast services	[106]–[111]
		Other preliminary ideas	[112]–[117]
	Multiuser MAC	OFDMA-based	[118]–[123]
		MU-MIMO-based	[81], [118], [119], [124]–[128]
	IBFD MAC	CSMA/CA-based	[70], [72], [74], [76], [129]–[132]
		Non CSMA/CA-based	[133]

ongoing research activities on MAC for HEWs, which can be classified into three main directions. The first research direction is to improve the IEEE 802.11 standard MAC techniques, which are mainly supported by the distributed coordination function (DCF) [3]. The second direction focuses on new MAC schemes for simultaneous multiuser transmission, based on the OFDMA or MU-MIMO technologies, as discussed in Subsections II-A and II-B respectively. The third direction attempts to develop MAC schemes to operate over an IBFD communication PHY layer, as explained in Subsection II-C. Here, the last two categories of MAC schemes are referred to as 'multiuser MAC' and 'IBFD MAC' respectively. The advances in each of the three research directions are discussed separately in the following, and a classification of the MAC strategies discussed in this section is provided in Table V.

A. IEEE 802.11 MAC Improvements

1) DCF Background: The DCF is the basic IEEE 802.11 MAC procedure, which provides services to the other IEEE 802.11 access methods, namely the hybrid coordination function (HCF) and mesh coordination function (MCF) [3]. Hence, any enhancement in the DCF operation will be eventually reflected to the HCF and MCF access schemes. The DCF is based on a carrier sense multiple access with collision avoidance (CSMA/CA) technique, which has not been notably improved since the release of the legacy IEEE 802.11 standard in 1999. According to the DCF, when a STA needs to transmit a frame but senses the wireless channel as busy (due to another ongoing transmission), the STA should wait until the channel becomes idle. This point of time (i.e., when the channel becomes idle after a busy period) is when the highest probability of a transmission 'collision' occurs, since many STAs may have been waiting to transmit their frames during the previous busy period of the channel. Hence, in order to disperse the channel access attempts of these contending STAs, each STA selects a random back-off time (calculated as an integer number of time slots) equally likely in a certain time interval, referred to as the contention window. The STA which selects the minimum back-off time is the one that is going to access the channel, while the other STAs defer their transmissions and resume the back-off process when the channel becomes idle again. If a transmission collision happens, e.g., due to more than one STA selecting the same back-off time, the contention window size is doubled (to reduce the probability of a similar back-off time selection by STAs) until it reaches a certain maximum value. The contention window size is reset to its minimum value after each successful transmission. Mathematical analysis of the DCF stability, aggregate throughput, and access delay performance is presented in [134].

2) Enhanced Back-off Schemes: The fundamentals of the DCF back-off process are recently analyzed in [135], mainly in terms of the probability distribution function of the per-STA back-off time, as well as the resulting short-term fairness among contending STAs–a metric originally introduced in [136]. Note that, short-term unfairness may occur due to the fact that the contention window size is reset to its initial value after each successful transmission, which gives the advantage to a successful STA to succeed again in the channel contention [137]. To deal with this issue, novel back-off schemes can be applied to enhance the DCF short-term fairness, or equivalently reduce the channel access delay jitter, which is crucial for HEW real-time audio and video applications. For instance, instead of doubling the contention window size after each transmission collision detection (as discussed in Subsection III-A1), a *polynomial back-off* scheme increases the contention window as $W \times (1+i)^x$, where W is the initial contention window size, i is an integer that is incremented (from 0 to a maximum value) after a transmission collision detection, and x is a nonnegative integer that determines the growth rate of the contention window size [82]. The *polynomial back-off* scheme provides an upper bound on the access delay jitter for any finite number of contending STAs [82]. Alternatively, a *back-off with penalty* scheme assigns a large contention window size (as a penalty) to a STA that successfully transmits a frame, in order to give a higher chance for the other contending STAs to access the channel [83]. In contrast, in *rollback back-off* and *inverse binary exponential back-off* schemes, the STAs originally start the contention with the maximum contention window size, and only the STAs which encounter a transmission collision can reduce their contention window sizes [83] [84]. Other back-off approaches either adapt the size of the contention window based on the intensity of channel contention [85], or select the back-off time by exchanging information (such as the frame queue length) among the contending STAs [86].

Apart from improving the DCF short-term fairness, a novel back-off scheme should provide guaranteed channel access for colliding STAs, in order to prevent dropping a colliding frame if the maximum number of allowed retransmissions is reached. One approach to achieve this objective, when a transmission collision happens, is by allowing the receiver STA to determine the set of colliding STAs, and to broadcast a deterministic back-off time for each colliding STA such as to avoid further transmission collisions [87]. Another direction of developing novel back-off schemes is based on migrating the back-off process from the time domain to the frequency domain, based on an OFDM PHY layer [88] [89]. That is, instead of selecting a random back-off time, a contending STA randomly selects an OFDM sub-carrier for transmission of a short signal. And, by determining the set of active sub-carriers simultaneously during the transmission of this short signal (using additional hardware for energy detection per sub-carrier), scheduled transmissions can be realized after each contention period, e.g., with the same order of the sub-carrier index that each STA randomly selects for signalling.

3) Efficient Handshaking and Frame Aggregation Mechanisms: By employing CSMA/CA, if two STAs are physically separated such that they cannot sense the transmission of each other, their transmissions may collide at another STA which is located within the communication range of both transmitting STAs. To deal with this problem, known as the hidden terminal problem, the IEEE 802.11 standard performs request-to-send/clear-to-send (RTS/CTS) handshaking between a transmitter and a receiver STA, before the actual transmission of data occurs [3]. When the surrounding STAs receive the RTS/CTS frames, they defer accessing the channel to avoid any transmission collision, until the transmitter STA sends a data frame and the receiver STA replies by an acknowledgement (ACK) frame. However, the employment of RTS/CTS introduces another problem, referred to as the exposed terminal problem, which may unnecessarily prevent a surrounding STA from accessing the channel even if such channel access will not disrupt the ongoing transmission (an exposed terminal problem is discussed in Subsection IV-A and illustrated in Fig. 8). To mitigate the exposed terminal problem, several approaches can be employed in HEWs, either based on adapting the transmission range of the RTS or CTS frame [90] [91], or by modifying the conditions based on which a STA defers its transmission, e.g., if it receives an RTS but does not receive the corresponding CTS [92]. Note that, although the RTS/CTS exchange can reduce the probability of a transmission collision among hidden STAs, it represents an additional MAC overhead. To reduce this overhead, a distributed technique can be employed by each STA to detect its hidden STAs, e.g., based on MAC layer statistics, and to decide whether or not to exchange RTS/CTS accordingly [93]. Alternatively, the use of RTS/CTS in a BSS can be centrally controlled by the AP on a per-STA basis, based on the observed channel conditions and the BSS topology [94]. Also, in the IEEE 802.11n amendment [138], instead of exchanging RTS/CTS for each data frame, the technique of frame aggregation is introduced, allowing a STA to group multiple data frames into one large frame. This technique not only reduces the amount of RTS/CTS exchange, but more importantly decreases the overhead associated with PHY layer header, channel contention time, and ACK frame transmission (since the receiver STA replies with a block ACK frame that acknowledges all the 'sub-frames' of the received aggregate frame). The frame aggregation and block ACK features are enhanced in the recent IEEE 802.11ac/ad amendments [81] [139]. Further enhancements are under study in the IEEE 802.11ax task group, including adapting the aggregate frame length based on the number of successfully delivered 'sub-frames', as indicated by a previously received block ACK [95]. Note that, the IEEE 802.11 frame aggregation schemes, being MAC layer protocol data unit (MPDU) or MAC layer service data unit (MSDU) aggregation [3], require all the aggregated units to be destined to the same receiver STA. This standard 'one-to-one' frame aggregation can be improved in HEWs to enable a multi-STA frame aggregation mechanism, e.g., allowing an AP to aggregate the frames destined to multiple STAs [96]–[98].

4) Other Improvements: As an attempt to improve the CSMA/CA performance in supporting QoS requirements, a time-division unbalanced CSMA (TD-uCSMA) scheme is proposed by the IEEE 802.11ax task group as a potential technology for HEWs [99], [100]. The TD-uCSMA is based on the EDCA scheme (introduced in the IEEE 802.11e amendment [4]) and is consequently compatible with the IEEE 802.11 standard, as highlighted in [101]. The TD-uCSMA scheme allows for a TDMA-like operation of a BSS, by providing a set of high priority EDCA parameters (which guarantee channel access) to each STA on a time division basis. The performance of the TD-uCSMA scheme is evaluated for single-hop [99] [101] and multi-hop scenarios [102] via computer simulations, and specifically for supporting video communications [104]. Also, the scheme is implemented on top of the IEEE 802.11 on an Atheros chip [103], and then experimentally tested for video, audio, and data applications [105].

Another inefficient IEEE 802.11 mechanism that requires significant QoS improvement is the mechanism used for multicast and broadcast communications. The main reason of this inefficiency is the lack of retransmission and ACK techniques for multicast and broadcast frames [106], [140]–[143]. Multicast and broadcast services are particularly important for supporting video/audio streaming applications, especially in highly STA-dense scenarios, such as in a stadium, exhibition, or classroom, which are among the essential HEW usage models. Hence, the IEEE 802.11ax task group aims at enhancing the legacy multicast and broadcast mechanisms [106], such as by allocating a dedicated multicast/broadcast channel to be used only by the AP in a BSS [107]. To improve the IEEE 802.11 multicast service, an Adaptive Multicast Services (AMuSe) scheme selects some of the multicast receiver STAs to periodically send feedback information of the channel quality to the sender STA [108]. The AMuSe scheme is implemented in the Open Access Research Testbed for Next-Generation Wireless Networks (ORBIT) [144], and evaluated via large scale experiments, by using approximately 250 WiFi STAs and a single multicast AP [108] [109]. Other works deal with multiple AP coordination [110] or optimal association of STAs with APs [111] for an improved IEEE 802.11 multicast service.

Other preliminary ideas for improving the IEEE 802.11 MAC, which are currently under consideration by the IEEE 802.11ax task group, include: a) reporting STAs' MAC layer statistics to the AP, which accordingly adapts its and STAs' MAC/PHY behavior to enhance user experience [112], b) realizing fairness among STAs in channel time occupancy versus transmission opportunity, in order to prevent the frames transmitted at a low bit rate from occupying a large amount of channel time (thus reducing the aggregate BSS throughput) [113] [114], c) employing a frame collision detection method at each STA for better MAC layer control and management, such as adapting the transmission power, contention window size, or clear channel assessment (CCA, Subsection IV-A) level [115], d) adding a second level of prioritization within each EDCA access category for a higher flexibility of the EDCA scheme in dealing with a diversity of MSDU types, e.g., in terms of MSDU size and QoS requirements [116], and e) improving the reliability and efficiency of the periodic transmission of beacon frames (which announce for the existence of an AP and carry important management information [3]) from different APs in a highly dense HEW deployment scenario [117].

B. Multiuser MAC

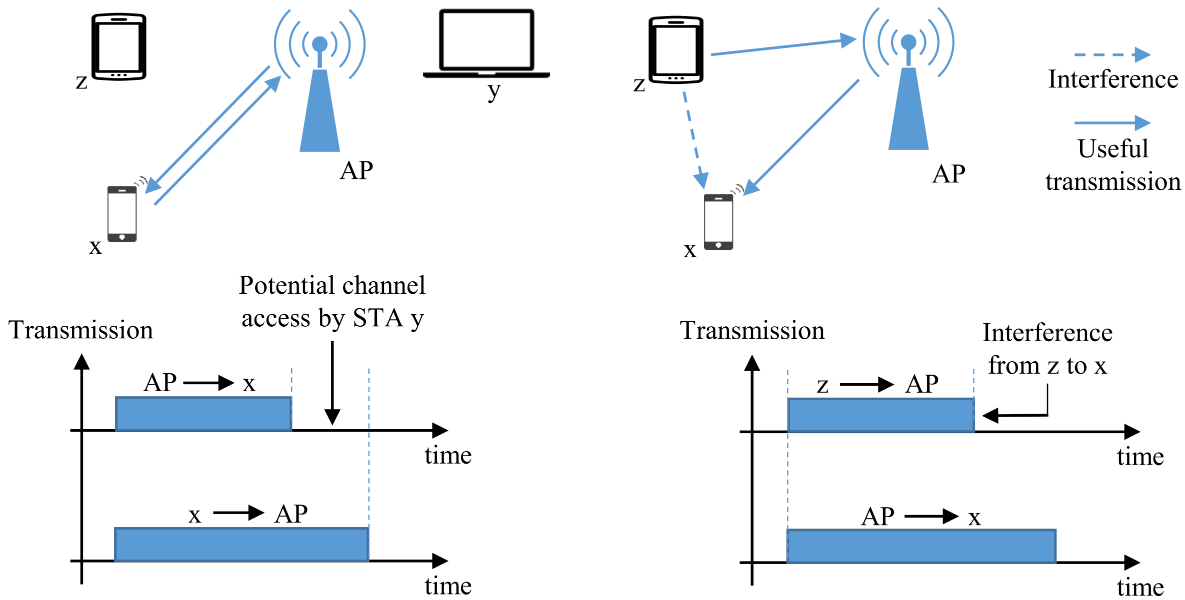
The term 'multiuser channel access' refers to a technique by which multiple STAs, each with one or more antennas, either simultaneously transmit to a single STA or simultaneously receive from a single STA independent data streams over the same frequency channel[4]. Multiuser channel access is supported by a PHY layer technology such as OFDMA or MU-MIMO (Subsections II-A and II-B) for uplink or downlink communication, i.e., for the AP to transmit/receive data to/from multiple STAs simultaneously. However, the employment of OFDMA or MU-MIMO technologies at the PHY layer requires a suitable MAC scheme that can achieve the maximum benefit of multiuser channel access. Downlink multiuser transmission is recently introduced in the IEEE 802.11ac amendment [81], based on MU-MIMO [145]. Also, a comparison between the downlink MU-MIMO and downlink OFDMA technologies is presented in [118] and [119], in terms of throughput gain and additional control overhead with respect to single-user channel access. On the other hand, uplink multiuser channel access is not supported in any of the IEEE 802.11 amendments and is currently under consideration by the IEEE 802.11ax task group [146].

The challenge in realizing uplink multiuser channel access originates from the requirement to synchronize transmissions from different STAs to the AP. One approach to achieve this synchronization is to use the AP as a central controller to trigger transmissions from its associated STAs [147], but the main issue with this centralized approach is that the AP is not aware of the transmission demands from all STAs without exchange of additional control information [148]. The control overhead required for uplink OFDMA multiuser transmission is related via mathematical analysis in [149] with the number of STAs in a BSS, the data payload size, and the throughput gain with respect to single-user transmission. To efficiently employ OFDMA for uplink multiuser channel access, several issues still need to be addressed, as discussed in Subsection VII-B. Similarly, while there exist some uplink MU-MIMO MAC protocols proposed in the literature [145], either with the AP coordinating uplink transmission of sending STAs [124] [125] or without AP coordination [126]–[128], it is still unclear which approach can be adopted for the IEEE 802.11ax standard to achieve efficient uplink multiuser transmission, while preserving backward compatibility with the IEEE 802.11 standard and its previous amendments.

C. IBFD MAC

The recent advancement in IBFD technology breaks the fundamental assumption made in the original design of the IEEE 802.11 MAC: a STA can either transmit or receive at a certain time instant on the same frequency band. IBFD communications can realize a significant throughput increase for HEWs, as investigated in [77] for indoor and outdoor scenarios. However, before employing an IBFD technology for HEWs, several MAC issues need to be considered, in order to have the expected increase in the aggregate throughput of a BSS [78]. For example, consider an AP that is involved in an IBFD communication with a STA, x, and assume that the two frames being exchanged between the AP and STA x have different lengths, as shown in Fig. 7a. In this scenario, it is possible that the surrounding STA y accesses the channel when it senses the channel as idle after the AP transmission, resulting in a collision between the transmissions of STAs x and y at the AP. This transmission collision cannot be prevented by the standard RTS/CTS exchange, since at the time that the AP sends the RTS frame (which should include the duration that the channel has to be reserved to exchange the data and ACK frames), the AP is not aware of the length of the frame that STA x needs to transmit (if any). Consequently, the surrounding STAs that receive the RTS frame cannot determine how long they should defer their channel access. The same issue happens even if the two frames exchanged between the AP and STA x have the same length, but the transmissions of the two frames do not start at the same time instant. Also, at the end of the IBFD transmission of data frames, there should

[4]The terms 'multiuser channel access' and 'multiuser transmission' are used interchangeably.



(a) Potential transmission collision caused by surrounding STAs

(b) Interference among STAs involved in non-pairwise IBFD communications

Fig. 7: IBFD MAC design issues

be a mechanism to determine when and how the AP and STA x will exchange the ACK frames. Another issue is that, all the STAs located within the communication range of both the AP and STA x, such as STA z, will receive a corrupted frame as a result of the two simultaneous transmissions from the AP and STA x. Hence, according to the IEEE 802.11 standard, after the IBFD data exchange between the AP and STA x is complete, STA z will defer its transmission for a much longer duration (equal to the value of extended inter-frame spacing (EIFS) instead of the DCF inter-frame spacing (DIFS) [3]), as compared to the other STAs which can successfully decode any of the two frames transmitted by the AP and STA x. Hence, this potential unfairness caused by IBFD communications should be reduced. Additionally, as shown in Fig. 7b, if the AP employs IBFD to communicate with two STAs, x and z, instead of one, it is possible that the transmission from STA z interferes with the AP transmission to STA x. Consequently, a suitable scheme should be employed to initiate this non-pairwise IBFD communications[5], without causing any interference among all the involved STAs.

There have been several studies for developing a MAC protocol operating over an IBFD PHY layer for WLANs. For instance, an IBFD MAC protocol, known as ContraFlow, exploits the IBFD capability to mitigate the hidden terminal problem, to early detect a transmission collision, and to enhance the spatial reuse by allowing both pairwise and non-pairwise IBFD communications [129]. Similarly, FD-MAC is proposed to operate over an OFDM IBFD PHY layer, subject to a PHY layer constraint that a STA cannot start a transmission while it is already receiving a frame [72]. The FD-MAC is implemented based on the Wireless Open-Access Research Platform (WARP) [150] and tested by using two STAs, where FD-MAC is used to initiate IBFD communications between the two STAs whenever possible. Also, based on WARP, another IBFD MAC protocol is implemented in [70] over an OFDM PHY layer, and tested by using an AP and four associated STAs. However, this MAC protocol only allows for pairwise IBFD communications. Similarly, focusing only on pairwise IBFD communications, an AP-client initiated MAC protocol with dynamic contention window (AC-MAC/DCW) is proposed [130]. The AC-MAC/DCW protocol dynamically adjusts the contention window size of the AP based on its MAC layer queue length, in order to increase the chance of IBFD communications when the uplink and downlink traffic are unbalanced. On the other hand, a centralized MAC protocol that is not based on CSMA/CA, known as Janus, is presented and implemented in [133]. In Janus, the AP continuously collects information regarding the length of the frame that each STA needs to transmit and the interference level around each STA. Accordingly, the AP schedules uplink and downlink frames for IBFD exchange, decides whether to use IBFD or half-duplex transmission for each frame, and determines a suitable data rate for each transmission. It is shown that, Janus achieves a significantly increased throughput as compared with CSMA/CA using three STAs and one AP on the WARP hardware [133] and with ContraFlow in single and multiple AP scenarios [151]. Unlike Janus, which is incompatible with

[5]The IBFD communications happening between two STAs only (Fig. 7a) is referred to as pairwise IBFD communications, while that involving more than two STAs (Fig. 7b) is referred to as non-pairwise IBFD communications.

TABLE VI: Comparison of IBFD MAC protocols

IBFD MAC	Year	CSMA/CA based	IBFD communication type		IBFD capability		Directional antennas	Implementation platform
			Pairwise	Non-pairwise	AP	Non-AP		
ContraFlow [129]	2011	Yes	Supported	Supported	Required	Required	No	FPGA
FD-MAC [72]	2011	Yes	Supported	Supported	Required	Required	No	WARP
[70]	2011	Yes	Supported	Not supported	Required	Required	No	WARP
AC-MAC/DCW [130]	2012	Yes	Supported	Not supported	Required	Required	No	WARP
[76]	2012	Yes	Not supported	Supported	Required	Required	Yes	Not implemented
Janus [133]	2013	No	Supported	Supported	Required	Required	No	WARP
[74]	2014	Yes	Supported	Not supported	Required	Required	No	Not implemented
[132]	2014	Yes	Not supported	Supported	Required	Not required	No	Not implemented
[131]	2015	Yes	Not supported	Not supported	Required	Required	No	Not implemented

CSMA/CA, a simplified IBFD MAC protocol is described in [131] based on CSMA/CA, and evaluated in terms of saturation throughput via mathematical analysis and computer simulations. This MAC protocol employs the IBFD capability only for early detection of a transmission collision, not for initiating IBFD communications. Similarly, another CSMA/CA-compatible IBFD MAC protocol supports coexistence of both IBFD and non-IBFD STAs [74]. This protocol modifies the WiFi standard DCF with RTS/CTS exchange in order to discover and transmit IBFD frames (in a pairwise manner between the AP and one of the associated STAs), manage the transmission of ACK frames, and control the channel access of surrounding STAs during and after an IBFD channel access. The MAC operates over an IBFD PHY layer which employs multiple omni-directional antennas [74]. Alternatively, based on a directional-antenna IBFD design, a MAC protocol is proposed and evaluated via computer simulations to show the potential improvements in the end-to-end throughput for multihop linear-topology networks [76]. Different from the previously mentioned IBFD MAC protocols, with the inherent assumption that all the STAs have IBFD PHY layers, a simplified MAC protocol discussed in [132] requires only the AP to have IBFD capability. Table VI summarizes the main differences among the IBFD MAC protocols discussed in this subsection for HEWs, and various IBFD MAC protocols proposed for infrastructure-based, ad-hoc, and cognitive radio networks are compared in [79].

In summary, this section presents potential MAC strategies that can be applied for future HEWs. The IEEE 802.11 standard MAC techniques can be improved by employing enhanced back-off schemes, improved handshaking (RTS/CTS) and acknowledgment mechanisms, novel frame aggregation techniques, reliable multicast/broadcast services, efficient beacon transmission by APs, or better MAC layer management via frame collision detection methods or additional EDCA prioritization levels. Also, novel MAC schemes for multiuser channel access should be developed for HEWs which employ PHY technologies such as OFDMA and MU-MIMO. While downlink multiuser transmission is recently supported by the IEEE 802.11ac standard, uplink multiuser transmission is not considered by any IEEE 802.11 amendment, and remains a challenging task, mainly due to the requirement to synchronize transmissions from multiple STAs to the AP. Additionally, to apply IFBD communications for HEWs, it is necessary to employ a MAC scheme that is designed to operate over an IBFD communication PHY layer, in order to deal with the MAC issues introduced by this PHY technology and achieve the expected increase in the aggregate BSS throughput. Although increasing the throughput of a single BSS can be achieved by employing enhanced PHY and MAC techniques, improving the overall HEW performance requires minimizing the interference among OBSSs via efficient spatial frequency reuse, especially in dense HEW deployment scenarios. In the following section, spatial frequency reuse methods for HEWs are presented.

IV. Spatial Frequency Reuse

The efficient reuse of the available frequency band by geographically separated BSSs is particularly important for HEWs to manage interference among OBSSs, especially in dense HEW deployment scenarios. In the following, we discuss potential techniques for improving spatial frequency reuse in HEWs, based on enhanced CCA and FFR, as summarized in Table VII.

A. Enhanced CCA

The CCA is a function defined in the IEEE 802.11 standard to determine the current state of the wireless channel, i.e., busy or idle, either by WiFi or non-WiFi signals [3]. If a WiFi signal is detected above a pre-defined threshold, referred to as the CCA carrier sensing (CCA-CS) level, or a non-WiFi signal is detected above another pre-defined threshold, referred to as the CCA energy detection (CCA-ED) level, the CCA function indicates that the wireless channel is currently captured by another STA or non-WiFi devices. Thus, the STA which detects the wireless channel as busy defers its channel access, as discussed in Subsection III-A1, in order to avoid interference. In the IEEE 802.11 standard, the CCA-CS and CCA-ED levels have constant values, which are listed in Table VIII. The CCA levels are set to the very low values in order to: a) increase the communication range among STAs, b) decrease the interference power level that is allowed at a receiver STA, and c) reduce the impact of the hidden terminal problem, since a hidden STA defers its channel access only if it receives a signal (e.g., an RTS or CTS frame) with power above the CCA level. These low CCA levels can work well in

TABLE VII: Classification of potential HEW spatial frequency reuse schemes

HEW Spatial Frequency Reuse Schemes	**Enhanced CCA**	Fixed CCA enhancements	[152]–[156]
		Dynamic CCA enhancements	[157]–[161]
		Enhanced CCA with transmit power control	[152], [162]–[164]
		Enhanced CCA with BSS coloring	[165]–[168]
	FFR	Static FFR schemes	[169]–[175]
		Dynamic FFR schemes	[58], [176]–[183]

WLANs with low AP densities and with a proper AP channel selection algorithm. However, in a dense HEW deployment scenario, a low CCA level may cause an ongoing transmission in a BSS to prevent many STAs in the OBSSs from accessing the channel, which degrades the overall performance of HEWs. Hence, in order to allow for concurrent transmissions with high transmission rates in adjacent BSSs, enhanced CCA mechanisms are required to improve the spatial frequency reuse for HEWs.

To further clarify the basic concept of enhanced CCA mechanisms, consider the scenario in Fig. 8 [159]. STA_x transmits to AP_x and STA_y transmits to AP_y, such that the received signal power at AP_x (from STA_x) and that at AP_y (from STA_y) are both -50 dBm. Due to signal path loss and wall penetration, AP_x and STA_x receive signals with powers of -80 dBm and -70 dBm, respectively, from STA_y. By comparing the received signal power (e.g., STA_x to AP_x) with the interference signal power (e.g., STA_y to AP_x), STA_x and STA_y can both transmit successfully due to a large received signal-to-interference-plus-noise ratio (SINR). However, if the original CCA mechanism is employed (with the CCA levels in Table VIII), only one STA can transmit, while the other one is suppressed from transmitting due to detecting a signal above the CCA level (e.g., STA_y to STA_x). This exposed terminal problem is particularly important to consider in an HEW with a high STA density, since a single transmission may suppress simultaneous transmissions from many other surrounding STAs, which can greatly degrade the network performance. An enhanced CCA mechanism can be employed to solve the problem. For example, if the CCA level is set to a higher value, e.g., -65 dBm, both STA_x and STA_y can simultaneously transmit to the APs they are associated with, which greatly improves the spatial frequency reuse. In the following, enhanced CCA mechanisms which can be adapted to HEWs are discussed.

1) Fixed CCA Enhancements: A straightforward solution to enhance the CCA function is to increase the CCA thresh-

TABLE VIII: CCA levels defined in [184]

Bandwidth	CCA-CS level	CCA-ED level
5 MHz	-88 dBm	-78 dBm
10 MHz	-85 dBm	-75 dBm
20 MHz	-82 dBm	-72 dBm

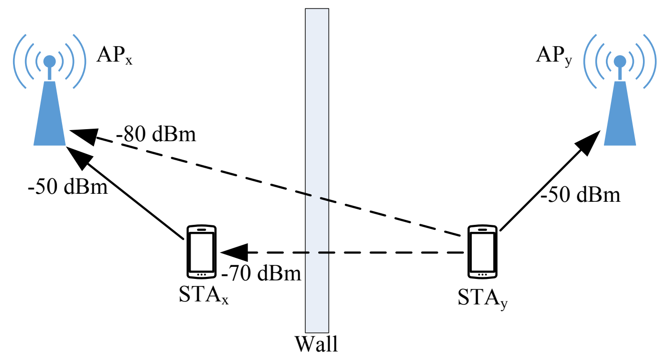


Fig. 8: Illustration of concurrent and interfering STA-to-AP transmissions

old (CCAT), i.e., the minimum of the CCA-CS and CCA-ED levels, to a certain value such that HEW STAs can transmit despite the presence of signals from OBSS STAs. The advantages of this CCA enhancement are implementation simplicity and possible high throughput. Increasing CCAT can potentially increase the average per-STA throughput due to allowing more concurrent transmissions in the same area. However, increasing CCAT can reduce the minimum per-STA throughput at the edge of the BSA (i.e., 5th percentile of the per-STA throughput as defined in Subsection VI-B) [152]. The reason is that STAs located at the edge of a BSA experience lower SINR, due to a) a lower signal power received from the AP and b) a higher interference resulting from the OBSS STA transmissions, which are more likely as a result of increasing the CCAT. With a higher CCAT, the allowed interference power at a receiver STA increases and the probability of a transmission collision also increases, since more concurrent transmissions are permitted [152]. Choosing the CCAT value creates a tradeoff between the amount of spatial reuse and the amount of interference. As a result, the impact of concurrent transmissions, interference, and transmission collisions on the HEW performance needs to be jointly considered when determining the value of CCAT. The CCAT value should be chosen such that the positive impact of more concurrent transmissions (i.e., better spatial frequency reuse) dominates the negative impact of transmission collisions and interference in dense HEW scenarios [153]. The CCAT value that optimizes the HEW performance (in terms of average and 5th percentile PER-STA throughputs) changing with the spatial distribution of APs and the associated STAs in the considered HEW scenario [155], [156]. It should be noted that, increasing the CCAT for HEWs may result in a critical unfairness issue among HEW STAs and other STAs supporting a previous IEEE 802.11 amendment, referred to as legacy STAs, as discussed in Subsection VII-C.

2) Dynamic CCA Enhancements: Fixed CCA enhancement methods, as discussed earlier, can be efficient in scenarios where BSSs are deployed in a planned way (e.g., with identical distances among adjacent APs, such as in a hexagonal network topology [153]) and the STAs have low mobility. However, in a more complex scenario, where a large number of BSSs are densely deployed in an unmanaged way and the STAs are frequently moving with high speeds, fixed CCA enhancement methods may not be able to maximize HEW performance. Therefore, dynamic CCA schemes are required to be adaptive to complex HEW deployment scenarios and STA mobility. Since dynamic CCA methods are used to dynamically adjust the receiver sensitivity, they are usually referred to as dynamic sensitivity control (DSC) methods.

DSC methods can be either centralized or distributed. A centralized DSC method is executed by a central controller that dynamically adjusts CCAT values for APs/STAs according to their current status. The status of APs/STAs can be determined either by APs-to-STAs interference calculations [157] or from APs/STAs topology information (e.g., use of cameras to obtain APs/STAs positions [158]). A centralized method can improve spatial frequency reuse at the expense of the control overhead required to collect global network information [157], [158], [185]. On the other hand, a distributed DSC method enables a STA to adjust its own CCAT value independently, using only local information. Local STA information can be based on packet loss rate, channel idle-busy ratio [160], or received signal strength from the AP [159]. Although distributed DSC methods enhance robustness to HEWs topological changes, they can evoke fairness and hidden terminal problems, as CCAT values can be set too high. One way to address this problem is by setting an upper bound on the CCAT value that is large enough to guarantee acceptable SINR and deal with sudden changes in the received signal strength of the AP beacons [159]. A dynamic DSC method can adopt CCAT value adjustment for each PHY layer convergence procedure (PLCP) protocol data unit (PPDU) [161]. That is, a transmitting STA dynamically adjusts and announces the CCAT value for surrounding STAs. The aim of the dynamic adjustment is that, if a STA successfully transmits PPDUs successively, the surrounding STAs can use a higher CCAT value to improve the spatial frequency reuse. But, if a transmission fails, the STA resets the CCAT value for the surrounding STAs to a lower level, in order to successfully transmit the following PPDUs.

3) Enhanced CCA with Transmit Power Control: Power control is used to enhance the spatial frequency reuse in HEWs. By properly adjusting the transmit power, the interference among nearby APs and STAs can be mitigated and the overlap among the BSAs of neighboring BSSs can be reduced. As a result, transmission collisions are reduced and concurrent transmission opportunities are increased [162], [163].

The CCA enhancement (Subsection IV-A) can reduce the coverage of BSSs and increase the number of concurrent transmissions, at the expense of introducing a fairness problem with legacy STAs, as discussed in Subsection VII-C. On the other hand, transmit power control can decrease the interference among STAs and control the SINR as required, without causing any fairness issue. However, relying only on power control is not effective enough to reduce the BSS coverage and improve the spatial frequency reuse. Therefore, joint CCA and transmit power control schemes are expected to realize spatial frequency reuse while maintaining acceptable fairness level among HEW and legacy WLAN STAs [152], [164].

4) Enhanced CCA with BSS Coloring: BSS coloring was first introduced in the IEEE 802.11h standard in 2003 [165]. With BSS coloring, each BSS has a different color (consisting of a fixed number of bits), which allows a STA to determine whether or not a certain transmission is from its own BSS or from an OBSS. Therefore, in high density HEWs, BSS coloring can be used to protect an intra-BSS transmission against transmissions from OBSSs. BSS coloring can also be used to address the asynchronous interference issue in an OBSS scenario, where a STA decodes a received frame if and only if the BSS color, encoded in the frame's header, is the same as the STA's own BBS color [167]. This comes at the expense of coloring overhead, especially with a large number of OBSSs in dense HEW scenarios.

BSS coloring can be combined with enhanced CCA to further improve the spatial frequency reuse and resolve issues caused by enhanced CCA schemes [166], [168]. As discussed in Subsections IV-A1 and IV-A2, an enhanced CCA scheme increases the CCAT level to allow for more concurrent transmissions among OBSSs. Without BSS coloring, the CCAT increase can prevent a STA from decoding a useful frame received from its own BSS, due to a low received signal power that is below the CCAT level. Such loss of intra-BSS transmitted frames may degrade the BSS throughput performance, especially for STAs located at the edge of a BSA. Additionally, increasing the CCAT level results in a decrease in the coverage area of an AP. On the other hand, when BSS coloring is used with enhanced CCA, a STA becomes aware of whether a detected frame is from its own BSS or from an OBSS (by decoding the color bits in the frame header). Hence, if the detected frame is from an OBSS, the enhanced (increased) CCAT level is employed; while if the detected frame is from the STA's own BSS, the original CCAT level is used. In this way, neither the transmitted frames within a BSS nor the AP coverage are affected by the increased CCAT level, different from the case when enhanced CCA is employed without BSS coloring. Fig. 9 illustrates the difference between enhanced CCA with and without BSS coloring.

B. Fractional Frequency Reuse

If OFDMA is employed for HEWs (as discussed in Section II-A), FFR can be applied to efficiently improve the frequency reuse and manage interference among adjacent

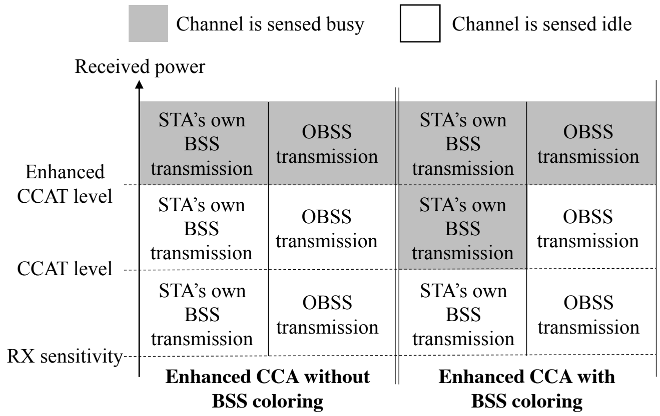


Fig. 9: Enhanced CCA with and without BSS coloring

BSSs. Although FFR schemes have been extensively studied in OFDMA systems, such as LTE, LTE-advanced, and WiMAX, there are few studies investigating how to achieve FFR in WiFi networks. When FFR is applied for cellular networks, the total bandwidth is divided into two groups, the major group (major band) and the minor group (minor band), serving cell-edge users and cell-center users, respectively [186]. In general, a smaller frequency reuse factor (FRF)[6] is allocated to cell-center users to improve the frequency reuse, while a larger FRF is allocated to cell-edge users, who are affected to a larger extent by inter-cell interference (ICI). According to whether or not an FFR scheme can dynamically adapt to the network conditions, FFR schemes are divided into two categories: static FFR schemes and dynamic FFR schemes. In static FFR schemes, the allocation of network resources (such as OFDMA sub-carriers and transmit power levels) to each class of users is achieved during the radio planning phase and remains static throughout the network operation. Such static schemes are easy to implement, since there is no requirement for dynamic resource reallocation. However, static schemes may not work well for all network conditions in terms of cell load, ICI level, etc. Hence, dynamic FFR schemes are proposed to dynamically allocate network resources based on the current network conditions, through interactions among neighboring cell base stations. In the following, we first present the static and dynamic FFR schemes proposed for OFDMA systems, and then discuss the issues in employing FFR for HEWs.

1) Static FFR Schemes: There are three main categories of static FFR schemes: partial frequency reuse (PFR), soft frequency reuse (SFR), and intelligent frequency reuse schemes [186]. In PFR schemes, frequency bands are allocated such that some bands are not used by the cell-edge users, as illustrated in Fig. 10 [169]. In Fig. 10, the employed PFR scheme achieves FRFs of 1 and 3 respectively in the cell-center and cell-edge regions. Hence, if the total available bandwidth is B, with major band B_0 (for the cell-edge regions) and minor band B_1 (for cell-center regions), the 'effective' FRF, denoted by η, can be calculated by [170]

$$\eta = \frac{B}{B_1 + B_0/3}, \tag{1}$$

which is greater than 1. When the cell-edge users of neighboring cells use distinct frequency bands, as shown in Fig. 10, PFR is sometimes referred to as FFR with full isolation, since the cell-edge users are fully isolated from ICI [187]. However, it is also possible to achieve PFR with some overlap among the frequency bands used by neighboring cell-edge regions. For instance, the PFR scheme proposed in [172] allocates a frequency band of $2/3\ B_0$ to cell-edge users, thus enhancing the spatial frequency reuse for cell-edge regions as compared to the PFR scheme in Fig. 10, at the expense of allowing for additional ICI, as a result of a maximum of $1/3\ B_0$ frequency band overlap between two neighboring cell-edge regions. While PFR can achieve a significant increase in the SINR, in both line-of-sight (LoS) and non-LoS scenarios [171], it may result in under-utilization of frequency resources, since some frequency bands are never used by a cell.

To further improve the spatial frequency reuse realized by PFR schemes, SFR is proposed [169], [173]. SFR schemes provide more flexibility in accessing the major and minor frequency bands, as compared to PFR schemes. For instance, a cell-center region may use the frequency band assigned to the cell-edge regions of neighboring cells, as well as the frequency band assigned to its own cell-edge region when there is no cell-edge users [173]. Furthermore, in some SFR schemes, cell-center users are always allowed to access the minor band, provided that the transmit power level is sufficiently low, in order to prevent excessive ICI [169]. However, even by controlling the transmit power, SFR schemes cannot completely eliminate ICI. In addition, reducing the transmit power for some cell

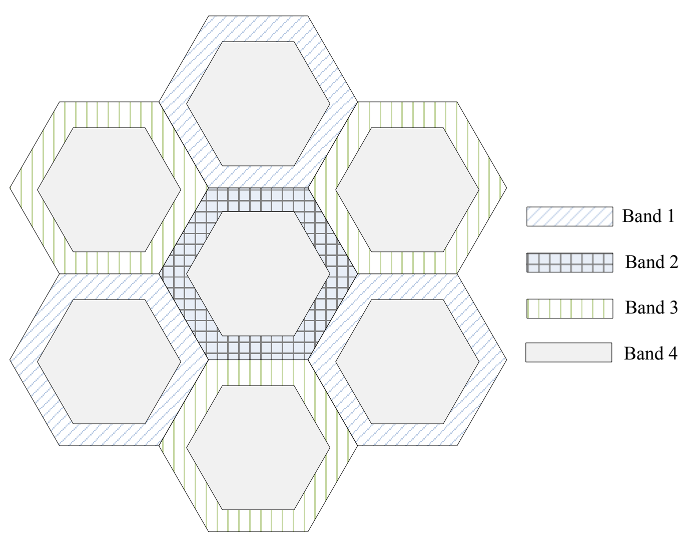


Fig. 10: A PFR scheme with cell-center FRF of 1 and cell-edge FRF of 3. Each of the frequency bands 1-3 is equal to $B_0/3$, while frequency band 4 is equal to B_1.

[6]The FRF is defined as the maximum number of cells, K, which cannot use the same frequencies for transmission. In other literature, the FRF is sometimes defined as $1/K$, which represents the rate (per cell) at which the available frequencies can be reused.

users results in a reduction in spectral efficiency, especially when the cell is highly loaded [174]. In order to address the ICI and low spectral efficiency issues of SFR schemes, intelligent reuse schemes are developed, such as incremental frequency reuse (IFR) and enhanced fractional frequency reuse (EFFR) [174], [175].

2) Dynamic FFR Schemes: Different from static FFR schemes, dynamic FFR schemes do not need prior frequency planning, and performs real-time frequency resource allocation. Dynamic FFR schemes can be centralized, coordinated-distributed, and autonomous-distributed, as discussed in the following.

In centralized FFR schemes, a central control unit collects the CSI from the user handsets and allocates frequency resources to each base station, in a way that achieves a certain optimization objective, such as minimizing interference, maximizing throughput, or minimizing power consumption [176]–[179], [186]. Although such centralized approaches can achieve high overall performance, they introduce significant signalling overhead, require high computational complexity, and are difficult to implement in modern communication systems, such as LTE-advanced, due to the absence of a central unit that controls the eNBs. Therefore, distributed schemes are proposed to achieve FFR, without the need of any central controller.

In coordinated-distributed schemes, the resource allocation is conducted by each cell base station, based on coordination (i.e., information exchange) among neighboring cells [180], [181]. Such cell coordination can be carried out through signalling interfaces among base stations, e.g., via the X2 interface in LTE cellular networks. For instance, information exchange among neighboring base stations can be used to minimize the ICI and guarantee a minimum data rate for the users in a cell [180], or to dynamically adjust the boundary between the cell center and cell edge in order to maximize the cell throughput [181]. However, the real-time information exchange among base stations, which is needed to apply a coordinated-distributed scheme, practically requires non-negligible latency. Consequently, autonomous-distributed schemes are proposed to achieve resource allocation solely based on the local information collected from the users in a cell, without any coordination with other cells [182], [183]. The main advantages of such schemes are the simplicity of implementation and the rapid response to the time-varying network condition, since neither a central controller nor information exchange among cells is needed.

3) FFR for HEWs: In HEWs, if two adjacent BSSs operate on the same frequency channel, the STAs located at the edges of the BSAs may suffer from severe co-channel interference, which significantly degrades each BSS throughput performance. As discussed in Section II-A, since OFDMA is one of the potential PHY techniques for HEWs, FFR can be utilized to reduce interference among OBSSs and improve the spectral efficiency. In [58], an FFR scheme for HEWs is presented based on the IEEE 802.11ac channelization. As shown in Fig. 11, a BSA is divided in two regions: an "OBSS free" region,

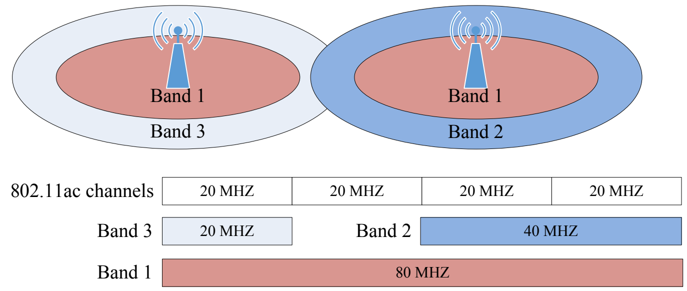


Fig. 11: FFR in HEWs using IEEE 802.11ac channelization

where there is no signal received from any OBSS, and an outer region, which is subject to interference from OBSSs. STAs located in the "OBSS free" region of a BSA can access all the OFDM sub-carriers, while other STAs located in the outer region of the BSA are allowed to access only a subset of the available sub-carriers. Also, the subset of sub-carriers allocated to the outer regions of adjacent BSAs should be disjoint. In other words, while in the "OBSS free" regions the available frequency channels can be reused with FRF of 1, in the outer regions the FRF should be greater than 1 to avoid interference. In this way, a high spectral efficiency can be achieved in the "OBSS free" regions, and the interference can be efficiently managed in the outer regions of BSAs. It is obvious that, the size of the "OBSS free" region greatly affects the overall spectral efficiency. Hence, to maximize the size of this region, sectorization and beamforming techniques can be employed [58].

FFR can be applied for HEWs based on centralized or distributed techniques [58], which is analogous to the application of dynamic FFR in cellular OFDMA networks, as discussed in Subsection IV-B2. In a managed (planned) HEW deployment, such as carrier WiFi [188], a centralized FFR approach is suitable, since the APs can exchange information with a central controller through a backbone network. In this scenario, the central controller performs the channel allocation for various APs, in order to mitigate co-channel interference and enhance the spatial frequency reuse throughout the whole HEW deployment region [189]. On the other hand, in an unplanned HEW deployment scenario, coordination among APs can be employed to conduct frequency resource allocation in a distributed way. Such AP coordination can be achieved either via direct communication among APs, or with the assistance of other STAs. For instance, two APs belonging to OBSSs can exchange necessary information (such as the BSS load) through the STAs located in the overlap of the BSAs, i.e., which can receive the beacon frames of both APs. These STAs can include the information required for AP coordination in their transmitted control frames, such as the RTS or CTS frames.

To summarize, this section discusses the potential techniques to improve spatial frequency reuse and mitigate the effect of interference among OBSSs in HEWs. The CCA mechanism of the IEEE 802.11 standard is used to avoid interference with on-going transmissions in a busy channel. However, the low CCA levels set in the IEEE 802.11 standard may cause a BSS transmission to prevent many STAs in the OBSSs from accessing the channel, which is particularly undesired in dense HEW deployment. In this section, potential fixed and dynamic CCA enhancement methods that improve spatial frequency reuse are presented and compared in terms of performance improvement, implementation simplicity, and suitability for different HEW scenarios. Enhanced CCA can be combined with BSS coloring for an enhancement in spatial frequency reuse, while maintaining the coverage of a BSS AP and preventing the loss of intra-BSS transmissions that results due to an increase of the CCAT level. Also, transmit power control can be used in conjunction with an enhanced CCA scheme, in order to provide another way for controlling the SINR, without fairness issues among HEW and legacy WLAN STAs. On the other hand, if OFDMA is adopted for HEWs, FFR can be employed for spatial frequency reuse and interference management among adjacent BSSs. FFR can be applied for HEWs either in a centralized or distributed way, similar to the application of dynamic FFR schemes in cellular OFDMA networks. In the following, we discuss the power consumption associated with different STA modes and potential power saving mechanisms for HEWs.

V. Power Efficiency

Power efficiency is an important aspect of developing next generation HEWs. The radio interface consumes a significant amount of energy in a mobile device. For instance, the energy consumption measurements in [199], [200] show that a WiFi radio consumes more than 70% of the total energy in a smartphone when the screen is off, which is reduced to 50% when the power saving mode is enabled. A radio interface can be in transmit, receive, idle, and sleep mode. Table IX shows the power consumption of a *Cisco Aironet 350 series* in different modes.

In the transmit mode of a radio interface, the energy consumption increases with the transmit power level. Hence, in traditional transmit power control schemes, the data frames are transmitted at the minimum required power level to reduce energy consumption, while the RTS/CTS control frames are transmitted at the maximum power level (covering a larger region around the transmitter and receiver STAs) to avoid collision of data frames [210]–[213]. However, reducing the transmit power level of data frames also leads to a lower data transmission rate, as a result of a lower SINR at the receiver STA. In addition, exchanging the RTS/CTS control frames at a

TABLE IX: Power consumption of a Cisco Aironet 350 series in different modes [190]

Mode	Transmit (100 mW)	Receive	Idle	Sleep
Power consumption	2.25W	1.25W	1.25W	0.075W

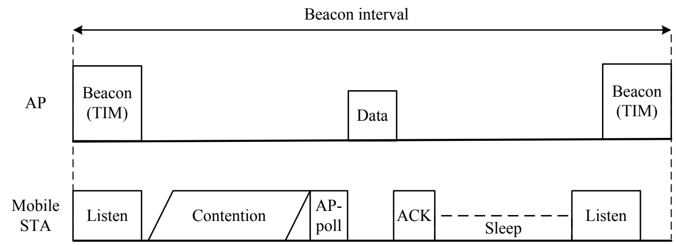


Fig. 12: The operation of the PSM of the IEEE 802.11 standard in infrastructure mode

high transmit power level imposes an overhead that increases the energy consumption in the transmitter and receiver STAs.

In the idle mode, when the radio interface does not receive or transmit any frame, the STA continuously senses the channel for incoming frames. Consequently, in the idle mode, the radio interface consumes a similar amount of energy as in the receive mode. The energy consumption in the idle mode can be reduced by switching to a sleep mode, in which some parts of the radio interface are shut down to save energy. However, in the sleep mode, the radio interface cannot receive incoming frames. Hence, the power saving mechanisms tend to periodically put the radio interface into sleep mode to save energy and coordinate the awake periods to prevent missing incoming frames during the sleep mode [3], [191]–[209], [214]–[217]. In the following, we review potential HEW power saving mechanisms, for infrastructure-based and ad hoc HEW modes separately, as summarized in Table X.

A. Infrastructure-based Mode

In an infrastructure-based HEW mode, each non-AP STA is associated with an AP. In this mode, the legacy IEEE 802.11 provides a power saving mechanism (PSM), as shown in Fig. 12 [3]. During the sleeping periods, an AP buffers the incoming frames for its sleeping STAs. The AP periodically (at the beginning of each beacon interval) broadcasts a traffic indication message (TIM) to inform the power saving STAs to which it has frames to deliver. Power saving STAs stay awake at the beginning of each beacon interval to receive the TIM message. The STAs that are included in the TIM stay awake during the rest of the beacon interval and poll the AP to receive the frames.

There are several ways that can be performed at the STA/AP to improve power efficiency in an infrastructure-based HEW mode. One way is to separate the delay-sensitive traffic (e.g., Telnet) from the delay-tolerant traffic (e.g., FTP) at the STA, in order to batch the frames of delay-tolerant traffic and send them as bursts, thus extending the STAs' sleep time [191]. Another way is to allow an AP to prioritize its service to power saving STAs over constantly awake STAs, in order to decrease their waiting time for service (which consequently reduces their energy consumption) [192]. A third way is to timely distribute the TIM transmission instants of different APs to avoid traffic bursts [193]. Such approach ensures that the STAs associated with different APs are active during non-

TABLE X: Classification of potential HEW power saving mechanisms

HEW Power Saving Mechanisms	**Sleep Scheduling**	Infrastructure-based mode	[3], [191]–[204]
		Ad hoc mode	[3], [205]–[209]
	Transmit Power Control		[210]–[213]

overlapping time windows, which decreases the contention among STAs in OBSSs [193].

In addition to PSM, the IEEE 802.11e [3] has introduced new automatic power save delivery and notification (APSD) mechanisms for QoS STAs[7]. The APSD provides two methods for power save delivery: unscheduled APSD (U-APSD) and scheduled APSD (S-APSD). In the U-APSD method, a QoS STA wakes up when it has a frame to transmit or expects buffered frames at the AP. During the awake period, the QoS STA transmits its buffered frames or a null frame to inform the AP that it is awake to receive any DL frames buffered at the AP. The AP informs the STA whether or not it has additional frames for the STA by including this information in the data frame. After receiving all the buffered frames, the power saving STA goes back to the sleep mode. On the other hand, in the S-APSD method, power saving QoS STAs wake up at predefined service time periods to transmit their frames and receive the buffered frames from the AP. Thus, the power saving STAs do not need to poll the AP to receive the frames, which helps to reduce the overhead and energy consumption. Other power saving protocols proposed in literature deploy another low power interface (e.g., ZigBee) along with a WiFi interface [199]–[202] or require PHY layer modifications [203], [204].

The current power saving mechanisms for infrastructure-based WLANs can achieve low energy consumption for a single BSS, i.e., for one AP. However, in an HEW with OBSSs, several APs are closely located in the same area and have to contend with each other to access the shared channels, which increases the idle listening periods and results in a lower energy efficiency.

B. Ad Hoc Mode

The IEEE 802.11 standard also defines a PSM for a BSS operating in an ad hoc mode (i.e., without an AP), referred to as an independent BSS (IBSS) [3], as shown in Fig. 13. In the ad hoc mode PSM, the time is partitioned into beacon intervals, and a distributed beacon transmission algorithm is used to synchronize the BSS member STAs. At the beginning of each beacon interval, all the STAs stay awake during an ad hoc TIM (ATIM) window. In this window, a sender STA informs a receiver STA of the frames that the sender STA has to deliver by transmitting an ATIM frame. The ATIM frame is acknowledged by the receiver STA via an ATIM-ACK frame, in the same ATIM window. Then, the sender and receiver STAs (that have successfully exchanged ATIM and ATIM-ACK frames) stay awake during the rest of the beacon interval (data transmission period) to transmit/receive data frames.

The performance of PSM in terms of throughput and energy consumption depends on the ATIM window size [205]. If the ATIM window is too small, some sender STAs may not have enough time to transmit their ATIM frames. On the other hand, when the ATIM window is very large, the data transmission period is reduced and the STAs may not be able to exchange all the data frames that have been announced for in the ATIM window. Additionally, a very large ATIM window increases the energy consumption, since all the STAs should stay awake during this time. Therefore, a dynamic adjustment of the ATIM window size based on the network load is preferred, in order to increase the throughput and reduce the energy consumption for a time-varying network traffic load [206], [207]. By exchanging control frames in the ATIM window, a sender STA reserves contention-free transmission slots in the data transmission period, which decreases the awake time of STAs during the data transmission period and further reduces energy consumption. The control message overhead required in STAs' contention/scheduling should also be considered in order to balance power consumption and network throughput [208].

In summary, reducing power consumption by decreasing the transmit power and utilizing sleep modes can jeopardize the data transmission and reception rates. In this section, we review potential HEW power saving mechanisms for infrastructure-based and ad hoc HEW modes. In an infrastructure-based HEW mode, the AP can buffer incoming frames for sleeping STAs, sort the frames according to their urgency, or prioritize power saving STAs. In an ad hoc mode,

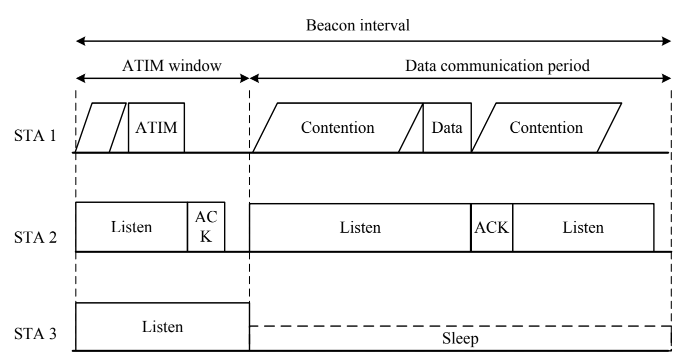


Fig. 13: The operation of the PSM of the IEEE 802.11 standard in ad hoc mode

[7] A QoS STA is a STA that implements a set of enhanced functions, channel access rules, frame formats, frame exchange sequences, and managed objects used to provide parameterized and prioritized QoS [3].

IEEE 802.11 standard defines a PSM for an IBSS, which is based on exchanging ATIM and ATIM-ACK frames within an ATIM time window. For efficient ad hoc based PSM, the ATIM window size should be adjusted automatically based on the network load such that the tradeoff between network throughput and energy consumption is balanced.

VI. Evaluation Methodologies

Stemmed from the nature of HEWs, the performance evaluation of an HEW solution should account for the dense deployment of APs/STAs, isolated BSSs, OBSSs, and the associated complexities in the MAC and PHY layers. Performance evaluation can be done through computer simulations, mathematical analysis, or field/in-lab experiments, as indicated in Table I. However, we focus only on computer simulations, which are the main evaluation methodology being discussed by the IEEE 802.11ax task group. In this section, we present an overview of performance evaluation methodologies for HEWs in terms of simulation methods, performance metrics, simulation scenarios, and associated data traffic and channel models.

A. Simulation Methods

Two levels of simulation methods are proposed for HEWs: link-level simulations and system-level simulations.

1) Link-level Simulations: Link-level simulations, also referred to as packet error rate (PER) simulations, are used to assess point-to-point (P2P) performance of new PHY layer solutions. Conducting PER simulations for different settings (data rates and antenna configurations) results in waterfall curves for PER versus SINR, which can be used to determine PHY layer impairments (e.g., power amplitude non-linearity, phase noise, and synchronization error) for the settings. In addition, PER simulations can be utilized to evaluate channel estimation methods [218] and modulation and coding schemes (MCSs) [219].

However, the main research efforts for HEWs revolve around proposing techniques that improve network performance in the presence of dense OBSSs, and therefore provide not only efficient P2P communications, but also a higher multi-BSS aggregate throughput. Hence, system-level simulations are needed.

2) System-level Simulations: Here, we describe simulations that provide system-wise (multi-BSS, multi-STA) performance evaluation with three different level of details: PHY system simulations, MAC system simulations, and integrated system simulations. In a nutshell, PHY system-level simulations provide system-wise performance assessment with emphasis on PHY layer accuracy and simplified MAC. On the other hand, MAC system-level simulations provide system-wise performance evaluation with emphasis on MAC accuracy and a very simple PHY layer. Integrated system simulations describe both MAC and PHY layers in details, in order to evaluate the performance of a close-to-real system with an integrated MAC and PHY layers.

PHY system-level simulations rely on a method, so called *PHY abstraction*, to describe link layer performance. The objective of PHY abstraction is to accurately predict PER simulation results in a computationally inexpensive way to enable running system simulations in a timely manner. Although traditional methods suffice with PER as a function of the average SINR to measure the link layer performance, this is only valid when each transmitted packet experiences the same channel conditions. For HEWs, PHY abstraction methods should account for the instantaneous channel and interference conditions. Generically, a PHY abstraction method a) extracts a set of quality measures from different elements (e.g., inter-BSS interference, power allocation, shadowing); b) compresses the quality measures (e.g., SINR) into one or two scalars in order to reduce the complexity of the PHY abstraction process; and finally, c) maps the quality measures to the corresponding PER [220]. Essentially, PHY abstraction aims at calculating an average effective SINR, SINR_{eff}, in a given OFDM symbol, which can be calculated by the following general formula [220]

$$\text{SINR}_{\text{eff}} = \Phi^{-1}\left\{\frac{1}{N}\sum_{n=1}^{N}\Phi(\text{SINR}_n)\right\} \qquad (2)$$

where SINR_n is the post processing SINR at the n^{th} sub-carrier, N is the number of symbols for a coded block or the number of data sub-carriers used in an OFDM system, Φ and Φ^{-1} are respectively the effective SINR mapping (ESM) function and its inverse. Different PHY abstraction methods have different ESM functions, i.e., Φ is a model-specific function. PHY abstraction ESM functions include exponential ESM [220], mean mutual information per bit (MMIB), constrained capacity (CC) [221], and received bit mutual rate (RBIR)[8] [222]. The MMIB provides a more accurate calculation of PER, however it is more complex to implement [221]. Since the objective of PHY abstraction is to accurately predict link layer performance in a computationally inexpensive way, techniques of reducing the implementation complexity of MMIB should be adopted. Also, different code block sizes provide different PER values. Nevertheless, if the sampling rate is reduced, less SINR values have to be calculated and processed for each code word during system simulations. That is, for each MCS level, SINR_{eff} is calculated for several code block sizes, and then the SINR_{eff} for other code block sizes can be calculated via interpolation [221], thus reducing the implementation complexity.

MAC system simulations provide system-level evaluation of the MAC performance while assuming a simplified PHY, e.g., a SISO configuration running over an additive white Gaussian noise (AWGN) channel is adequate [222]. To accurately model the MAC layer, system simulations need to describe different MAC parameters, such as beacon periodicity, aggregation policy, usage of RTS/CTS frames, EDCA parameters (e.g., minimum and maximum contention window sizes), DCF back-

[8] RBIR is also known as mutual information ESM (MIESM).

off procedures, energy and preamble detection, and basic rate set. A packet reception and preamble detection procedure, i.e., a *PPDU capture* procedure, should be executed in the MAC system simulations in order to account for the multi-BSS deployment and the associated interference from OBSSs. A capture window size should be specified in the PPDU capture procedure. During this window, the PPDU received with the strongest power is captured and its preamble is decoded, while a PPDU received with power less than the receiver sensitivity is dropped. The rest of the PPDUs arriving during the captured PPDU's preamble are considered as interference.

While a PHY/MAC system simulation focuses on evaluating the performance of PHY/MAC assuming a simplified MAC/PHY layer, an integrated system-level simulation is one that accounts for both PHY and MAC features with sufficient details, such that an overall HEW system performance in real-world usage scenarios can be evaluated. An integrated system simulation is a discrete-time event simulation, which accurately models the behaviors of both PHY and MAC layers as a discrete-time event sequence. Integrated system simulations follow mainly three procedures: a) *Initialization:* during which a set of drops (i.e., the locations of APs and STAs) are positioned according to the considered scenario, the channel model is chosen, the association among the STAs and APs is determined, and the main event list is created; b) *Event creation and processes:* during which multiple transmission opportunities are created along with the MAC and PHY layer events; and c) *Statistics collection:* during which simulation results are collected according to the performance evaluation metrics (to be discussed later in this section).

3) Choice of Simulation Methodology: The main objective of HEW simulations is to perform realistic performance evaluation. Although an integrated system simulation provides a close-to-real assessment of the whole network, it can be unnecessary in intermediate design stages. On the contrary, the complexity of the integrated system simulations may provide misleading and uninformed results. Stand-alone link level or PHY/MAC system-level simulations can simplify and speed-up the development and can provide insights to the specific reasons behind performance gains/losses. For example, to evaluate the performance of a newly proposed MAC scheduler, MAC system simulations are adequate. On the other hand, to investigate the implementation losses of current and new PHY layer models, PER simulations should be chosen. PER simulations should also be used to investigate possible errors that are not well captured by system simulations due to PHY abstraction inaccuracies. Despite the aforementioned benefits of stand-alone simulations, these types of simulations fail to provide accurate real-world performance evaluation. For instance, PHY system simulations cannot show potential trade-off between PHY rate enhancement and MAC efficiency. Additionally, MAC system simulations are incapable of showing the impact of fluctuating wireless channels. Using integrated system simulations, strong insights on PHY-MAC interworking can be obtained, e.g., the performance gain from joint effects of both PHY and MAC layers, or the performance trade-off resulting from enhancement in PHY layer and degradation in MAC layer performances. Furthermore, PHY-MAC cross-layer designs can be evaluated in the context of multi-BSS using integrated system simulations.

B. Performance Metrics

Following link- or system- level simulations, statistics of a set of metrics are collected. Insights about the performance of the PHY and MAC layer techniques can then be inferred from these statistics. Performance metrics of HEWs can be categorized into: throughput metrics, latency metrics, reliability metrics, and energy metrics.

One initially proposed throughput metric is the *area throughput*, which refers to the rate of data that is successfully delivered to all the STAs in a deployed network divided by the deployment area, and is calculated in bits per second per unit area [223], [224]. However, this metric does not reflect the user experience. Consider a highly dense BSS (i.e., a high number of STAs associated with an AP), as the STA density increases, the BSS area throughput can possibly remain the same while the average throughput per STA decreases [225]. Therefore, *per-STA throughput* is considered to be a more suitable performance metric than the area throughput, as it reflects the impact of dense deployment on the performance of HEWs. The (5^{th} *percentile-*, 50^{th} *percentile-*, and 95^{th} *percentile-*) *per-STA throughput* measures the (minimum, median, and peak) throughput performance for a STA located (at the edge of a BSA, between the edge and the center of a BSA, and at the center of a BSA), respectively. Another throughput metric is the *per-BSS throughput*, which equals the aggregated per-STA throughput of all STAs in a BSS [222]. This metric can more accurately compare different HEW deployment densities, as well as heterogeneous deployment scenarios of HEWs with previous IEEE 802.11 WLANs.

Existing latency metrics for HEWs include a) link set-up latency; b) hand-off latency, which measures the link re-establishment delay as the STA moves from one BSS to another; and c) transmission latency, which measures the time delay for a STA to access the channel and start its transmission [226].

Reliability metrics are concerned with measuring the network robustness and outage in high interference and dense deployment scenarios. A frame loss metric is used to evaluate the network robustness in dense deployment scenario, which is defined as the ratio of the number of frames not delivered (in time) to the total number of frames. Network outage can be measured by the percentage of STAs having a per-STA throughput less than a certain threshold. This metric is important for admission control. A typical energy metric is per-STA energy per transmit/receive bit, measured in joules per bit, which describes the total energy consumed by a STA divided by the total number of successful data bits transmitted/received by the STA.

TABLE XI: Simulation scenarios for HEW performance evaluation

Scenario	Environment	Topology		Deployment density	
		AP positions	AP spacing	BSS	STA
Residential	multi-floor apartment building	unmanaged/random	$\sim$10-20m	high	medium-low
Enterprise	office floor	managed/grid	$\sim$10-20m	high	high
Indoor Small BSS Hotspot	transit station/mall	managed/hexagonal	$\sim$10-20m	high	high
Outdoor Large BSS Hotspot	urban street	managed/hexagonal	$\sim$100-200m	low	high
Stadium	stadium	managed/arena	$\sim$12-20m	high	high

C. Simulation Scenarios

HEWs research focuses on the development of efficient PHY and MAC techniques that are adaptive to the HEW deployment environment in the presence of interfering sources and dense heterogeneous networks. Therefore, to accurately assess the feasibility of proposed HEW solutions, different simulation scenarios should be considered to reflect real world networks. Mainly, five reference simulation scenarios are proposed for HEW performance evaluation: residential, enterprise, indoor small BSS hotspot, outdoor large BSS hotspot, and stadium. It should be noted that the former four scenarios are classical and are used to evaluate other WLANs as well [227]. However, the simulation parameters (e.g., AP density), and the issues arising (e.g., level of OBSSs) are different for an HEW. Here, we discuss the objectives and characteristics of different HEW simulation scenarios, as listed in Table XI.

1) Residential: A classical simulation scenario that describes a network deployment with high density of APs and low-to-medium density of STAs per AP is the residential scenario. This can be a large apartment building or a community WiFi. In a multi-floor apartment building scenario, an AP is randomly located in each apartment, and STAs are randomly placed within each apartment as part of an unmanaged (unplanned) network. In order to evaluate whether or not a proposed HEW solution is effective in real deployments, simulation parameters such as the proportion of connected devices (i.e., number of active apartments) should be tuned to different values. Since each AP is located in a separate apartment, the wall and floor penetration losses result in significant increase in throughput, as a result of a small interference level among OBSSs [228].

2) Enterprise: Another typical simulation scenario is the enterprise scenario. It corresponds to a network deployment with a managed high density of APs and high density of STAs per AP, e.g., a dense wireless office, a lecture hall, or a manufacturing floor. APs are positioned at fixed locations within an enterprise office floor (possibly on the ceiling). The floor is divided into cubicles, each containing a number of STAs randomly located within the cubicle. The topology of the enterprise scenario differs from that of the residential scenario due to the different layout of the managed and open APs (i.e., STAs access is not restricted to a certain AP as in the residential scenario). As a result, evaluating proposed solutions for an enterprise scenario provides a measurement of the effect of OBSS interference. Additionally, different interference models should be adopted to characterize interference with APs belonging to different ESSs managed by multiple operators, and interference with unmanaged networks [i.e., P2P links].

3) Indoor Small BSS Hotspot: The objective of simulating an indoor small BSS hotspot scenario is to characterize the high density of STAs and BSSs in hotspots, within environments such as airport/train stations, shopping malls, and exhibition halls. High user demand for WiFi any time and everywhere in such environments poses challenges in maintaining high levels of QoS provisioning. Unlike the enterprise scenario, STA mobility in an indoor hotspot can cause performance degradation due to frequent handovers and wireless channel variations. Assessing the performance of an HEW solution in an indoor hotspot scenario can provide useful guidelines for the most suitable HEW infrastructure design and the maximum number of users that can be supported within an indoor hotspot. Additionally, the effect of OBSS interference can be characterized, including interference with APs within the same managed ESS, APs from different managed ESSs, unmanaged stand-alone APs, and unmanaged P2P links.

4) Outdoor Large BSS Hotspot: The objective of this simulation scenario is to capture the issues in a real world outdoor deployment with a high STA density and a high separation between two adjacent APs (around 100-200 m [229]). Examples of an outdoor large BSS hotspot are dense urban street deployement, pico-cell street deployment, and macro-cell street deployment. In such environments, the network infrastructure is managed (planned) and the AP deployment can be assumed to follow a hexagonal grid topology for implementation simplicity. Since the inter-AP distances are relatively large, the interference among OBSSs belonging to the same managed ESS is low, yet it can still be captured by simulations. Additionally, OBSS interference with an AP belonging to a different managed ESS can be captured in this simulation scenario.

Another simulation scenario for HEWs performance evaluation is a mixture of the outdoor large BSS hotspot and the residential scenario. An example use case is an ethnic festival in a residential neighborhood. In this scenario, APs are a mixture of two sets: one is deployed on a hexagonal grid and another randomly deployed. For implementation simplicity of this scenario, one residential building that consists of only one

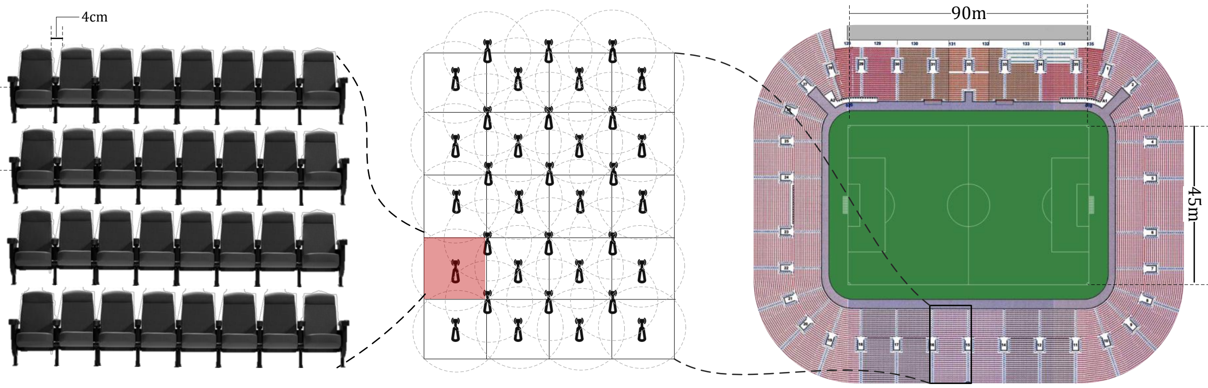


Fig. 14: An illustration of the stadium scenario proposed for HEW performance evaluation

floor can be assumed.

5) Stadium: A newly proposed evaluation scenario for HEWs is the stadium scenario. The objective of simulating this scenario is to capture the issues emerging in real-world stadium deployments with very high STA density and a relatively low separation among APs in an outdoor environment. The spacing between seats in the arena is very small[9]. As a result, the density of STAs in a stadium is extremely high and each AP covers $25-125$ seats. Additionally, all STAs should be considered active with high bandwidth demand (e.g., photo and video uploads after a goal is scored). The stadium scenario is not considered a use case of outdoor large BSS hotspot due to the large density of APs. On the other hand, the stadium scenario differs from an indoor small BSS hotspot in the channel model and the directional AP antennas. Therefore, it is listed as a separate simulation scenario. A high AP density is considered with inter-AP spacing on the same row and between rows set to 12 and 10-25 m, respectively, as illustrated in Fig. 14 [230].

When simulating a stadium scenario, the arena can be divided into 2D sections. Each section can be considered independently, and the edge effect can be ignored by wrapping the two edges around, such that all APs and STAs in the considered section undergo the same interference effect [230]. Another main issue to be captured in this scenario is the interference originating from APs across the pitch [230]. To evaluate the affect of this interference on HEW efficiency, two sections of the arena can be simulated, separated by the width of the pitch ($45-90$ m). A more realistic, yet challenging, 3D layout of the arena can also be considered, where the different sections of the arena seating overlap with one another. Furthermore, new simulation scenarios should be designed, which exploit the use of IBFD communications, in order to assess the performance of HEWs in the presence of self-interference [231].

[9]The gap between neighboring seats on the same row and on consecutive rows is less than 4 and 32 cm, respectively.

D. Traffic Models

Data traffic models that should be adopted in simulating an HEW depend not only on the simulation scenario but also on the application type. Consider the stadium scenario, different users may choose to share a photo, upload a video, and/or tweet about an incident in the stadium. Therefore, the data traffic should first be defined per STA in different simulation scenarios. The baseline of traffic models in simulations is the full buffer model, i.e., STAs always have data to send and receive. There are two levels of traffic modeling: a) application-level, which describes the traffic generated by each application, and b) STA-level, which describes a mixture of traffic generated by different applications at a certain STA. A STA can run many different applications, such as file transfer, web browsing, video streaming, online gaming, etc. The traffic load in HEWs is foreseen to be dominated by video traffic [232], [233]. It is forecast that the consumer internet video traffic will be 80–90% of all consumer Internet traffic in 2019 [233]. Next, we focus on traffic models for the video applications listed in Table XII.

Wireless display of lightly compressed video is a unidirectional single-hop (from computer to monitor) application. In simulating this application for HEWs, video frames are generated at a fixed rate and delivered directly to the MAC layer. A widely used application is the buffered video streaming. This is a multi-hop unidirectional application, since the generated video frames in a server need to traverse through

TABLE XII: Video traffic applications

Application	**AP-STA Route**	**Direction**	**Delay Tolerant**
Wireless display	single hop	unidirectional	no
Video streaming	multi-hop	unidirectional	yes
Video conference	multi-hop	bidirectional	no
Multicast video	multi-hop	unidirectional	yes
Online gaming	single hop	bidirectional	no

the internet until it reaches the AP for transmission to the associated STAs. Therefore, the network jitter experienced by the video frames should be accounted for in the simulation. A typical video streaming traffic model can be summarized by three steps: a) randomly generate video frame size (in bytes) according to Weibull distribution, b) fragment video frames into Transmission Control Protocol (TCP) segments, and c) append a random network latency (according to Gamma distribution) to the arrival time of the TCP/IP packets at the AP for transmission [222]. Similarly, video conferencing traffic can be modeled using the previous steps. However, since video conferencing is a bidirectional application, only video traffic that is transmitted from an AP to an STA can be simulated by steps a) to c). On the other hand, for transmitting video from an STA to an AP, only steps a) and b) are required, since the traffic does not undergo network jitter. Multicast video streaming traffic can be modelled with steps a) to c), while taking into account the multicast addressing from an AP to the multiple destination STAs. Recently, online gaming has been widely spreading among youths, especially when played in groups over a network, so called *massively multiplayer online* (MMO) game. A popular example of MMO games is first person shooter, which requires real-time bidirectional video traffic transmission over the Internet. An MMO game application can be modeled by generating initial packet arrival time for different users using a uniform distribution and generating packet inter-arrival times and packet sizes using a largest extreme value distribution [222].

Given the traffic model of each application, the STA-level traffic model can be extracted. First, the application profile of an STA should be decided, i.e., which applications are running on the STA. Second, the STA application profile needs to be configured to specify the arrival pattern of application events, i.e., the start time, order, and duration of the applications in the STA profile. For the STA profile configuration, two methods can be used: *random pattern* and *peaked pattern* configurations. Random pattern is based on the Poisson model, which is suitable to describe many users, each generating some traffic for some time. A peaked pattern is based on hyper-exponential model and describes users requesting network access in big spikes around a mean.

E. Channel Models

Accurate channel models are essential to assess the performance of HEWs in a realistic environment. HEWs should exploit characteristics of the wireless channels to meet the demand on bit rate, QoS, spectrum efficiency, etc. For example, a MIMO system for HEWs aims at exploiting the wireless channel degrees of freedom in space and time. Thus, optimizing the parameters of an HEW by using accurate channel models plays a crucial role in achieving high HEW performance.

As discussed in Subsection VI-A, five simulation scenarios are proposed for HEW performance evaluation. The first three scenarios (i.e., residential, enterprise, and indoor small BSS hotspot) mainly focus on the HEW performance in indoors while the last two scenarios (i.e., outdoor large BSS hotspot and stadium) focus on that in outdoors. Hence, indoor and outdoor channel models are used for the first three and the last two scenarios, respectively. Furthermore, outdoor-to-indoor channel models are also used in these scenarios, especially when simulating a mixture of residential and outdoor large BSS hotspot scenarios.

1) Indoor Channel Models: For an indoor scenarios, the channel models developed in the IEEE 802.11n/ac task groups (TGn and TGac) can be used [234], [235]. The TGn has defined six channel models (A to F) for different propagation scenarios. For example channel-B for intra-room and inter-room communications, and channel-D for office environments, open areas, large class rooms, etc. The TGn channel models support a bandwidth up to 40 MHz, which is the maximum bandwidth supported by the IEEE 802.11n amendment. The TGac has extended the TGn channel models to support a bandwidth up to 1.28 GHz [235]. The supported bandwidth of a channel can be extended by increasing the sampling frequency of the channel. That is, generating new taps in the power delay profile of the channel via linear interpolation of the taps that are defined in the TGn channel models.

The TGn channel-B model can be used for the first HEW simulation scenario, while the TGn channel-D model can be used for the second and the third scenarios. For the first two simulation scenarios, the path losses defined by TGn for channel-B and channel-D models should be used with additional indoor wall and floor penetration losses [236]. For the third scenario, the path loss defined for the channel-D model can be directly applied.

2) Outdoor Channel Models: The IEEE 802.11ax task group has adopted the ITU-R[10] Urban Micro (UMi) and ITU-R Urban Macro (UMa) channel models for outdoor simulation scenarios, upon considering WINNER II[11] and ITU-R channel models [227], [236], [237]. It should be noted that the ITU-R channel models are derived from the WINNER II models. Hence, both ITU-R and WINNER II provide detailed modeling of spatio-temporal characteristics of the MIMO channels. However, the key difference between these two channel models is in the selection of parameter values.

Among ITU-R UMi and UMa channel models, ITU-R UMi is the primary channel model for evaluating HEW performance in outdoor scenarios [227], [236]. ITU-R UMi focuses on smal cells with high user densities, and assumes that the transmitter and receiver antenna heights are well below the building heights. Moreover, it contains an outdoor-to-indoor channel model in addition to the LoS and non-LoS outdoor channel models. On the other hand, ITU-R UMa focuses on large cells, assumes that the mobile user is located at the street level while the base station is located well above the surrounding buildings, and only contains LoS and non-LoS outdoor channel models. Therefore, ITU-R UMi is the primary channel model for evaluating HEW performance in outdoors,

[10]International Telecommunication Union Radio Communication Sector
[11]Wireless World Initiative New Radio consortium II

while ITU-R UMa is considered as a complementary outdoor channel model.

ITU-R UMi and UMa are geometry-based stochastic channel models, and are for systems with bandwidth up to 100 MHz over the carrier frequency range from 2 GHz to 6 GHz [227]. When the bandwidth of the simulated system is higher than 100 MHz, the channel samples, generated at default 5ns intervals (i.e., at a sampling frequency of 200 MHz), can be interpolated to generate more samples with shorter intervals, such that the sampling frequencies of the channel and the system are matched.

In outdoor HEW performance evaluations, outdoor LOS and NLOS channels can use the path loss model of the ITU-R UMi channel model without any changes. For outdoor-to-indoor channels, the path loss defined in the ITU-R UMi model should be used with 20 dB of building penetration loss. Further details on implementation of these channels to suit HEWs are given in [236].

To sum up this section, we give an overview of the HEW performance evaluation methods in terms of simulation methodologies and simulation set-up (including simulation metrics, simulation scenarios, data traffic models, and channel models). While link-level simulation methods are used to assess channel estimation methods and MCSs, system-level simulations are required to provide aggregated system (i.e., multi-BSS and multi-STA) performance evaluation of HEW solutions. During an early design stage, PHY/MAC system simulations are required to obtain informed results and accurately assess the performance of an HEW solution. Integrated system simulations can be conducted in final design stages to provide a close-to-real assessment of the whole network. The set of performance metrics that are attained from simulating an HEW should include a) throughput metrics that reflect user experience in a densely deployed HEW for STAs located at different parts of the BSA; b) latency metrics that measure time required to set up a link, access the channel for transmission, and perform a handoff between two neighboring BSSs; c) reliability metrics that measure network robustness to high interference in dense deployments; and d) energy metrics that measure the power consumption of STAs with respect to the successful data transmitted/received by the STA. Simulating an HEW should cover different scenarios that mimic different HEW deployments in terms their BSS/STA density and AP distribution, and should utilize the corresponding channel model that accurately emulates realistic HEW indoor/outdoor environments. A data traffic model adopted in an HEW simulation should account for both the simulation scenario and the application type which is foreseen to be dominated by video applications.

VII. Discussion

A. PHY

As mentioned in Subsection II-A, the PHY layer of current WLAN standards is mainly based on OFDM. If OFDM is applied for HEWs in an outdoor environment, where there is a noticeable multipath signal propagation with a large delay spread (due to reflection from obstacles located over a large area), HEWs should employ a longer cyclic prefix (CP) duration[12], in order to facilitate robust communications, combating long delay spreads [238]. However, since the CP does not carry any information, increasing the CP length results in a reduction in STA goodput. In the IEEE 802.11n/ac standards, the CP can be as long as 1.6 μs while the useful OFDM symbol duration is 3.2 μs [81], [138]. Therefore, to enhance the STA goodput in HEWs, the duration of the useful part of the OFDM symbol should be increased as well. The OFDM symbol duration can be increased by reducing the sub-channel bandwidth, i.e., the frequency difference between two successive sub-carriers, thus allowing the use of more sub-carriers, or equivalently a higher FFT size, to transmit each OFDM symbol [238]. However, to preserve backward compatibility with previous WLAN standards, the FFT size should be determined such that the sub-channel bandwidth is equivalent to that of the previous IEEE 802.11 amendments based on OFDM, e.g., 312.5 KHz for the IEEE 802.11n/ac amendments. Therefore, new signal processing schemes for modulating/demodulating OFDM signals with different sub-channel bandwidths are required for HEWs deploying OFDM with a large FFT size.

Also, as discussed in Subsection II-A, if OFDMA is deployed in HEWs: a) interference management can be achieved among adjacent BSSs through FFR (Subsection IV-B), b) per-BSS throughput can be increased through proper sub-carrier allocation schemes, and c) backward compatibility can be preserved with previous IEEE 802.11 amendments that employ OFDM. Adopting OFDMA for downlink communications is much simpler than for uplink communications. For the downlink, an AP can select the STAs to which the AP wants to simultaneously transmit data in the next downlink data frame, and (centrally) determine the sub-carrier allocation to each STA. Then, each STA can be informed, through a Beacon management frame, of the sub-carrier indices over which it will receive data in the next data frame. To determine the downlink sub-carrier allocation, various algorithms that have been proposed for OFDMA-based cellular networks can be employed [239], [240], [240]. On the other hand, the key issue in adopting OFDMA for uplink communications is how to coordinate the STAs for simultaneous uplink transmissions. Based on the IEEE 802.11 DCF-based MAC layer, it is not clear how the AP can select, inform, and synchronize multiple STAs for uplink transmissions. If the time difference between two transmissions over different sub-carriers is longer than the CP length, these transmissions result in inter-carrier interference [241], [242]. Additionally, achieving efficient uplink sub-carrier allocation in a way that avoids CCI in a BSS and maximizes the multiuser and frequency diversity gains still needs further investigation. Moreover, if

[12] The CP is a part of the end of the OFDM symbol that is appended to the beginning of the symbol. The key purpose of the CP is to simplify the frequency-domain processing of the received OFDM signal, e.g., by using a single tab equalizer, provided that the CP length is longer than the duration of the channel impulse response [80].

FFR is employed for managing CCI among adjacent BSSs, the sub-carrier allocation becomes more challenging, given the expected dense and unmanaged deployment of HEWs, different from cellular networks.

B. MAC

Although research on enhancing the IEEE 802.11 standard DCF scheme may increase the average BSS throughput and achieve better short-term fairness among BSS members, the performance breakthrough required for HEWs is more likely to be based on multiuser channel access and IBFD communication techniques. Hence, future research on the HEW MAC layer should focus on developing efficient multiuser and IBFD MAC schemes, rather than achieving incremental improvements in the DCF performance. As mentioned in Subsection III-B, while downlink multiuser channel access is adopted in the IEEE 802.11ac based on MU-MIMO, realizing uplink multiuser channel access is a more challenging task. Several MAC layer research issues need to be addressed for uplink multiuser channel access, including: a) how to initiate uplink multiuser transmissions (i.e., AP-initiated or STA-initiated) [120] [121], b) which STAs should be selected for multiuser transmission [122], c) how to transmit an ACK frame from the AP to each sending STA [123], and d) how to avoid the hidden terminal problem for each STA involved in uplink multiuser transmission, especially in OBSS scenarios [122]. Also, by employing IBFD communications at the PHY layer, the overlaying MAC scheme should account for the new types of transmission collisions introduced by pairwise and non-pairwise IBFD communications, as well as the ACK frame transmission and potential unfairness problems, as discussed in Subsection III-C. In addition to existing IBFD MAC research on these issues, performance evaluation of the proposed IBFD MAC schemes should be investigated in dense HEW deployment scenarios with OBSSs, both via computer simulations and large scale experimental testing. Furthermore, combining both IBFD communication and multiuser channel access technologies is a promising MAC research direction, which has not been studied so far to the best of our knowledge.

C. Spatial Frequency Reuse

Although enhanced CCA schemes can significantly improve the spatial frequency reuse by allowing for more concurrent transmissions (Subsection IV-A), a fairness problem may arise, resulting in HEW STAs having a higher throughput as compared to legacy STAs. Consider a scenario in which CCA-enhanced HEWs and other IEEE 802.11 WLANs coexist densely, where HEW STAs have a higher CCA level. In this case, an HEW STA can have a much higher transmission opportunity than a legacy STA. For all the received power levels that are above a legacy STA's CCA level and below an HEW STA's CCA level, the HEW STA is allowed to transmit while the legacy STA is not. This unfairness results in a legacy STA having a throughput as low as 2 Kbps, with an HEW STA having a much higher throughput of 14 Mbps [154]. Also, in a residential scenario, it is shown that by changing the CCA level from -82 dBm to -62 dBm, the throughput of an HEW STA increases by 36%, while that of a legacy STA reduces by 48% [243]. There are two reasons for the fairness issue between HEW and legacy STAs. First, if a transmission from an HEW (CCA-enhanced) STA concurrently happens during the transmission of a legacy STA (without any transmission collision), the next legacy STA's transmission will be delayed until the end of transmission of the HEW STA [244]. In other words, an HEW STA transmission may silent a surrounding legacy STA, while the opposite is not true. A potential solution to reduce this effect is to limit the HEW channel access time to the remaining time till the end of the legacy STA's channel access [244]. Second, as mentioned previously, since a legacy STA transmission (being a data frame or an RTS/CTS control frame) may not silent all the surrounding HEW STAs, a concurrent transmission initiated by an HEW STA can cause a transmission collision at a receiving legacy STAs, resulting in a high power consumption (required for retransmission) and reduced throughput. This issue can be addressed by proper transmit power control at HEW STAs [244]. A careful and thorough study is required before implementing a CCA-enhanced method for HEWs, in order to ensure acceptable performance for the current IEEE 802.11 WLANs when coexist with HEWs.

The current WLANs are mainly noise-limited systems, where the noise effect dominates the interference effect at a receiver STA, for two reasons. First, in existing WLANs, since the BSSs are relatively sparsely deployed with proper channel selection schemes, the co-channel interference can be efficiently controlled. Second, given the small CCA levels used by the standard IEEE 802.11 CCA scheme (Table VIII), the possible power level that can interfere with an STA reception is accordingly small. However, in HEWs, the situation is different. The dense and unmanaged HEW deployment leads to OBSSs, where the co-channel interference can hardly be addressed solely via channel selection. In addition, HEW STAs employing enhanced CCA schemes may have higher CCA levels, which result in an increase in the interference power level allowed at receiver STAs. Therefore, effective interference cancellation/management is required in order to guarantee the QoS provisioning for HEW users.

D. Power Efficiency

To effectively reduce the energy consumption of mobile STAs, which is one of the major requirements in HEWs, several issues need to be studied. First, the IEEE 802.11 power saving mode, which periodically allows idle STAs to sleep, can reduce the idle listening power consumption. However, idle listening power is a main source of energy consumption in mobile STAs, as the STAs that have data to transmit/receive need to stay awake and contend with each other according to the standard IEEE 802.11 MAC. Hence, effective power saving should reduce the idle listening power consumption of STAs. This issue becomes especially more challenging in a dense HEW deployment scenario, where several APs belonging to OBSSs are in the transmission range of each other and have to contend to access the shared wireless channel.

Transmit power control plays a significant role in HEWs, not only to reduce the energy consumption for STAs (Section V), but also to achieve better spatial frequency reuse and higher throughput performance (Subsection IV-A3). While reducing the transmit power level reduces the energy consumption of an STA in the transmit mode, it also reduces the data transmission rate, which in turn increases the time required by the STA to complete the transmission of a frame. Therefore, transmitting at the minimum power level may not ultimately reduce the energy consumption of an STA. In the standard IEEE 802.11 DCF-based MAC, using different transmit power levels by STAs may result in a hidden terminal problem, even if the RTS/CTS frame exchange is employed. Furthermore, the STAs with lower transmit power levels suffer from a higher probability of a transmission collision from the adjacent STAs that transmit at higher power levels. If a transmission collision happens, the entire energy and bandwidth used to transmit the colliding frames are wasted. Hence, efficient joint scheduling and power control with low signaling overhead are required to reduce the energy consumption and enhance the performance of HEWs.

VIII. Conclusions

The increasing dependence on WiFi technology for Internet access is expected to result in a considerable expansion in deploying dense WiFi networks in the near future. In order to support this expected explosion in size and density of WiFi networks, it is crucial to develop new solutions for HEWs, to guarantee a satisfactory level of QoS provisioning for various HEW user applications in indoor and outdoor environments.

Adopting an advanced PHY layer technology to HEW STAs is likely to be a milestone step toward HEW development. PHY layer enhancements can be based on improving the current WLANs' OFDM and MU-MIMO techniques, and/or on employing other technologies such as OFDMA and IBFD communications. Further research issues include how to implement OFDM with a larger FFT size (while preserving backward compatibility) and how to apply OFDMA for uplink transmission via efficient STA selection, synchronization, and sub-carrier allocation.

On the BSS level, to maximize the throughput gain from an enhanced PHY layer technology, the MAC layer needs to be re-designed. MAC layer research must be directed not only to enhance the IEEE 802.11 standard DCF (e.g., through better back-off schemes, RTS/CTS exchange, etc.), but more importantly to allow multiuser channel access and IBFD communications among BSS member STAs. Multiuser MAC should solve uplink multiuser transmission issues in a BSS, while IBFD MAC should prevent the new types of transmission collisions and any short-term unfairness introduced by IBFD communications.

In addition to increasing the throughput in a single BSS via enhanced HEW PHY and MAC layers, improving system level performance through efficient spatial frequency reuse is particularly important in dense HEW deployment scenarios. Spatial frequency reuse have been studied for HEWs based on enhanced fixed/dynamic CCA, together with transmit power control and BSS coloring. Further investigations are required to achieve service fairness when HEW STAs (with enhanced CCA) coexist with legacy STAs. Also, if higher CCA levels are employed, interference cancellation/management techniques are needed for HEWs to address the high interference level among OBSSs, different from the current WLANs in which the noise power usually exceeds the interference power at a receiver STA. Should OFDMA be adopted for HEWs, FFR can be applied for efficient interference management and spatial frequency reuse, based on centralized or distributed techniques.

In addition to achieving high BSS and system level performances, increasing the power efficiency is a main objective for HEW STAs, in both HEW infrastructure-based and ad hoc modes. Specifically, power saving mechanisms are required to reduce the energy consumption during idle listening periods, which are expected to be high in a dense HEW deployment due to channel contention among STAs in OBSSs. As well, efficient joint scheduling and transmit power control are necessary to address the hidden terminal problem resulting from asymmetric wireless channels among STAs transmitting at different power levels.

Computer simulations to evaluate the performance of HEWs should be conducted in scenarios representing real HEW usage environments, with suitable application-level and STA-level traffic models, under appropriate STA density and indoor/outdoor channels models, using throughput, latency, and reliability metrics that reflect HEW user experience. Any new solution proposed for HEWs should achieve technical feasibility, economic feasibility, backward compatibility and coexistence with the widely deployed IEEE 802.11 WLANs.

References

[1] iPass Inc. press. iPass WiFi growth map shows 1 public hotspot for every 20 people on earth by 2018. http://www.ipass.com/press-releases/ipass-wi-fi-growth-map-shows-one-public-hotspot-for-every-20-people-on-earth-by-2018/. 2014.

[2] Cisco, *The zettabyte era: trends and analysis*. Cisco White paper, 2015.

[3] "IEEE standard for information technology–telecommunications and information exchange between systems local and metropolitan area networks–specific requirements part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications," pp. 1–2793, Mar. 2012.

[4] "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 8: Medium access control (MAC) quality of service enhancements," pp. 1–212, 2005.

[5] Y. Gao, X. Sun, and L. Dai, "IEEE 802.11e EDCA networks: Modeling, differentiation and optimization," *IEEE Trans. Wireless Communications*, vol. 13, no. 7, pp. 3863–3879, 2014.

[6] Q. Zhao, D. Tsang, and T. Sakurai, "A scalable and accurate nonsaturated ieee 802.11e edca model for an arbitrary buffer size," *IEEE Trans. Mobile Computing*, vol. 12, no. 12, pp. 2455–2469, 2013.

[7] C.-L. Huang and W. Liao, "Throughput and delay performance of IEEE 802.11e enhanced distributed channel access (EDCA) under saturation condition," *IEEE Trans. Wireless Communications*, vol. 6, no. 1, pp. 136–145, 2007.

[8] A. Banchs, P. Serrano, and L. Vollero, "Providing service guarantees in 802.11e EDCA WLANs with legacy stations," *IEEE Trans. Mobile Computing*, vol. 9, no. 8, pp. 1057–1071, 2010.
[9] L. Zhao, L. Cong, H. Zhang, W. Ding, and J. Zhang, "Game-theoretic EDCA in IEEE 802.11e WLANs," in *Proc. IEEE VTC*, 2008, pp. 1–5.
[10] C. Huang and S. Shioda, "Detailed analysis for IEEE 802.11e EDCA in non-saturated conditions - frame-transmission-cycle approach," in *Proc. IEEE WiOpt*, 2013, pp. 601–608.
[11] Z. Wang and X. Guo, "Priority-based parameter performance optimization for EDCA," in *Proc. IEEE ICCSNT*, 2013, pp. 685–688.
[12] E. Charfi, L. Chaari, and L. Kamoun, "PHY/MAC enhancements and QoS mechanisms for very high throughput WLANs: A survey," *IEEE Communications Surveys Tutorials*, vol. 15, no. 4, pp. 1714–1735, 2013.
[13] H. Lee, S. Byeon, B. Kim, K. B. Lee, and S. Choi, "Enhancing voice over WLAN via rate adaptation and retry scheduling," *IEEE Trans. Mobile Computing,*, vol. 13, no. 12, pp. 2791–2805, 2014.
[14] Z.-T. Chou, C.-Q. Huang, and J. Chang, "QoS provisioning for wireless LANs with multi-beam access point," *IEEE Trans. Mobile Computing,*, vol. 13, no. 9, pp. 2113–2127, 2014.
[15] M. Santos, J. Villalon, and L. Orozco-Barbosa, "A novel QoE-aware multicast mechanism for video communications over IEEE 802.11 WLANs," *IEEE Journal on Selected Areas in Communications*, vol. 30, no. 7, pp. 1205–1214, August 2012.
[16] M. Hegde, P. Kumar, K. Vasudev, N. Sowmya, S. Anand, A. Kumar, and J. Kuri, "Experiences with a centralized scheduling approach for performance management of IEEE 802.11 wireless LANs," *IEEE/ACM Trans. Networking*, vol. 21, no. 2, pp. 648–662, 2013.
[17] "FCC frees up vacant TV airwaves for super WI-FI technologies," United States Federal Communications Commission, 2010. [Online]. Available: https://apps.fcc.gov/edocs_public/attachmatch/DOC-301650A1.pdf
[18] "IEEE standard for information technology– telecommunications and information exchange between systems local and metropolitan area networks– specific requirements–part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications amendment 5: Television white spaces (TVWS) operation," *IEEE Std 802.11af-2013 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012, IEEE Std 802.11aa-2012, IEEE Std 802.11ad-2012, and IEEE Std 802.11ac-2013)*, pp. 1–198, 2014.
[19] A. B. Flores, R. E. Guerra, E. W. Knightly, P. Ecclesine, and S. Pandey, "IEEE 802.11 af: a standard for TV white space spectrum sharing," *IEEE Communications Magazine*, vol. 51, no. 10, pp. 92–100, 2013.
[20] P. Bahl, R. Chandra, T. Moscibroda, R. Murty, and M. Welsh, "White space networking with wi-fi like connectivity," *ACM SIGCOMM Computer Communication Review*, vol. 39, no. 4, pp. 27–38, 2009.
[21] S. Deb, V. Srinivasan, and R. Maheshwari, "Dynamic spectrum access in DTV whitespaces: design rules, architecture and algorithms," in *Proc. ACM MobiCom*, 2009, pp. 1–12.
[22] L. Yu, C. Liu, W. Zhu, S. Hua, and W. Wang, "Bandwidth efficient and rate-adaptive video delivery in TV white space," *EEE Trans. Circuits and Systems for Video Technology*, vol. 24, no. 9, pp. 1605–1619, 2014.
[23] "The standards development lifecycle," IEEE Standards Association, 2016. [Online]. Available: http://standards.ieee.org/develop/
[24] "Official IEEE 802.11 working group project timelines - 2016-02-02," IEEE 802.11 wireless local area networks (the working group for WLAN standards), 2016. [Online]. Available: http://grouper.ieee.org/groups/802/11/Reports/802.11_Timelines.htm
[25] D. Priya and M. Devi, "Efficient architecture and implementation of PHY WLAN receiver on reconfigurable platforms," in *Proc. IEEE ICCCT*, 2014, pp. 1–6.
[26] H. Setiawan, L. Lanante, M. Kurosaki, and H. Ochi, "Hardware design of spatial mapper for 1.73Gbps multi-user MIMO system of IEEE 802.11ac," in *Proc. IEEE ICICI-BME*, 2013, pp. 111–114.
[27] S. Aust, R. Prasad, and I. Niemegeers, "Performance study of MIMO-OFDM platform in narrow-band sub-1 GHz wireless LANs," in *Proc. International Symposium on Modeling Optimization in Mobile, Ad Hoc Wireless Networks (WiOpt)*, 2013, pp. 89–94.
[28] IEEE 802.11-15/0101r1, "Preamble structure for 11ax system," 2015.
[29] IEEE 802.11-13/0360r1, "Preamble auto-detection in 802.11ax," 2015.
[30] L. Nasraoui, L. Atallah, and M. Siala, "Synchronization technique for MIMO-OFDM WLAN systems with space time diversity," in *Proc. IEEE IWCMC*, 2015, pp. 250–255.
[31] R. Khan and H. Karl, "MAC protocols for cooperative diversity in wireless LANs and wireless sensor networks," *IEEE Communications Surveys Tutorials*, vol. 16, no. 1, pp. 46–63, 2014.
[32] P. Ju, W. Song, and D. Zhou, "Survey on cooperative medium access control protocols," *IET Communications*, vol. 7, no. 9, pp. 893–902, 2013.
[33] F. Vazquez Gallego, J. Alonso-Zarate, C. Verikoukis, and L. Alonso, "A survey on prototyping platforms for the development and experimental evaluation of medium access control protocols," *IEEE Wireless Communications*, vol. 19, no. 1, pp. 74–81, 2012.
[34] P. Di Francesco, S. McGettrick, U. Anyanwu, J. O'Sullivan, A. MacKenzie, and L. DaSilva, "A split MAC approach for SDR platforms," *IEEE Trans. Computers*, vol. 64, no. 4, pp. 912–924, 2015.
[35] T. Honda, M. Ikeda, and L. Barolli, "Performance analysis of user connectivity by optimizing placement of wireless access points," in *Proc. IEEE NBiS*, 2013, pp. 488–493.
[36] E. Bulut and B. K. Szymanski, "WiFi access point deployment for efficient mobile data offloading," in *Proc. ACM PINGEN*, 2012, pp. 45–50.
[37] S. Zirazi, P. Canalda, H. Mabed, and F. Spies, "Wi-Fi access point placement within stand-alone, hybrid and combined wireless positioning systems," in *Proc. IEEE ICCE*, 2012, pp. 279–284.
[38] S. Kang, G. Chen, and J. Rogers, "Wireless LAN access point location planning," in *Proc. the Institute of Industrial Engineers Asian Conference*, 2013, pp. 907–914.
[39] J. Kim, N.-O. Song, B. H. Jung, H. Leem, and D. K. Sung, "Placement of WiFi access points for efficient WiFi offloading in an overlay network," in *Proc. IEEE PIMRC*, 2013, pp. 3066–3070.
[40] W. Lingzhi, H. Cunqing, Z. Rong, and N. Rui, "Online channel selection and user association in high-density WiFi networks," in *Proc. IEEE ICC*, 2015, pp. 1571–1576.
[41] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, and K. Almeroth, "Intelligent channel bonding in 802.11n WLANs," *IEEE Trans. Mobile Computing*, vol. 13, no. 6, pp. 1242–1255, 2014.
[42] X. Wang, M. Derakhshani, and T. Le-Ngoc, "Self-organizing channel assignment for high density 802.11 WLANs," in *IEEE PIMRC*, 2014, pp. 1637–1641.
[43] B. Amiri and H. Sadjadpour, "A new approach for WLAN channel selection based on outage capacity," in *Proc. IEEE MILCOM*, 2013, pp. 1657–1662.
[44] Y. Wang and R. Naylor, "Challenges in designing 5 GHz 802.11ac WiFi power amplifiers," in *Proc. IEEE PAWR*, 2014, pp. 16–18.
[45] S.-W. Yoon, T.-S. Dang, N.-D.-H. Lai, and J. Park, "Efficient Wi-Fi power amplifier LTCC module using a buck converter with a power inductor implemented in ferrite-filled PCB technology," *IEEE Trans. Components, Packaging and Manufacturing Technology*, vol. 5, no. 7, pp. 887–894, 2015.
[46] Y.-H. Chung, P.-Y. Chang, M.-H. Hung, M.-Y. Hsu, C.-H. Liao, and C.-W. Lin, "Dual-band integrated Wi-Fi PAs with load-line adjustment and phase compensated power detector," in *Proc. IEEE RFIC*, 2015, pp. 223–226.
[47] P. Li, "Recent developments in WiFi system and related challenges in power amplifier design," in *Proc. IEEE ICSICT*, 2012, pp. 1–4.
[48] R. Palacios, D. Kliazovich, and F. Granelli, "Reverse direction transmissions and network coding for energy-efficient Wi-Fi networks," in *Proc. IEEE CAMAD*, 2014, pp. 100–104.
[49] K.-H. Lee, S. Cho, and J.-H. Kim, "Performance evaluation of network coding in IEEE 802.11 wireless ad hoc networks," *Ad Hoc Netw.*, vol. 16, pp. 131–141, 2014.
[50] K. Xiao, Y. Zhang, G. Feng, X. Duan, J. Zhu, and Z. Liu, "eCOPE: Energy efficient network coding scheme in multi-rate wireless networks," in *Proc. IEEE WCNCW*, 2013, pp. 18–23.
[51] W. Wang, A. X. Liu, M. Shahzad, K. Ling, and S. Lu, "Understanding and modeling of Wi-Fi signal based human activity recognition," in *Proc. ACM Mobicomm*, 2015, pp. 65–76.
[52] S. Datta and S. K. Das, "Performance analysis of real-time traffic in Wi-Fi networks: A markov chain-based approach," in *Proc. IEEE WCNC*, 2013, pp. 2102–2107.
[53] K. Medepalli and F. A. Tobagi, "Towards performance modeling of IEEE 802.11 based wireless networks: A unified framework and its applications," in *Proc. IEEE INFOCOM*, 2006, pp. 1–12.
[54] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Selected Areas in Communications (JSAC)*, vol. 18, no. 3, pp. 535–547, 2000.

[55] Y. Yiakoumis, M. Bansal, A. Covington, J. van Reijendam, S. Katti, and N. McKeown, “BeHop: A testbed for dense WiFi networks,” *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 18, no. 3, pp. 71–80, 2015.
[56] M. Hegde, P. Kumar, K. Vasudev, N. N. Sowmya, S. Anand, A. Kumar, and J. Kuri, “Experiences with a centralized scheduling approach for performance management of IEEE 802.11 wireless LANs,” *IEEE/ACM Trans. Networking*, vol. 21, no. 2, pp. 648–662, 2013.
[57] P. Salvador, L. Cominardi, F. Gringoli, and P. Serrano, “A first implementation and evaluation of the IEEE 802.11 aa group addressed transmission service,” *ACM SIGCOMM Computer Communication Review*, vol. 44, no. 1, pp. 35–41, 2013.
[58] IEEE 802.11-13/0871r0, “Discussion on potential techniques for HEW,” 2013.
[59] M. S. Alam, J. W. Mark, and X. S. Shen, “Relay selection and resource allocation for multi-user cooperative OFDMA networks,” *IEEE Trans. Wireless Communications*, vol. 12, no. 5, pp. 2193–2205, 2013.
[60] IEEE 802.11-10/0317r1, “DL-OFDMA for mixed clients,” 2010.
[61] A. Goldsmith, S. A. Jafar, N. Jindal, and S. Vishwanath, “Capacity limits of MIMO channels,” *IEEE J. Selected Areas in Communications (JSAC)*, vol. 21, no. 5, pp. 684–702, 2003.
[62] H. Weingarten, Y. Steinberg, and S. Shamai, “The capacity region of the gaussian multiple-input multiple-output broadcast channel,” *IEEE Trans. Information Theory*, vol. 52, no. 9, pp. 3936–3964, 2006.
[63] Q. Spencer, C. Peel, A. Swindlehurst, and M. Haardt, “An introduction to the multi-user MIMO downlink,” *IEEE Communications Magazine*, vol. 42, no. 10, pp. 60–67, 2004.
[64] T. Yoo, N. Jindal, and A. Goldsmith, “Multi-antenna downlink channels with limited feedback and user selection,” *IEEE J. Selected Areas in Communications (JSAC)*, vol. 25, no. 7, pp. 1478–1491, 2007.
[65] V. Cadambe and S. Jafar, “Interference alignment and spatial degrees of freedom for the K user interference channel,” in *Proc. IEEE ICC*, 2008, pp. 971–975.
[66] D. Gesbert, S. Hanly, H. Huang, S. Shamai Shitz, O. Simeone, and W. Yu, “Multi-cell MIMO cooperative networks: A new look at interference,” *IEEE J. Selected Areas in Communications (JSAC)*, vol. 28, no. 9, pp. 1380–1408, 2010.
[67] IEEE 802.11-13/1154r1, “DL-MU-MIMO transmission with unequal bandwidth,” 2013.
[68] IEEE 802.11-13/1046r2, “Discussion on massive MIMO for HEW,” 2013.
[69] A. Sabharwal, P. Schniter, D. Guo, D. Bliss, S. Rangarajan, and R. Wichman, “In-band full-duplex wireless: Challenges and opportunities,” *IEEE J. Selected Areas in Communications (JSAC)*, vol. 32, no. 9, pp. 1637–1652, 2014.
[70] M. Jain, J. I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, “Practical, real-time, full duplex wireless,” in *Proc. ACM MobiCom*, 2011, pp. 301–312.
[71] J. I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, “Achieving single channel, full duplex wireless communication,” in *Proc. ACM MobiCom*, 2010, pp. 1–12.
[72] A. Sahai, G. Patel, and A. Sabharwal, “Pushing the limits of full-duplex: Design and real-time implementation,” Rice Tech. Rep., Tech. Rep., 2011.
[73] M. Duarte and A. Sabharwal, “Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results,” in *Proc. ASILOMAR*, 2010, pp. 1558–1562.
[74] M. Duarte, A. Sabharwal, V. Aggarwal, R. Jana, K. Ramakrishnan, C. Rice, and N. Shankaranarayanan, “Design and characterization of a full-duplex multiantenna system for WiFi networks,” *IEEE Trans. Vehicular Technology*, vol. 63, no. 3, pp. 1160–1177, 2014.
[75] D. Bharadia, E. McMilin, and S. Katti, “Full duplex radios,” *Proc. ACM SIGCOMM*, vol. 43, no. 4, pp. 375–386, 2013.
[76] K. Miura and M. Bandai, “Node architecture and MAC protocol for full duplex wireless and directional antennas,” in *Proc. IEEE PIMRC*, 2012, pp. 369–374.
[77] IEEE 802.11-15-0043-01-00ax, “In-band full duplex radios and system performance,” 2015.
[78] IEEE 802.11-13/1122r1, “Considerations for in-band simultaneous transmit and receive (STR) feature in HEW,” 2013.
[79] D. Kim, H. Lee, and D. Hong, “A survey of in-band full-duplex transmission: From the perspective of PHY and MAC layers,” *IEEE Communications Surveys and Tutorials*, 2015, In press.
[80] J. G. Andrews, A. Ghosh, and R. Muhamed, *Fundamentals of WiMAX: understanding broadband wireless networking*. Pearson Education, 2007.
[81] “IEEE standard for information technology– telecommunications and information exchange between systems local and metropolitan area networks– specific requirements–part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications– amendment 4: Enhancements for very high throughput for operation in bands below 6 GHz,” pp. 1–425, 2013.
[82] X. Sun and L. Dai, “Backoff design for IEEE 802.11 DCF networks: Fundamental tradeoff and design criterion,” *IEEE/ACM Trans. Networking*, vol. 23, no. 1, pp. 300–316, 2015.
[83] D. Kuptsov, B. Nechaev, A. Lukyanenko, and A. Gurtov, “How penalty leads to improvement: A measurement study of wireless backoff in IEEE 802.11 networks,” *Computer Networks*, vol. 75, Part A, pp. 37–57, 2014.
[84] K. H. Almotairi, “Inverse binary exponential backoff: Enhancing short-term fairness for IEEE 802.11 networks,” in *Proc. ISWCS*, 2013, pp. 1–5.
[85] N. Xie, L. Zhang, J. Wu, and H. Wang, “An adaptive backoff algorithm based on channel utilization for IEEE 802.11,” *Wireless Personal Communications*, vol. 83, no. 4, pp. 2965–2973, 2015.
[86] R. Ranganathan and K. Kannan, “Enhancing the selection of backoff interval using fuzzy logic over wireless ad hoc networks,” *The Scientific World Journal*, p. 13, 2015.
[87] S. Misra and M. Khatua, “Semi-distributed backoff: Collision-aware migration from random to deterministic backoff,” *IEEE Trans. Mobile Computing*, vol. 14, no. 5, pp. 1071–1084, 2015.
[88] S. Sen, R. Roy Choudhury, and S. Nelakuditi, “No time to countdown: Migrating backoff to the frequency domain,” in *Proc. ACM MobiCom*, 2011, pp. 241–252.
[89] P. Huang, X. Yang, and L. Xiao, “WiFi-BA: Choosing arbitration over backoff in high speed multicarrier wireless networks,” in *Proc. IEEE INFOCOM*, 2013, pp. 1375–1383.
[90] A. Matoba, M. Hanada, and M. W. Kim, “Throughput improvement by adjusting RTS transmission range for WLAN ad hoc network,” in *Proc. FedCSIS*, 2014, pp. 941–946.
[91] R. Hunjet, “A capacity enhancing modification to RTS/CTS,” in *Proc. IEEE ICT*, 2015, pp. 67–73.
[92] IEEE 802.11-14/1381r1, “Novel RTS/CTS procedure,” 2014.
[93] M. Kim and C.-H. Choi, “Hidden-node detection in IEEE 802.11n wireless LANs,” *IEEE Trans. Vehicular Technology*, vol. 62, no. 6, pp. 2724–2734, 2013.
[94] IEEE 802.11-15/0059r1, “Uplink RTS/CTS control,” 2015.
[95] IEEE 802.11-14-0613-00-00ax, “Discussions on adaptive frame length in MAC based on block ACK,” 2014.
[96] Y. Chosokabe, T. Uwai, Y. Nagao, L. Lanante, and H. Ochi, “A channel adaptive hybrid aggregation scheme for next generation wireless LAN,” in *Proc. IEEE WCNC Workshops*, 2015, pp. 153–158.
[97] C. Shin, H. Park, and H. Kwon, “PHY-supported frame aggregation for wireless local area networks,” *IEEE Trans. Mobile Computing*, vol. PP, pp. 1–1, 2013.
[98] W. Wang, Y. Chen, Q. Zhang, K. Wu, and J. Zhang, “Less transmissions, more throughput: Bringing carpool to public WLANs,” *IEEE Trans. Mobile Computing*, 2015, In press.
[99] A. Vesco and R. Scopigno, “Time-division access priority in CSMA/CA,” in *Proc. IEEE PIMRC*, 2009, pp. 2162–2166.
[100] IEEE 11-13/0768r0, “TD-uCSMA,” 2013.
[101] A. Vesco and R. Scopigno, “Advances on time-division unbalanced carrier sense multiple access,” in *Proc. IEEE ICCCN*, 2011, pp. 1–6.
[102] R. Scopigno and A. Vesco, “A distributed bandwidth management scheme for multi-hop wireless access networks,” in *Proc. IEEE IWCMC*, 2011, pp. 534–539.
[103] A. Vesco, G. Toso, and R. Scopigno, “Prototyping of time-division unbalanced carrier sense multiple access and first experiments,” in *Proc. IEEE GLOBECOM*, 2012, pp. 5500–5505.
[104] A. Vesco, E. Masala, and R. Scopigno, “Efficient support for video communications in wireless home networks,” in *Proc. IEEE ICNC*, 2013, pp. 599–604.
[105] A. Vesco, R. Scopigno, and E. Masala, “Supporting triple-play communications with TD-uCSMA and first experiments,” in *Proc. IEEE WCNC*, 2014, pp. 3260–3265.
[106] IEEE 802.11-14/1172r2, “Multicast performance in OBSS,” 2014.
[107] IEEE 802.11-13/1061r0, “Multicast transmission for HEW,” 2013.

[108] Y. Bejerano, J. Ferragut, K. Guo, V. Gupta, C. Gutterman, T. Nandagopal, and G. Zussman, “Scalable WiFi multicast services for very large groups,” in *Proc. IEEE ICNP*, 2013, pp. 1–12.
[109] Y. Bejerano, J. Ferragut, K. Guo, V. Gupta, C. Gutterman, T. Nandagopal, G. Zussman, “Experimental evaluation of a scalable WiFi multicast scheme in the ORBIT testbed,” in *Proc. IEEE GENI*, 2014, pp. 36–42.
[110] M. Choi, W. Sun, J. Koo, S. Choi, and K. Shin, “Reliable video multicast over Wi-Fi networks with coordinated multiple APs,” in *Proc. IEEE INFOCOM*, 2014, pp. 424–432.
[111] D. Bhaumick and S. Ghosh, “Efficient multicast association to improve the throughput in IEEE 802.11 WLAN,” in *Proc. QShine*, 2014, pp. 83–89.
[112] IEEE 802.11-13/0849r1, “New technique - enabling real world improvement by exposing internal MAC state,” 2013.
[113] IEEE 802.11-13/1349r0, “Access control enhancement,” 2013.
[114] IEEE 802.11-13/1073r1, “Access control enhancement,” 2013.
[115] IEEE 802.11-14/1106r1, “WLAN frame collision information,” 2014.
[116] IEEE 802.11-13/1077r1, “EDCA enhancements for HEW,” 2013.
[117] IEEE 802.11-15/0362r0, “Beacon transmission issues,” 2015.
[118] IEEE 802.11-14/1186r2, “Comparisons of simultaneous downlink transmissions,” 2014.
[119] IEEE 802.11-14/1436r0, “Overhead analysis for simultaneous downlink transmissions,” 2014.
[120] B. Li, Q. Qu, Z. Yan, and M. Yang, “Survey on OFDMA based MAC protocols for the next generation WLAN,” in *Proc. IEEE WCNC Workshops*, 2015, pp. 131–135.
[121] IEEE 802.11-15/0376r2, “UL-MU MAC throughput under non-full buffer traffic,” 2015.
[122] IEEE 802.11-15/0091r1, “UL-OFDMA procedure in IEEE 802.11ax,” 2015.
[123] IEEE 802.11-15/0366r1, “Multi-STA acknowledgment,” 2015.
[124] S. Barghi, H. Jafarkhani, and H. Yousefi’zadeh, “MIMO-assisted MPR-aware MAC design for asynchronous WLANs,” *IEEE/ACM Trans. Networking*, vol. 19, no. 6, pp. 1652–1665, Dec. 2011.
[125] D. Jung, R. Kim, and H. Lim, “Asynchronous medium access protocol for multi-user MIMO based uplink WLANs,” *IEEE Trans. Communications*, vol. 60, no. 12, pp. 3745–3754, 2012.
[126] K. Tan, H. Liu, J. Fang, W. Wang, J. Zhang, M. Chen, and G. M. Voelker, “SAM: Enabling practical spatial multiple access in wireless LAN,” in *Proc. ACM MobiCom*, 2009, pp. 49–60.
[127] T.-H. Lin and H. Kung, “Concurrent channel access and estimation for scalable multiuser MIMO networking,” in *Proc. IEEE INFOCOM*, 2013, pp. 140–144.
[128] H. Li, K. Wu, Q. Zhang, and L. Ni, “CUTS: Improving channel utilization in both time and spatial domain in WLANs,” *IEEE Trans. Parallel and Distributed Systems*, vol. 25, no. 6, pp. 1413–1423, 2014.
[129] N. Singh, D. Gunawardena, A. Proutiere, B. Radunovic, H. Balan, and P. Key, “Efficient and fair MAC for wireless networks with self-interference cancellation,” in *Proc. IEEE WiOpt*, 2011, pp. 94–101.
[130] S. Oashi and M. Bandai, “Performance of medium access control protocols for full-duplex wireless LANs,” in *Proc. IEICE APSITT*, 2012, pp. 1–4.
[131] Y. Liao, K. Bian, L. Song, and Z. Han, “Full-duplex MAC protocol design and analysis,” *IEEE Communications Letter*, vol. 19, no. 7, pp. 1185–1188, 2015.
[132] IEEE 802.11-14/0339-00hew, “A simplified simultaneous transmit and receive mechanism,” 2014.
[133] J. Y. Kim, O. Mashayekhi, H. Qu, M. Kazadiieva, and P. Levis, “Janus: A novel mac protocol for full duplex radio,” *CSTR*, vol. 2, no. 7, p. 23, 2013.
[134] L. Dai and X. Sun, “A unified analysis of IEEE 802.11 DCF networks: Stability, throughput, and delay,” *IEEE Trans. Mobile Computing*, vol. 12, no. 8, pp. 1558–1572, 2013.
[135] J.-W. Cho and Y. Jiang, “Fundamentals of the backoff process in 802.11: Dichotomy of the aggregation,” *IEEE Trans. Information Theory*, vol. 61, no. 4, pp. 1687–1701, 2015.
[136] C. E. Koksal, H. Kassab, and H. Balakrishnan, “An analysis of short-term fairness in wireless media access protocols,” in *Proc. ACM SIGMETRICS*, 2000, pp. 118–119.
[137] H. Jiang, P. Wang, and W. Zhuang, “A distributed channel access scheme with guaranteed priority and enhanced fairness,” *IEEE Trans. Wireless Communications*, vol. 6, no. 6, pp. 2114–2125, 2007.
[138] “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 5: Enhancements for higher throughput,” pp. 1–565, 2009.
[139] “IEEE standard for information technology–telecommunications and information exchange between systems–local and metropolitan area networks–specific requirements-part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications amendment 3: Enhancements for very high throughput in the 60 ghz band,” pp. 1–628, 2012.
[140] H. A. Omar, W. Zhuang, and L. Li, “VeMAC: A TDMA-based MAC protocol for reliable broadcast in VANETs,” *IEEE Trans. Mobile Computing*, vol. 12, no. 9, pp. 1724–1736, 2013.
[141] B. Bulut, D. Berkovskyy, D. Kong, A. Doufexi, and A. Nix, “A raptor enabled data carousel for enhanced file delivery and QoS in 802.11 multicast networks,” in *Proc. IEEE WCNC*, 2015, pp. 2032–2037.
[142] C. Chousidis, R. Nilavalan, and L. Lipan, “Expanding the use of CTS-to-self mechanism for reliable broadcasting on IEEE 802.11 networks,” in *Proc. IEEE IWCMC*, 2014, pp. 1051–1056.
[143] H. A. Omar, W. Zhuang, A. Abdrabou, and L. Li, “Performance evaluation of VeMAC supporting safety applications in vehicular networks,” *IEEE Trans. Emerging Topics in Computing*, vol. 1, no. 1, pp. 69–83, 2013.
[144] Orbit: Open-access research testbed for next-generation wireless networks. http://www.orbit-lab.org/.
[145] R. Liao, B. Bellalta, M. Oliver, and Z. Niu, “MU-MIMO MAC protocols for wireless local area networks: A survey,” *IEEE Communications Surveys and Tutorials*, 2014, In press.
[146] IEEE 802.11-14/0598r0, “Uplink multi-user MAC protocol for 11ax,” 2014.
[147] IEEE 802.11-15/0365r0, “UL MU procedure,” 2015.
[148] IEEE 802.11-15/0362r0, “Consideration on UL-MU overheads,” 2015.
[149] IEEE 802.11-15/0336r1, “MAC overhead analysis of MU transmissions,” 2015.
[150] Wireless open-access research platform (WARP).
[151] IEEE 802.11-13/1421r1, “STR radios and STR media access,” 2013.
[152] IEEE 802.11-14/1207, “OBSS reuse mechanism which preserves fairness,” 2014.
[153] I. Jamil, L. Cariou, and J.-F. Helard, “Improving the capacity of future IEEE 802.11 high efficiency WLANs,” in *Proc. of IEEE ICT*, 2014, pp. 303–307.
[154] A. E. Xhafa, A. Batra, and A. Zaks, “On the coexistence of overlapping BSSs in WLANs,” in *Proc. IEEE VTC*, 2007, pp. 189–193.
[155] I. 802.11-14/0889, “Performance gains from CCA optimization,” 2014.
[156] IEEE 802.11-14/0846, “CCA study in residential scenario,” 2014.
[157] T. Nakahira, K. Ishihara, Y. Asai, Y. Takatori, R. Kudo, and M. Mizoguchi, “Centralized control of carrier sense threshold and channel bandwidth in high-density WLANs,” in *Proc. IEEE APMC*, 2014, pp. 570–572.
[158] K. Murakami, T. Ito, and S. Ishihara, “Improving the spatial reuse of IEEE 802.11 WLAN by adaptive carrier sense threshold of access points based on node positions,” in *Proc. IEEE ICMU*, 2015, pp. 132–137.
[159] IEEE 802.11-13/1012, “Dynamic sensitivity control,” 2014.
[160] Y. Hua, Q. Zhang, and Z. Niu, “Distributed physical carrier sensing adaptation scheme in cooperative MAP WLAN,” in *Proc. IEEE GLOBECOM*, 2009, pp. 1–6.
[161] IEEE 802.11-14/0872, “A protocol framework for dynamic CCA,” 2014.
[162] Y. Wu, Y. Sun, Y. Ji, J. Mao, and Y. Liu, “A joint channel allocation and power control scheme for interference mitigation in high-density WLANs,” in *Proc. IEEE ICCT*, 2013, pp. 98–103.
[163] K.-P. Shih, C.-M. Chou, M.-Y. Lu, and S.-M. Chen, “A distributed spatial reuse (DSR) MAC protocol for IEEE 802.11 ad-hoc wireless LANs,” in *Proc. IEEE ISCC*, 2005, pp. 658–663.
[164] Z. Zhou, Y. Zhu, Z. Niu, and J. Zhu, “Joint tuning of physical carrier sensing, power and rate in high-density WLAN,” in *Proc. of IEEE APCC*, 2007, pp. 131–134.
[165] IEEE, “Specification 802.11-2003,” 2003.
[166] IEEE 802.11-14/0847, “Further considerations on enhanced CCA for 11ax,” 2014.
[167] IEEE 802.11-14/1148, “Consideration of asynchronous interference in OBSS environment,” 2014.

[168] IEEE 802.11-14/1403, "Performance analysis of BSS color and DSC," 2014.
[169] F. Khan, *LTE for 4G mobile broadband: air interface technologies and performance*. Cambridge University Press, 2009.
[170] M. Rahman and H. Yanikomeroglu, "Enhancing cell-edge performance: a downlink dynamic interference avoidance scheme with inter-cell coordination," *IEEE Trans. Wireless Communications*, vol. 9, no. 4, pp. 1414–1425, 2010.
[171] M. Porjazoski and B. Popovski, "Analysis of intercell interference coordination by fractional frequency reuse in LTE," in *Proc. IEEE SoftCOM*, 2010, pp. 160–164.
[172] R. Ghaffar and R. Knopp, "Fractional frequency reuse and interference suppression for OFDMA networks," in *Proc. IEEE WiOpt*, 2010, pp. 273–277.
[173] Huawei, "Soft frequency reuse scheme for UTRAN LTE," 2005. [Online]. Available: ftp://ftp.3gpp.org/tsg_ran/WG1_RL1/TSGR1_41/Docs/R1-050507.zip
[174] K. T. Kim and S. K. Oh, "An incremental frequency reuse scheme for an OFDMA cellular system and its performance," in *Proc. IEEE VTC*, 2008, pp. 1504–1508.
[175] Z. Xie and B. Walke, "Resource allocation and reuse for inter-cell interference mitigation in OFDMA based communication networks," in *Proc. IEEE WICON*, 2010, pp. 1–6.
[176] A. Gjendemsjø, D. Gesbert, G. E. Øien, and S. G. Kiani, "Optimal power allocation and scheduling for two-cell capacity maximization," in *Proc. IEEE WiOpt*, 2006, pp. 1–6.
[177] T. Bonald, S. Borst, and A. Proutiere, "Inter-cell scheduling in wireless data networks," in *Proc. European Wireless*, 2005, pp. 1–7.
[178] M. Rahman and H. Yanikomeroglu, "Multicell downlink OFDM sub-channel allocations using dynamic intercell coordination," in *Proc. IEEE GLOBECOM*, 2007, pp. 5220–5225.
[179] G. Li and H. Liu, "Downlink radio resource allocation for multi-cell OFDMA system," *IEEE Trans. Wireless Communications*, vol. 5, no. 12, pp. 3451–3459, 2006.
[180] A. Triki and L. Nuaymi, "Intercell interference coordination algorithms in OFDMA wireless systems," in *Proc. IEEE VTC-Spring*, 2011, pp. 1–6.
[181] D. Kimura, Y. Harada, and H. Seki, "De-centralized dynamic ICIC using X2 interfaces for downlink LTE systems," in *Proc. IEEE VTC-Spring*, 2011, pp. 1–5.
[182] A. L. Stolyar and H. Viswanathan, "Self-organizing dynamic fractional frequency reuse in OFDMA systems," in *Proc. IEEE INFOCOM*, 2008.
[183] S. Ko, H. Seo, H. Kwon, and B. G. Lee, "Distributed power allocation for efficient inter-cell interference management in multi-cell ofdma systems," in *Proc. IEEE APCC*, 2010, pp. 243–248.
[184] IEEE, "Especificacion 802.11-2007," 2007.
[185] H. Huang, P. Li, S. Guo, and W. Zhuang, "Software-defined wireless mesh networks: Architecture and traffic orchestration," *IEEE Networks*, vol. 29, no. 4, pp. 24–30, 2015.
[186] A. S. Hamza, S. S. Khalifa, H. S. Hamza, and K. Elsayed, "A survey on inter-cell interference coordination techniques in OFDMA-based cellular networks," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 4, pp. 1642–1670, 2013.
[187] R. Kwan and C. Leung, "A survey of scheduling and interference mitigation in LTE," *Journal of Electrical and Computer Engineering*, 2010.
[188] "Universal software radio peripheral (usrp)." [Online]. Available: http://home.ettus.com/
[189] A. Goldsmith, V. Chandrasekhar, R. K. Madan, and S. Krishna, "Interference management and network performance optimization in dense Wi-Fi networks," in *US patent application (US13857096)*, 2013.
[190] R. Doe, "Cisco aironet wireless LAN adapters 350 series," http://www.cisco.com/en/US/docs/wireless/wlan_adapter/350_cb20a/user/linux/configuration/guide/icglappA.html, Cisco, 2013.
[191] F. R. Dogar, P. Steenkiste, and K. Papagiannaki, "Catnap: exploiting high bandwidth wireless interfaces to save energy for mobile devices," in *Proc. ACM MobiSys*, 2010, pp. 107–122.
[192] E. Rozner, V. Navda, R. Ramjee, and S. Rayanchu, "NAPman: network-assisted power management for WiFi devices," in *Proc. ACM MobiSys*, 2010, pp. 91–106.
[193] J. Manweiler and R. Roy Choudhury, "Avoiding the rush hours: WiFi energy management via traffic isolation," *IEEE Trans. Mobile Computing*, vol. 11, no. 5, pp. 739–752, 2012.
[194] Z. Zeng, Y. Gao, and P. R. Kumar, "SOFA: A sleep-optimal fair-attention scheduler for the power-saving mode of WLANs," in *Proc. IEEE ICDCS*, 2011, pp. 87–98.
[195] M. Anand, E. B. Nightingale, and J. Flinn, "Self-tuning wireless network power management," in *Proc. ACM MobiCom*, 2003, pp. 176–189.
[196] D. Qiao and K. G. Shin, "Smart power-saving mode for IEEE 802.11 wireless LANs," in *Proc. IEEE INFOCOM*, 2005, pp. 1573–1583.
[197] V. Namboodiri and L. Gao, "Energy-efficient VoIP over wireless LANs," *IEEE Trans. Mobile Computing*, vol. 9, no. 4, pp. 566–581, 2010.
[198] R. Krashinsky and H. Balakrishnan, "Minimizing energy for wireless web access with bounded slowdown," *Wireless Networks*, vol. 11, no. 1-2, pp. 135–148, 2005.
[199] T. Pering, Y. Agarwal, R. Gupta, and R. Want, "CoolSpots: reducing the power consumption of wireless mobile devices with multiple radio interfaces," in *Proc. ACM MobiSys*, 2006, pp. 220–232.
[200] T. Jin, G. Noubir, and B. Sheng, "WiZi-Cloud: application-transparent dual ZigBee-WiFi radios for low power internet access," in *Proc. IEEE INFOCOM*, 2011, pp. 1593–1601.
[201] M. J. Miller and N. F. Vaidya, "A MAC protocol to reduce sensor network energy consumption using a wakeup radio," *IEEE Trans. Mobile Computing*, vol. 4, no. 3, pp. 228–242, 2005.
[202] E. Shih, P. Bahl, and M. J. Sinclair, "Wake on wireless: an event driven energy saving strategy for battery operated devices," in *Proc. ACM MobiCom*, 2002, pp. 160–171.
[203] J. Liu and L. Zhong, "Micro power management of active 802.11 interfaces," in *Proc. ACM MobiSys*, 2008, pp. 146–159.
[204] X. Zhang and K. G. Shin, "E-MiLi: energy-minimizing idle listening in wireless networks," in *Proc. ACM MobiCom*, 2011, pp. 205–216.
[205] H. Woesner, J.-P. Ebert, M. Schlager, and A. Wolisz, "Power-saving mechanisms in emerging standards for wireless LANs: the MAC level perspective," *IEEE Personal Communications*, vol. 5, no. 3, pp. 40–48, 1998.
[206] E.-S. Jung and N. H. Vaidya, "An energy efficient MAC protocol for wireless LANs," in *Proc. IEEE INFOCOM*, 2002, pp. 1756–1764.
[207] J. Zhang, G. Zhou, C. Huang, S. Son, and J. A. Stankovic, "TMMAC: An energy efficient multi-channel MAC protocol for ad hoc networks," in *Proc. IEEE ICC*, 2007, pp. 3554–3561.
[208] K. Rahimi Malekshan and W. Zhuang, "An energy efficient MAC protocol for fully-connected wireless networks," in *Proc. IEEE ICC*, 2013, pp. 1538–1542.
[209] K. Rahimi Malekshan, W. Zhuang, and Y. Lostanlen, "An energy efficient MAC protocol for fully connected wireless ad hoc networks," *IEEE Trans. Wireless Communications*, vol. 13, no. 10, pp. 5729–5740, 2014.
[210] E.-S. Jung and N. H. Vaidya, "A power control MAC protocol for ad hoc networks," *ACM Tran. Wireless Networks*, vol. 11, no. 1-2, pp. 55–66, 2005.
[211] J. P. Monks, V. Bharghavan, and W.-M. W. Hwu, "A power controlled multiple access protocol for wireless packet networks," in *Proc. IEEE INFOCOM*, 2001, pp. 219–228.
[212] S.-L. Wu, Y.-C. Tseng, and J.-P. Sheu, "Intelligent medium access for mobile ad hoc networks with busy tones and power control," *IEEE J. Selected Areas in Communications (JSAC)*, vol. 18, no. 9, pp. 1647–1657, 2000.
[213] A. Muqattash and M. Krunz, "Power controlled dual channel (PCDC) medium access protocol for wireless ad hoc networks," in *Proc. IEEE INFOCOM*, 2003, pp. 470–480.
[214] J.-C. Cano and P. Manzoni, "Evaluating the energy-consumption reduction in a MANET by dynamically switching-off network interfaces," in *Proc. IEEE ICC*, 2001, pp. 186–191.
[215] S. Singh and C. S. Raghavendra, "PAMAS: power aware multi-access protocol with signalling for ad hoc networks," *ACM SIGCOMM Computer Communication Review*, vol. 28, no. 3, pp. 5–26, 1998.
[216] Y.-C. Tseng, C.-S. Hsu, and T.-Y. Hsieh, "Power-saving protocols for IEEE 802.11-based multi-hop ad hoc networks," in *Proc. IEEE INFOCOM*, vol. 1, 2002, pp. 200–209.
[217] K. Rahimi Malekshan, W. Zhuang, and Y. Lostanlen, "Coordination-based medium access control with space-reservation for wireless ad hoc networks," *IEEE Trans. Wireless Communications*, vol. 15, no. 2, pp. 1617–1628, 2016.
[218] T. Schenk, *RF imperfections in high-rate wireless systems: impact and digital compensation*. Springer Science & Business Media, 2008.

[219] M. Lampe, T. Giebel, H. Rohling, and W. Zirwas, "PER-prediction for PHY mode selection in OFDM communication systems," in *Proc. IEEE GLOBECOM*, 2003, pp. 25–29.
[220] K. Brueninghaus, D. Astély, T. Salzer, S. Visuri, A. Alexiou, S. Karger, and G.-A. Seraji, "Link performance models for system level simulations of broadband radio access systems," in *Proc. IEEE PIMRC*, 2005, pp. 2306–2311.
[221] IEEE 802.11-13/1059, "PHY abstraction for HEW evaluation methodology," 2013.
[222] IEEE P802.11 Wireless LANs, "11ax evaluation methodology," 2015.
[223] J. G. Andrews *et al.*, "What will 5G be?" *IEEE J. Selected Areas in Communications (JSAC)*, vol. 32, no. 6, pp. 1065–1082, 2014.
[224] IEEE 802.11-13/1137-r2, "The definition of performance metrics for HEW," 2013.
[225] IEEE 802.11-13/0805-r2, "On definition of dense networks and performance metric," 2013.
[226] IEEE 802.11-14/0107, "HEW evaluation metrics," 2014.
[227] "Guidelines for evaluation of radio interface technologies for IMT-advanced," International Telecommunication Union- Radiocommunication sector (ITU-R), Tech. Rep. ITU-R M.2135-1, 2010.
[228] IEEE 802.11-14/0578, "Residential scenario CCA-TPC simulation discussion," 2014.
[229] IEEE P802.11 Wireless LANs, "11ax simulation scenarios," 2015.
[230] IEEE 802.11-14/0381, "Stadium scenario for HEW," 2014.
[231] Y. Wang, J. Xu, and L. Jiang, "Challenges of system-level simulations and performance evaluation for 5G wireless networks," *IEEE Access*, vol. 2, pp. 1553–1561, 2014.
[232] J. Qiao, X. Shen, J. Mark, and L. Lei, "Video quality provisioning for millimeter wave 5G cellular networks with link outage," *IEEE Trans. Wireless Communications*, vol. 14, no. 10, pp. 5692–5703, 2015.
[233] Cisco, *Cisco Visual Networking Index: Forecast and Methodology, 2014-2019*. Cisco White paper, 2015.
[234] IEEE 802.11-09/308r12, "Tgac channel model addendum," 2010.
[235] IEEE 802.11-03/940r4, "Tgn channel models," 2004.
[236] IEEE 802.11-14/0882r3, "IEEE 802.11ax channel model document," 2014.
[237] IST-WINNER II, "Winner ii channel models," IST-WINNER II, Tech. Rep. Tech. Rep. 1.1.2 v.1.2, 2007.
[238] IEEE 802.11-14/0804r1, "Envisioning 11ax PHY structure - part i," 2014.
[239] S. Sadr, A. Anpalagan, and K. Raahemifar, "A novel subcarrier allocation algorithm for multiuser OFDM system with fairness: User's perspective," in *Proc. IEEE VTC*, 2007, pp. 1772–1776.
[240] B. Bai, W. Chen, Z. Cao, and K. Letaief, "Achieving high frequency diversity with subcarrier allocation in OFDMA systems," in *Proc. IEEE GLOBECOM*, Nov. 2008, pp. 1–5.
[241] A. P. Gamage and N. Rajatheva, "A simple equalization technique to minimize ICI in OFDMA-based femtocell networks," in *Proc. IEEE PIMRC*, 2011, pp. 112–116.
[242] H. Wang, R. Song, and S.-H. Leung, "Analysis of uplink intercarrier interference in OFDMA femtocell networks," *IEEE Trans. Vehicular Technology*, vol. 64, no. 3, pp. 998–1013, 2015.
[243] IEEE 802.11-14/0372, "HEW system level simulations on increased spatial reuse," 2014.
[244] IEEE 802.11-14/0637, "Spatial reuse and coexistence with legacy devices," 2014.

Hassan Aboubakr Omar received the Ph.D. (2014) degree in Electrical and Computer Engineering from the University of Waterloo, Canada, the M.Sc. (2009) degree in Engineering Mathematics and the B.Sc. degree (2005) in Electronics and Communications Engineering, both from Cairo University, Egypt. Since 2014, he has been a Postdoctoral Fellow at the University of Waterloo's Department of Electrical and Computer Engineering. From 2005 to 2008, Dr. Omar was a Research Assistant at the Science and Technology Research Center at the American University in Cairo, and he is currently an Assistant Professor at the Engineering Mathematics and Physics Department, Cairo University, Egypt. Dr. Omar is the recipient of the Best Paper Award from the IEEE Globecom 2013, and his current research interest includes vehicular communication networks, heterogeneous networks, and optimization.

Khadige Abboud received the Ph.D. and MASc degrees in Electrical and Computer Engineering, University of Waterloo, Ontario, Canada in 2009 and 2015, respectively, and the B.Sc degree in Electrical Engineering from Kuwait University, Kuwait in 2007. Her research interests include vehicle mobility modeling, node cluster stability, and cellular-DSRC interworking for vehicular communications. Dr. Abboud is the recipient of the Best Paper Award from the ACM MSWiM 2014. She is serving as a Fellowship Co-Chair for ACM N^{2}Women and has served as a TPC member in the IEEE ScalCom 2014, IEEE Globecom (2015-2016), and IEEE VTC-fall 2016 conferences. Since 2015, she has been a Postdoctoral Fellow with the Department of Electrical and Computer Engineering, University of Waterloo.

Nan Cheng (S'13) is currently a Ph.D. candidate at the department of Electrical and Computer Engineering (ECE), the University of Waterloo, Waterloo, ON, Canada. He received his B.S. degree and M.S. degree from Tongji University, China, in 2009 and 2012, respectively. Since 2012, he has been a research assistant with the Broadband Communication Research group in the ECE department, the University of Waterloo. His research interests include vehicular communication networks, cellular traffic offloading, cognitive radio networks, and device-to-device communications.

Kamal Rahimi Malekshan (S'11) received the B.Sc. degree in electrical engineering from the University of Isfahan, Isfahan, Iran, and the M.Sc. degree in electrical engineering from the University of Tehran, Tehran, Iran, in 2008 and 2011, respectively. Currently, he is pursuing the Ph.D. degree at the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. His research interests include medium access control (MAC), power management, and transmission power control (TPC) in wireless ad hoc networks.

Amila Tharaperiya Gamage (S'07-M'16) received his Ph.D. degree in Electrical and Computer Engineering from the University of Waterloo, Canada, in 2016. He received the M.E. degree in Telecommunications Engineering from Asian Institute of Technology, Thailand, in 2011, and the B.E. degree in Electronics and Telecommunications Engineering from Multimedia University, Malaysia, in 2008. From 2008 to 2009, he was a Solutions Architect with Dialog Telekom PLC, Sri Lanka. Currently he is a Software Engineer with Cisco, Canada, and involves in developing MPLS network solutions and IoT products. His research interests are in the areas of wireless communications, networking, IoT, cloud computing, and big data. He is a corecipient of the Best Paper Awards from the IEEE International Conference on Communications (ICC) 2014.

Weihua Zhuang (M'93-SM'01-F'08) has been with the Department of Electrical and Computer Engineering, University of Waterloo, Canada, since 1993, where she is a Professor and a Tier I Canada Research Chair in Wireless Communication Networks. Her current research focuses on resource allocation and QoS provisioning in wireless networks, and on smart grid. She is a co-recipient of several best paper awards from IEEE conferences. Dr. Zhuang was the Editor-in-Chief of IEEE Transactions on Vehicular Technology (2007-2013), and the TPC Co-Chair of IEEE VTC Fall 2016. She is a Fellow of the IEEE, a Fellow of the Canadian Academy of Engineering, a Fellow of the Engineering Institute of Canada, and an elected member in the Board of Governors and VP Publications of the IEEE Vehicular Technology Society.