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Research Article

ADAS: Adaptive Switching between Full-Duplex and MU-MIMO for Wi-Fi Networks

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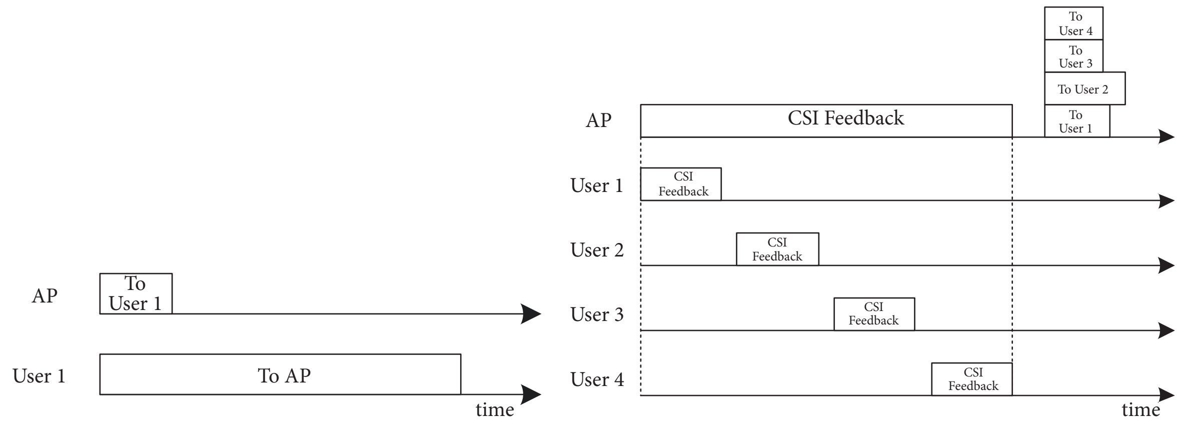
Full-duplex (FD) and multiuser multi-input multioutput (MU-MIMO) approaches have been attracting much attention as core technologies of next-generation Wi-Fi systems, since they have vast potential to improve communication performance. In particular, the system throughput can be significantly increased if both technologies are used in harmony, based on a solid understanding of the characteristics of each technology. To realise this, it is essential and important for a node using both technologies to acquire a priori channel and queue information about the receiving nodes. Unfortunately, it is very challenging to obtain this information in Wi-Fi networks in which there are no separate channels or proper protocols. In this paper, a new MAC protocol for Wi-Fi networks is proposed, called ADAS, which selects the transmission strategy that best matches the given network environment. By fully utilising the conventional CSI acquisition protocol, an ADAS access point (AP) effectively obtains the necessary information and exploits it appropriately, in order to yield higher throughput gains. Through extensive Matlab simulations, the author proves that ADAS maintains high system throughputs for dynamic network changes.

1. Introduction

Two different antenna technologies, full-duplex (FD) and multiuser multi-input multioutput (MU-MIMO), have both been attracting much attention as core functionalities of next-generation Wi-Fi systems. MU-MIMO can greatly increase the network capacity by concurrently sending multiple data streams to many different receivers, while FD can serve a variety of purposes, such as detecting frame collisions, providing immediate ACK feedback, and resolving the hidden terminal problem by successfully removing residual self-interference (RSI) [1–3] and by several proposed MAC protocols [4–6].

In order to fully enjoy the benefits of both technologies, researchers have been attempting to optimise network performance under the assumption that a node with high computing capacity, such as an access point (AP) or base station, is capable of both FD and MU-MIMO functionalities. These two technologies have different characteristics, and their performances may therefore vary greatly depending on the given network environment: RSI generally results in SINR loss in FD transmissions, while the performance of MU-MIMO is highly affected by the channel status of the receiver set. If the channels between the receivers are not sufficiently orthogonal to each other, the gain becomes marginal, and, in severe cases, the performance may be much lower than when MU-MIMO is not enabled. The size of the queued data in transmitting nodes also has a strong effect on the performance of the two techniques; the FD gain is significantly reduced if the transmission time difference of the two nodes is large (Figure 1(a)), while if there is only a small amount of data to be transmitted, the CSI overhead may overwhelm the gain from MU-MIMO (Figure 1(b)). It is therefore essential to devise an appropriate transmission strategy that considers these characteristics appropriately, so that the advantages of both technologies can be fully utilised.

In this paper, a new MAC protocol is proposed for Wi-Fi networks called ADAptive Switching (ADAS) between FD and MU-MIMO. The idea of ADAS is simple: it selects the transmission strategy that best matches the given network environment. An ADAS AP exploits channel and queue information collected about user stations to calculate the expected throughput that it can achieve through FD or MU-MIMO. By comparing these values, it chooses a suitable transmission strategy that will yield higher throughput gains.



(a) FD case

(b) MU-MIMO case

Figure 1: **Cases of inefficient transmission in FD and MU-MIMO.** (a) The case in which the AP initiates an FD transmission when it wins the channel contention. If the transmission time of the receiving node is too long, the AP may have to wait a longer time to send the next frame than when FD is not used; (b) if the data for transmission is not sufficiently large, the CSI overhead may overwhelm the gain from MU-MIMO.

This allows ADAS to find the most appropriate receiver set among the given candidates, resulting in enhancement of the performance of both MU-MIMO and FD. This process is performed each time the AP has a transmission opportunity, thus enabling ADAS to adapt quickly to a dynamically changing network environment.

The design of ADAS is challenging for the following reasons. Firstly, it is difficult for the AP to know the channel and queue information of user stations a priori. The CSI acquisition method used by existing protocols [7, 8] is insufficient here, since it only considers the channel information. For compatibility with existing protocols, the existing CSI acquisition protocol is adopted into ADAS, and on top of this, a new frame is developed called *Queue and Channel State Information* (QCSI), which includes user queue information in the legacy CSI frame. Since only a small number of bits are needed to represent the queue information, no modification to the legacy frame structure is required if we fully use the reserved bits.

Secondly, since ADAS is built on the conventional CSI acquisition protocol, it inherits the overhead problem. It is a well-known fact that the conventional CSI acquisition method can limit the MU-MIMO gain, due to the excessive protocol overhead. The CSI feedback overhead can reach up to 25x compared to the data transmission time in case of 160 MHz of bandwidth and 4 x 1 MIMO [9]. To reduce the possible QCSI feedback overhead, in ADAS, the AP does not always request QCSI feedback for all candidate user stations. Instead, it decides whether or not to send a QCSI feedback request by carefully estimating the expected throughput gain. As a result, ADAS eliminates unnecessary requests and thus effectively reduces the overhead. Lastly, FD transmissions may suffer from inefficiency if there is a large imbalance between transmission times. To handle this issue, the proposed ADAS AP piggybacks its own queue information onto a QCSI feedback request, making it possible for FD candidate users to adjust their frame aggregation level to optimise the FD performance.

To evaluate the performance of ADAS, it is implemented with other protocols in a MATLAB simulator, and extensive simulations are conducted. The results show that ADAS is able to reduce the QCSI feedback overhead by 33% and 37% compared with those of 802.11ac [7] and OPUS (Orthogonal Probing based User Selection) [10], respectively, and also outperforms other protocols in terms of the system throughput. Note that OPUS is a MU-MIMO performance enhancement technique based on user selection; it finds the user with the best orthogonal channel to the channel subspace of the previously selected users in each round of CSI feedback. ADAS achieves performance improvements of 15% and 8% compared to schemes using only FD and 802.11ac, respectively. In addition, the low QCSI feedback overhead and improvements to both the FD and MU-MIMO techniques in ADAS lead to performance that is comparable to that of OPUS in most cases.

The remainder of this paper is organised as follows. Section 2 provides research results related to ADAS, and the network model presented in this paper is described in Section 3. Next, the ADAS mechanism is explained in greater detail in Section 4. Section 5 presents the results of a performance evaluation, and the paper is concluded in Section 6.

2. Related Work

This section presents the results of a literature survey on MU-MIMO and FD techniques related to ADAS.

2.1. MU-MIMO. MU-MIMO has been applied to many wireless communication systems, as it has the major advantage of being able to send data to multiple different nodes at the same time. MU-MIMO has been supported since LTE Release 8 [11] for cellular communication, while, for Wi-Fi networks, downlink and uplink MU-MIMO were standardised in IEEE 802.11ac [7] and IEEE 802.11ax [8], respectively.

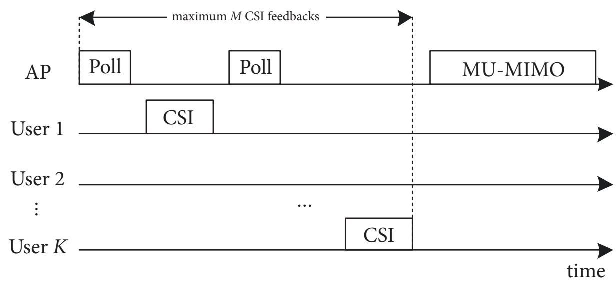


Figure 2: **The conventional CSI acquisition protocol in 802.11ac [1] and 802.11ax [8]**. The control frames of this protocol are transmitted at the basic data rate, and the size of the CSI feedback frame grows as the number of AP antennas increases. If the channels of the receiving group are not orthogonal with each other, then the CSI overhead may greatly degrade the MU-MIMO gain.

The most challenging task in realising MU-MIMO is to remove the signal interference between receiving nodes, and for this reason, most systems involve careful design of the transmission beamforming with CSI feedback from receivers; in other words, a transmitting node needs to acquire CSI from the receiving nodes in advance before the actual data transmission. For this purpose, existing Wi-Fi standards [7, 8] use polling-based CSI acquisition, as shown in Figure 2.

As stated above, this CSI feedback procedure may lead to a large protocol overhead; since all frames are exchanged at the basic data rate during the procedure, the overhead significantly increases as the number of candidates requesting CSI or the number of antennas increases. Several schemes have been proposed to overcome this inefficiency. The aforementioned Wi-Fi standards use frame aggregation schemes as mandatory, but these are effective only if the transmission queue has enough data to aggregate. Another way of reducing the CSI overhead is to use compression based on the codebook and quantisation techniques [7, 8, 11], which can reduce the number of bits in the CSI feedback frame. AFC (Adaptive Feedback Compression) [9] further reduces the overhead by decreasing the amount of feedback using the statistical model of channel coherence time. Although these schemes reduce the size and number of feedback overheads, the MU-MIMO performance may be degraded due to the fact that lower CSI feedback may offer diminishing returns.

User selection, which builds the best user set among the candidates in order to increase the network capacity for MU-MIMO, has been also highlighted [10, 12, 13]. These schemes can be applied to ADAS as a way of enhancing the performance of MU-MIMO itself. Note, however, that the main contribution of this paper does not involve improving the performance of MU-MIMO itself but the effective collaboration with FD.

2.2. Full-Duplex. Several recent advances in signal processing addressing the well-known RSI problem have proven the feasibility of wireless FD systems [1–3], and researchers are now developing joint FD and MU-MIMO systems in which downlink and uplink user stations receive and transmit data streams, respectively, from/to the base stations (or the AP) [14, 15]. Most of these attempt to find an optimal beamforming scheme to effectively remove both inter-user interference and self-interference and thus maximise the system throughput. However, as mentioned earlier, it is very challenging to realise such schemes, especially in Wi-Fi networks, where there is no separate feedback channel.

Although PHY techniques for wireless full-duplex approaches are highly evolved, MAC protocols for Wi-Fi networks to fully exploit these have not yet been studied thoroughly. Since the legacy MAC protocols are designed only for half-duplex, we cannot directly adopt them into FD Wi-Fi networks, and thus it is essential to provide an appropriate mechanism for enabling FD. One easy way to realise FD communications is to use an opportunistic method: once the receiver obtains the information about the transmitting user in the header of a received frame, a frame can be sent to the transmitter in full-duplex mode [4–6]. However, such simple opportunistic methods do not guarantee sufficient FD transmissions, and this may limit the FD throughput gain, especially under nonsaturation traffic conditions [16]. There are other proposed schemes that support more diverse types of FD transmissions at the expense of the increase of protocol complexity, such as new control frames and the variants of RTS/CTS [17–19], new channel access methods [20], and centralised scheduling [21]. Although these may improve the FD performance, major modifications to the legacy protocols are required, thus raising a compatibility issue.

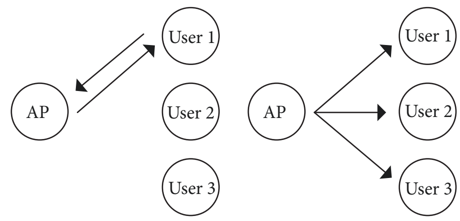
3. Network Model

In this section, the network model and terminology used in this paper are explained.

A Wi-Fi network is assumed that consists of one AP equipped with M antennas and K single antenna user stations (simply denoted as "user"). In particular, the author assumes that the AP can transmit only in either FD (Figure 3(a)) or MU-MIMO mode (Figure 3(b)), but not both simultaneously. User-initiated FD transmissions are not considered in this paper, since the impact of these affects the overall system performance, making ADAS performance analysis more difficult.

The FD transmissions are assumed to occur only in a symmetric link between the AP and a single user in an opportunistic manner (i.e., random access); when the AP wins the channel contention and starts to transmit a frame, the receiving node can simultaneously start another transmission to the AP if it has frames to send. In addition, the author assumes a fixed data rate (denoted as r^{fd}) in all FD transmissions, taking the impact of RSI into account.

In MU-MIMO, the AP computes transmission set S, where $|S| \leq M$, from its transmission queue, before starting the channel contention. The queue is assumed to be FIFO (First In, First Out), and S consists of up to M receiving users in order of the queued frames. The AP uses precoding to send multiple data streams to selected users. In this paper, the author incorporates ZFBF (Zero-Forcing Beamforming) as the precoding strategy, since it effectively removes the mutual



(a) Full-Duplex Transmission Mode (b) MU-MIMO Transmission Mode

Figure 3: **Two transmission modes of the AP**. (a) The AP can initiate an FD transmission to a certain user in an opportunistic manner; or (b) it can simultaneously send multiple data to a receiver group via MU-MIMO.

interference among concurrent transmissions by using a precoding matrix computation. In ZFBF, the precoding matrix for transmission set S, denoted by $W(S)$, is obtained as follows:

$$W(S) = H(S)^{\dagger} = H(S)^{*}\left(H(S)H(S)^{*}\right)^{-1}, \quad (1)$$

where $(\cdot)^{\dagger}$, $(\cdot)^{*}$, and $H(S)$ represent a pseudoinverse, conjugate transpose, and the channel matrix of S, respectively.

Let P be the maximum transmitting power of the AP. This is assumed to be allocated equally among users (i.e., equal power allocation). Then, the capacity for user s is modelled as follows:

$$\log\left(1 + \frac{P}{|S|}\frac{1}{\|w_s\|^2}\right), \quad (2)$$

where w_s is an element of $W(S)$. Note that the data rate can be determined based on (2).

For each element of the channel matrix, let h^s be the M by 1 channel vector from the AP to user s, and let each element of h^s be an independent zero-mean complex Gaussian random variable with unitary variance [22]. Although this channel model may seem unrealistic, the use of an uncorrelated channel model is sufficient to achieve the goal of this paper, since no specific network environment is considered and since the logic of the algorithm is scarcely affected by the model. A study of correlated channel models is left for future work.

The $\frown$ notation is used when the QCSI used to compute certain values is not the actual feedback from a user. The superscript X is used for some variables, indicating either FD or MU-MIMO.

4. ADAS

4.1. Overview. Figure 4 illustrates the operation of ADAS. As mentioned earlier, the QCSI acquisition process essentially resembles the conventional CSI feedback protocol [7, 8]; the only difference is that, in ADAS, the queue information is also exchanged during the process. Let us consider the case in which the AP obtains QCSI feedback from user s, meaning that the AP has gathered all queue and channel information about users 1 to $s-1$ at this point. The AP now computes the expected maximum throughput that it can achieve, based on the information collected thus far. Let C_s and G be the expected throughput that the AP can obtain when acquiring all QCSI feedback overheads from the first user to s-th user and the subset of $\{1, \ldots, s\}$ to achieve this value of C_s, respectively. Then, the AP decides whether or not to ask the next user (i.e., user $s+1$) for QCSI, by comparing C_s to another estimated throughput that can be obtained when acquiring the next user's information (i.e., $\widehat{C}_{s+1}$). If there is likely to be a benefit from using the next user's QCSI (i.e., $C_s < \widehat{C}_{s+1}$), the AP will ask the next user for its QCSI; otherwise, it immediately initiates the downlink transmission with the best transmission configuration (i.e., G), omitting the unnecessary CSI acquisition process.

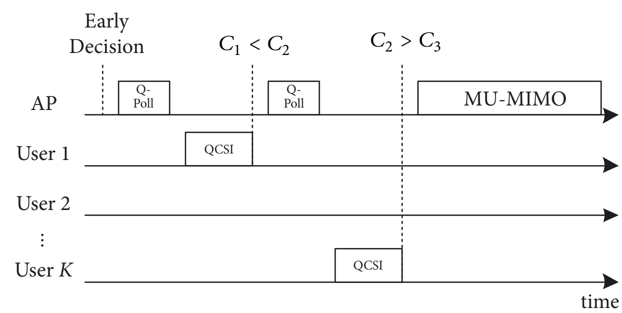


Figure 4: **Example of the operation of ADAS**. ADAS exploits the QCSI of users to select the best transmission strategy between FD and MU-MIMO. In addition, it can reduce the QCSI feedback overhead by intelligently removing unnecessary feedback requests.

In addition to the QCSI-based throughput estimation, two more schemes are developed here to enhance the performance of ADAS, called *Early Decision* and *Q-Poll*. Using Early Decision, the AP can further minimise the QCSI feedback overhead by comparing two estimates before entering the feedback process; Q-Poll mitigates the transmission time imbalance in FD transmissions. In the following subsections, more details are given about each scheme.

4.2. Throughput Estimation

4.2.1. Throughput Estimation after Obtaining QCSI Feedback. When an ADAS AP receives a QCSI feedback from user s, it computes C_s. Since the AP has two transmission options (i.e., FD and MU-MIMO), we have

$$C_s = \max\left(C_s^{fd}, C_s^{mu}\right), \tag{3}$$

where C_s^{fd} and C_s^{mu} are the expected maximum throughputs for FD and MU-MIMO, respectively. Recall that each time the AP computes C_s, it remembers the transmission configuration G to achieve C_s.

Each of these can be computed using the following equation:

$$C_s^X = \max_{G\subset\{1,\ldots s\}}\left(\frac{L_G^X}{T_s^{qcsi} + T_G^{data-X} + T^{ack}}\right), \tag{4}$$

where G is the user group (a subset of $\{1,\ldots,s\}$) that can maximise the throughput of FD (or MU-MIMO), L_G^X is the total data size to transmit for G, T_s^{qcsi} is the QCSI feedback overhead measured so far, T_G^{data-X} is the time for the data transmission, and T^{ack} is the time required for the ACK transmission.

For L_G^X, we have

$$L_G^{fd} = \sum_{g\in G}\left(b_g^{AP}\right) + b^g \tag{5}$$

$$L_G^{mu} = \sum_{g\in G}\left(b_g^{AP}\right), \tag{6}$$

where b_g^{AP} and b^g are the aggregate data size of the AP for user $g \in G$ and that of user g, respectively. Note that $|G| = 1$ for the FD case.

For T_G^{data-X}, we have

$$T_G^{data-fd} = \max_{g\in G}\left(\frac{b_g^{AP}}{r^{fd}}, \frac{b^g}{r^{fd}}\right) \tag{7}$$

$$T_G^{data-mu} = \max_{g\in G}\left(\frac{b_g^{AP}}{r^{mu}}\right), \tag{8}$$

where r_g^{mu} is the data rate for user g in the MU-MIMO mode, which can be obtained from user channel vectors as shown in Section 3.

4.2.2. Throughput Estimation before Obtaining QCSI Feedback. An ADAS AP needs to estimate both C_s and $\widehat{C}_{s+1}$ when it receives QCSI feedback from user s. To compute $\widehat{C}_{s+1}$, we can apply (4) here:

$$\widehat{C}_{s+1}^X = \max_{G\subset\{1,\ldots,k\}\cup\{s+1\}}\left(\frac{\widehat{L}_G^X}{T_{s+1}^{qcsi} + \widehat{T}_G^{data-X} + T^{ack}}\right), \tag{9}$$

where group G must include user $s+1$.

Unlike when computing C_s^X, the AP needs to estimate the throughput with a lack of information about user $s+1$, i.e., $\widehat{h}^{s+1}$ and $\widehat{b}^{s+1}$, meaning that we need to estimate $\widehat{L}_G^X$ and $\widehat{T}_G^{data-X}$ without any user information. To address this issue, probability distributions are used here. For $\widehat{h}^{s+1}$, the channel model described in Section 3 is used; that is, each element of $\widehat{h}^{s+1}$ is generated from a Gaussian distribution with zero-mean and unitary variance. The AP estimates $\widehat{b}^{s+1}$ empirically from the queue status statistics, and the values can be set as the expectation of the distribution (that is, $\widehat{b}^{s+1} = E[b]$, where $E[\bullet]$ represents the expectation of the distribution). As an example, the distribution of b according to the varying frame arrival rate q in the case where $M = 4$ and $K = 16$ is shown in Figure 5; for this figure, b values were measured whenever the AP obtained QCSI feedback from a user. From the result, we can see that the average number of frames queued at users at a given instant increases with the value of q, as expected.

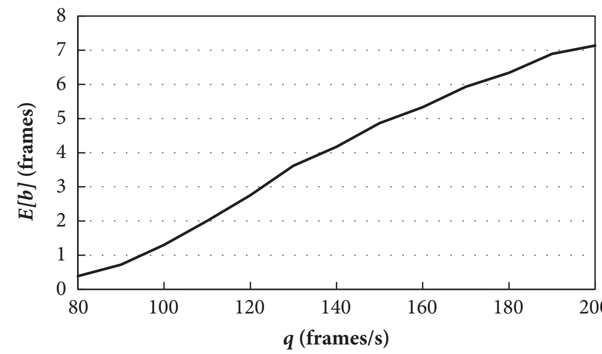


Figure 5: **Distribution of user queue status in case of $K = 16$, $M = 4$.** A high frame arrival rate (q) causes the transmission queue to fill up quickly, increasing the value of b.

4.3. Appending Queue Information. In order to increase the efficiency of FD, the imbalance in the data transmission time of the FD nodes needs to be small. Fortunately, ADAS can reduce this imbalance by utilising the process of obtaining QCSI. Consider the case in which the AP needs to send a QCSI request to user s. Then, when transmitting the request, the AP appends its queue status (i.e., b_s^{AP}) at the existing poll frame for user s, so that the receiving user s can reaggregate its frames to minimise the time difference. This frame is referred to here as *Q-Poll*. In this paper, since the fixed data rate is assumed for FD transmissions, b^s is set as $\min(b^s, b_s^{AP})$.

Conveying additional queue information in ADAS may seem to increase the protocol overhead and lead to modifications to the legacy frame; however, it actually consumes few bits if the data are appropriately quantised. To achieve this, the number of frames to be aggregated is used as queue information to be appended. In the case shown in Figure 5, four bits are sufficient to represent all aggregation levels, and these can be fully covered using the reserved bits of the existing MAC frame.

4.4. Early Decision. Although the QCSI feedback overhead is, in most cases, lower than that of existing schemes, it is still undesirable to require more than one QCSI feedback overhead per downlink transmission. For example, at a given

```
Input: AP's queue b^{AP}, candidate user group S;
Output: Transmission configuration G;
(Ĉ_0^{fd}, Ĉ_0^{mu}) ⟵ Early Decision (b^{AP});
if Ĉ_0^{fd} < Ĉ_0^{mu} then
    B = empty; // user queue matrix
    H = empty; // user channel maxtrix
    for s ∈ S do
        (h^s, b^s) ⟵ QCSI feedback from user s;
        H ⟵ H ∪  h^s;
        B ⟵ B ∪  b^s;
        (C_s, G) ⟵ Throughput estimation (b^{AP}, H, B);
        if s is not the last user of S then
            ĥ^{s+1} ⟵ generated by the channel model in Section 3;
            Ĥ ⟵ H ∪ ĥ^{s+1};
            b̂^{s+1} ⟵ E[b];
            Ĉ_{s+1} ⟵ Throughput estimation(b^{AP}, Ĥ, b̂^{s+1});
            if Ĉ_{s+1} < C_s then
                break;
            end
        end
    end
else
    G ⟵ (S = {1}); // FD Mode
end
Transmit with G;
```

Algorithm 1: ADAS.

point, if the data in the AP queue are only for a single user or if the aggregate level is insufficiently high, the MU-MIMO gain will be significantly lowered. If the maximum throughput via MU-MIMO is expected to be lower than that via FD, it may be better to try an FD transmission immediately, without acquiring QCSI feedback. This mechanism is referred to here as *Early Decision*. In other words, the AP will start an FD transmission if $\widehat{C}_0^{fd} \geq \widehat{C}_0^{mu}$ without the QCSI acquisition process, where $\widehat{C}_0^{fd}$ and $\widehat{C}_0^{mu}$ are the expected maximum throughputs estimated in the early decision stage for FD and MU-MIMO, respectively. Since in this case the information used is only the AP's queue status, i.e., b^{AP}, the technique described in Section 4.2.2 is employed to compute $\widehat{C}_0^{fd}$ and $\widehat{C}_0^{mu}$.

4.5. Summary. The overall algorithm of ADAS is summarised in Algorithm 1.

5. Performance Evaluation

5.1. Simulation Setting. The results of the performance evaluation of the proposed protocol are described in this section. To do this, a total of five MAC protocols are implemented, including ADAS on the MATLAB simulator. Most of the features of the IEEE 802.11 MAC layer have been implemented in the simulator, including channel contention (DCF (Distributed Coordination Function), binary exponential backoff), frame retransmission, and the channel state information acquisition process for downlink MU-MIMO, ACK, and RTS/CTS. A bandwidth of 20 MHz is used, and thus the maximum available data rate is 78 Mbps. The channel aggregation feature is not considered here. The implemented protocols are as follows:

(i) Legacy: this has no functionalities of FD or MU-MIMO

(ii) FD: the AP uses only FD on the downlink in an opportunistic manner

(iii) 802.11ac [7]: the AP uses only MU-MIMO transmissions on the downlink

(iv) OPUS [10]: the AP attempts MU-MIMO transmissions with user selection

(v) ADAS: it is the proposed scheme

The author sets the simulation parameters to the default values in Table 1 and the 802.11ac standard [7]. The AP and users generate traffic according to their average frame arrival rates. The author applies average frame arrival rates q and Kq to the users and the AP, respectively. The simulation time is set to five minutes, and the author measures the average value by running each simulation 100 times.

5.2. QCSI Feedback Overhead. Firstly, the QCSI feedback overhead of ADAS is evaluated by comparing it with that of 802.11ac and OPUS in Figure 6. From the result, it can be seen that as M increases, the overall overhead increases, since the

Table 1: Default simulation parameters.

Parameter	Value
Payload	1,500 B
Max. aggregation	6,000 B
q	160
M	4
K	16
r^{fd}	52 Mbps
Max. Data Rate	78 Mbps
Average SNR	25dB
Bandwidth	20 Mhz

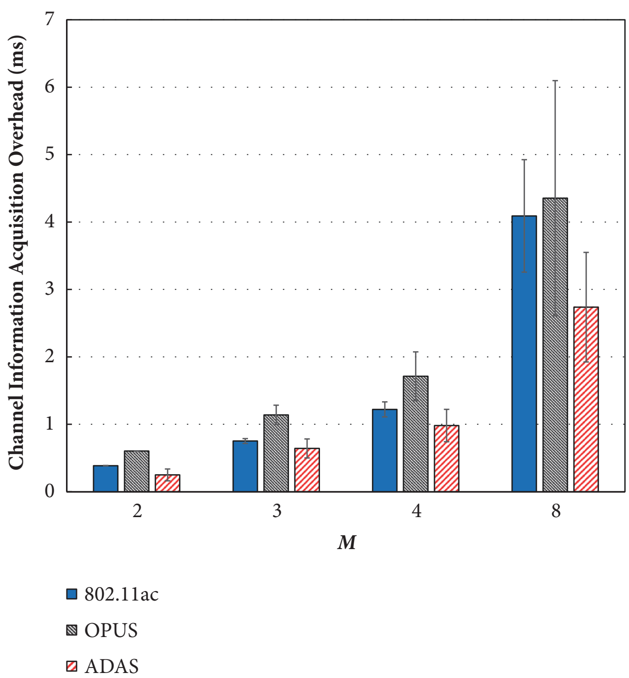


Figure 6: **QCSI feedback overhead compared to that of 802.11ac and OPUS.** ADAS shows the lowest overhead in all cases. This reduces the overhead by a maximum of 33% and 37% compared to that of 802.11ac and OPUS, respectively.

sizes of both the CSI and QCSI grow in proportion to M. For 802.11ac, the overhead increases drastically in the case of high M, since the 802.11ac AP always requests CSI feedback overheads for all candidate users (i.e., $|S| \leq M$ times). We can observe that OPUS shows a higher overhead than 802.11ac, due to the use of CSI feedback contention, which leads to the additional overhead. Note that it still benefits from much higher throughput than 802.11ac, thanks to the user selection scheme. ADAS shows the lowest overhead in all cases, compared to other protocols. In the case of $M = 8$, the overhead is reduced by 33% and 37% compared to that of 802.11ac and OPUS, respectively. This overhead reduction comes from the fact that ADAS does not require QCSI feedback overheads from all candidate users; it simply stops the QCSI acquisition if the throughput gain is no longer available.

5.3. Throughput. In this subsection, the throughput performance of ADAS is investigated. To do this, the following three metrics are used:

(i) AP throughput: this is the downlink throughput from the AP to the users. The AP can obtain throughput through FD or MU-MIMO if it wins the channel contention

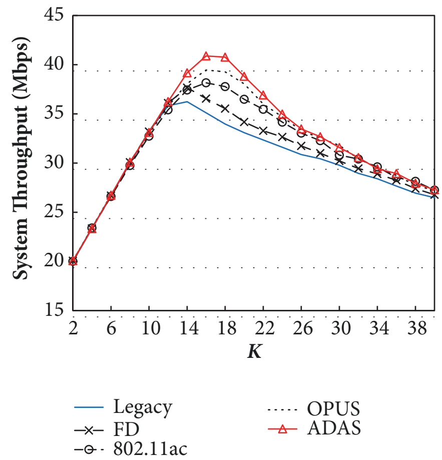
(ii) User throughput: this is the sum of the uplink throughputs from the users to the AP. Note that each user has two transmission opportunities: when it wins the channel contention and when the AP starts an FD transmission

(iii) System throughput: this is the sum of the AP throughput and the user throughput

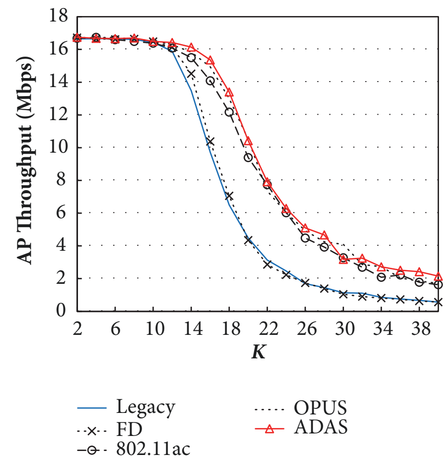
Figure 7 shows the throughput results of each protocol for different values of K and q. From Figure 7(a), we can observe that all protocols have similar throughput patterns; as K increases, the system throughput increases to a certain point, and it then decreases due to the heavy channel contention. As expected, Legacy shows the lowest performance, since it cannot take advantage of either MU-MIMO or FD. When compared to FD, both 802.11ac and OPUS show higher throughput performance, which indicates that the current network environment is favourable for MU-MIMO. From the figure, we can see that ADAS outperforms the other protocols. ADAS is, of course, better than 802.11ac, which lacks MU-MIMO enhancement techniques. In this scenario, ADAS experiences more throughput than FD, since it can benefit from active use of MU-MIMO. ADAS achieves performance improvements of 15% and 8% compared to schemes using only FD and 802.11ac, respectively. One unexpected result is that ADAS outperforms OPUS in most cases; this is because the QCSI feedback overhead is generally less than that of OPUS, as explained in the previous result of Figure 6. Also, in environments with low K, it is difficult to obtain sufficient diversity gains for OPUS.

For a more detailed analysis, the throughputs obtained by AP and users are plotted in Figures 7(b) and 7(c), respectively, for the case shown in Figure 7(a). The family of MU-MIMO protocols, 802.11ac and OPUS, show a dramatic increase in AP throughput, while the users' throughput is even less than that of Legacy. For FD, the result is opposite to that of 802.11ac or OPUS, although the gain or loss of the nodes is lower than that of MU-MIMO. The problem is that, in the case of OPUS or 802.11ac, if the gain in the AP is insufficiently large, the overall performance of the system can be limited. On the other hand, we can see that ADAS maintains the correct balance between performance of the AP and that of the users; both the AP and users achieve an equal or higher performance gain compared to Legacy.

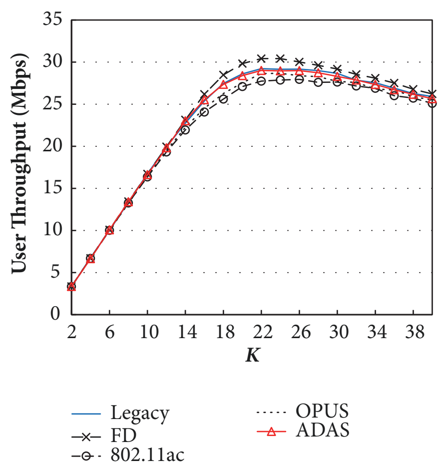
Figures 7(d), 7(e), and 7(f) show the result when the value of q is very low. As you can see from the result, FD has a higher performance than 802.11ac and OPUS. Unlike in the previous case, frame aggregation cannot be sufficiently achieved in this network environment, and thus the CSI overhead overwhelms the MU-MIMO gain. In particular, the



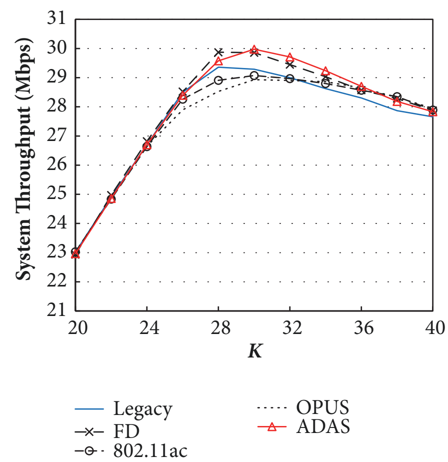
(a) System throughput ($q = 160$)



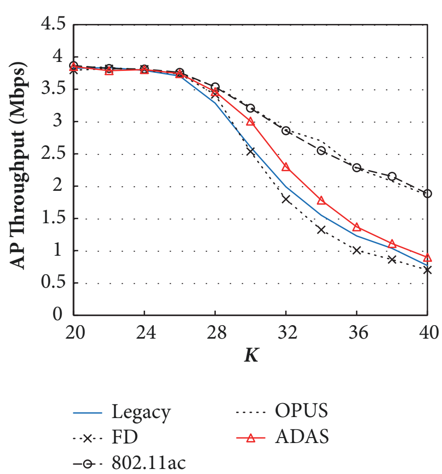
(b) AP throughput ($q = 160$)



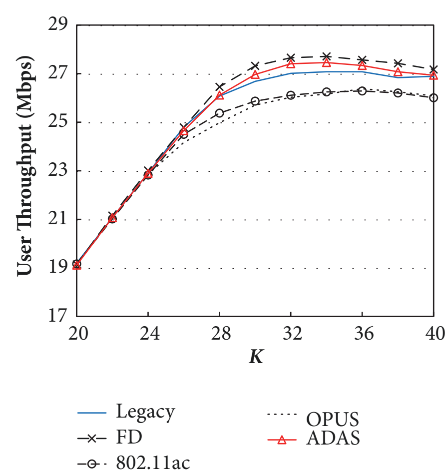
(c) User throughput ($q = 160$)



(d) System throughput ($q = 80$)



(e) AP throughput ($q = 80$)



(f) User throughput ($q = 80$)

FIGURE 7: **Throughput vs. *K*.** In this result, the network environment of $q = 160$ is favourable for MU-MIMO (a), (b), and (c), while that of $q = 80$ is favourable for FD (d), (e), and (f).

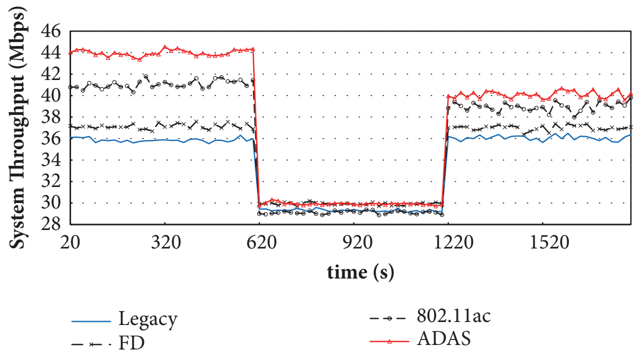


FIGURE 8: **Throughput comparison in a dynamically changing network environment.** While the existing protocols suffer from the high fluctuation in performance in dynamically changing networks, ADAS maintains high throughputs, indicating that it adapts well to dynamic network conditions.

reduction in the performance of K from 26 to 32 is lower than that of Legacy.

5.4. Dynamic Network Environment. To better analyse the performance of ADAS, the system throughput is measured while dynamically changing the network environment. The values of K and q are changed over three periods, with a total simulation time of 30 minutes. The average values of K and q are set to 16 and 160 in the first 10 minutes, 20 and 80 in the second 10 minutes, and 30 and 120 in the last 10 minutes.

Figure 8 shows the change in system throughput for each protocol. From these results, we can see that the first and the last sections are favourable for MU-MIMO, while the second is advantageous for FD. Although ADAS performs at its best in each situation, the existing protocols do not seem to adapt well to changes in network conditions. The throughputs of 802.11ac and OPUS are significantly higher in the first and last sections but suffer from performance degradation in the second section.

6. Conclusion

In this paper, a new MAC protocol is proposed called ADAS, which adaptively exploits FD and MU-MIMO technologies according to the given network environment. By effectively exchanging queue information between the AP and users, an ADAS AP can choose the best transmission strategy and enhance the performance of each technology. Rich simulation results show that ADAS can achieve higher performance gains than other protocols, especially in dynamic network environments.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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