

MU-MIMO MAC Protocols for Wireless Local Area Networks: A Survey

Ruizhi Liao, Boris Bellalta, Miquel Oliver, and Zhisheng Niu

Abstract

As smart devices boom and bandwidth-hungry applications (e.g., high-definition videos, telepresence and cloud storage services) get popular, today's Wireless Local Area Networks (WLANs) become not only crowded but also low at throughput. The employment of the Multiple-Input and Multiple-Output (MIMO) technique, especially the multi-user mode (MU-MIMO), has huge potentials to substantially increase the throughput, as well as to mitigate high collision rates in dense WLANs. However, before we can benefit from this physical layer's advance, Medium Access Control (MAC) protocols, that define how stations share the wireless channel, have to be modified to support the use of multiple antennas and simultaneous transmissions in WLANs.

This paper first reviews the evolution and the fundamental medium access scheme of IEEE 802.11 standards/amendments, and then identifies the key requirements for designing MU-MIMO MAC protocols in WLANs. After that, the most representative MU-MIMO MAC proposals in the literature are surveyed by benchmarking their MAC procedures, channel state information (CSI) acquisition, de/pre-coding schemes, scheduling schemes, key assumptions, evaluation methods and achieved performance gains. Classifications and underlying features of the surveyed MAC protocols are presented, based on which, the future research challenges for designing effective MU-MIMO MAC protocols are discussed and highlighted.

Index Terms

MAC, MU-MIMO, IEEE 802.11, WLANs.

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I. INTRODUCTION

IEEE 802.11 is a set of Physical Layer (PHY) and Medium Access Control (MAC) specifications for the prevalent Wireless Local Area Networks (WLANs). Current IEEE 802.11 WLANs contribute to approximate 40% of overall Internet Protocol (IP) traffic [1]. As wireless devices rapidly increase, and the wireless transmission evolves towards gigabits per second, IEEE 802.11 WLANs are set to dominate the way of Internet access at homes and working places in the future.

MAC protocols, used among multiple stations (STAs) to share a common wireless channel, have been studied from the pioneer ALOHA network in the 1970s [2] to the recent Multi-user Multiple-Input and Multiple-Output (MU-MIMO) communication system. There are two main MAC categories: (1) the fixed-assignment one, where the channel frequencies, the access time or the mutually orthogonal codes are predefined for each STA, e.g., FDMA, TDMA and CDMA, namely, Frequency Division, Time Division and Code Division Multiple Access; and (2) the random access one, where each STA independently determines when to compete for the channel, e.g., CSMA/CA, namely, Carrier Sense Multiple Access with Collision Avoidance. Due to nomadic STAs (i.e., STAs join or leave WLANs at any time), asymmetrical up/down-link traffic, and the implementation simplicity, the random access based CSMA/CA has dominated the MAC mechanism of WLANs.

MU-MIMO, introduced by IEEE 802.11ac [3], is one of the most crucial techniques that lead WLANs towards the gigabit era. Compared to Single-user MIMO (SU-MIMO), which focuses on transmitting to a single destination, MU-MIMO holds the following three advantages: (1) The increased throughput. By employing SU-MIMO, the theoretical capacity gain can be manifested by a multiplicative factor of $\min\{N_t, N_r\}$, where N_t and N_r are the number of transmitting and receiving antennas [4] [5]; while in the case of MU-MIMO, the multiplicative factor can be further extended to $\min\{aN_t, bN_r\}$, where a and b are the number of simultaneous transmitters and receivers; (2) The increased diversity gain. The spatially distributed STAs make the MU-MIMO system more immune to the channel rank loss and the antenna correlation, which may severely affect the SU-MIMO system performance [6]; (3) The reduced terminal cost. The MU-MIMO system supports multiple spatially separated STAs (even only equipped with a single antenna) to simultaneously communicate with the Access Point (AP), which makes the development of compact and low-cost user terminals possible.

Considerable research efforts have been made to approach the MIMO capacity at the PHY layer [7] [8], and a comprehensive overview can be found in [9]. Following the PHY advances, corresponding MAC

enhancements, especially the MU-MIMO based ones, have sprung up. Since the traditional IEEE 802.11 MAC mechanism only supports one single transmission at a time, which underutilizes the full potential of the spatial domain of MU-MIMO transmissions, thus, MU-MIMO MAC protocols have adapted the structure of frames, as well as their operation procedures to get control of parallel transmissions among STAs. The central point of the paper is to study random access based MAC mechanisms for MU-MIMO enabled WLANs.

The main contributions of the paper are twofold: (1) It reports the IEEE standard bodies' MAC progress, as well as surveys and classifies MU-MIMO MAC proposals for WLANs in the literature; (2) It discusses and identifies key requirements and research challenges that lie in designing effective MU-MIMO MAC protocols for WLANs. The rest of the paper is organized as follows. First, Section II briefly overviews the evolution of IEEE 802.11 standards/amendments and their fundamental MAC mechanisms to clarify the MAC development promoted by the IEEE standard body. Next, Section III identifies the key requirements for designing MU-MIMO MAC protocols in WLANs. Then, Section IV surveys and classifies the most prominent MU-MIMO MAC protocols in the literature. Afterwards, Section V discusses the research challenges and future directions. Finally, Section VI concludes the paper.

II. THE EVOLUTION OF IEEE 802.11 AND MAC SCHEMES

This section presents an evolutionary overview of IEEE 802.11 standards/amendments, and also introduces how the IEEE 802.11 specified MAC schemes work. This overview does not go through all aspects of IEEE 802.11 standards/amendments, but focuses on the background information that is closely related to the topic of the paper-medium access control.

A. IEEE 802.11 Standards/Amendments

1) *Standards*: Loosely speaking, both standards and amendments can be interchangeably used to refer to different variants of IEEE standards or amendments. However, a more strict nomenclature designates standards as documents with mandatory requirements (denoted as IEEE 802.11 followed by the published year, e.g., IEEE 802.11-2012), and amendments as documents that add to, remove from, or alter material in a portion of existing standards [10] (denoted as IEEE 802.11 followed by a non-capitalized letter or letters, e.g., IEEE 802.11n or 802.11ac).

Since 1997, IEEE has released four standards: 802.11-1997, 802.11-1999, 802.11-2007 and 802.11-2012. IEEE 802.11-2012 [11] is the latest and the only version that is currently in publication. Standards are continuously updated by amendments, e.g., 802.11-2012 is created by integrating ten amendments such as 802.11n and 802.11p with the base standard 802.11-2007, which was replaced since the release of 802.11-2012. In other words, each standard will be superseded by its successor in its entirety.

TABLE I
FEATURES OF RELATED IEEE 802.11 STANDARDS/AMENDMENTS

Version	Description	Incorporated Baselines	Frequency	Max. Data Rate	Modulation
802.11-1997	WLAN MAC and PHY Specifications	–	20 (MHz) @ 2.4 (GHz)	2 (Mbps)	DSSS, FHSS
802.11-1999	Part II WLAN MAC and PHY Specifications	–	20 @ 2.4	2	DSSS, FHSS
a	Higher Speed PHY Extension	802.11-1999	20 @ 5	54	OFDM
b	Higher Speed PHY Extension	802.11-1999, a, c	20 @ 2.4	11	DSSS
g	Further Higher Data Rate Extension	802.11-1999, a-d	20 @ 2.4	54	OFDM, DSSS
802.11-2007	Standard Maintenance Revision	802.11-1999, a-e, g-j	–	–	–
n	High Throughput	802.11-2007, k, r, y, w	20, 40 @ 2.4, 5	150 x 4	OFDM
802.11-2012	Accumulated Maintenance Changes	802.11-2007, k, n, p-s, u-w, y, z	–	–	–
ac	Very High Throughput	802.11-2012, aa, ad, ae	20, 40, 80, 160 @ 5	866.7 x 8	OFDM

2) *Amendments*: In 1999, two amendments were first introduced: (1) IEEE 802.11a operates in the 5 GHz band using the Orthogonal Frequency Division Multiplexing (OFDM) modulation with a maximum data rate of 54 Mbps; (2) IEEE 802.11b operates in the 2.4 GHz band using the Direct Sequence Spread Spectrum (DSSS) modulation with a maximum data rate of 11 Mbps. Compared to 802.11-1997, 802.11b substantially increases the data rate (from 2 Mbps to 11 Mbps) using the same modulation technique and the frequency band, which made 802.11b the then-definitive WLAN technology. In 2003, IEEE 802.11g, a new amendment working in the 2.4 GHz band was ratified. It extends 802.11b with a maximum data rate of 54 Mbps. IEEE 802.11n [12], ratified in 2009, operates in either 2.4 GHz or 5 GHz band. By utilizing MIMO, 802.11n significantly boosts the data rate to 150 Mbps (600 Mbps by 4 streams). Although each amendment is revoked as it is merged into the latest standard, the sign of IEEE 802.11a/b/g/n/ac is often employed by the industry to denote the capability and compatibility of products.

3) *Next Amendment-802.11ac*: The upcoming IEEE amendment 802.11ac [3] will be operating exclusively in the 5 GHz band. Driven by the need for higher speeds, 802.11ac aims to provide an aggregated multi-station throughput of at least 1 gigabit per second, namely, Very High Throughput (VHT) WLANs. Compared to 802.11n, this significant improvement is achieved by introducing novel PHY and MAC features, such as wider bandwidths (80 and 160 MHz), a denser modulation scheme (256-QAM: Quadrature Amplitude Modulation), a compulsory frame format (A-MPDU: Aggregated MAC Protocol Data Unit), and most importantly, downlink MU-MIMO transmissions (supporting simultaneous transmissions of up to 4 STAs with the maximum number of 8 streams).

The key features of the above mentioned IEEE 802.11 standards/amendments are given in Table I,

where FHSS stands for Frequency Hopping Spread Spectrum.

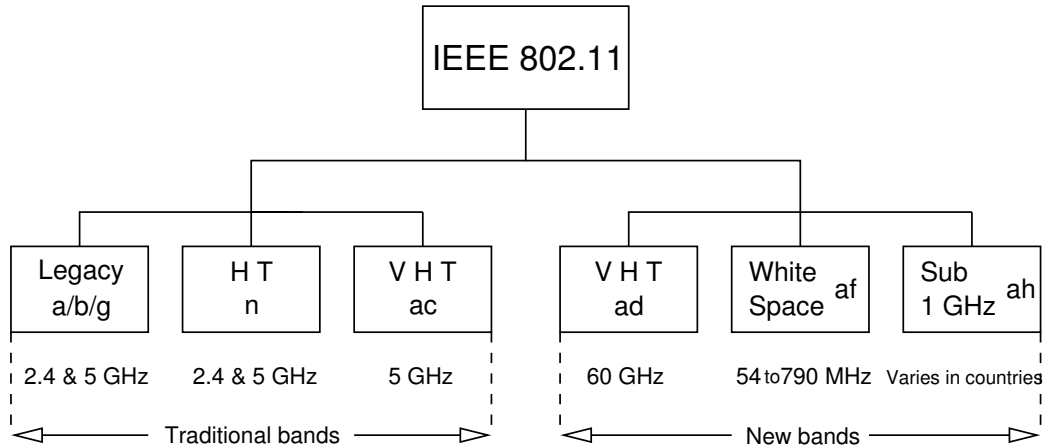


Fig. 1. IEEE 802.11 frequency bands

4) *New Frequency Bands of IEEE 802.11*: Besides the traditional frequency bands (2.4 and 5 GHz), IEEE 802.11 has extended to support other bands (Figure 1).

IEEE 802.11ad [13], another VHT WLAN amendment, will operate in the 60 GHz band and focus on multi-gigabits per second data transmissions in a short range point-to-point links (around 10 meters). A typical application scenario of 802.11ad is the wireless transmission of lightly compressed or uncompressed high-definition videos for home entertainment systems. Due to 60 GHz band's characteristics of high propagation loss and high attenuation, directional transmissions and receptions are required.

IEEE 802.11af [14] allows devices to operate in the TV white space spectrum between 54 and 790 MHz. The bands are ideal for long-range transmissions, e.g., broadband services for the rural area. A geographic database is employed by 802.11af to let devices to check and register the available channels.

IEEE 802.11ah [15] will operate in the sub-GHz band. The main purposes of the amendment are to introduce power saving and STA grouping mechanisms. A typical use case is a smart metering network with many sensor nodes, where high collision probability and hidden nodes are expected. 802.11ah will partition nodes into groups to save power and to reduce the channel contention by assigning the channel to nodes of a given group at a given time [16].

Due to the specific purpose of each amendment and unique features of the employed frequency, the MU-MIMO MAC schemes designed for WLANs of the traditional bands can not be directly applied to these new amendments. For example, 802.11ah relies on the highly centralized medium access scheme, while 802.11ad has to utilize the beam sweeping technique to detect STAs rather than the omnidirectional carrier sensing adopted by IEEE 802.11 Distributed Coordination Function (DCF). Therefore, this paper preserves its focus on MAC proposals for the traditional bands, i.e., 2.4 and 5 GHz. However, the potential collaborations at the MAC level between protocols of traditional and new bands will be discussed in

Section V-Future Directions.

B. IEEE 802.11 Medium Access Control

1) *Distributed Coordination Function*: DCF is the fundamental medium access scheme of IEEE 802.11 based WLANs. It relies on CSMA/CA to detect and share the wireless channel among STAs. DCF can either operate in the basic access scheme (Figure 2(a)) or the optional Request-to-Send/Clear-to-Send (RTS/CTS, Figure 2(b)) scheme. DCF mandates STAs to keep sensing the channel. If the channel has been idle for DCF Inter Frame Space (DIFS), each STA starts decreasing a backoff (BO) timer chosen from its Contention Window (CW) to compete for the channel. The STA with the lowest BO wins the channel contention and starts to transmit frames. Collisions occur if more than one STA happens to choose the same random BO. When a transmitted frame is successfully received, the receiver waits for a Short Inter Frame Space (SIFS) and then sends back an Acknowledgement (ACK). Note that as soon as the winning STA sends out a frame, other STAs will notice the channel has become busy, therefore immediately freeze their BO timers. These STAs will wait the channel to be idle for another DIFS, and resume decreasing the remaining BO timers. The STA who previously succeeded the channel contention will have a new BO timer at its next transmission attempt.

Examples of a successful transmission for the basic access and the RTS/CTS schemes are shown in Figure 2, where B denotes the channel is initially busy. Please refer to the IEEE standard 802.11-2012 [11] for more details about DCF.

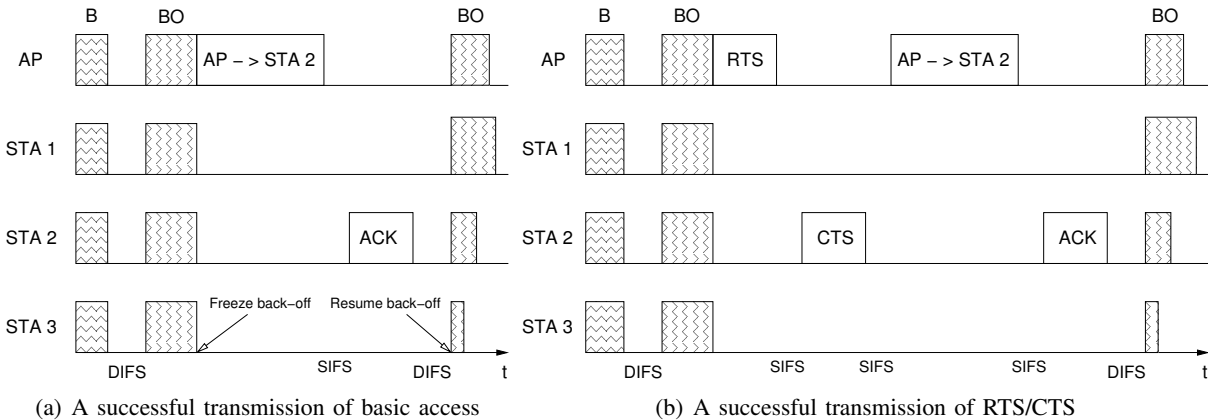


Fig. 2. DCF transmission procedures

2) *Enhanced Distribution Channel Access*: IEEE 802.11e [17] proposes an extension to DCF-Enhanced Distribution Channel Access (EDCA), as a response to the demand of Quality of Service (QoS) for voice and video applications. The main differences between DCF and EDCA are twofold. First, the former does not differentiate traffic from different applications, while the latter classifies traffic into four Access

Categories (ACs) with different priorities: Voice (AC_VO), Video (AC_VI), Best Effort (AC_BE) and Background (AC_BK). By doing so, EDCA is able to assign ACs with different parameters. For example, the maximum Transmit Opportunity (TXOP, a contention-free interval, during which a STA can transmit as many frames as possible) for AC_VO and AC_VI are 1.504 ms and 3.008 ms, respectively. Secondly, it is also different that the instant of time at which DCF and EDCA mandate STAs to decrease the BO timer. In DCF, STAs decrease the BO timer at the end of each slot, while in EDCA, the decrement occurs at the beginning of each slot. Please refer to [11] and [18] for detailed comparisons of DCF and EDCA, and [19] for QoS supports in WLANs.

Although IEEE 802.11 has specified other MAC mechanisms such as Point Coordination Function (PCF) and Hybrid Coordination Function Controlled Access (HCCA), this paper only focuses on the distributed and random access based MAC schemes, because PCF and HCCA (i.e., the centralized schemes) are neither widely adopted by the industry nor the academia.

III. REQUIREMENTS FOR DESIGNING MU-MIMO MAC PROTOCOLS IN WLANS

MU-MIMO transmissions in WLANs have two communication paths, the uplink one (i.e., STAs simultaneously transmit frames to the AP, which is also referred as the MIMO-MAC channel) and the downlink one (i.e., the AP sends data to a group of STAs in parallel, which is also referred as the MIMO-broadcast channel). The MU-MIMO uplink and downlink transmissions face different challenges, and hence, have different requirements in designing MAC protocols.

A. De/Pre-coding Schemes for Simultaneous Receptions/Transmissions

In the uplink, the AP needs to separate the simultaneously transmitted signals from STAs, which is the Multi-user Detection (MUD) problem. In the downlink, the AP has to, firstly, select a group of STAs based on a certain criterion such as the queue occupancy, given that the selected STAs have to be spatially non-correlated, which is the scheduling problem, and, secondly, precode the outgoing frames to null the interference among concurrent spatial streams, which is the Multi-user Interference Cancellation (MUIC) problem. An illustration of MU-MIMO uplink and downlink transmissions is given in Figure 3.

The design of MUD/MUIC schemes is beyond the topic of the paper. However, some of the most commonly used MUD/MUIC schemes, as well as their strong points and drawbacks, are sampled.

1) MUD Schemes for Simultaneous Uplink Receptions:

a) *Minimum Mean Square Error (MMSE)*: Received signals at each antenna of the AP are multiplied by a complex weight and then summed up. The weight is adjustable through minimizing the difference between the summation of the output signal and a reference that is known by both the AP and STAs. An example of the weight adjustment is to utilize the steepest descending algorithm. The performance of the MMSE MUD scheme improves as the number of AP's antennas increases, and degrades as the network scales up [20].

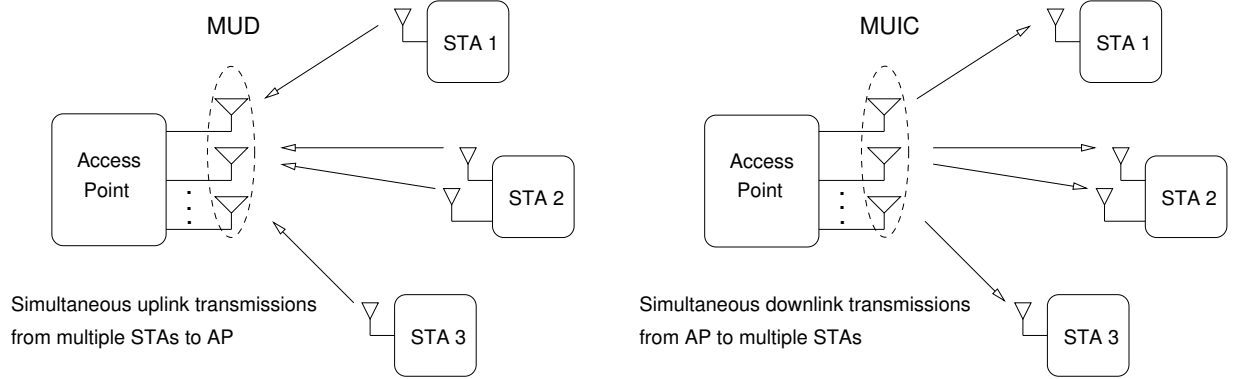


Fig. 3. Up/Down-link transmissions

b) Successive Interference Cancellation (SIC): The SIC MUD is an enhancement to MMSE. A detection algorithm is utilized by estimating of the received power at the AP. The signal with the highest power, which is the least interfered by others, is detected. This detected signal is then subtracted from mixed signals, and the next highest signal is singled out using the same process until the lowest STA signal is determined. The SIC MUD tends to be erroneous at the signal classification stage, which leads to the false deduction from composite STA signals and will affect the following calculations [21].

c) Maximum Likelihood (ML): The ML MUD conducts an exhaustive search to extract the transmitted signals. It provides the best detection performance, but comes with the highest complexity that increases exponentially with the number of STAs, which makes it infeasible in practical systems.

d) Sphere Decoding (SD): Some SD based MUD algorithms have been proposed to reduce the complexity of the pure ML MUD while to approach the performance of ML MUD. The idea is to decrease the radius of the search scope by focusing on the vicinity of the ML solution.

Other multi-user detection schemes for MU-MIMO uplink transmissions, such as Parallel Interference Cancellation (PIC), Least Squares (LS), Minimum Bit-Error Rate (MBER), QR Decomposition combined with the M-algorithm (QRD-M), Optimized Hierarchy Reduced Search Algorithm (OHRSA), Genetic Algorithm (GA) and Iterative GA (IGA), can be found in [20] [21]. The two categories of MUD algorithms are shown in Figure 4.

2) *MUIC Schemes for Simultaneous Downlink Transmissions:* Although simultaneous downlink transmissions from the AP to multiple STAs can be seen as a combination of several single-user transmissions, STAs' random and independent geolocations make it very challenging to jointly null multi-user interference at the STA side. Therefore, most proposals in the literature precode outgoing signals at the AP to minimize interference among simultaneous streams.

a) Zero Forcing (ZF): In the ZF scheme, the original signal is multiplied by the pseudo-inverse of the channel matrix to null the MUI. However, the ZF scheme also increases the error rate, because the

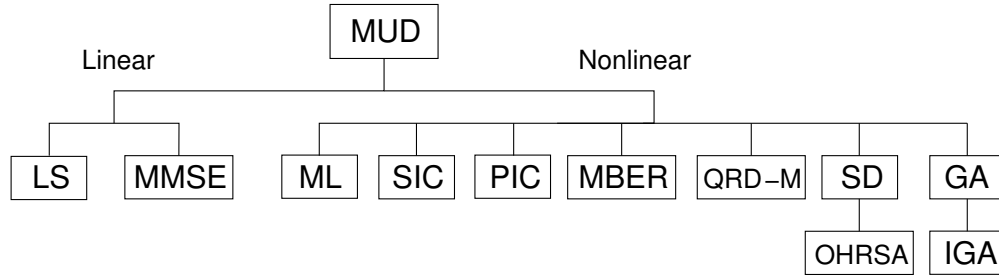


Fig. 4. MUD schemes [20]

noise vector is amplified by the pseudo-inverse weight. The amplified noise vector indicates that ZF can only perform well in the high Signal-to-Noise Ratio (SNR) region. In addition, the ZF scheme requires that the number of total receiving antennas is not less than that of transmitting antennas [22].

In comparison, the MMSE scheme can minimize the overall error rate without amplifying the noise. [21] and [22] show that the MMSE scheme performs better than ZF in the low SNR region, and approaches the performance of ZF in the high SNR region.

b) Dirty Paper Coding (DPC): DPC is a non-linear precoding scheme firstly introduced by Costa [23], which can achieve the optimum performance at the cost of significant computing complexity. The idea is to add an offset (the negative value of the interference that is known at the AP) to the transmitted signal, which is similar to the concept of writing letters on the dirty paper, where the dirt represents the interference.

Other precoding schemes, such as Block Diagonalization (BD), Successive optimization (SO), Vector Precoding (VP), Tomlinson-Harashima Precoding (THP) and Successive MMSE (SMMSE), can be found in [9] [21] [22]. The two categories of MUIC schemes are shown in Figure 5.

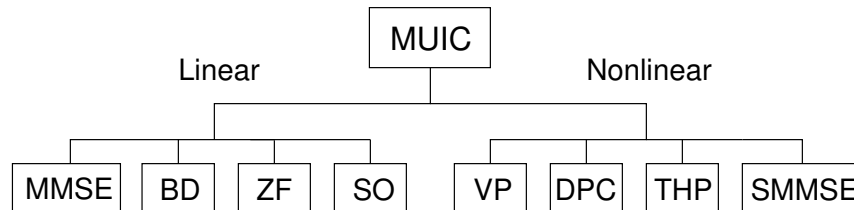


Fig. 5. MUIC schemes

3) Remarks on MU-MIMO Up/Down-links: MUD and MUIC schemes allow MU-MIMO systems to separate simultaneously received/transmitted frames, and achieve the spatial multiplexing gain. However, it is important to point out that, in the above discussion, the possession of Channel State Information (CSI) is assumed at the AP. In the literature, CSI feedback schemes are usually integrated into MAC operations. An exception to obtain the downlink multiplexing gain without needing to feedback CSI

is when STAs have more antennas than the AP, where STAs utilize the extra antennas to remove the co-stream interference.

B. Channel State Information

The CSI is required to fully obtain the multi-user transmission gain. Most proposals in the literature integrate the CSI acquisition into MAC operations. There are generally two types of CSI: the statistical CSI and the instantaneous one. The former employs the statistical characteristics of the channel (e.g., fading distribution, average channel gain and spatial correlation) to decide the CSI, which performs well in scenarios where the channel has a large mean component (i.e., a large Rician factor) or strong correlation (either in space, time, or frequency) [24].

The instantaneous CSI (or the short-term CSI) means the current channel state is known, which enables the transmitter to adapt its outgoing signal. Because wireless channel varies over time, the instantaneous CSI has to be estimated repeatedly on a short-term basis. The acquisition of CSI can be done by estimating a training sequence known by both transmitters and receivers. In the uplink, the AP can easily extract the uplink CSI from the PHY preambles of received frames. While, for transmissions in the downlink, the acquisition of the CSI is not that straightforward. Depending on who computes the CSI, there are two CSI feedback schemes: (1) the implicit feedback (Figure 6(a)), where the AP computes the CSI by estimating training sequences sent from STAs, and (2) the explicit one (Figure 6(b)), where STAs calculate the CSI by estimating the training sequence sent from the AP, and then STAs feedback the calculated CSI to the AP.

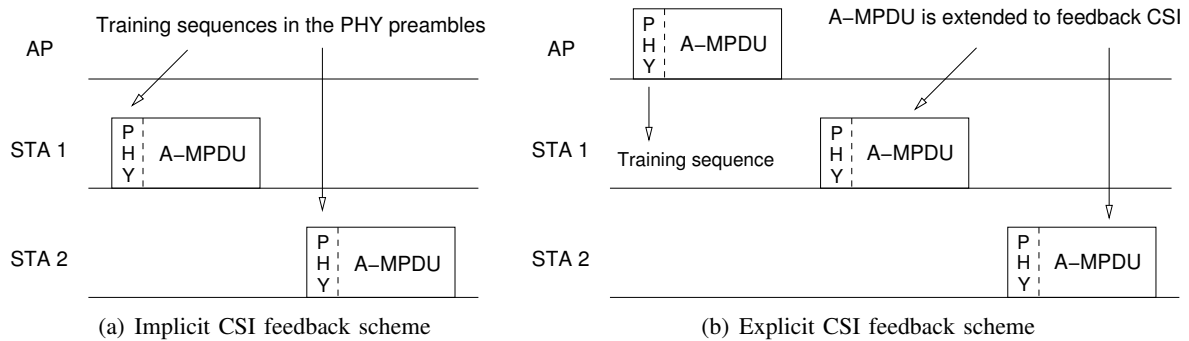


Fig. 6. CSI feedback procedures

By assuming the reciprocity of up/down-link channels, the implicit feedback scheme produces less overheads compared to the explicit one. However, in a practical WLAN system, the channel and interference seen by the STAs are generally not the same as those seen by the AP due to their different transmitting/receiving filters and PHY paths. Therefore, the antenna calibration [3] is usually needed to reduce the distortion if implicit feedback is adopted.

The explicit feedback scheme, i.e., STAs feedback the CSI, provides higher CSI resolution, but also higher overhead. MAC control frames are usually extended to support the CSI feedback in the literature, while an explicit compressed Feedback (ECFB) scheme is introduced by IEEE 802.11ac to schedule and compress the volume of CSI feedback.

No matter which CSI feedback scheme is applied, the implicit one or the explicit one, the frequency of CSI feedback would significantly affect the network performance. It is because the frequent CSI feedback increases overheads, while the infrequent one results in the outdated CSI that leads to interference among parallel streams. Please refer to [25] and [26] for more details about implicit and explicit CSI feedback schemes.

C. The Scheduling Scheme

Another key point for designing MU-MIMO MAC protocols is the scheduling scheme. It is used to select a group of STAs or frames for transmissions, which can optimize certain aspects of the system performance according to the specific grouping criteria. The design of the scheduling scheme can be divided into two parts: the scheduling in the uplink and downlink. The latter can be easily categorized by different scheduling algorithms (e.g., the STA based round-robin scheme or the frame based first in-first out scheme), while the characterization of the former is not straightforward.

1) *Scheduling in the Uplink*: In the uplink, it is very challenging to make a joint scheduling decision among spatially distributed STAs. Therefore, depending on whether the RTS/CTS exchanging process is employed (i.e., whether the AP has played a coordinating role in exchanging control frames before transmitting data), uplink transmissions can be categorized into the coordinated and the un-coordinated ones, as shown in Figure 7.

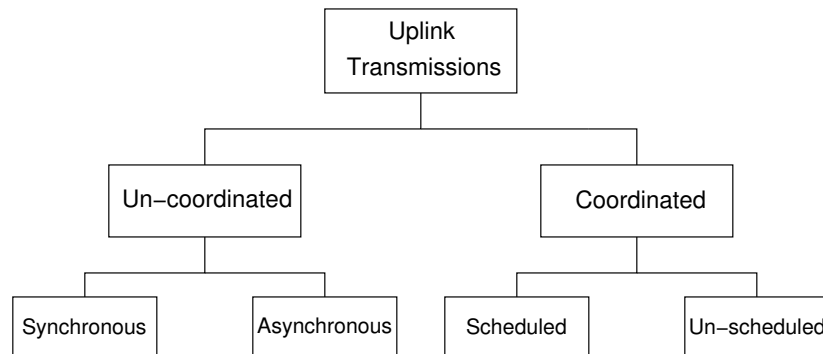


Fig. 7. Categories of uplink scheduling

In the un-coordinated scenario, STAs utilize the MAC random mechanism to decide who will be allowed for transmissions, which have two cases: synchronous [27] and asynchronous [28] data transmissions, as shown in Figure 8. The former lets multiple STAs that coincidentally choose the same BO to transmit

data frames simultaneously, while the latter allows STAs to transmit frames along with other ongoing transmissions.

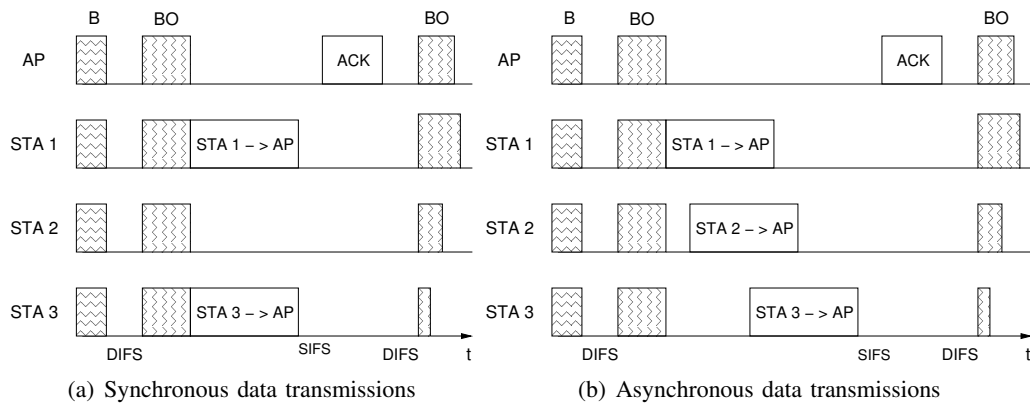


Fig. 8. Un-coordinated uplink channel access

In the coordinated scenario, STAs utilize the MAC random mechanism to contend for the channel, while let the AP to decide who will be involved in the followed parallel transmissions. The coordinated uplink access scheme implies the involvement of the AP (as a coordinator) and the employment of RTS/CTS exchanges [29]. The AP extracts the information of interest from RTSs sent by the contending STAs, and then makes scheduling decisions for simultaneous frame transmissions (i.e., the scheduled transmissions), or the AP just responds to the received RTSs to notify who have won the channel contention (i.e., the un-scheduled transmissions). A simple example of the coordinated uplink access is shown in Figure 9, which can account for both scheduled and un-scheduled cases depending on whether the CTS is extended to support scheduling.

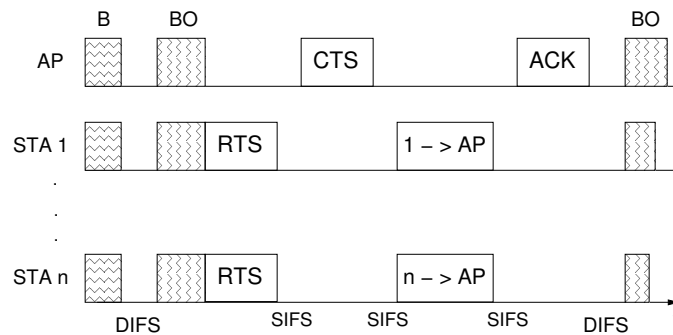


Fig. 9. Coordinated uplink channel access

Although the un-coordinated uplink channel access requires fewer modifications compared to the coordinated one, it is likely that the spatial domain will be underutilized. The reason is that the concurrent uplink access of the un-coordinated scheme is based on the randomness of the IEEE 802.11 backoff

mechanism. In comparison, the coordinated uplink channel access lets the AP to mediate the uplink transmissions by either just notifying a group of STAs that successfully won the channel contention or making a scheduling decision that aims to optimize the system performance. Obviously, the coordinated scheme will introduce overheads (e.g., extra fields of RTS/CTS) that are needed for the AP to best exploit the spatial domain.

2) *Scheduling in the Downlink*: Compared to the uplink, the AP plays a more direct role in the downlink scheduling, which can be classified into the packet based scheduling and the STA based one.

The packet based scheduling algorithms utilize the packet queueing status at the AP as the scheduling metric to assemble multiple packets for MU-MIMO downlink transmissions. The relevant packet based scheduling algorithms include First-in First-out (FIFO), priority-based, delay-based (i.e., the waiting time of packets), queue/packet length-based, etc.

The STA based scheduling employs some specific criteria to identify a set of STAs for simultaneous downlink transmissions. These criteria include the channel state, spatial compatibility, fairness, etc. The channel aware scheduling relies on the channel conditions between the AP and STAs to make a decision, while the spatial compatible one tries to minimize the interference by examining STAs' spatial correlations. Neither of them has taken the fairness into account, which is considered by the round-robin scheduling.

A combination of the above mentioned scheduling schemes is usually considered. For example, [30] and [31] explore the PHY channel condition as well as the packet queueing status; while [32] adopts a three-dimension scheduling scheme that takes the packet length, the packet waiting time and the spatial compatibility into consideration. A typical way to solve the scheduling problem is to formulate it as an optimization problem, e.g., maximizing the throughput with constraints [33] [34].

The combination of several criteria hints that parameters from different layers should be jointly considered [35], which is the concept of cross-layer scheduling as shown in Figure 10, where $q(t)$ and $H(t)$ represent the queueing and the channel states at the time t .

3) *Cross-layer Scheduling*: The cross-layer scheduling has the promise to achieve the optimal system performance by sharing and configuring parameters from different layers, such as the channel information at the PHY layer, the queueing state at the MAC layer and the routing information at the network layer. Unfortunately, the cross-layer scheduling remains far more complex than simply combining these parameters. The reason is that the interaction among the layers breaks the conventional Open System Interconnection (OSI) layered structures and creates tensions between the performance and the stability of systems, which could lead to unexpected consequences as the wireless network scales up [36].

In general, together with the CSI acquisition and other layers' key parameters, these following points should be taken into account for the cross-layer design.

- **System Complexity**: As the cross-layer design breaks the conventional layered structure, the new

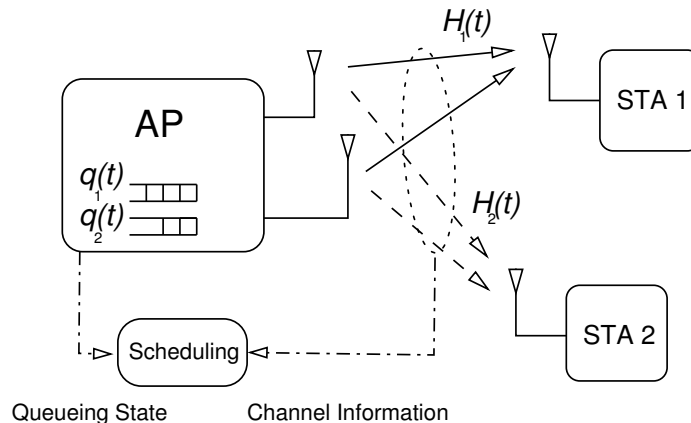


Fig. 10. Cross-layer scheduling

wireless system could be incompatible with conventional ones. Besides, since the maintenance or upgrade of the cross-layer protocol is no longer isolated within each layer, any parameter changes must be carefully traced and coordinated [36].

- **Design Constraints:** Various data rates are usually applied to spatially distributed STAs, which may cause interferences from stronger signals to weaker ones in the downlink or the near-far effect in the uplink. Therefore, a power control or a data rate selection scheme needs to be considered with the MAC design. In addition, some QoS metrics, such as the average delay and the jitter, are traditionally not in line with the MAC focus (e.g., decreasing collisions and increasing throughput). Sometimes, maximizing throughput means sacrificing transmission opportunities of some low-rate STAs. Thus, the tradeoff of different performance metrics needs to be jointly considered and given different weights [37] [38].

IV. SURVEY OF MU-MIMO MAC PROTOCOLS FOR WLANS

In this section, we look into prominent MU-MIMO MAC proposals in the literature by focusing on the required features, performance gains, evaluation tools, as well as the key assumptions they made.

A. MAC Proposals for The Uplink

1) Un-coordinated Channel Access:

a) *Synchronous Data Transmissions:* Jin et al. in [27] present a simple MU-MIMO MAC scheme that relies on the simultaneous transmissions from STAs. The MAC procedure is the same as illustrated in Figure 8(a). The authors assume each STA has an orthogonal preamble so that the AP can estimate the channel coefficients and differentiate STAs. Once the AP knows the channel, it employs the ZF scheme to separate the received signals. The authors extend the Markov chain model proposed by Bianchi in [39]

to analyze the performance of the proposed MU-MIMO scheme in saturated conditions. Compared with SU-MIMO, the numerical results show that the proposed MU-MIMO scheme obtains lower collision probability, shorter delay and higher throughput in the low SNR and small network conditions.

b) Asynchronous Data Transmissions: Babich et al. in [28] develop an analytical model of asynchronous Multi-Packet Reception (MPR), where a STA is allowed to transmit even if other STAs are already transmitting. More specifically, a STA is allowed to decrease its BO counter as long as the channel is empty or the sensed number of ongoing transmissions is below a threshold. A generic error correction code is assumed to protect data frames. The MAC procedure is shown in Figure 8(b). Based on the results obtained from the presented theoretical model and simulations, the authors claim that the asynchronous MAC scheme can provide considerable performance gains compared to the synchronous one due to higher utilization of the channel.

Mukhopadhyay et al. in [40] explore the ACK-delay problem that arises in asynchronous MPR. The ACK-delay problem refers to that, due to different transmission durations of asynchronous uplink transmissions, the delayed ACKs sent by the AP to those earlier-finished STAs can trigger STAs' ACK time-out counters, which could interrupt the ACK's transmission and degrade the network performance. Since Babich et al. in [28] did not consider the ACK-delay problem, the authors in [40] propose to change the ACK-waiting STAs' backoff timer to be decreased only when the channel has been idle for DIFS. The simultaneous transmissions are assumed to be decodable by the AP, and a single data rate is also assumed. Comparing to Babich's and IEEE 802.11 standard schemes, the results show that the proposed one not only decreases the frame collision probability and the average delay, but also increases the throughput.

Wu et al. in [41] propose a throughput analytical model for asynchronous uplink transmissions. A beacon sent by the AP will announce the maximum number of STAs that are allowed to transmit in parallel. Each STA maintains a transmission counter by detecting other STAs' frame preambles, and decides whether to contend for the channel. A fixed data rate is assumed and the network is saturated. By properly configuring the contention window size and other network parameters, the authors obtain the maximized uplink throughput. With those given parameters, the authors derive a threshold of the number of antennas at the AP, which shows no throughput benefit can be achieved by adding more antennas. The reasons for that are: 1) the available transmission time decreases as the number of STAs involved in the parallel transmission increases; and 2) the collision probability increases as more antennas are employed at the AP.

Tan et al. in [42] present a practical Spatial Multiple Access (SAM) scheme for WLANs. SAM relies on a distributed MAC scheme called Carrier Counting Multiple Access (CCMA) to allow asynchronous concurrent transmissions. A channel decoding technique to separate simultaneously received frames is adopted. CCMA follows a MAC procedure similar to the one described above, in [41]. SAM is evaluated

TABLE II
UN-COORDINATED UPLINK MU-MIMO MAC PROTOCOLS

Remarks	Evaluation Tool	CSI Scheme	MUD	Key Assumption	Scheduling
Jin [27], compare SU and MU-MIMO, 2008	Analysis	Implicit feedback	Zero forcing	Orthogonal preambles	-
Babich [28], asynchronous MPR, 2010	Analysis	-	-	Code correction scheme	-
Mukhopadhyay [40], ACK-aware MPR, 2012	Simulation + Analysis	-	-	MPR frames decodable	-
Wu [41], throughput model, 2013	Simulation + Analysis	Implicit feedback	-	Fixed data rate	-
Tan [42], carrier counting, 2009	Testbed	Implicit feedback	Chain decoding	-	-
Lin [44], delay packet decoding, 2013	Simulation + Testbed	Compressive sensing	Zero forcing	Fixed frame length	-

in SORA, a Software Defined Radio (SDR) platform developed by Microsoft [43]. Evaluation results show that the proposal can increase the throughput by 70% over the default IEEE 802.11 DCF.

Lin et al. in [44] propose a MIMO concurrent uplink transmission scheme called MIMO/CON, which can support both asynchronous and synchronous data transmissions. A compressive sensing technique [45] is utilized to estimate CSI from multiple concurrently received preambles, and ZF is adopted to separate the data frames. A delayed packet decoding mechanism, namely, using partially retransmitted information to decode the collided frames, is devised to avoid the complete retransmission of all corrupted frames. A fixed frame length is assumed, and the optimal transmission probability is assumed to be known by STAs. Tan's CCMA [42] is implemented to compare with MIMO/CON. The results show that CCMA outperforms MIMO/CON when the AP has fewer antennas, while MIMO/CON scales better as the number of antennas at the AP increases.

Table II summarizes the main characteristics of the surveyed un-coordinated uplink MU-MIMO MAC protocols.

2) Coordinated Channel Access:

a) *Scheduled Data Transmissions:* Huang et al. in [46] present an MPR MAC protocol that utilizes Code Division Multiple Access (CDMA) to separate the compound frames. When the STA's backoff counter reaches zero, a function that considers the number of STAs in the network, the current channel state and the MPR capability of the AP is used to schedule STAs. The MAC procedure is illustrated in Figure 9. The CSI is claimed to be obtained from the downlink transmission. Data frames are assumed to have the same length. Results obtained from the analytic model and simulations show that the proposed scheme reduces collisions and avoids considerable transmission errors.

Tandai et al. in [47] propose a synchronized access scheme coordinated by the AP. On receiving applying-RTSs (A-RTSs) from STAs, the AP responds with a pilot-requesting CTS (pR-CTS) to expect pilots. Based on the CSI estimated from the sequential pilots, the AP sends a Notifying-CTS (N-CTS) to inform the selected STAs for parallel transmissions. A unique subcarrier is assumed to be allocated to each STA to differentiate A-RTSs, and the MMSE decoder is adopted to separate the simultaneously received signals. According to the simulation results, the proposed scheme can reduce the overhead and increase the throughput.

b) Un-scheduled Data Transmissions: Zheng et al. in [29] propose a MU-MIMO MAC protocol called MPR-MAC, which extends CTS and ACK to accommodate multiple transmitters. The MPR-MAC procedure is the same as illustrated in Figure 9, where the STAs that won the channel contention will transmit RTSs at the same time. The AP then replies with an extended CTS that grants concurrent transmissions to the requesting STAs. A set of orthogonal training sequences are assigned to STAs by the AP to facilitate the channel estimation. A Finite Alphabet (FA) based blind detection scheme is adopted for the frame separation. The network is assumed to be saturated, and all data frames have the same length. Based on the numerical results obtained from the analytic model, the authors claim that the throughput increases nearly linearly with the number of antennas at the AP.

Since the MPR-MAC follows the conventional IEEE DCF access scheme, the probability of more than one STA choosing the same random BO is low. In order to increase the number of parallel transmissions, an enhancement called Two-Round RTS Contention (TRRC, Figure 11) is also proposed in [29]. Compared to MPR-MAC, TRRC has two RTS contention rounds. Namely, instead of sending a CTS after the first RTS round, the AP waits for an extra round to recruit more RTSs. The results show that TRRC obtains a further 7% throughput increase.

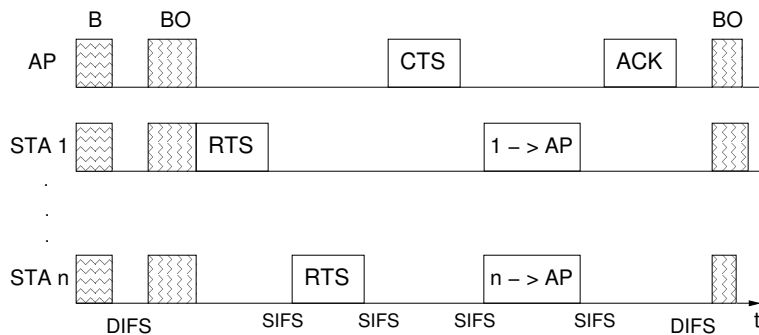


Fig. 11. TRRC

Jung et al. in [48] present an opportunistic MU-MIMO MAC protocol to coordinate simultaneous transmissions. On receiving several RTSs, the AP sends an adapted CTS to notify the group of STAs that won the channel contention, as well as to announce its still-available channel space. STAs that did

not send RTS will compete for the available channel space if their frame transmissions are shorter than the longest ongoing duration (τ_w), which is indicated in the duration field of CTS. Orthogonal preambles are assumed to be included in frames to enable the CSI estimation. The obtained results show that the proposed scheme outperforms other sampled counterparts.

Barghi et al. in [49] present an MPR-aware MAC protocol for receiving two concurrent frames by introducing a waiting time window (t_w) at the AP. Specifically, when the AP receives a first RTS, it will wait for a time period of t_w to recruit a second RTS for double-frame receptions. CTS and ACK are extended with an extra address field to accommodate two STAs. A space-time code (STC) scheme is adopted to detect multiple frames. The channel is assumed to be error-free and channel coefficients are assumed to be known. Based on the obtained results, the authors claim that, by widening t_w , (1) the probability of double-frame transmissions increases, while the probability of collision (i.e., the probability that the number of transmitted RTSs is more than two) increases as well; and (2) the performance of the proposed MPR-aware MAC scheme improves significantly compared to that of the IEEE 802.11 standard one.

Zhou et al. in [50] propose a two-round channel contention mechanism, which divides the MAC procedure into two parts. The two parts, namely, the random access and the data transmission, are illustrated in Figure 12. The random access finishes as soon as the AP receives M_{random} (the maximum number of STAs that can transmit simultaneously) successful RTSs, and then the data transmission starts. In the random access part, the AP delivers two types of CTSs: Pending CTS (PCTS) and Final CTS (FCTS). The former responds to RTS and the latter notifies all STAs about the start of data transmissions. Those STAs, who have sent RTSs within a predefined time threshold (T_{timeout}), will transmit simultaneously. If the number of contending users is less than M_{random} , the T_{timeout} will trigger data transmissions as well. The AP obtains the CSI from RTSs, and utilizes the MMSE detector to separate STAs' signals. Data frames are assumed to be of fixed length. Both simulation and analytic results show that the two-round contention scheme outperforms the IEEE 802.11 single-round one in terms of throughput and delay.

A similar work with two contention rounds is presented in [51]. Compared to [50], [51] devises a shorter second contention round, where a single message is used to reply all successfully received RTSs. In addition, a special focus is placed on 2-nd round Contention Window ($CW_{2\text{nd}}$), a parameter making the length of the second contention round elastic. By evaluating the proposal in simulations, a set of optimal $CW_{2\text{nd}}$ values that can obtain the highest system performance are identified.

Zhang in [52] further extends two contention rounds to multiple rounds, which give STAs more opportunities to compete for the channel based on a threshold derived from an optimal stopping algorithm. Meanwhile, an auto fall-back to single-round scheme is also proposed in case the traffic is low and the single-round scheme can provide higher throughput. Frame arrivals are assumed to follow the Poisson

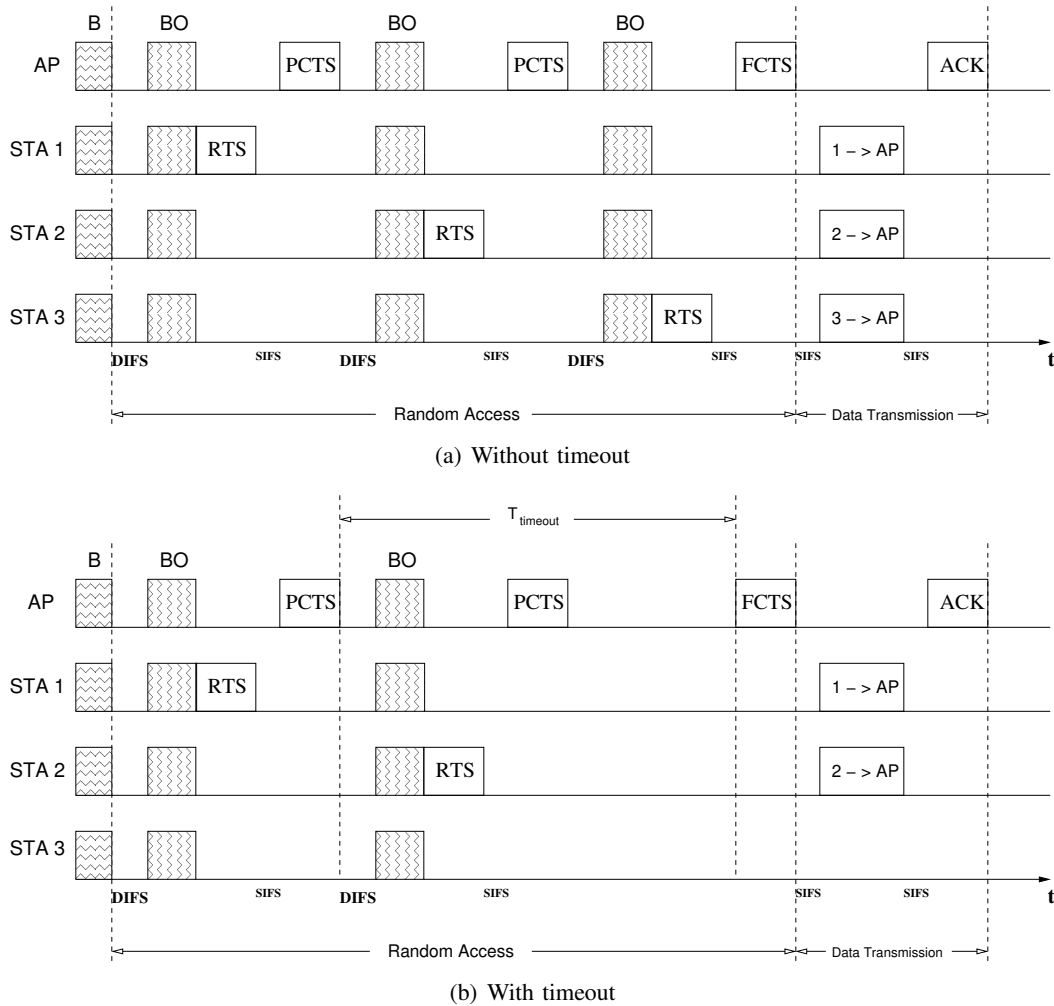


Fig. 12. Two-round MAC procedures with $M_{\text{random}} = 3$

distribution. Results obtained from simulations and the analytical model show the multi-round contention can increase the channel utilization rate in a small to moderate network.

Jung et al. in [53] present an asynchronous uplink MPR scheme, where the AP informs STAs about its MPR vacancy through an additional feedback channel. The proposed MAC procedure is shown in Figure 13. On receiving an RTS from STA2, the AP replies with a CTS that includes the MPR vacancy (the remaining space for parallel uplink transmissions). STAs who overhear the MPR vacancy will compete for the channel to transmit along with STA2. Once a STA finishes transmitting ahead of the other one, the AP immediately sends an ACK with the updated MPR vacancy information through the additional channel to allow other STAs to compete for the newly available MPR space. The authors assume an orthogonal training sequence is included in the preamble of each frame for estimating the channel. Based on results

obtained from the analytic model and simulations, the authors claim that the proposed scheme coordinated by the AP achieves higher channel efficiency in scenarios where the frame size and transmission rates are dynamically varying.

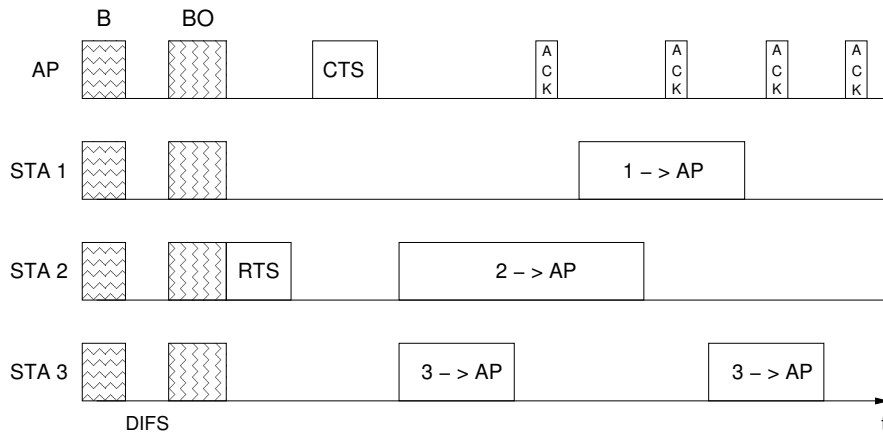


Fig. 13. Asynchronous data transmissions with 1 MPR vacancy

Table III summarizes the main characteristics of the surveyed coordinated uplink MU-MIMO MAC protocols.

B. MAC Proposals for The Downlink

A commonly used MAC procedure for MU-MIMO downlink transmissions is illustrated in Figure 14. The AP firstly sends out a modified RTS containing a group of targeted STAs. On receiving the RTS, those listed STAs estimate the channel, integrate the CSI into the extended CTS and send it back. As soon as the AP receives all successful CTSs, it precodes the outgoing frames based on the feedback CSI.

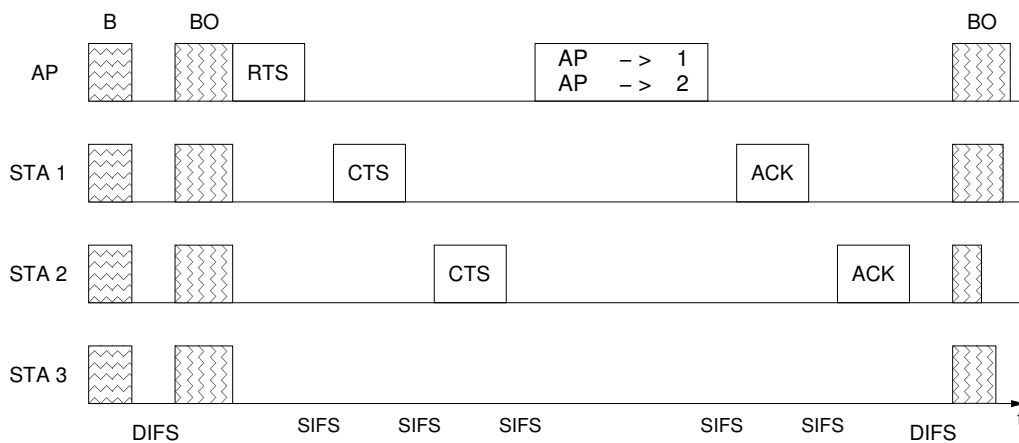


Fig. 14. Downlink MU-MIMO transmissions

TABLE III
COORDINATED UPLINK MU-MIMO MAC PROTOCOLS

Remarks	Evaluation Tool	CSI Scheme	MUD	Key Assumption	Scheduling
Huang [46], SNR based MPR, 2008	Simulation + Analysis	Downlink estimation	CDMA	Fixed data length	Optimal SNR
Tandai [47], TDMA signalling, 2009	Simulation	Implicit feedback	MMSE	Unique subcarrier	Best CSI
Zheng [29], DCF based MPR, 2006	Analysis	Implicit feedback	Blind detection	Fixed data length	-
Jung [48], τ_w based transmission, 2011	Analysis	Implicit feedback	-	Orthogonal preamble	-
Barghi [49], MPR-aware MAC, 2011	Simulation + Analysis	-	STC	Perfect channel	-
Zhou [50], two-round contentions, 2010	Simulation + Analysis	Implicit feedback	MMSE	Fixed data length	-
Liao [51], elastic 2-nd round, 2012	Simulation	Implicit feedback	-	Error-free channel	-
Zhang [52], multi-round contentions, 2010	Simulation + Analysis	-	-	Poisson arrivals	-
Jung [53], asynchronous MPR, 2012	Simulation + Analysis	Implicit feedback	-	Extra ACK channel	-

Cai et al. in [54] propose a distributed MU-MIMO MAC protocol with extended RTS/CTS frames. The CSI is obtained from the RTS/CTS exchange. An additive white Gaussian noise (AWGN) channel is assumed, and a leakage-based precoding scheme is utilized to cancel interference. The authors adopt a queue based scheduling scheme, which prioritizes frames with the longer waiting time in the AP buffer. The results derived from the analytic model and simulations show the proposed multi-user MAC substantially outperforms the single-user one.

Liao et al. in [55] present a MAC protocol for downlink MU-MIMO transmissions, where frames are scheduled to each STA by FIFO. The CSI is obtained through estimating the training sequence included in the CTS preamble. The channel is assumed to be error-free and independently fade from frame to frame, which creates independent channels from the AP to STAs. Simulation results show that a significant throughput gain is obtained by exploiting the spatial domain of the channel.

Li et al. in [56], propose a Multi-user MAC (MU-MAC) protocol, which supports Multi-Packet Transmission (MPT) in the downlink and multiple control packets (e.g., CTSs or ACKs) reception in the uplink. Orthogonal OFDM preambles are utilized to facilitate the CSI extraction from the simultaneously received control frames. The frame errors are assumed to come from collisions only, and all frames are transmitted with the same rate. The scheduling scheme jointly considers the CSI history, the AP's

queueing state and the frames' application categories. By observing the results, the authors claim that MU-MAC outperforms MPT-only MAC in terms of the maximum number of supported STAs, and this gain will increase further as the AP employs more transmitting antennas.

Gong et al. in [57] propose a modified CSMA/CA protocol with three different ACK-replying mechanisms, namely, the polled ACK response, the scheduled ACK response and the failed ACK recovery. A weighted queueing mechanism that associates ACs with the value of contention window is also proposed to address the fairness concern. The MMSE precoding scheme is adopted and the CSI is assumed to be known. The simulation results show that the proposed protocol provides a considerable performance improvement against the IEEE 802.11n beamforming based approach when the SNR is high.

Kartsakli et al. in [58] propose four multi-user scheduling schemes for concurrent frame transmissions, namely, MU-Basic, MU-Deterministic, Mu-Threshold Selective, and MU-Probability. The opportunistic beamforming that selects STAs with the highest signal-to-interference-plus-noise ratio (SINR) for each randomly generated beam is utilized. The CSI is feedback by STAs during the channel contention phase. A block fading channel is assumed, which means the channel remains constant during a frame transmission time. Based on simulation results, the authors argue that the proposed schemes achieve notable gains against the single-user case, although there is still considerable space for improvements compared to the theoretical capacity.

Zhang et al. in [59] present a One-Sender-Multiple-Receiver (OSMR) transmission scheme for WLANs. The authors firstly implement an OSMR prototype using a Universal Software Radio Peripheral (USRP) [60] platform to explore the feasibility of OSMR at the PHY level. Then, based on the study of the OSMR PHY characteristics, they modify the RTS/CTS frames to support the channel estimation. Simulations of the proposed extension are conducted at the MAC level. A greedy scheduling algorithm is proposed to transmit as many frames as possible in a TXOP with the urgent frames being prioritized over the normal ones. The ZF precoding scheme is adopted, while a flat fading channel is assumed. The simulation results show that a significant performance gain is achieved by employing OSMR transmissions.

Redieteb et al. in [61] investigate three different transmission schemes in a PHY and MAC cross-layer platform, which are SU-MIMO, MU-MIMO with multi-user interference and MU-MIMO without multi-user interference. An IEEE 802.11ac channel model [62] is utilized to represent channel variations. The MAC layer is made to be compliant with the 802.11ac specification draft, thus, the amendment defined ECFB protocol is employed to obtain the CSI. The ZF channel-inversion precoding scheme is used to decode frames. Based on the simulation results, the authors conclude that multi-user interference has important effects on MU-MIMO transmissions, e.g., it results in less throughput and are less stable than SU-MIMO ones. Therefore, an automatic switching algorithm between SU-MIMO and MU-MIMO is suggested by the authors.

Cha et al. in [63] compare the performance of downlink MU-MIMO to Space Time Block Coding.

The ZF precoder is utilized, and the CSI is obtained at the AP by receivers' feedback. A Rayleigh fading and error-free channel is assumed. The results show that the downlink MU-MIMO scheme produces a higher throughput than the STBC one if transmitted frames are of similar length, while the results reverse in a fast-varying channel due to high overheads of the CSI feedback .

Balan et al. in [64] implement a distributed MU-MIMO system that consists of several multi-antenna APs, which are connected and assumed to be synchronous by a coordinating server. The authors employ Zero Forcing Beamforming (ZFBF) and THP for the frame separation. The CSI is acquired from uplink pilot symbols. Blind Interference Alignment (BIA) is used when the CSI is unavailable. The system is evaluated in the Wireless Open-Access Research Platform (WARP) platform [65]. The experimental results show that the presented MU-MIMO system can achieve high data rates and approach the theoretical maximum throughput.

Zhu et al. in [66] investigate required modifications for TXOP to support multi-user transmissions. The proposed scheme, called multi-user TXOP (MU-TXOP), enables a STA whose AC won the TXOP to share the transmission period with MPDUs of other ACs. The authors assume all STAs can be grouped for multi-user downlink transmissions. Simulation results show that the proposed scheme not only obtains a higher throughput, but is also more fair compared to the conventional one.

Ji et al. in [67] present a cooperative transmission scheme that addresses the redundant Network Allocation Vector (NAV) setting and the outdated SINR problems. The redundant NAV setting usually occurs at STAs located in the overlapped areas of neighbouring WLANs, while the outdated SINR problem is caused due to the delay between the channel estimation and the data transmission. The authors utilize reserved bits in control frames to announce the last frame of a transmission to synchronize the NAV setting, and employ STAs' ACKs to re-estimate and correct the SINR. The analysis model assumes frames that arrive to STAs to follow the Poisson process. The results obtained from the model and simulations show the enhanced scheme can achieve noticeable performance gains compared to the sampled one.

Table IV summarizes the main characteristics of the surveyed downlink MU-MIMO MAC protocols.

C. Integrated Up-down/link MAC Proposals for WLANs

Only a few works have considered both MU-MIMO uplink and downlink transmissions in a single MAC protocol.

Shen et al. in [68] present a High Throughput MIMO (HT-MIMO) MAC protocol that utilizes frequency signatures to differentiate simultaneously received control frames. HT-MIMO works in the PCF mode, hence both uplink and downlink transmissions can only be initiated by the AP. The CSI is obtained by a channel measurement method. The uplink and downlink channels are assumed to be symmetrical. A greedy scheduling algorithm is adopted with the consideration of fairness and the queue occupancy. The results obtained from the analytical model show that the HT-MIMO MAC outperforms the implemented

TABLE IV
DOWNLINK MU-MIMO MAC PROTOCOLS

Remarks	Evaluation Tool	CSI Scheme	MUIC	Key Assumption	Scheduling
Cai [54], reduce AP-bottleneck effect, 2008	Simulation + Analysis	Explicit feedback	Leakage coding	AWGN channel	Priority queue
Liao [55], throughput and delay gain, 2011	Simulation	Implicit feedback	-	Error-free channel	Per-STA FIFO
Li [56], MU-MAC, 2010	Simulation + Analysis	Explicit feedback	-	Error-free channel	History CSI
Gong [57], ACK-replying schemes, 2010	Simulation	-	MMSE	Assume CSI known	Weighted queue
Kartsakli [58], 4 scheduling schemes, 2009	Simulation	Explicit feedback	Beamforming	Block fading	Highest SINR
Zhang [59], OSMR, 2010	Simulation + Testbed	Explicit feedback	Zero Forcing	Flat fading	Greedy
Redieteb [61], PHY+MAC platform, 2012	Simulation	Explicit feedback	Zero Forcing	-	-
Cha [63], STBC & MU-MIMO, 2012	Analysis	Explicit feedback	Zero Forcing	Error-free channel	-
Balan [64], multi-AP system, 2012	Simulation + Testbed	Implicit feedback	ZFBF, THP, BIA	Phase synchronous	-
Zhu [66], multi-user TXOP, 2012	Simulation	-	-	All STAs groupalbe	-
Ji [67], outdated NAV and SINR, 2014	Simulation + Analysis	Explicit feedback	-	Poisson arrivals	-

SU-MIMO and MU-MIMO protocols.

Kim et al. in [69] devise a down/up-link back-to-back transmission scheme to synchronize STAs. The scheme is called Per-flow MAC (PF-MAC, Figure 15), where RIFS stands for Reduced Inter Frame Space. The AP first sends a Group-RTS (GRTS) that includes a list of STA addresses to initiate the downlink transmission. As soon as the AP received expected CTSs, it sends data frames to the listed STAs. The STAs who received frames then send back ACKs sequentially. Through the downlink transmission and a Ready to Receive (RTR) frame from the AP, STAs are synchronized for the parallel uplink transmission. The CSI is estimated from uplink frames. The limitation of the proposal is that the uplink transmission can only be started by the downlink one, which may not be desirable in some scenarios where the uplink access is urgent. Note that the proposal is just a conceptual model without any simulation or analytic results.

Liao et al. in [70] propose a unified MU-MIMO MAC protocol (Uni-MUMAC) for IEEE 802.11ac

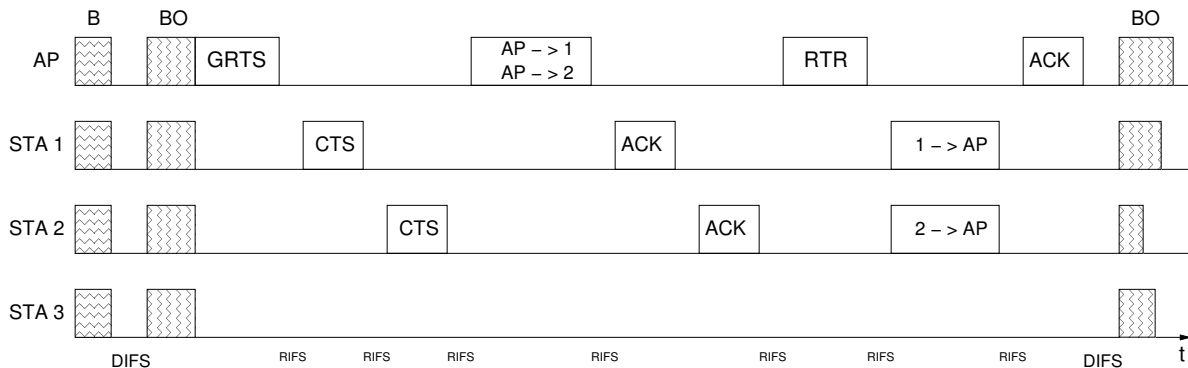


Fig. 15. PF-MAC

WLANs by integrating the uplink and downlink transmissions. The AP has been extended to support simultaneous data and ACK transmissions/receptions. The implicit CSI acquisition scheme is adopted by assuming the channel reciprocity. Through adaptively tuning CW_{2nd} (a parameter introduced in [51]), the number of assembled frames and the buffer size of the AP, a WLAN that employs Uni-MUMAC is observed performing well in both the traditional downlink-dominant and the emerging down/up-link balanced traffic scenarios.

Yun et al. in [71] present a multi-point to multi-point MIMO system, where the uplink multiplexing is implemented in the SORA platform, while the downlink is implemented in the USRP platform. Multiple APs are coordinated by a controller, and connected via an Ethernet cable. A leader concept is adopted for both the uplink and downlink medium access. A trigger frame that includes co-senders' addresses is sent out by the leader who first won the channel contention. Then, the co-senders transmit preambles sequentially as specified in the trigger frame for the CSI estimation. The downlink scheduling is based on the packet arrival time and the length of waiting time in the queue, while the co-senders' selection in the uplink is randomly made. ZF is employed in both the uplink and downlink for frames' de/pre-coding.

Table V summarizes the main characteristics of the up-down/link MU-MIMO MAC protocols.

V. FUTURE DIRECTIONS

Based on the above studies, we discuss possible future research directions for MU-MIMO MAC protocols through a micro perspective (i.e., the further research efforts needed for MU-MIMO transmissions in WLANs) and a macro perspective (i.e., the potential research aspects rising from possible cooperation or integration between MU-MIMO based WLANs and other networks).

A. The Micro Perspective: Within MU-MIMO Based WLANs

1) *What Does 802.11ac Not Specify?:* The downlink MU-MIMO transmission is one of the most significant features introduced by IEEE 802.11ac. In order to perform multi-user transmissions, the

TABLE V
INTEGRATED UP-DOWN/LINK MU-MIMO MAC PROTOCOLS

Remarks	Evaluation Tool	CSI Scheme	MUD & MUIC	Key Assumption	Scheduling
Shen [68], control frames' encoding, 2012	Analysis	-	-	Symmetrical channel	Greedy
Kim [69], back-to-back transmissions, 2008	Conceptual model	Implicit feedback	-	-	-
Liao [70], unified up/downlink MAC, 2013	Simulation	Implicit feedback	-	Channel reciprocity	FIFO
Yun [71], multi-APs to multi-STAs, 2013	Testbed	Sequential preambles	Zero Forcing	-	FIFO

amendment proposes the ECFB scheme to feedback the AP with the required CSI, and devises a group identifier (Group-ID) field in the PHY preamble to facilitate grouping STAs. However, the following two related factors are not specified in the amendment.

- **Scope and frequency of CSI feedback:** [72] and [73] have shown the significant impact of the CSI feedback on the system performance. A clear dilemma regarding the scope and the frequency of the CSI feedback is that a large scale (e.g., all STAs in the network) and frequent CSI requests will introduce huge overheads, while the opposite way leads to that the rendered channel information might be outdated. Therefore, adaptive algorithms are needed to dynamically adjust the scope and the frequency of CSI feedback.
- **Conditions to group/re-group STAs:** Although it can be argued that the way of grouping STAs depends on the specific application, a smart grouping algorithm has to be designed to identify STAs that can be co-scheduled as well as conditions that would trigger STAs' re-grouping.

2) *How to Improve MAC Efficiency?:* As shown in the paper, significant research efforts have been made to adapt the IEEE 802.11 MAC to advances such as the multi-antenna technique. However, the MAC throughput is still much lower than the PHY raw rate (lower than 70% in most cases [74]). The throughput loss mainly comes from the so-called overheads, which include the management frames (e.g., association requests/responses), control frames (e.g., RTS/CTS/ACK), frame headers (e.g., PHY preambles, PHY/MAC headers) and the compulsory idle duration (e.g., the random BO, DIFS/SIFS). Other non-overhead factors contributing to the throughput loss include frame collisions and the airtime unfairness caused by low rate STAs that monopolize the channel. These fundamental IEEE 802.11 mechanisms and features limit the MAC efficiency. In a packet capture test conducted in a dense area of Tokyo [75], the results show that data frames only account for 23% of all types of frames (46% management frames, 30% control frames, 1% others), and moreover, most of management frames are in

the 802.11b format and transmitted at 1 Mbps to ensure the interoperability.

IEEE has recently created a new study group called High Efficiency WLAN (HEW) [76]. It aims to improve the efficiency of WLANs by not only increasing the data rate, but also trying to introduce a novel structure that can provide QoS guarantees in both indoor and outdoor heavily-loaded environments. Here, we give our thoughts on possible solutions to improve the MAC efficiency.

- **Cooperation among multiple bands:** Management frames, control frames and frames headers are necessary to facilitate correct receptions of data. They can not be eliminated in the current 802.11 communication architecture. At least from the legacy IEEE 802.11-1997 to 802.11ac, what we have seen is an ever-increasing length of PHY preamble. Cooperation among multiple bands could be an effective way to control overheads. More specifically, a future smart device is likely to be equipped with multiple interfaces operating in multiple bands [77]. Thus, 802.11ac at 5 GHz, could be a candidate for the carrier sense and data transmissions across rooms; 802.11ah below 1 GHz, could be utilized to transmit management and control frames; while 802.11ad at 60 GHz, could be used for very high speed data transmissions in the line of sight. [78] has already suggested a possible usage model that using 802.11ah for signalling among APs while 802.11ac for data frames.
- **Revise the backoff scheme:** The random BO scheme is a key function employed by IEEE 802.11 to avoid collisions. Unfortunately, collisions can not be eliminated and remain as one of the most degrading factors to the system performance. [79] proposes a collision-free solution, where STAs adopt a deterministic BO instead of a random one after successful transmissions for single-antenna based WLANs. This innovative idea can be considered to extend to multi-antenna based WLANs in both downlink and uplink.
- **Uplink MU-MIMO transmissions:** The Internet traffic has evolved from mainly web browsing and file transfers to a wide variety of applications, which include considerable amount of content-rich files generated by users, such as the video conferencing, social networks and cloud uploading services. Although the enhancement for uplink transmissions has recently gained attention, there is still much space for improvements since IEEE 802.11ac will not support uplink MU-MIMO transmissions. In addition, there are a few works that focus on unifying MU-MIMO downlink and uplink in a single communication system.
- **Full-duplex transmissions:** The current form of communications in WLANs is half-duplex, namely, transmissions and receptions are allocated to different time slots or frequency bands. The full-duplex transmission has the potential to double the channel capacity by allowing simultaneous transmissions and receptions with the same frequency [80] [81]. On the other hand, the coming of full-duplex transmissions hints us to rethink the IEEE 802.11 fundamental MAC mechanism-CSMA/CA, which is employed based on the long-held assumption that radios can not transmit and receive at the same time [82]. The research on full-duplex transmissions has just started in recent years. Although the

challenging part is to cancel self-interference at the full-duplex transceiver, the MAC scheme needs to be revised as well [83] [84].

B. The Macro Perspective: Integration with Heterogeneous Networks

It seems to be a trend that in the future there will be a huge and smart network that integrates heterogeneous networks (e.g., WLANs, broadband mobile networks and sensor networks), which means individual network will have to collaborate with others to provide services, rather than just coexist. Obviously, the integration and the inclusion of WLANs require some unique changes at the MAC layer.

1) *How, who and when to collaborate?:* With the PHY layer's focus on the air interface and the network layer's focus on the routing, the MAC layer plays a role in deciding how to collaborate, who to collaborate and when to collaborate [85] [86]. For example, imagining a scenario that a sink of a smart metering sensor network requests an AP to forward the collected data to a user's mobile phone, the AP first checks whether the mobile phone is in its vicinity to decide whether to forward the data by itself or to relay the data to other APs. And then, the AP checks the channel condition and the queueing status to decide who and when to transmit the data. Regardless the scale and the type of collaborations, management frames and control frames exchanges to build connections with other entities are needed. Note that today's device-to-device communications already account for a significant part of total wireless traffic, and they are regarded as one of the most important challenges for 5G networks [87] [88]. Therefore, the MAC scheme for the integrated network has to take how, who and when to collaborate into account.

2) *Multi-hop links:* In addition to the above consideration, it is inevitable for MAC protocols of integrated networks to support multi-hop indirected links, where the hidden-node problem, cooperative diversity, MPT/MPR functionalities and the joint MAC-routing design need to be addressed [89].

3) *Outdoor and mobile WLANs:* The inclusion of WLANs to outdoors presents some significant challenges to the traditional MAC, as which is designed to support limited mobility. First, due to the user movement and the large scale fading, the outdoor channel is varying faster than that of indoors, even with the same moving speed [90]. For that reason, the CSI feedback scheme needs to be reconsidered to report the channel state timely, while maintaining low channel estimation overheads. Secondly, the cellular operators may offload traffic to public or proprietary WLANs (e.g., the carrier class Wi-Fi [91]) in a dense public stadium, in which case, the seamless transfer and the QoS promised by the cellular network need to be assured at the MAC layer.

VI. CONCLUDING REMARKS

The uplink and downlink MU-MIMO MAC protocols for WLANs are investigated and categorized in the paper. Some typical MUD and MUIC techniques for de/pre-coding are sampled, and the requirements

for designing MU-MIMO MAC protocols are identified. Based on the study, discussions are carried out to clarify what challenges and future directions could be for designing effective MU-MIMO MAC protocols.

Despite considerable research has been conducted, there still exists under-explored areas toward simple, yet highly efficient MAC protocols for MU-MIMO based WLANs, especially in the context of the rapid growth of wireless devices. Therefore, we have given some of our thoughts in that regard. We hope this survey paper would help the readers to summarize the current research progress and inspire their future work.

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