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A novel multi-channel MAC protocol with directional antenna for enhancing spatial reuse and bandwidth utilization in WLANs☆

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ABSTRACT

This paper aims at developing an efficient MAC protocol for wireless LAN by considering multi-channel and directional antennae. Extending IEEE 802.11 to a multi-channel environment not only exploits the bandwidth utilization but also reduces the degree of contentions. Involving directional antennae in designing multi-channel MAC protocol additionally increases the spatial reuse, allowing more parallel communications. This study proposes an efficient Multi-Channel MAC protocol with a Directional Antenna (MCDA) for WLAN. Since each station is only equipped with a single antenna, communicating pairs that progress their communications on data channels cannot maintain the channel usage information which is only obtained from the control channel, raising the channel collision problem. The proposed protocol adopts the channel switch sequence (CSS) mechanism to cope with the channel collision problem and to reduce message exchange overhead for switching channels. According to the state management, MCDA then controls directional antenna transmitting data on a selected channel to exploit the opportunities of spatial reuse, and to maintain fairness among communicating pairs. Simulation results show that the proposed MCDA protocol maintains the fairness and significantly improves bandwidth utilization and throughput.

1. Introduction

IEEE 802.11 defines a contention-based MAC protocol that adopts techniques including CSMA (Carrier Sense Multiple Access), *RTS/CTS* (Request To Send/Clear To Send), and Random Backoff to avoid transmission collision, maintain the fairness among wireless stations in communication, and efficiently use bandwidth resources. However, it was designed for the single-channel environment. Extending 802.11 MAC (Medium Access Control) to the multi-channel environment can improve the channel utilization and reduce the overhead raised by data retransmissions. Moreover, a multi-channel communication environment, which allows multiple communicating pairs to transmit data simultaneously, can improve the throughput and fairness.

In the literature, some MAC protocols [10,12,13,2,8] have been proposed for extending the 802.11 MAC to the multi-channel environment. In [8], simulation results indicate that the multi-channel takes advantage of distributing stations over multiple channels and alleviates the phenomenon of transmission collision. In [12], an on-demand channel assignment protocol is developed for a multi-channel environment. However, a station that uses an antenna to communicate with another station on a specific data channel cannot overhear the channel usage information from the control channel.

The biggest challenge in developing multi-channel MAC protocol is the maintenance of the status of multiple channels. A large number of previous works [10,2] partition the bandwidth into one control channel with narrow bandwidth and several data channels. Sender and receiver that intend to communicate with each other should negotiate an available data channel by exchanging *RTS/CTS* on the control channel. All stations that stay on the control channel can maintain the status of data channels by overhearing the *RTS/CTS* message, which indicates the data channel, the communicative pair intends to use. However, when a communicative pair switches to the data channel for communication, they cannot overhear the *RTS/CTS* messages of control channel and thus cannot maintain the usage status of each data channel. When the communicative pair switches from the data channel to the control channel and intends to communicate with the other stations, they may select a channel that is currently in use since they did not maintain the valid status of data channels. To resolve the problem of missing *RTS/CTS* on the control channel, previous work [2] uses one antenna in the data channel for communication and another antenna in the

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control channel for maintaining the status of the data channel usage. However, the use of two antennae increases the hardware cost.

Additionally, MMAC [10] considers the power saving mode in a multi-channel environment by using *ATIM/ATIM-ACK/ATIM-RES* negotiations with single half-duplex transceiver to inform the neighbors of communicating pair about the data channel selection. Multiple communicating pairs located at the nearby locations can thus use different channels for communication without interference. Although several proposed MAC protocols enable multiple communicating pairs to exchange data on the multi-channel simultaneously and therefore increase throughput and channel utilization, they use an omni-directional antenna for *RTS/CTS* negotiation, resulting in inefficient spatial reuse.

Directional antenna provides more opportunities for spatial reuse. Transmission using directional antenna creates a directional signal which only interferes with other receivers in that direction. Therefore, using directional antenna enables more communicating pairs to communicate simultaneously, exploiting the spatial reuse opportunities. Previous researches [5,3,6,7,1,11,4,9] incorporate directional antennae in the design of MAC protocol to increase spatial reuse, decrease end-to-end transmission delay, and reduce power consumptions in data transmission. However, the exploitation of spatial reuse is constrained in the single-channel environment.
Developing a MAC protocol that considers both the directional antennae and multi-channel environments will exploit opportunities of spatial reuse, increase the bandwidth usage, reduce the degree of contention, and thus improve the overall performance for data transmission.

This study investigates the problems raised by considering both multi-channel and directional antennae. Collision cases are analyzed and overcome by developing an efficient multi-channel MAC protocol with a directional antenna. Performance results reveal that the protocol efficiently explores the spatial reuse opportunities, increases bandwidth utilization and reduces the packet loss, improving the network throughput.

The rest of this study is organized as follows. Section 2 introduces the preliminary. Section 3 presents the communication model and the problem statement. Section 4 gives the detail of the proposed multi-channel MAC Protocol with a directional antenna. Section 5 investigates the performance study of the proposed MCDA protocol. Conclusions are finally drawn in Section 6.

2. Preliminaries

The following subsections firstly overview the IEEE 802.11 MAC protocol. Then the characteristics of multi-channel and directional antenna are presented.

2.1. IEEE 801.11 Basic MAC protocol

IEEE 802.11 defines a contention-based MAC protocol that adopts techniques including *CSMA*, *RTS/CTS*, and Random Backoff to avoid transmission collision and maintain the fairness among wireless stations in a single-channel environment. Let a and b be the sender and receiver, respectively. In the *CSMA* technique, the sender a has to first listen to the channel for a predetermined amount of time so as to check if there is any activity on the channel. In case that the channel is sensed "idle", sender a is allowed to access channel for transmitting data to receiver b. Otherwise, sender a has to defer its transmission. Though *CSMA* technique can efficiently prevent the current transmission from collision, however, it cannot cope with the hidden node problem. Herein, an example is given below to illustrate the hidden node problem. Given three stations S, R and H, if H is "hidden" from S, it could happen that the data signal sent from S to R cannot be sensed by station H. As a result, station H might transmit data to its receiver and hence a collision is occurred at station R. To cope with the hidden node problem, the *RTS/CTS* technique should be applied. A sender S intending to exchange data with a receiver R should firstly send the *RTS* packet. Upon receiving the*RTS* packet, the receiver R simply replies with a *CTS* packet. All the other nodes that receive the *RTS* or *CTS* packets should defer their transmissions until the data exchange between S and R is finished. Furthermore, a Random Backoff mechanism is proposed in 802.11 MAC to prevent the transmissions of multiple *RTS*s from collision.

2.2. Characteristics of multi-channel and directional antenna

In wireless networks, there are three important resources, namely time, bandwidth and space. The network throughput highly depends on the management and usage of these three resources. The IEEE 802.11 MAC protocol is mainly designed for single-channel environment. Let the provided bandwidth be b. Since the time durations for inter-frame spacing including one DIFS and three SIFS are fixed, the degraded throughput can be measured by $b * (\text{DIFS} + 3 * \text{SIFS})$ for each data exchange. Therefore, a single channel with a broad bandwidth b will result in a significant impact on throughput. Alternatively, by equally partitioning bandwidth into n channels, each channel will have a bandwidth of b/n. The degraded throughput can be measured by $(b/n) * (\text{DIFS} + 3 * \text{SIFS})$. As a result, partitioning a broad bandwidth into multiple channels can improve the network throughput.

In addition, the throughput degrades as excessive competitions occurred in single-channel environment. Partitioning the overall bandwidth into multiple channels and carefully distributing the communicating pairs onto different channels will help reduce the throughput overhead raised by contention and collision. To efficiently exploit the usage of bandwidth resources, it is important to develop an efficient multi-channel MAC protocol that arranges multiple communicating pairs on different channels to proceed for their communications in parallel.

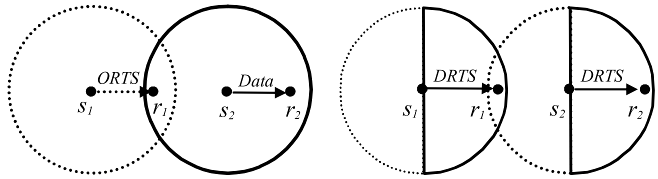
In addition to taking advantages from the good use of time and bandwidth, exploiting spatial reuse opportunities can also improve the network throughput. The use of directional antennae creates more opportunities for spatial reuse than omni-directional. The use of directional antennae in the single-channel environment has been widely discussed in previous studies [5,3,1,11,4,9]. Applying the CSMA scheme, a station transmitting data with an omni-directional antenna will block the other communications within a specific region. Fig. 1 demonstrates the advantages obtained from the use of a directional antenna.

As shown in Fig. 1(a), station s_2 uses an omni-directional antenna to communicate with station r_2. However, station r_1 is located within the communication range of s_2 and can overhear the *RTS* packet sent from s_2. As a result, station r_1 should wait for a duration defined in the *RTS* packet. Alternatively, as depicted in Fig. 1(b), if s_2 uses a directional antenna to communicate with r_2, the transmission in the left-side direction of s_2 can be set by "block" state so that the transmission of s_2 will not raise interference to r_1. Therefore the two pairs can transmit data in parallel by using directional antenna. This paper aims to develop a multi-channel MAC protocol with directional antenna to make good use of time, bandwidth and the space resources, improving the network throughput.

3. Communication model and problem statement

3.1. Communication model

The proposed protocol operates in a multi-channel communication environment with one control channel and $n-1$ data channels. Each station is equipped with a 180° directional antenna to exploit



(a) Omni-directional antenna. (b) Directional antenna.

Fig. 1. An example to illustrate the spatial reuse opportunities by using directional antenna.

the opportunities of spatial reuse in the wireless network. The operations of the directional antenna are described as follows. Each station may receive data omni-directionally, but packet collision might occur when receiving different signals at the same time. Each station can optionally block its transmission in a specific direction if necessary. Moreover, all stations need not be synchronized.

3.2. Problem statement and its challenges

In developing a MAC protocol, both the issues of network throughput and the fairness should be taken into account. A good use of the multi-channel resource that arranges several simultaneous transmissions on different channels helps reduce contention and collision of packet transmission and improve the network throughput. In addition, an appreciate control of directional antenna also helps in exploiting spatial reuse opportunities.

Using a single antenna in a multi-channel environment will encounter the challenge that the channel usage information is difficult to be maintained. For example, when a station x uses its antenna to communicate with a station y on a specific data channel, it cannot maintain the channel usage information at the same time since it does not have an additional antenna to overhear the channel usage information which only can be obtained on the control channel. Therefore, the next communication of station x may encounter the problem that it does not know which channel is available. Most previous researches use two antennae, one is used for communication on the data channel and another stays on the control channel to maintain the channel usage information. However, two antennae increase the hardware cost. How to develop a MAC protocol that uses a single antenna on a multi-channel environment but prevents the packet transmissions from collision and contention is the main goal of this paper.

Since the fact that a single antenna cannot maintain the channel usage information, one possible way is to execute the carrier sensing operation for a DIFS duration when a pair of stations, say x and y, switches to a new data channel and intends to communicate with each other on the data channel. However, in case that the selected channel is busy, the pair x and y should negotiate the next data channel, raising a large amount of control packet and time delay waiting for the available time slots to negotiate the next available channel.

This study mainly addresses the problem of how to make good use of the multi-channel resource and maintain the transmission fairness among multiple communicating pairs by carefully controlling the directional antenna. A mechanism of *Channel Switch Sequence* (*CSS*) is adopted to reduce the control overhead so that a communication pair may directly switch to the next data channel without negotiation when a busy channel is encountered. All communicating pairs can proceed for their communications simultaneously without interference while the fairness among stations can be maintained.

3.3. Definitions and notations

This subsection introduces the commonly used notations in the protocol.

Definition (*Pair*(s_i, r_i) *and Role of a Station*). *Pair*(s_i, r_i) denotes sender s_i and receiver r_i that intend to communicate with each other. The term *role* denotes the role of station. For a *pair*(s_i, r_i), *role*(s_i) is *sender* and *role*(r_i) is *receiver*. ■

For example, as shown in Fig. 2(a), station s_1 intends to communicate with station r_1. The two stations are denoted by *pair*(s_1, r_1), where *role*(s_1) is *sender* and *role*(r_1) is *receiver*.

Definition (*State*). The *state* of each station is denoted by *Action/Packet type* where *Action* might be *Listen, Send* or *Receive*, and *Packet type* might be *RTS*, *CTS*, *Data*, or *Ack*. If a station is sensing the carrier, its Action is *Listen*, and the *Packet type* has a null value. Additionally, if station is transmitting a packet, its state is *S/Packet Type*. If station is receiving a packet, its state is *R/Packet Type*, and the *packet type* could be *RTS, CTS, Data,* or *Ack*. ■

As shown in Fig. 2(a), since station *a* does not participate in any communication, the Action of station *a* is *Listen*. However, station s_1 transmits an *RTS* packet to station r_1. Therefore the state of s_1 is S/RTS, and the state of r_1 is R/RTS.

Definition (*Direction Property*). The symbols '*D*' and '*O*' are appended in the leftmost position of *Action* to respectively denote that the directional or omni-directional antenna is used for the action. ■

In Fig. 2(a), s_1 transmits an *RTS* packet to r_1 using its omni-directional antenna. Therefore the state of s_1 is denoted by *OS/RTS*. Station r_1 uses its omni-directional antenna to receive the *RTS* packet sent from s_1. Therefore the state of r_1 is denoted by *OR/RTS*. Furthermore, in Fig. 2(b), s_2 transmits a data packet to r_2 using its directional antenna. The states of s_2 and r_2 are denoted by *DS/Data* and *DR/Data*, respectively.

4. Multi-channel MAC protocol with directional antenna

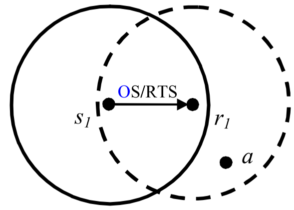
MCDA mainly consists of three Phases, namely the *Negotiation Phase*, *Communication Phase*, and *Block Phase*. In the Negotiation Phase, the sender and receiver firstly exchange the *RTS/CTS* packets on the control channel to derive the *Channel Switch Sequence* and identify their relative positions. Then the communicating pair exchanges the *RTS* and *CTS* packets on data channels to avoid the hidden terminal problem. In the Communication Phase, the communicating pair that succeeds in *RTS/CTS* negotiation on both the control and data channels can exchange data on the data channels. The Block Phase aims to handle the situation that the demanding traffic is far larger than the network capacity. Protocols developed in Block Phase will prevent that all stations inefficiently switch over the busy data channels. The following presents the detail of each phase.

4.1. The Negotiation Phase

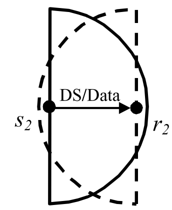
This subsection presents the protocol design and the state diagram of the negotiation phase. Then examples that illustrate the operations in the negotiation phase are given.

4.1.1. The protocol design

The proposed protocol is an extension of IEEE 802.11 DCF standard. The operations defined in IEEE 802.11 DCF are briefly



(a) Stations s_1 and r_1 exchange *RTS/CTS* on the control channel.



(b) Stations s_2 and r_2 exchange data on a data channel.

Fig. 2. Stations use an omni-directional antenna to exchange *RTS/CTS* on the control channel and use a directional antenna to exchange data on a data channel.

described in the following. The DCF proposed in 802.11 employs a CSMA/CA distributed algorithm and an optional virtual carrier sense using RTS and CTS control Frame. DCF requires a station wishing to transmit to listen for the channel status for a DIFS internal. If the channel is found busy during the DIFS interval, the station defers its transmission. The CSMA/CA and RTS/CTS schemes efficiently prevent the packet transmission from collision. However, when multiple stations sense the channel busy and defer their accesses, they will also simultaneously find that the channel is released and then try to seize the channel. As a result, collision can be occurred. In order to avoid the collision, DCF also specifies random backoff, which forces a station to defer its access to the channel for an extra period.

In Negotiation Phase, the communication pair firstly stays on the control channel, trying to access the channel for *RTS/CTS* negotiation. The competition rules for the sender to send an *RTS* packet are similar to those defined in 802.11 DCF. Therefore, in case that the receiver does not stay on the control channel, the sender will try to send the *RTS* again by applying the aforementioned rules defined in 802.11 DCF. However, the duration defined in the *RTS* packet is the number of slots required only for *RTS/CTS* negotiation. Since the Data packet is transmitted in the data channel, the time for data transmission is not taken into account in the duration field of *RTS*. Because the sender is not aware of the receiver's location, the sender should use an omni-directional antenna to transmit the *RTS* packet (*OS/RTS*) on the control channel.

Upon receiving the *RTS* packet (*OR/RTS*), the receiver extracts the *Sender ID* from the *RTS* packet and uses their *ID*s to generate a *Channel Switch Sequence* (*CSS*). Then the receiver identifies the sender's relative location according to the direction of received *RTS* packet. After that, the receiver waits for a SIFS duration and uses its directional antenna to send a *CTS* packet (*DS/CTS*) on the control channel. Notice that the duration field of the *CTS* packet is set by null value. Upon receiving the *CTS* packet, the sender also identifies the receiver's direction and extracts the *Receiver ID* from the *CTS* packet. Finally, the sender and receiver will derive a *CSS* based on their *ID*s, as a reference for the data channel selection. Because the *CSS* is generated by *ID*s of both the sender and the receiver, they derive the same *CSS*. The *CSS*s of different communication pairs are likely to be different since their *ID*s are different. This implies that different communication pairs likely select different data channels for communication, avoiding collision occurred in the same data channel. After the *RTS/CTS* negotiation of a communicating pair on the control channel, the other senders can exchange *ID*s with their receivers by *RTS/CTS* negotiation on the control channel. The design of *CSS* exhibits several advantages. A major advantage is that when a communication pair, say $pair(s_i, r_i)$ selects a data channel which is in use by the other communication pair, $pair(s_i, r_i)$ may select another data channel without negotiation on the data channel since sender s_i and receiver r_i have a common *CSS*.

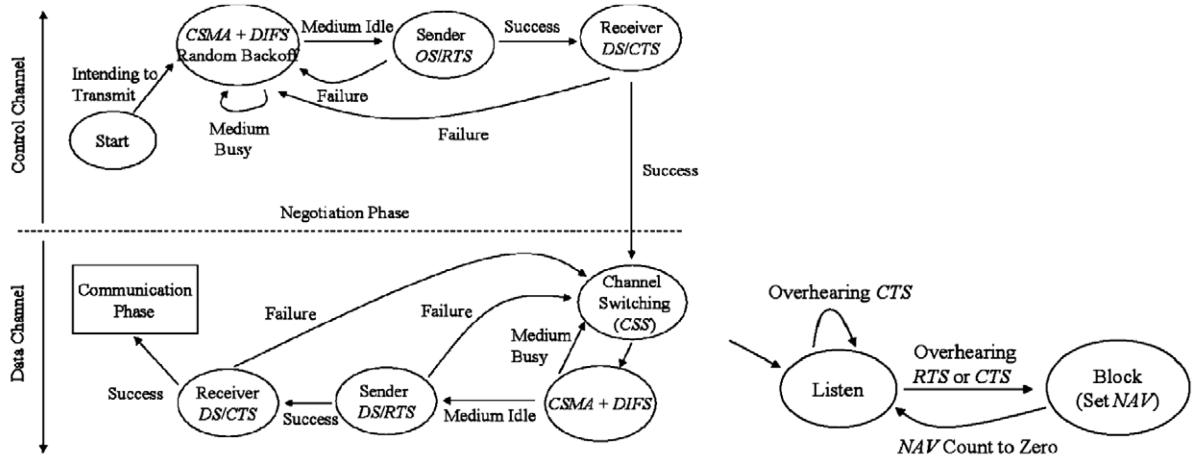
After completing the RTS/CTS negotiation on the control channel, an additional RTS/CTS negotiation on the data channel is required in the Negotiation Phase. Although the use of *CSS* has significantly reduced the probability of collision, however, two communicating pairs might switch to the same data channel because their *CSS*s have common channels. Therefore, *RTS/CTS* negotiation is required on the data channel.

When the communicating pair completes the *RTS/CTS* negotiation on the control channel, they switch to a data channel according to the *CSS*. This pair waits for a DIFS duration on the data channel to ensure that the medium is idle. Then the sender uses its directional antenna to transmit an *RTS* packet to the receiver (*DS/RTS*). Upon receiving the *RTS* packet successfully, the receiver listens for an SIFS duration. In case that the medium is idle, the receiver uses its directional antenna to transmit a *CTS* packet to sender. In the meanwhile, the sender uses an omni-directional antenna to receive the *CTS* packet. Then both sender and receiver enter the Communication Phase. However, if the sender detects that the medium is busy during the carrier sense period, the sender immediately switches to the next channel according to the *CSS*. This will cause the receiver to be unable to receive any message. After listening for a DIFS duration, the receiver also switches to the next channel.

In case that the receiver detects the busy medium during the carrier sense period, it will check whether or not the received signal source is located at the same side with its sender. If yes, the receiver will immediately use its directional antenna to transmit a *Warning* packet to its sender, preventing the sender from transmitting *RTS* packet and notifying sender to switch channel immediately. Then the sender and receiver switch to another data channel according to their *CSS* and compete for the opportunity of transmitting *Data/Ack* again. On the contrary, if the signal source is located at the different side with the sender, the receiver will immediately switch to the next data channel. After transmitting the *RTS* packet, if the sender waits for a SIFS duration but does not receive any *CTS* packet, the sender will switch to another data channel according to the *CSS* and compete to access that channel. The state diagram of the negotiation phase is shown in Fig. 3.

4.1.2. Example of Negotiation Phase

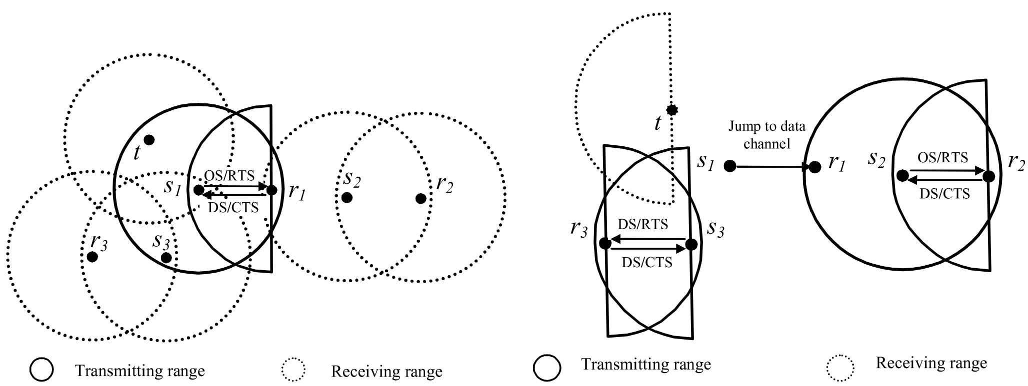
This subsection gives an example to illustrate the operations of negotiation phase. As shown in Fig. 4(a), sender s_1 intends to communicate with receiver r_1. Sender s_1 uses an omni-directional antenna to send an *RTS* packet (*OS/RTS*) to r_1 on the control channel. Upon receiving the *RTS* packet from s_1, r_1 uses the directional antenna to reply with a *CTS* packet (*DS/CTS*) to s_1. Herein, because both stations s_3 and t overhear *RTS* packet transmitted from s_1, they will block their right-side directional antennae for a duration defined in the duration field of *RTS* packet. As shown in Fig. 4(b), if station s_3 intends to communicate with receiver r_3, s_3 will firstly use the directional antenna to send the *RTS* (*DS/RTS*) in the unblocked direction. When s_1 and r_1 finish *RTS/CTS* negotiation, they will independently derive a *CSS* according to their *ID*s and then switch to the selected data channel based on *CSS*. Another pair (s_2, r_2) then starts to exchange *RTS/CTS* on the control channel. Notice that the *RTS* transmitted by s_2 cannot be overheard by r_1 since r_1 has switched to the data channel at that time.



(a) State diagram of sender and receiver in the Negotiation Phase.

(b) State diagram of other stations in the Negotiation Phase.

Fig. 3. State diagram of sender, receiver and other stations in the Negotiation Phase.



(a) Sender s_1 uses an omni-directional antenna to transmit an *RTS* (*OS/RTS*) to r_1. Receiver r_1 replies with a *CTS* packet (*DS/CTS*) by using the directional antenna.

(b) *Pair*(s_1, r_1) switches to the data channel after completing *RTS/CTS* negotiation. Then *pair*(s_2, r_2) and *pair*(s_3, r_3) start their *RTS/CTS* negotiations.

Fig. 4. An example for illustrating the operations designed in the Negotiation Phase.

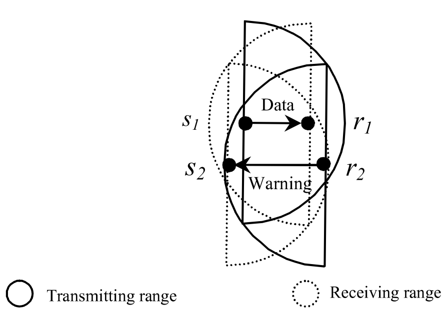


Fig. 5. Cases of *pair*(s_2, r_2) switching from one data channel to another by using the Warning packet.

Fig. 5 shows the scenario that *pair*(s_2, r_2) switches from one data channel to another. After *pair*(s_2, r_2) switches to the *j*th data channel, station r_2 detects that the medium is busy and uses the left-side directional antenna to send a Warning packet to s_2, informing s_2 to switch channel immediately. Thus, *pair*(s_1, r_1), which is already in communication, can proceed for their communication without interference raised by the later communicating pairs.

In the Negotiation Phase, the sender and receiver will execute the *RTS/CTS* negotiation on both control and data channels to protect the data transmission from interference. After executing the Negotiation Phase, the communicating pair selects an idle channel for communication. The sender and receiver then execute the operations illustrated in the Communication Phase.

4.2. The Communication Phase

4.2.1. The protocol design

The communicating pairs that complete the Negotiation Phase can obtain the opportunity of data transmission on the data channel. Thus, the sender and receiver enter the Communication Phase and use directional antenna to send *Data* and *Ack*, respectively. Although the *CSS* can distribute multiple pairs onto different channels in most cases, however, it might occur that two pairs select the same data channel. Therefore, an overhearing for a duration of DIFS and an *RTS/CTS* exchange are required before *Data/Ack* transmission.

According to the above-mentioned policy, the proposed protocol naturally exhibits the *first-come-stay* policy to maintain fairness. That is, the communicating pair that switches to the data channel earlier stays on the data channel if a collision occurs. To achieve this, the priority is assigned according to the order of packet types transmitting on the data channel. As shown in Fig. 6, the priority values of the "carrier sense", "transmitting *RTS* packet", "transmitting *CTS* packet", and "transmitting *Data* or *Ack* packets", is 'lowest', 'low', 'middle', and 'high', respectively. When collision occurs in the data channel, the pair with a lower priority will switch

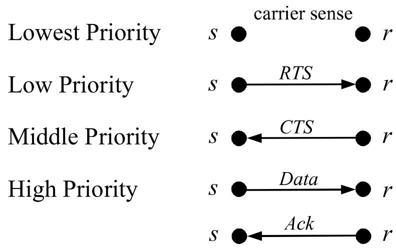


Fig. 6. The priorities of packet transmissions.

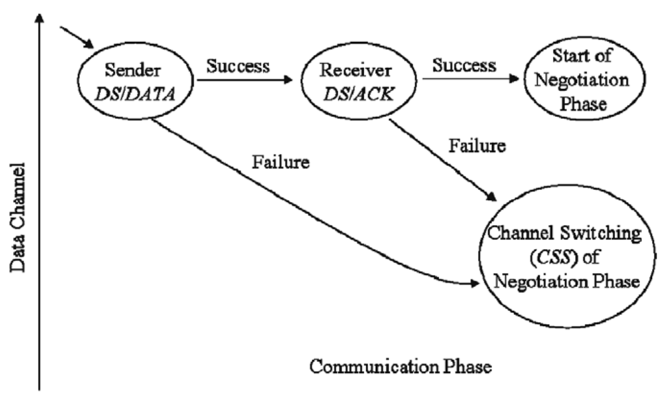


Fig. 7. State diagram of *Communication* Phase.

to the other data channels and then again compete for the opportunity of channel access.

The state diagram of the Communication Phase is shown in Fig. 7.

4.2.2. Example of Communication Phase

Herein, two examples are given to illustrate the operations in the Communication Phase. Fig. 8(a) depicts an example that illustrates the competition of two transmissions with 'Lowest' and 'Low' priorities. Station s_1 is transmitting *RTS* packet on some specific data channel. Meanwhile, *pair*(s_2, r_2) also switches to the same data channel. Since s_2 is located within the transmission range of s_1, s_2 executes carrier sense and detects that the medium is busy. Hereafter, s_2 immediately transmits a Warning packet to r_2 using directional antenna and then switches to another data channel according to its *CSS*. Upon receiving the Warning packet, r_2 will also switch to the next data channel. Fig. 8(b) shows another competition of transmissions with 'Middle' and 'High' priorities. Assume that *pair*(s_1, r_1) and *pair*(s_2, r_2) select the same data channel. Let sender s_1 transmit data (High Priority) to receiver r_1 and station r_2 detects that the medium is busy. Station r_2 will uses the left-side directional antenna to send a Warning packet to s_2, informing s_2 of channel switching. Thus, stations s_1 and r_1 which is communicating with each other will not be interfered by the later communicating pairs.

In the Communication Phase, the proposed protocol guarantees that the pair with higher priority can stay on the occupied channel for maintaining the transmission fairness. The pair that earlier accessed the data channel will not suffer interference from later pairs which also intends to access the same data channel. In the worst case in which many pairs with the same priority intend to access the same data channel, the protocol also guarantees at least one pair for successful communication. Other pairs use their channel switch sequences to switch to the other channels.

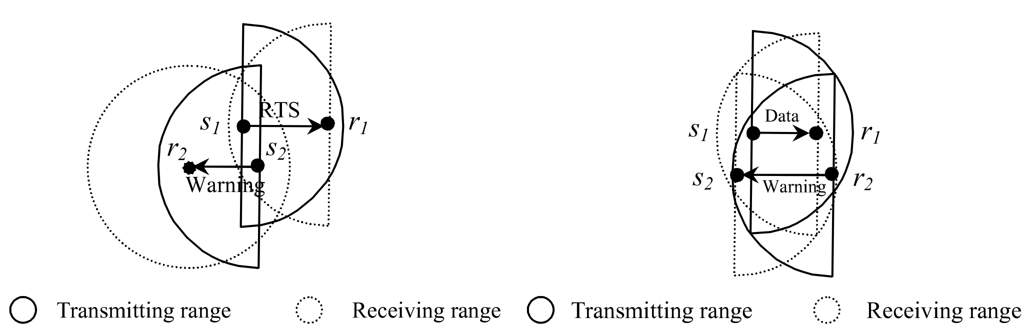
4.3. The Block Phase

4.3.1. The protocol design

The design of *CSS* enables the communicating pair to select a data channel without negotiation. However, in case that the number of available data channels is far smaller than the number of pairs that intends to communicate or the demanding traffic is larger than the network capacity, communicating pairs might incessantly switch data channels, increasing the channel switching overhead and power dissipation. This study proposes a Block Phase to cope with this situation. Initially, each communicating pair switches channels according to its own *CSS*. If a communicating pair is still unable to communicate after visiting all data channels, this pair switches to Block Phase. The communicating pairs that stay in Block Phase switches to the first data channel in its *CSS*, waiting for a channel access opportunity until the medium is idle. Since there may exist some communicating pair using directional antenna to proceed for their communication, some rules should be involved in the design of Block Phase to avoid the packet collision.

Rule1: If the receiver overhears packets from the direction of its sender, the receiver immediately sends 'Stop' packet to its sender using its directional antenna toward the direction of its sender. A duration field will be included in the Stop packet. The receiver will set its *Network Allocation Vector*(*NAV*) according to the overheard packet and copy the NAV value to the duration field of the Stop packet, notifying the sender to wait for the same duration and then start to compete the access right of the channel.

Rule2: If the receiver overhears packets from the opposite direction of its sender, the receiver waits for an SIFS duration, and then sends a 'Stop' packet to its sender using directional antenna toward the direction of its sender.



(a) When sender s_2 detects a busy medium, it transmits a Warning packet to receiver r_2, notifying receiver for channel switch.

(b) If receiver r_2 detects a busy medium, it sends a Warning packet to sender s_2, notifying sender for channel switch.

Fig. 8. Examples showing that the *pair*(s_2, r_2) switches from one data channel to another by using a Warning packet.

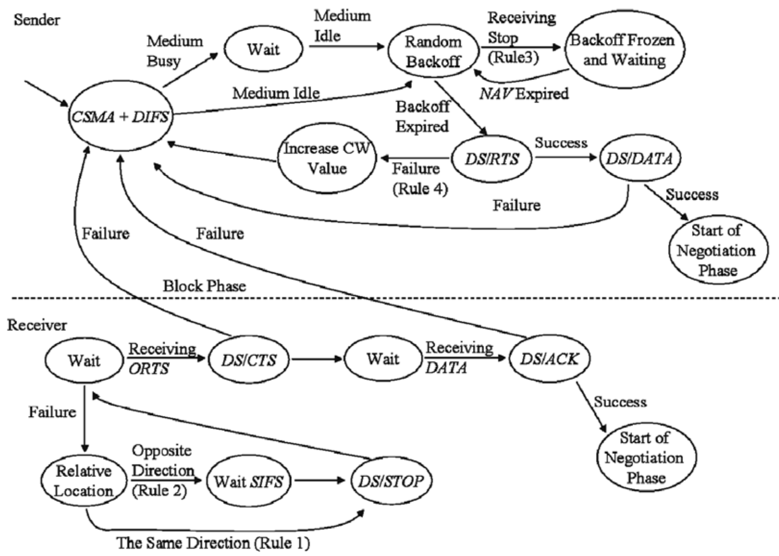
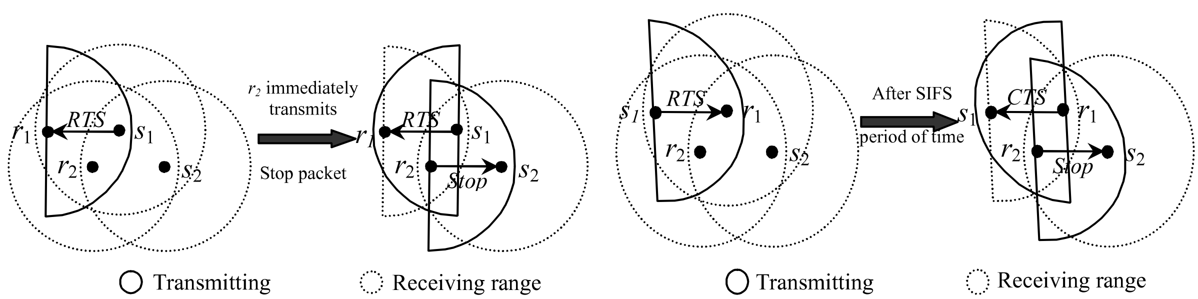


Fig. 9. State diagram of sender and receiver in Block Phase.



(a) Rules 1 and 3 designed in Block Phase.

(b) Rules 2 and 3 designed in Block Phase.

Fig. 10. *Pair*(s_2, r_2) which has switched over all data channels but still unable to access the data channel will enter the Block Phase.

Rule3: If the sender receives a Stop packet from its receiver, the sender immediately stops its Backoff timer countdown, sets its NAV filed by value according to the duration field of the received Stop packet, blocks the directional antenna toward the origin of the Stop packet, and waits for a competition for channel access.

Rule4: If the sender sends an *RTS* packet and does not receive the *CTS* packet from its receiver after waiting for an SIFS period of time, then it has lost the channel access competition. The sender then increases its CW (Contention Window) value and resets its Random Backoff timer.

The state diagram of the block phase is given in Fig. 9.

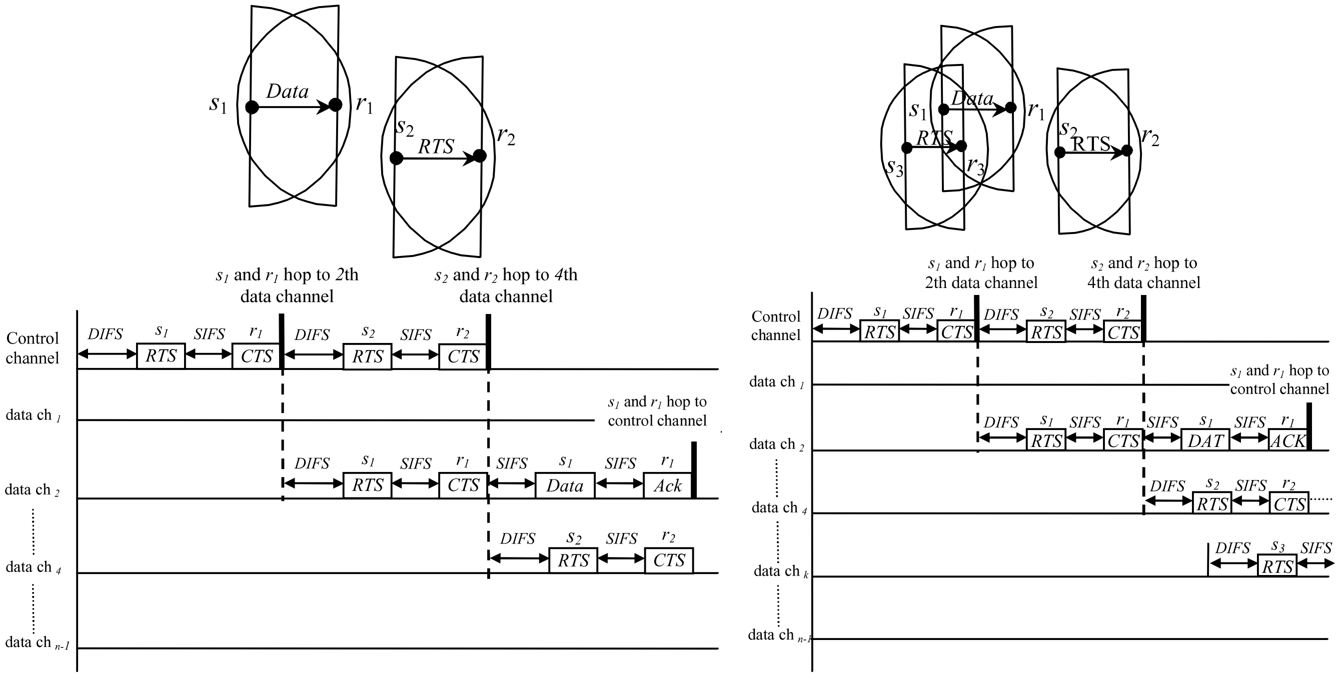
4.3.2. Example of Block Phase

Fig. 10 gives an example to illustrate Block Phase operations. Assume that the communicating pairs far outnumber the data channels. If *pair*(s_2, r_2) has switched over all the data channels according to its *CSS*, then *pair*(s_2, r_2) switches to the first data channel in its *CSS*, enters Block Phase, and waits for another channel access opportunity on the data channel. As Fig. 10(a) depicts, when station r_2 stays in Block Phase but overhears an *RTS* packet from other station in the same direction as station s_2, r_2 immediately uses its right-side directional antenna to send a Stop packet to s_2. Upon receiving the Stop packet from r_2, s_2 immediately stops its Backoff timer countdown, sets its *NAV* counter, and blocks its left-side directional antenna. Station s_2 continues its Backoff timer countdown after waiting for an *NAV* duration, and competes for an *RTS/CTS* negotiation opportunity. As Fig. 10(b) depicts, station r_2 enters Block Phase but overhears the *RTS* packet from another pair in the opposite direction of s_2, station r_2 sends a Stop packet using its right-side directional antenna after waiting for an SIFS period of time. Upon receiving the Stop packet from r_2, s_2 immediately stops its Backoff timer countdown, sets its *NAV* counter, and blocks its left-side directional antenna. After waiting for the *NAV* duration, s_2 continues its Backoff timer countdown, competing for the opportunity of channel access. Finally, if s_2 sends an *RTS* packet and does not receive a *CTS* packet from its receiver after SIFS duration, then it has lost the channel access opportunity. The sender station increments its CW value and resets its Random Backoff counter.

The Block Phase is designed to prevent communicating pairs from incessantly switching over data channels owing to the crowded data channels, thus alleviating the increase in channel switching overhead.

4.4. Examples by applying the MCDA protocol

This subsection gives complete running examples to illustrate the execution of MCDA protocol. Fig. 11 illustrates the basic concept of the proposed protocol. Let *pair*(s_1, r_1) obtain the opportunity to access the control channel firstly, and use their *IDs* to create a data channel switch sequence (2, 5, 4, 1, 3). As shown in Fig. 11(a), after the negotiation of *RTS/CTS* on the control channel, *pair*(s_1, r_1) switches to the data channel 2 and waits for a DIFS duration. Since channel 2 is idle, s_1 uses its right directional antenna to transmit *RTS* to r_1. Upon receiving the *RTS* packet, r_1 uses its left directional antenna to reply s_1 with a *CTS* packet.



(a) An example in which two pairs proceed for their communications on different channels.

(b) $Pair(s_1, r_1)$ and $pair(s_3, r_3)$ select a common data channel. The first $pair(s_1, r_1)$ stays on the selected channel and another pair uses channel switch sequence to select another channel for communication.

Fig. 11. The proposed MAC protocol uses a directional antenna and channel switch sequence to select a data channel from the multi-channel, exploiting opportunities of spatial reuse and alleviating the contention phenomenon.

Then s_1 and r_1 use directional antennae to exchange *Data* and *Ack* on the data channel 2. After the negotiation of *RTS/CTS* on the control channel, $pair(s_2, r_2)$ also derives its data channel switch sequence, say (4, 1, 3, 5, 2). Therefore, $pair(s_2, r_2)$ switches to the data channel 4 and exchanges *RTS/CTS/Data/Ack* on channel 4. Thus $pair(s_1, r_1)$ and $pair(s_2, r_2)$ can proceed for their communication simultaneously.

Because the *IDs* of $pair(s_1, r_1)$ and $pair(s_2, r_2)$ are different from each other, the two pairs are likely creating different channel switch sequences and select different channels for transmitting data. Moreover, since the channel switch sequence is created by the *IDs* of sender and receiver, which could be obtained from the *RTS/CTS* packets on the control channel, the sender and receiver can derive the same channel switch sequence and require no further negotiation for channel switch on a data channel, even though the data channel they intend to access is busy. Fig. 11(b) gives another example that two pairs switch to the same channel. Let pair (s_3, r_3) also derives a channel switch sequence after obtaining the opportunity of *RTS/CTS* negotiation on the control channel. Stations s_3 and r_3 switch to the data channel 2 based on the channel switch sequence. Before transmitting data, station r_3 performs carrier sense and overhears the data packet transmitted from s_1. When r_3 detects that s_1 and s_3 are both located at its same side, the transmission of r_3 using left-side directional antenna will not interfere with the packet reception at r_1 which is located at the right side of s_1. Then, r_3 uses the left-side directional antenna to transmit a *Warning* packet to s_3 immediately and switches to the next channel, say channel k, according to the channel switch sequence. Upon receiving the *Warning* packet, s_3 also switches to channel k. Both s_3 and r_3 listen for a DIFS duration and ensure that the medium is idle. Then s_3 and r_3 communicate on channel k. Consequently, all communicating pairs can proceed for their communication simultaneously without interference. The fairness also can be maintained since the late-arriving pair will switch to another channel if there are two or more pairs staying on the same data channel. The above example also shows that multi-channel and directional antenna are involved in the design to exploit the reuse opportunities for space, time, and channel resources.

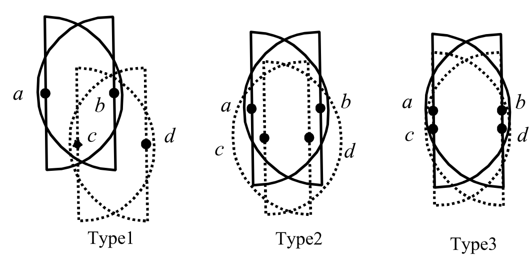
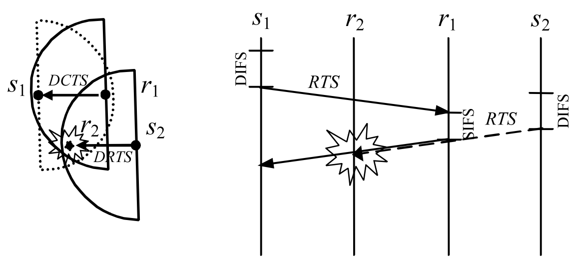


Fig. 12. The solid and dash lines denote two different communicating pairs. According to the relative position of these four stations, interference occurring in the two pairs can be categorized by three types.

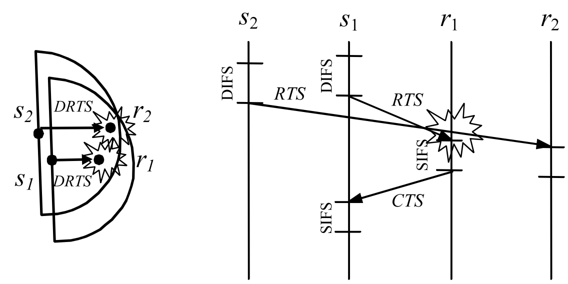
4.5. Analysis of interference types and the proposed MAC handling

This subsection analyzes the interference cases resulting from exploiting spatial reuse using a directional antenna. The proposed protocol is applied in each case to show its correctness and efficiency. Consider two communicating pairs, pair of a and b and pair of c and d. To analyze all possible interference cases, none of these four stations are assigned a specific role (sender or receiver). That is, if station a plays a sender role, station b plays the receiver role, and vice versa. According to the relative location of the two pairs, the interference cases can be categorized into three types as depicted in Fig. 12. In Type 1 interference, only one station, say c, suffers interference from another communicating pair a and b. In Type 2 interference, both stations c and d suffers interference from the other two stations a and b. Type 3 is more complicated. Pair of a and b and pair of c and d are interfered with each other.

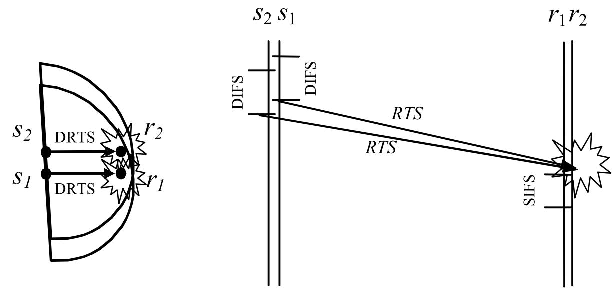
In the following, examples are taken to illustrate how the proposed protocol handles each interference type. Fig. 13(a) illustrates Type 1 interference. On a specified data channel, there is a communication pair (s_1, r_1). When s_1 transmits the *RTS* packet using



(a) Example of Type 1 interference.



(b) Example of Type 2 interference.



(c) Example of Type 3 interference.

Fig. 13. Cases of three types of interference.

the right-side directional antenna (*DS/RTS*), another communicating pair, sender s_2 and receiver r_2, also switches to the same data channel. However, s_2 is not located in the communication range of s_1, resulting in s_2 missing the *RTS* packet. Therefore, when executing carrier sense for a DIFS duration, s_2 also sends *RTS* packet to r_2 using the left-side directional antenna (*DS/RTS*). Meanwhile, r_1 has successfully received the *RTS* packet from s_1, and replies s_1 with a *CTS* packet using its left-side directional antenna (*DS/CTS*). However, r_2 is located within the communication range of r_1, causing collision to occur at r_2. Since *pair*(s_2, r_2) has exchanged the *RTS/CTS* packet on the control channel, station r_2 is aware that station s_2 is located at the right side of r_2. To handle this situation (Type 1 interference), r_2 switches to the next data channel according to its *CSS*. When s_2 waits for a duration but does not receive any control packet from r_2 on the data channel, s_2 will also switch to the next data channel according to its *CSS*. *Pair*(s_1, r_1), that first switches to the common data channel, can therefore transmit data successfully while the fairness is maintained.

Fig. 13(b) shows a case of Type 2 interference. *Pair*(s_1, r_1) switches to a certain data channel prior to *pair*(s_2, r_2). Assume that r_2 overhears the *RTS* packet sent by s_1 and detects that s_1 and s_2 are located at the same side. Station r_2 immediately uses its left-side directional antenna to send a Warning packet to s_2. The transmission of the Warning packet will not interfere with r_1 since r_1 and r_2 are located at the same side. The Warning packet is a short packet and is transmitted by a directional antenna. The use of Warning packet makes sender s_2 to be aware that the medium is busy. Upon receiving the Warning packet, the sender s_2 should switch to another data channel according to its *CSS* and compete again for the access right of that channel.

Fig. 13(c) illustrates the case of Type 3 interference. Similar to previous assumption, *pair*(s_1, r_1) switches to a certain data channel prior to *pair*(s_2, r_2). After carrier sensing for a DIFS duration, s_1 immediately uses its right-side directional antenna to send an *RTS* packet (*DS/RTS*) to r_1. Meanwhile, both s_2 and r_2 overhear the *RTS* packet sent by s_1 because s_1 and s_2 are closed to each other and r_1 and r_2 are closed to each other. When $r_2$overhears the *RTS*packet sent by s_1 and detects that s_1 and s_2 are located at the same side, r_2 uses its left-side directional antenna to send a Warning packet to s_2 and then switches to the next data channel. Meanwhile, s_2 also overhears the *RTS* packet sent by s_1 and immediately switches to the next data channel. Therefore, *pair*(s_2, r_2) switches to another data channel according to their channel switch sequence. However, pair (s_1, r_1) also switches to another data channel due to the receiving of Warning packet sent by r_2. Since this type of interference is raised due to the locations of senders and receivers of two communication pairs are very closed which will be happened in a very small probability in real cases, therefore the case of Type 3 interference will not significantly impact the overall performance. From the above descriptions, the Warning packet incorporated with the *CSS* can avoid the collision raised by two pairs selecting a common channel and to maintain fairness among multiple communicating pairs.

Since the directional antenna is adopted, a communication pair may not be aware of the communication of another pair on the same data channel, causing co-channel interference. The protocol uses Warning packets in conjunction with directional antenna to prevent the transmissions from collision on data channels and to maintain fairness. Communicating pairs that require to switch to another data channel also save the negotiation process of channel selection because the channel switch sequence is already known by both sender and receiver.

5. Performance study

This section presents the performance study of the proposed MAC protocol in terms of throughput, packet delay, and channel utilization. The performance results are obtained from the average values of ten experiments. The size of network was set to 1000 m $\times$ 1000 m, while the radio transmission range of a station was set by a constant 250 m and the bandwidth of each channel was set by 2 Mbps. The size of each packet was 512 bytes, and memory buffer held up to 50 packets. Performance was evaluated in both single-channel and multi-channel environments. In the single-channel environment, only one channel is used for control and data transmissions whereas the multi-channel environment has one control channel and three data channels. In the multi-channel environment, stations applying IEEE 802.11, MMAC [10], D-MAC [5], and OPDMAC [1] protocols randomly selected a data

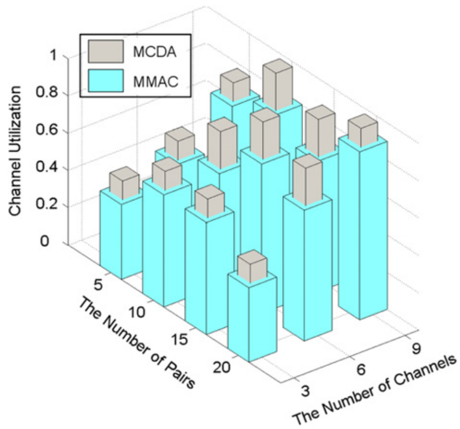


Fig. 14. The comparison of MCDA and MMAC in terms of channel utilization.

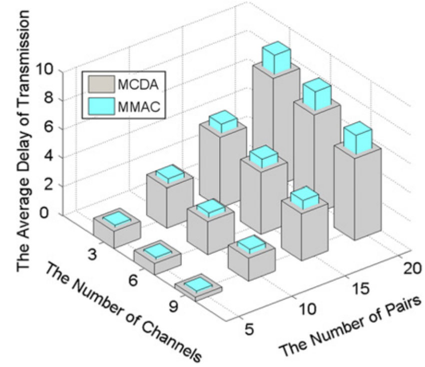


Fig. 15. The comparison of MCDA and MMAC in terms of average transmission delay with different numbers of communication pairs and channels.

channel for communication. In case a channel was selected by more than one communicating pairs, these pairs competed for channel access.

First, the proposed protocol (denoted as MCDA) was compared with the MMAC [10] which is major designed for a multi-channel environment. The MMAC assumes that each wireless device is equipped with an omni-directional antenna. Different from the MMAC protocol, the proposed MCDA protocol is equipped with the directional antenna, and therefore, the performance of the propose MCDA obviously outperforms the MMAC in terms of channel utilization, average delay of transmission, and throughput because of the spatial reuse. In order to fairly compare these two protocols, the network environment of the proposed MCDA protocol should be changed. We assume that each station is equipped with an omni-directional antenna. The following two figures compare the proposed MCDA and MMAC in terms of channel utilization and average delay of transmission.

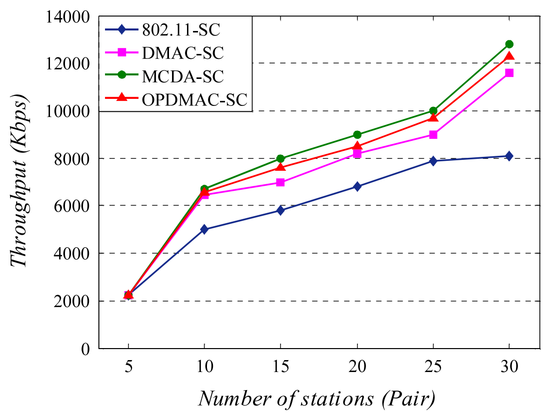
Fig. 14 compares the proposed MCDA and MMAC in terms of channel utilization whose value is normalized between 0 and 1. The channel utilization is measured by the ratio of idle time and the total experimental time. When the number of channels are three, the proposed MCDA outperforms MMAC in terms of channel utilization in all cases because that MMAC asks all stations switching to the same channel in each ATIM-window and all the other channels are idle during the ATIM-window, resulting in a low channel utilization.

Fig. 15 compares MCDA and MMAC in terms of average transmission delay by varying the number of channels and the number of communication pairs. When the number of channel is fixed, the average transmission delays of both MCDA and MMAC are increased with the number of pairs due to the increased contentions and collisions. However, when the number of pairs is fixed, a broader bandwidth can reduce the average transmission delay. Therefore, the average transmission delays of both MCDA and MMAC are decreased with the number of channels. In general, the proposed MCDA uses channel switch sequence to distribute all communication pairs onto the data channels and hence reduces the number of contentions and collisions. Although the MMAC arranges the communication pairs to different data channels, however, the delay raised from the negotiation in the ATIM-Window and the collision and contentions in the data channel result in a significant average transmission delay.

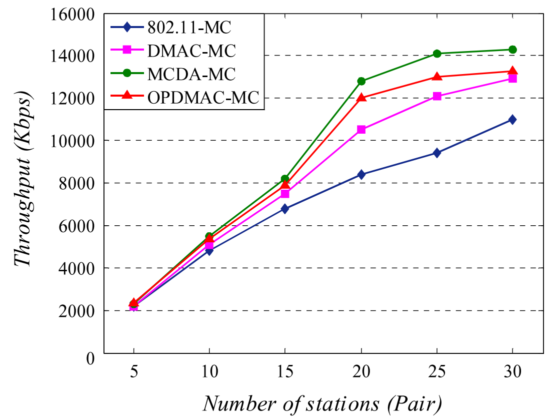
Afterward, the proposed MCDA protocol was compared with IEEE 802.11 (denoted as 802.11), D-MAC (denoted as DMAC), and OPDMAC protocols which equip with the directional antennae. In [5,1], n directional antennae were applied. Herein, D-MAC and OPDMAC with $n = 2$ were compared with the proposed protocol. Performance was evaluated in both single-channel (denoted by SC) and multi-channel (denoted by MC) environments. Two parameters, the number of stations and packet arrival rate, were varied to investigate their impacts on throughput, transmission delay, and channel utilization. The number of pairs of stations is ranging from 5 to 30 while the packet arrival rate is controlled from 150 to 1000 packets/s.

Fig. 16(a) compares the throughput of four protocols in a single-channel environment. The packet arrival rate was set by 1000 packets/s. The throughput of all four protocols increased with the number of stations. In the IEEE 802.11 protocol, since the transmissions of *RTS*, *CTS*, *Data*, and *Ack* are omni-directional, few opportunities of spatial reuse were exploited, increasing the contentions and collisions. Therefore, the throughput of 802.11 increases slowly when the number of pairs exceeds twenty. When the number of communication pair larger than 25, the throughput of 802.11 keeps a constant value. This indicates the capacity for communications is saturated. However, in the single-channel environment, D-MAC, OPDMAC and MCDA effectively explore the opportunities of spatial reuse. Therefore, the throughput increases with the number of communication pairs. Compared with 802.11 MAC protocol, the throughput improvement of D-MAC, OPDMAC and MCDA achieves 25%–40%. When the number of communication pairs exceeds 30, the throughput of D-MAC, OPDMAC and MCDA keeps a constant value owing to the full utilization of communication capacity. Because that MCDA worked in a single-channel environment cannot use the channel switch sequence for distributing communicating pairs over multiple channels, its throughput was similar to that of D-MAC, and OPDMAC.

Fig. 16(b) shows the throughput of the four protocols in a multi-channel environment. In 802.11, D-MAC, and OPDMAC, using random selection as the channel selection policy may arrange more than one communication pairs on the same channel. In this case, too many communication pairs compete to access the channel, raising collision and contention problem and therefore resulting poor performance in throughput. The proposed MCDA uses *CSS* to effectively distribute the communication pairs on different data channels. Although it is possible that two or more pairs switch to the same channel, the priority scheme designed in MCDA protects the pair that first switches to the channel and all the other pairs will automatically switch to the next channel according to their *CSS* without any additional negotiation. Therefore MCDA allows more communication pairs to proceed their communicating simultaneously, improving the performance in terms of throughput. As shown in Fig. 16(b), the throughputs of four mechanisms are similar when the number of communication pairs is few. However, when the number of communication pairs increases, the throughputs of D-MAC and OPDMAC are better than one of 802.11 because that D-MAC and OPDMCA exploit the spatial reuse opportunities. Moreover, the OPDMAC outperforms the DMAC

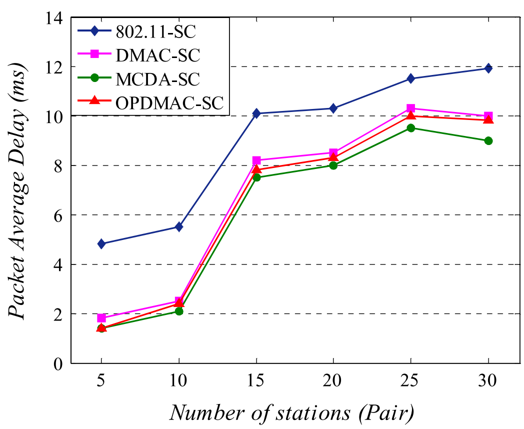


(a) Throughput study in a single-channel environment.

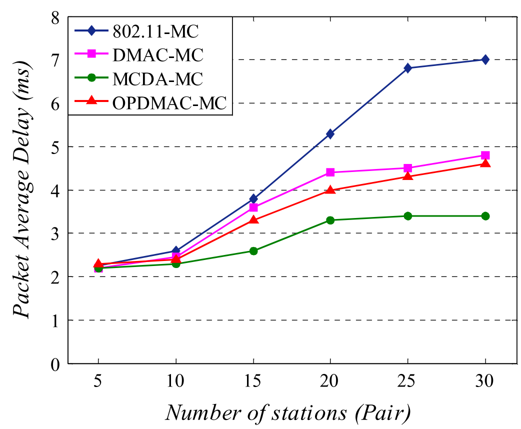


(b) Throughput study in a multi-channel environment.

Fig. 16. On the comparison of four protocols in terms of throughput in the single-channel and multi-channel environments.



(a) Study of average packet delay in a single-channel environment.



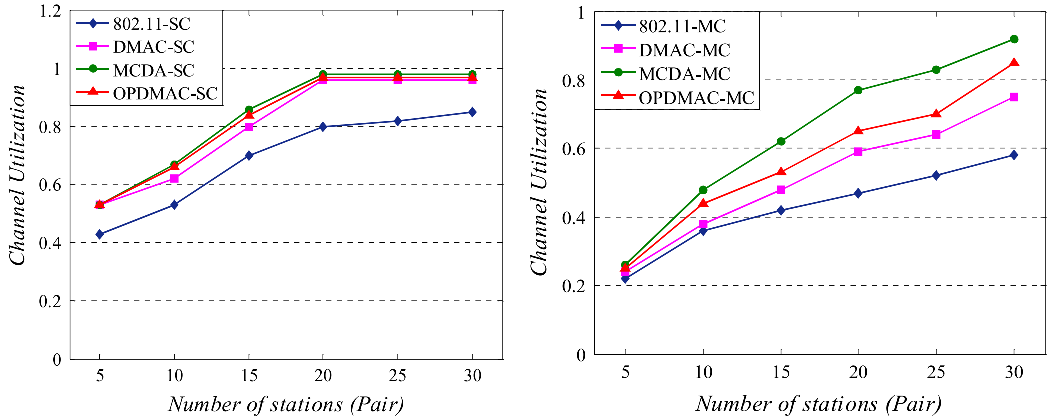
(b) Average packet delay in a multi-channel environment.

Fig. 17. The impact of the number of stations on packet average delay.

because that OPDMAC does not force the nodes to resort to idle backoff when a node experiences contention in one direction. In general, MCDA outperforms the other three mechanisms in terms of throughput when the number of communication pairs increases.

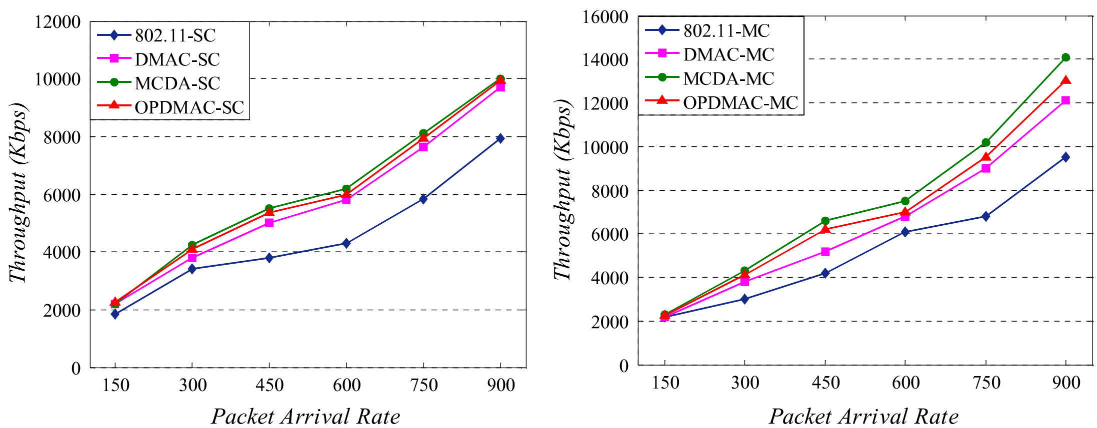
Fig. 17 shows the impact of the number of stations on packet delay. The packet delay is measured by the duration from the time the packet arrives in memory buffer to the time the packet has been sent successfully. Fig. 17(a) shows the comparison of packet delay of the four protocols in a single-channel environment. Generally, the average packet delay increased with the number of stations owing to the increasing number of competitors for channel access in network. The 802.11 mechanism that uses an omni-directional antenna blocks parallel communications and thus increases the packet delay time. As shown in Fig. 17(a), the average packet delay of 802.11 increases with the number of communication pairs. In comparison with 802.11 in single-channel environment, the D-MAC, OPDMAC, and MCDA use directional antenna to exploit the spatial reuse opportunities, allow more parallel communications. Therefore the average packet delay increases more slowly than 802.11. In the single-channel environment, MCDA cannot use channel switch sequence to improve the collision and contention problem, thus its performance in packet delay is similar to D-MAC and OPDMAC.

Fig. 17(b) compares the average packet delay of four protocols in a multi-channel environment. D-MAC, OPDMAC and 802.11 randomly select a data channel for communication. Some neighboring pairs may select different channels, reducing the degree of contentions occurred in a single-channel environment. Therefore, the average packet delay of D-MAC, OPDMAC, and 802.11 is smaller than that in the single-channel environment. In general, both D-MAC and OPDAMC have smaller packet delay than 802.11 due to the exploiting of spatial reuse opportunities. Moreover, the OPDMAC outperforms the DMAC in terms of packet delay because OPDMAC allows the node to recheck its queue and tries to send another packet in another unblocked direction when the original transmission direction is blocked. Different from the other protocols, the MCDA uses *CSS* to distribute multiple communications on different channels. Even if there are more than one communication pairs selecting the same channel, the first pair that switches to the channel will stay on the original channel and proceed their communication without interference and all the other pairs will immediately switch to the next channel according to *CSS* without negotiation. Therefore, MCDA outperformed 802.11, D-MAC, and OPDMAC protocols in terms of average packet delay. As shown in Fig. 17(b), the average packet delays of four mechanisms are constant in case that the number of communication pairs is smaller than six. Since the simulation uses three data channels. In the best case, there are three pairs can proceed their communication at the same time. Therefore, when the number of communication pairs is small, the packet delay remains constant. However, the packet delay of 802.11 increases rapidly with the number of communication pairs. As for D-MAC and OPDMAC, the average packet delay increases slower than 802.11. The MCDA uses *CSS* to select idle data channel for communication. Some stations switch to block phase



(a) Single-channel environment. (b) Multi-channel environment.

Fig. 18. The comparison of four protocols in terms of channel utilization.



(a) Single-channel environment. (b) Multi-channel environment.

Fig. 19. The impact of packet arrival rate on network throughput.

when the number of communicating pair exceeds 15. Since the station in Block Phase will stay on the first channel of CSS to compete for channel access, the average delay increases significantly when the number of communicating pairs exceeds 15. However, MCDA outperforms the other three mechanisms in average packet delay.

Fig. 18 investigates the performance improvement in terms of channel utilization. Herein, the Channel Utilization refers to the ratio of the number of utilized channel to the number of available channels. The channel utilization of the four protocols increases with the number of stations. This phenomenon appears significantly in the multi-channel environment. Fig. 18(a) demonstrates the channel utilization of a single-channel environment. The channel utilizations of D-MAC, OPDMAC and MCDA have a better performance than 802.11 since they allow more pairs proceeding their communications simultaneously on different channels. Fig. 18(b) demonstrates the channel utilization in a multi-channel environment. Because that D-MAC, OPDMAC, and 802.11 randomly select a data channel for communication, those stations that select a common channel will compete for channel access, increasing the opportunities of contentions and collisions. In addition, some channels are idle, resulting in a negative effect in the channel utilization. The proposed MCDA adopts *CSS* to switch channels when several pairs switch to the same channel. As a result, MCDA outperforms D-MAC, OPDMAC and 802.11 as the number of communicating pairs increase.

Fig. 19 depicts the impact of packet arrival rate on throughput. Herein, the number of pairs was set by 25. The packet arrival rate was controlled by various values including 150, 300, 450, 600,

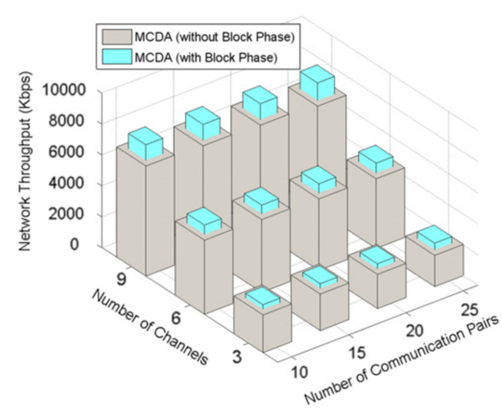
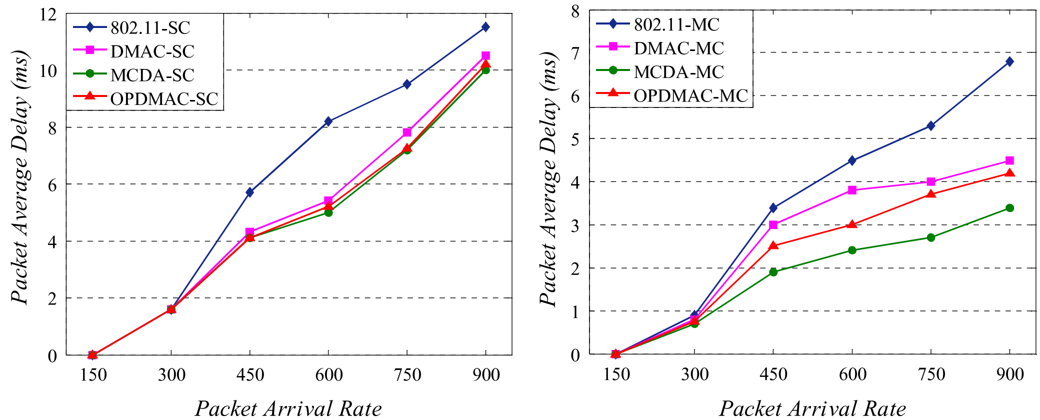


Fig. 20. The comparison of MCDA with Block Phase and without Block Phase in terms of network throughput.

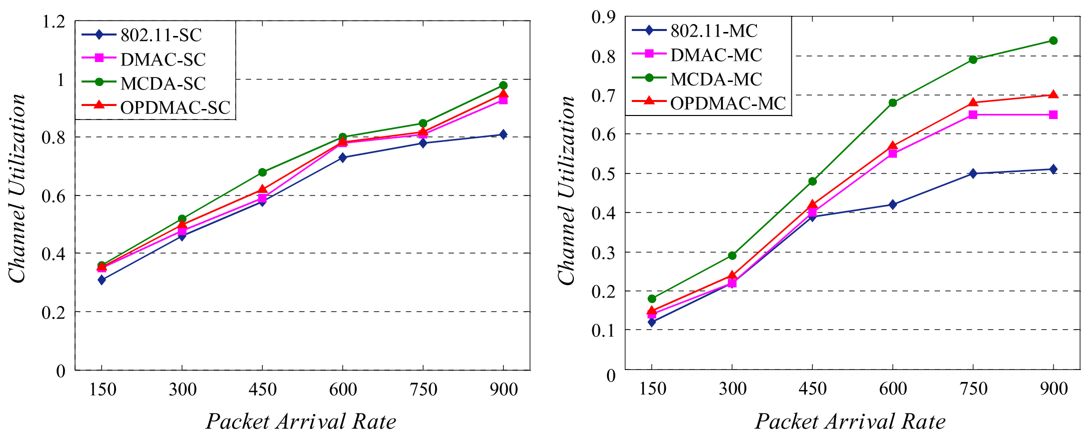
750, and 1000 packets/s. Fig. 19(a) and (b) show the throughputs in single-channel and multi-channel environments, respectively. In general, the throughput increases with the packet arrival rate. Because D-MAC, OPDMAC and MCDA allow more parallel communications, they had a better throughput than IEEE 802.11. In the single-channel environment, the D-MAC and OPDMAC had similar performance with MCDA. Fig. 19(b) depicts the throughput of compared four mechanisms in the multi-channel environment. However, the throughputs of the four mechanisms achieve saturation and thus increase slowly as the packet arrival rate larger than



(a) Single-channel environment.

(b) Multi-channel environment.

Fig. 21. The impact of packet arrival rate on packet delay.



(a) Single-channel environment.

(b) Multi-channel environment.

Fig. 22. The impact of packet arrival rate on channel utilization.

1000. The proposed MCDA effectively adopted the CSS to increase the number of parallel transmissions when the traffic load is heavy. Therefore MCDA outperformed D-MAC, OPDMAC and 802.11 in terms of throughput efficiency.

Fig. 20 aims to investigate the performance improvement of the Block Phase in terms of network throughput. In Fig. 20, the protocol applying Block Phase outperforms that without applying the Block Phase because the Block Phase alleviates the blind channel switching and hence improves the network throughput.

Fig. 21(a) and (b) show the effect of packet arrival rate on average transmission delay. In the single-channel environment, when the packet arrival rate is 150 packets/s, the packets were immediately sent out from the memory buffer when they arrive, resulting the delay time for buffering packet to be close to zero. When the packet arrival rate is lager than 300 packets/s, D-MAC, OPDMAC and MCDA allow more pairs to proceed for their communication simultaneously. Therefore the average packet delay of D-MAC, OPDMAC, and MCDA is smaller than 802.11. Since the number of packets buffered in memory increases with the packet arrival rate, the average packet delay of four mechanisms increases with the packet arrival rate. In a multi-channel environment, when the packet arrival rate is larger than 300 packets/s, MCDA works well in terms of packet delay due to the use of *CSS*. Applying the proposed MCDA mechanism, the increasing pairs can select different idle channels for communication, resulting slow incensement of packet delay. As a result, MCDA works better than D-MAC, OPDMAC and 802.11 in terms of average packet delay.

Finally, Fig. 22 compares the four protocols in terms of channel utilization. Increasing the packet arrival rate can improve the channel usage. As shown in Fig. 22(a), in case of low packet arrival rate and the number of communication pairs is small, the four mechanisms have similar channel utilizations. However, when the packet arrival rate was higher than 600 packets/s, D-MAC, OPDMAC and the proposed MCDA significantly outperformed 802.11. In the multi-channel environment, four mechanisms have poor performance in terms of channel utilization in case that the traffic load is light. This is because that few stations intend to send data when the traffic load is light. The channel utilization increases with the traffic load. The proposed MCDA effectively distributes the communication pairs to different data channels and thus has a significant improvement in channel utilization against the other three mechanisms. Since there are more communication pairs selecting the same channel in D-MAC, OPDMAC and 802.11, some channels are busy while the other channels are idle, resulting in low channel utilization. As for D-MAC and 802.11, in case that some communication pairs intend to select the data channel again, they should go back to the control channel and execute channel selection procedure again, creating negotiation overhead, reducing the throughput, and increasing the transmission delay. As shown in Fig. 22(b), MCDA outperformed the other three protocols in terms of channel utilization.

6. Conclusion

This study presents a novel MCDA protocol, incorporating multi-channel and directional antenna into protocol design. Applying the proposed MCDA, stations that are located at the nearby locations but intend to access the same channel will use directional antenna to send data simultaneously, exploiting opportunities of spatial reuse. With the *RTS/CTS* negotiation in the control channel, sender and receiver can derive a unique *CSS* and detect the relative direction of each other. The *CSS* helps in distributing multiple communication pairs on different data channels, reducing the contention and collision probability and therefore improving the utilization of the time and bandwidth resources. In addition, cases of collisions occurred in the multi-channel and directional antenna environment are analyzed and how MCDA handles these cases is presented. Performance study showed that the proposed MCDA protocol significantly increases the throughput and channel utilization and reduces the packet transmission delay in the situation of high packet arrival rate or large number of stations.

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