Balanced Media Access Methods for Wireless Networks

Timucin Ozugur[a], Mahmoud Naghshineh[b], Parviz Kermani[b], C. Michael Olsen[b], Babak Rezvani[b] and John A. Copeland[a]

[a] Communications Systems Center, Georgia Institute of Technology, Atlanta, GA 30332
[b] IBM Thomas J. Watson Research Center, Yorktown Heights, NY 10598
E-mail : {ozugur, copeland}@gcatt.gatech.edu
{mahmoud, kermani, cmolsen, babak}@watson.ibm.com

Abstract

The wireless medium is a scarce shared resource in mobile computing. Consequently, the media access control (MAC) layer influences the fairness and robustness of the wireless network. According to the current MAC protocols, stations are not able to gain access equally to the shared wireless medium. This problem is commonly known as the *fairness problem*. The fairness problem occurs mostly because of the existence of hidden stations and the presumption of a non-fully connected wireless network topology. This paper addresses solutions to the fairness problem in wireless networks. p-persistent carrier sense multiple access based algorithms are proposed in which a fair wireless access for each user is accomplished using a pre-calculated link access probability, p_{ij}, that represents the link access probability from station i to j. Link access probabilities are calculated at the source station in two ways using *connection-based* and *time-based* media access methods. According to the used methods, each active user broadcasts information on either the number of logical connections or the average contention time to the stations within the communication reach. This information exchange provides partial understanding of the topology of the network to the stations. Each station reserves a specific priority for itself to gain access to the shared medium. It is suggested that the information is exchanged during the link access discovery procedure for the connection-based method, and periodically for the time-based method. Link access probabilities are modified every time the exchanged information is received. The proposed algorithms are dynamic and sensitive to the changes in the network topology. The algorithms have been implemented in a specific media access control protocol [1], but they are applicable to all media access control protocols. Simulation results show that the algorithms result in an order of magnitude performance improvement in terms of throughput in a wireless network.

1 Introduction

The emergence of portable terminals in work and living environments is accelerating the introduction of wireless networks, which will play an important role in the personal communications systems. A wireless local area network (LAN) is a way to connect portable computers over radio or infrared wireless links that are in a small area such as an office or home environment. Wireless LANs are much flexible and cheaper to install than wired LANs.

Wireless LANs have two configurations: *Infrastructured* and *ad-hoc* wireless LANs. In a typical ad-hoc wireless LAN, stations establish peer-to-peer communication among themselves independently in their small area. Note that ad-hoc networks presume a non-fully connected network topology. Infrastructured wireless LANs establish the communication between stations with the help of an infrastructure such as a wired or wireless backbone.

The wireless medium is a shared resource. Consequently, it is critical that a medium access control (MAC) protocol provides fairness and robustness to the wireless network. The MAC protocols rely on the features of the multiple access protocols. There are many proposed multiple access protocols for wireless LANs, such as *carrier sense multiple access* (CSMA), *polling*, and *time division multiple access* (TDMA). In this paper, we focus on CSMA protocols, which is a member of the ALOHA family protocols. CSMA is designed for radio networks even though it is also successfully applied in the wired networks, such as Ethernet. Carrier sensing is not always possible in a wireless medium due to the *hidden station problem*. In a wireless LAN in which not all the stations are within transmission range of one another, a station with a packet to send cannot accurately ascertain if its transmission will arrive without collisions at an intended receiver, because it cannot hear the transmissions from other senders that might arrive at the same intended receiver. This is referred to as hidden station problem. For example, directed infrared (IR) media is an environment in which there is a high chance of hidden stations. Figure 1 shows an example of the hidden station problem, where station A is within communication reach of both stations B and C. However, station B and C cannot hear each other, therefore they are hidden stations for each other. When station B attempts to reserve the channel according to the IEEE 802.11 standard, it sends a request-to-send (RTS) packet before transmitting the data. Only station A receives the RTS packet, but station C does not. Station A replies to station B with clear-to-send (CTS) packet. Both stations B and C receive the CTS packet. CTS packet is the only way for station C to get informed about channel reservation. If station C does not receive the CTS packet due to the physical obstructions of the line-of-sight, or receives it in error, station C may attempt to reserve the channel while station B is transmitting its data. It results in collision at station A although station B has reserved the channel successfully.

CSMA with collision avoidance (CSMA/CA) is proposed to alleviate the hidden station problem. CSMA/CA with a four-way handshake is used to combat the problem of an indoor fading channels [6]. CSMA/CA is proposed by the IEEE 802.11 committee. According to CSMA/CA, the channel is reserved by RTS/CTS exchange, and then data transmission is ensured by data/ACK exchange. CSMA/CA protocol is based on Multiple Access Collision Avoidance (MACA) [3]. MACA has been introduced for single hop datagram service in wireless LANs. The MACA protocol attempts to detect collisions at the receiver,

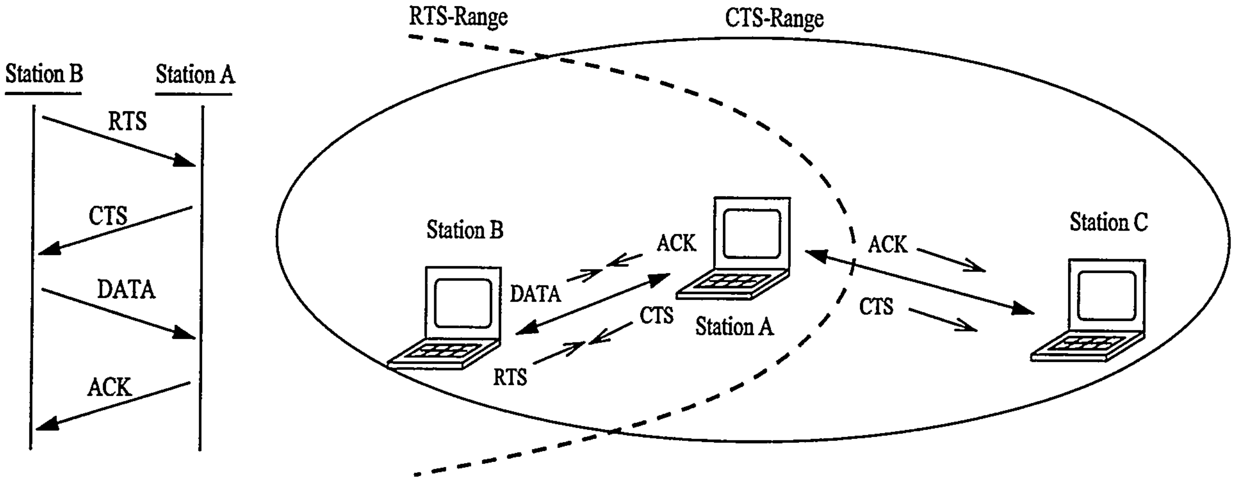

Figure 1: Illustration of the hidden station problem, where station A is within the communication reach of both stations B and C; stations B and C can not hear each other; and station B reserves the channel by RTS/CTS exchange to communicate station A.

rather than at the sender, and it is simply a three-way handshake (RTS, CTS, data). Several other MAC protocols have been proposed, which are based on RTS-CTS exchanges, or RTSs followed by pauses. Later, the wireless MAC was refined by MACAW, Floor Acquisition Multiple Access (FAMA) protocols, and the IEEE 802.11 standard [2, 4, 5]. In MACAW, the MACA protocol is augmented with additional message types and backoff and retransmission strategies to improve throughput. In addition, floor acquisition protocol gives the ability for a sender to take over control of the channel and transmit one or multiple data packets without contentions. Although the motivation for MACA, IEEE 802.11, MACAW and FAMA is to solve the hidden station problem and also to provide a fair and robust network, stations still cannot gain access to the medium equally. This is referred to as *fairness problem.* The current MAC protocols solves collisions raising because of hidden stations, however they can not solve the fairness problem due to the presumption of a non-fully connected wireless network topology.

The objective of this paper is to provide new, efficient, and simple wireless MAC algorithms for having stations equally share the medium in a wireless network. This paper addresses some solutions for the fairness problem in wireless networks, which are called *balanced media access methods.* These methods are easy to implement in a commercial wireless LAN. Balanced media access methods are p-persistent CSMA based algorithms in which a fair wireless access for each user is accomplished using a pre-calculated link access probability, p_{ij}, that represents the link access probability from station i to j. According to the methods, link access probabilities are calculated at the source station in two ways: *Connection-based* and *time-based* media access methods. According to the used methods, each active user broadcasts information either on the number of logical connections, or the average contention time to the stations within the communication reach. This information exchange provides a partial understanding of the topology of the network to the stations. Each station reserves a specific priority for itself to gain access to the shared medium. The proposed algorithms are dynamic and sensitive to the changes in the network topology. Link access probabilities are modified every time the exchanged information is received. It is suggested that the information is exchanged during the link access discovery procedure for the connection-based method, and periodically for the time-based method. This information exchange is simple and easily implemented. Note that the methods are applicable to all media access control protocols. In our simulations, we use the wireless network architecture based on AIR specifications [1] to explore the performance of our algorithms in wireless ad-hoc LANs.

This paper has 5 sections. In Section 2, we provide some background on the media access control protocols, the back-off algorithm, and the window exchange algorithm used in our simulations. In Section 3, we introduce the balanced media access methods intended to solve the fairness problem in wireless networks. In Section 4, we evaluate the performances of the balanced media access methods using several different wireless ad-hoc network configurations. In Section 5, we summarize our findings.

2 Wireless LAN Architecture

In this paper, we introduce balanced media access methods with a wireless MAC protocol based on AIR specification [1]. The MAC protocol is a four-way handshake (RTS, CTS, data, ACK) with multiple data-packet transmissions in each reservation. This is referred to as *burst transmission.* Since implementation issues of this MAC protocol are beyond the scope of this paper, the MAC protocol is overviewed briefly (see [1] for details).

The MAC protocol can be summarized as follows: Source station sends a request-to-send (RTS) packet to the destination station. The intended destination replies with a clear-to-send (CTS) packet. Upon receiving the CTS, the source station sends its data immediately. Any station overhearing an RTS and/or CTS message, defers all transmissions until for a period that allows the associated transmission to be finished. According to this RTS/CTS exchange, stations that receive the RTS and/or CTS packet, but not a part of RTS/CTS exchange, enter into the *non-participant* mode. After every successful channel reservation, multiple data packets are transmitted. After the transmission of multiple data and their ACK packets, the source station sends an End-of-Burst (EOB) packet, and waits for an End-of-Burst-Confirmation (EOBC) packet from the intended receiver. In this system, other stations overhearing the RTS/CTS exchange and/or data transmission, defer their own transmissions until

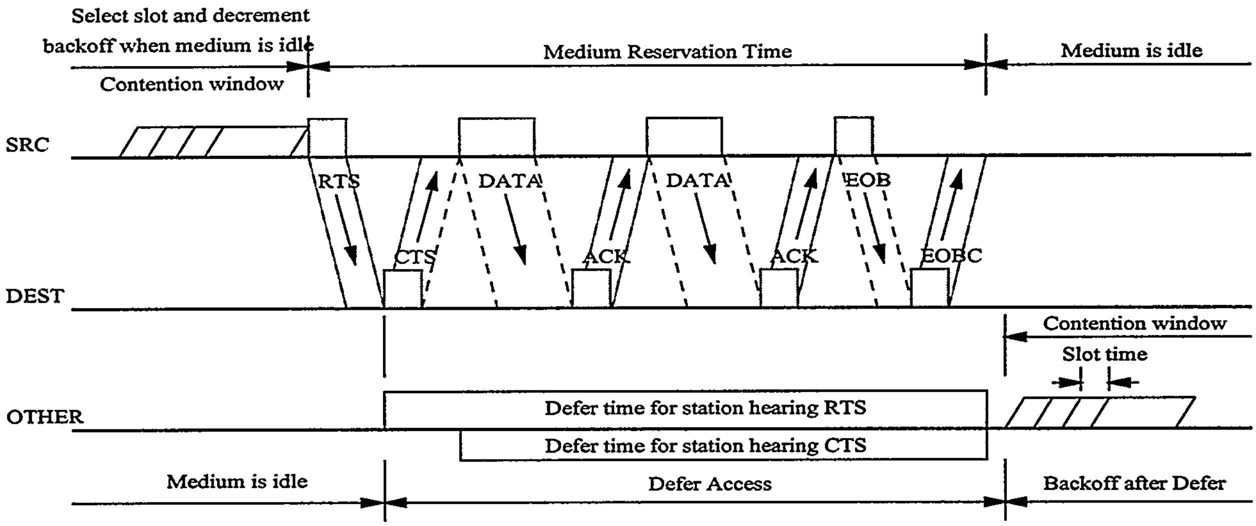

Figure 2: Illustration of the media access protocol based on AIR specifications [1].

EOB/EOBC exchange. Figure 2 illustrates the described MAC protocol where two packets are transmitted within a successful reservation. The performance of other stations that can not hear the RTS/CTS exchange, may also be affected. Figure 3 illustrates how the network topology affects the transmission. Referring to Figure 3, station 3 reserves the channel by sending a RTS packet to station 4. Station 4 replies back with a CTS packet. Then, station 3 transmits its data, and station 4 replies back with an ACK packet. Station 2 receives the RTS packet since it is within the communication reach of station 3. However, station 2 can not receive the CTS packet because it is not within the communication reach of station 4. Station 1 does not receive neither the RTS nor the CTS packet since station 1 is within the communication reach of station 2 only. Meanwhile, if station 1 has a packet to send to station 2, it may not send its packet since station 2 turns out to be in non-participant mode because of the communication between stations 3 and 4. In this case, since the medium is idle from station 1 point of view, station 1 sends its RTS packet to reserve the channel after backing off. Since station 2 can not issue a CTS packet, station 1 increases its back-off window size and backs off again after timing out. Data transmission between stations 3 and 4 may end during this time. Since station 1 has backed off with a larger back-off window size, stations 2, 3 or 4 have higher chance to reserve the channel again rather than station 1, because they have smaller back-off window sizes. This example shows that a new access method is necessary to provide a fair access chance to each station for each logical connection.

2.1 The Back-off Mechanism

The goal of CSMA protocols is to prevent stations from colliding with other stations within their transmission ranges by asking stations to listen before they transmit. According to the protocol, every station senses the media before transmitting. As described in the IEEE 802.11 standard, a station with a packet to send starts a back-off timer when the channel is idle. If the station senses any transmission in the media, it stops the back-off timer without resetting it. The back-off timer is restarted when the channel is available again. The station sends the packet when the counter reaches the end of the back-off period. In our wireless LAN system, we assume that every station has at most eight attempts to reserve the channel. If a station is not able to capture the channel after eight attempts, it aborts its transmission. The source station backs off by selecting random back-off periods from a range of $[0, BO]$ slots where BO represents the back-off window size. Source station keeps the value of its own last back-off window size, which is used in the last reservation. After each successful reservation, the station decreases its back-off window size BO to $BO/2$. If the reservation attempt is unsuccessful, the back-off window size BO is increased to $2 \times BO$. The back-off window size cannot be more than 128 slots, or less than 8 slots.

2.2 Window-exchange Algorithm

The goal of the window-exchange algorithm is to prevent stations from having high back-off window sizes. According to the algorithm used in our wireless LAN system, the transmitting station inserts the information of the last back-off window size into the RTS packet. Any station receiving this information calculates its new back-off window using

$$min\{\text{current } BO, \text{received } BO\}.$$

The intended receiver inserts the received back-off window information into the CTS packet. Therefore, hidden stations of the source station may also receive the back-off window information.

3 Balanced Media Access Methods

The goal of the balanced media access methods is to provide desired fair media access for each station in any wireless network configuration. The methods we introduce are based on p-persistent protocol where stations send packets with probability p, which is referred to as *link access probability*, after the back-off period, or back off again with probability $1-p$ using the same back-off window size. The probability p is constant in classical p-persistent protocols, and it is not defined how to calculate the probability p in dynamic environments. The balanced media access methods show how to calculate the probability p dynamically in wireless medium using a distributed approach. According to the balanced media access methods, link access probabilities are calculated at the source station in two ways either with a connection-based or a time-based media access method.

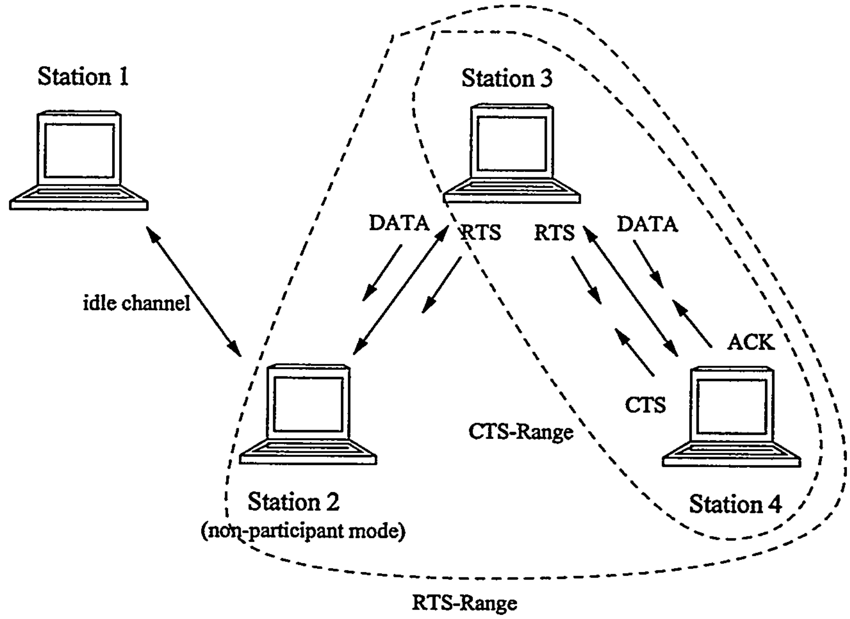

Figure 3: Example of the effect of non-fully connected network topology; where station 3 reserves the channel to communicate station 4 by sending a RTS packet, station 4 replies back with a CTS packet.

3.1 Connection-based Balanced Media Access Method

In this method, stations calculate link access probabilities for their logical links based on the information of the number of connections of themselves and neighbor stations. A logical link represents the link between a station and its visible station. An example of a wireless network topology is given in Figure 4(a). Assume that station A_i is the source station. A group of stations, B_j, are visible stations of station A_i. A group of stations, C_k, are the hidden stations of station A_i. Each C_k is connected to at least one B_j. The rest of the stations in the network are denoted by D_l. Source station A_i attempts to send its RTS packet to station B_j after the back-off period using a pre-calculated probability, p_{ij}, or backs off again with probability $1 - p_{ij}$ using the same back-off window size. Each station broadcasts information on the number of connections to the stations within the communication reach. Referring to Figure 4(a), station A_i broadcasts to the neighbor stations (B_j, $j = 1, \ldots, 4$) that it has 4 logical links. Station B_1 broadcasts to its three neighbor stations (A_i, C_1 and C_2) that it has 3 logical links, and so on. This information exchange can preferably be done when a station discovers a change in the network topology. In wireless networks, a link control layer protocol is necessary to discover stations in the environment. According to the link control layer, when a station turns on in a wireless environment, it performs a discovery process. Stations hearing this discovery process update the number of logical connections. Then, they broadcast the connection information to other stations within their communication reach. Stations also broadcast the connection information when they realize that a station within their communication reach turns off. For example, Figure 4(b) shows that station C_3 is disconnected. Hence, stations B_3, C_4 and D_1 broadcast the information to their neighbor stations that they now have 4, 1 and 1 logical links, respectively. According to the figure, only the broadcast message of station B_3 affects link access probabilities of station A_i since B_3 is the only neighbor station of station A_i whose the number of connections are changed.

In the following, the computation of link access probabilities using the connection-based media access method is described only for station A_i. The link access probabilities of the other stations can be calculated in the same manner.

The set of stations that are visible to the source station A_i is referred to as *visible set* and is denoted by $\mathbf{V}_i$. The members of this set correspond to the station labeled as stations B_j ($j = 1, \ldots, N$) in Figure 4. Referring to Figure 4, N is 4. Every station B_j in the visible set broadcasts the information on the number of its logical connections, which is denoted by S_j, $j = 1, \ldots, N$, i.e.,. S_j is equal to the number of logical connections of station B_j. The set that contains S_j's of each station B_j is referred to as *connection set* and denoted by $\mathbf{S}$. Referring to Figure 4(a), the visible set $\mathbf{V}$ and the connection set $\mathbf{S}$ are given as $\mathbf{V}_i = \{B_1, B_2, B_3, B_4\}$, and $\mathbf{S} = \{S_1 = 3, S_2 = 1, S_3 = 5, S_4 = 2\}$. Source station A_i keeps track of the values in the connection set $\mathbf{S}$. The number of connections of the source station A_i is denoted by S_A. S_A is referred to as *connection value*. Referring to Figure 4(a), the connection value is 4, $S_A = 4$. The connection value has a property of

$$S_A \leq \sum_{j \in \mathbf{V}_i} S_j \qquad (1)$$

The maximum value of members of the connection set $\mathbf{S}$ is defined in order to calculate the link access probabilities, and it is denoted by

$$S_A^{Max} = max_{j \in \mathbf{V}_i} \{ \; S_j \; \} \qquad (2)$$

S_A^{Max} is referred to as *maximum connection value*. Note that one or more stations in the visible set $\mathbf{V}_i$, may have the maximum value of $S_j = S_A^{Max}$.

If $S_A = \sum_{j \in \mathbf{V}_i} S_j$, which means that the cumulative total of the connection set, $\mathbf{S}$, are equal to the connection value S_A, then the source station A_i chooses the link access probability as $p_{ij} = 1$, $\forall j \in \mathbf{V}_i$ for all its logical connections to the stations

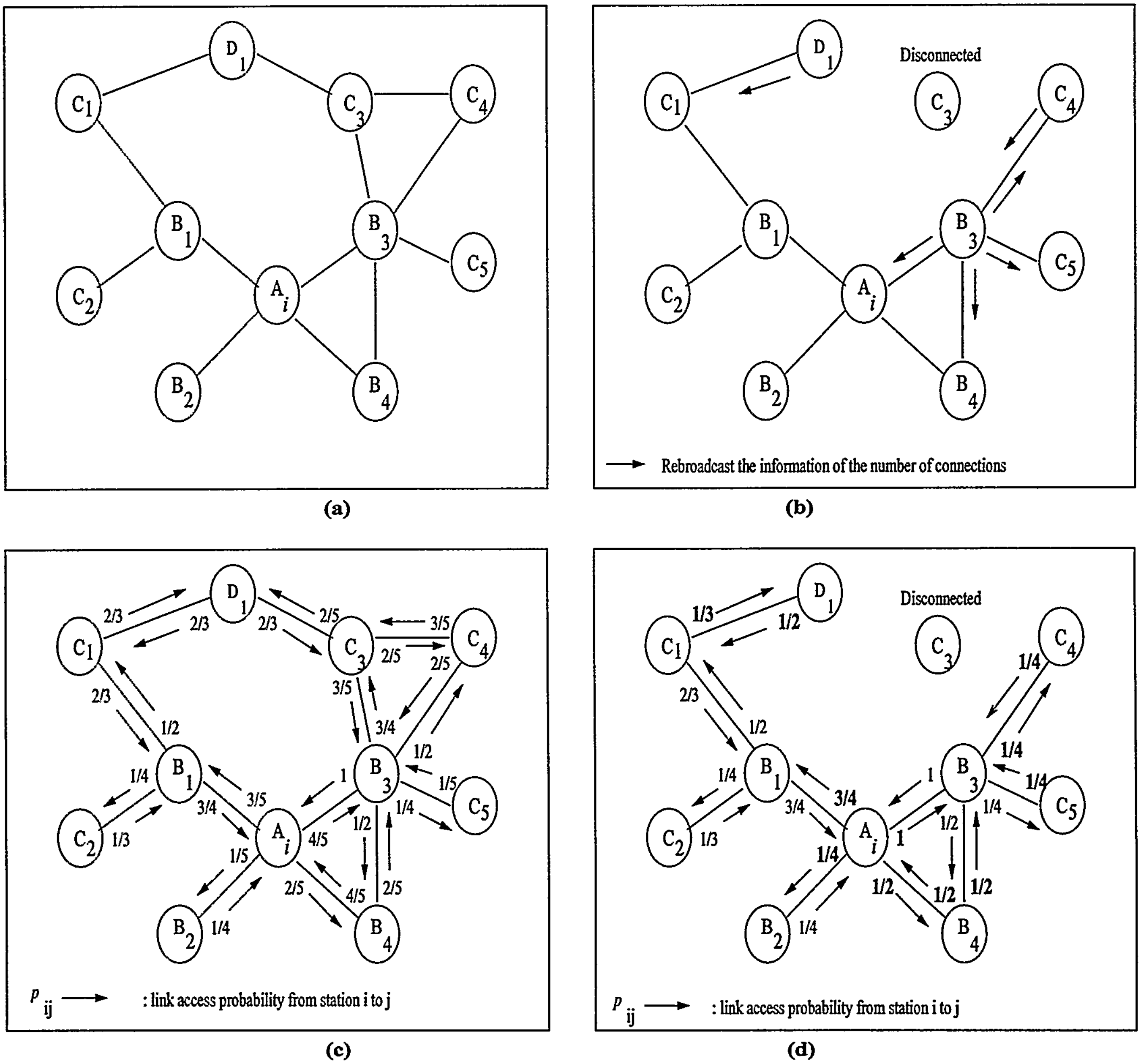

Figure 4: (a) An example of a wireless network topology illustrating visible and hidden stations, (b) broadcasting the information on the number of connections when the network topology is changed, (c) link access probabilities, p_{ij}, according to the connection-based media access method, (d) link access probabilities after the network topology is changed.

B_j, $j = 1, \ldots, N$. This equality, $p_{ij} = 1$, shows that source station is a center station and it has no hidden stations.

If $S_A < \sum_{j \in \mathbf{V}_i} S_j$, which means that the connection value is less than the cumulative total of the connection set **S**, then either the source station A_i has hidden stations, or there is at least one connection between at least one pair of B_j stations. In both cases, the maximum connection value S_A^{Max} is compared to S_j's.

If $S_A < \sum_{j \in \mathbf{V}_i} S_j$ and $S_j = S_A^{Max}$, the link access probability p_{ij} from source station A_i to the station B_j will be

$$p_{ij} = min\left\{ 1, \frac{S_A}{S_A^{Max}} \right\} \tag{3}$$

Specifically, Eq. (3) is valid if the number of connections of station B_j is equal to the maximum connection value and the connection value S_A is less than the cumulative total of the connection set **S**.

If $S_A < \sum_{j \in \mathbf{V}_i} S_j$ and $S_j \neq S_A^{Max}$, the link access probability p_{ij} from source station A_i to the station B_j will be

$$p_{ij} = \frac{S_j}{S_A^{Max}} \tag{4}$$

Specifically, Eq. (4) is valid if the number of connections of station B_j is not equal to the maximum connection value, and the connection value S_A is less than the cumulative total of the connection set **S**. The method gives higher priority to the link which has the maximum connection value since the station with the maximum connection value has higher data traffic than the other stations in a fully-loaded network. The priorities of the other links are proportioned according to the maximum connection value.

We calculate link access probabilities for the network configuration given in Figure 4(a) using the connection-based method. The results are given in Figure 4(c). Since the connection value S_A is 4, and less than the cumulative total of the connection set S, which is 11 ($\sum_{j \in \mathbf{V}_i} S_j = 11$), we use Eqs. (3) and (4) to calculate link access probabilities from source station A_i to the stations B_j, $j = 1, \ldots, 4$. Note that the maximum connection value is 5 ($S_A^{Max} = 5$), which is the number of connections of station B_3. In order to calculate the link access probabilities from station A_i to the stations B_1, B_2, B_4, we use Eq. (4) since the number of connections of each station is not equal than the maximum connection value ($S_j \neq S_A^{Max}$ for $j = 1, 2, 4$). The resulting link access probabilities are 3/5, 1/5 and 2/5, respectively. Since the number of connections of station B_3 is equal to the maximum connection value ($S_j = S_A^{Max}$ for $j = 3$), we use Eq. (3) for the link from station A_i to the station B_3. The resulting link access probability is 4/5. The link access probabilities of the other stations are calculated in the same manner. We also give link access probabilities for the case where station C_3 is disconnected. The results are shown in Figure 4(d). Link access probabilities that are affected by the disconnection of the station C_3 are written in bold type. Note that the link access probabilities of the source station A_i are changed since the maximum connection value that is the number of connections of station B_3 is now 4.

3.2 Time-based Balanced Media Access Method

In this method, link access probabilities are calculated based on the average contention period. An average contention period is a time interval between packet arrival to the MAC layer and transmission of the packet to the destination. Note that an average contention period covers collisions, the back-off periods, and the listening periods, in which another station captures the channel. As we discussed in Section 2, a listening period is a time interval in which the intended sender would be a non-participant station until the channel is idle again.

According to the time-based media access method, every station periodically broadcasts a packet to its all logical links. The packet carries the information of both the average contention period of that specific link and a link traffic descriptor, L_{ij}. Stations update link access probabilities every time they receive new information about the contention period and the link traffic descriptor. The link traffic descriptor, L_{ij}, is defined as

$$L_{ij} = \begin{cases} 1 & \text{if station } i \text{ had traffic for station } j \\ & \text{in the previous period} \\ 0 & \text{if otherwise} \end{cases} \tag{5}$$

The link access probability of the link from station i to station j is defined as

$$p_{ij} = \frac{T_{ij}^{\gamma}}{\frac{1}{\sum_{k \in \mathbf{V}_i (k \neq i)} (L_{ki} + L_{ik})} \sum_{k \in \mathbf{V}_i (k \neq i)} (T_{ki}^{\gamma} L_{ki} + T_{ik}^{\gamma} L_{ik})} \tag{6}$$

where T_{ij} is an average contention period from station i to station j, γ is a weight factor of an average contention period, and $\mathbf{V}_i$ is the visible set as discussed in Section 3.1. Specifically, the time-based method calculates the link access probability of the link by simply dividing its average contention period by the mean value of the contention periods of all neighbor links. If the link is blocked, the average contention period of that specific link (numerator in Eq. (6)) increases, eventually, the contention periods of the neighbor links (denominator in Eq. (6) is the mean of those contention periods) decreases. Thus, Eq. (6) will raise the access probability of the blocked link. In this way, we give a higher priority to a link that is blocked and less priority to a link that is dominant over the other links. The weight factor, γ, controls the increase rate of the link access probability according to the average contention period. For $\gamma < 1$, the link access probability is always higher than the case in which $\gamma > 1$ (see Fig. 7). In the algorithm, the link traffic descriptor carries the information of the traffic demand in the previous period. In this way, a link with no traffic is not taken into consideration. As a result, we will show that the time-based approach gives better result as the traffic distribution is different among the links (see Section 4.4). In the next section, we simulate wireless ad-hoc networks with and without the algorithms.

4 Performance Evaluation

In this section, we investigate the performance of our algorithms. The wireless ad-hoc network configurations used in the simulation are shown in Figure 5. Figure 5(a) is referred to as *client-server* scenario, where station 1 is a server and the other stations are clients. Figure 5(b)-(d) are referred to as *4-station* scenario, *5-station* scenario, and *6-station* scenario, respectively. The scenarios cover the general wireless ad-hoc LAN topologies since the presence of hidden stations and the presence of one or more simultaneous communication are the general features of the scenarios. Referring to client-server scenario, there can be at most one simultaneous communication in the network. However, in the other scenarios, there may be two simultaneous communications in the network. For example, in the 5-station scenario, it is possible to have communications between stations 1 and 2, and stations 4 and 5, at the same time.

In our simulation model, a fully loaded network is assumed. In other words, stations always have a packet to send.

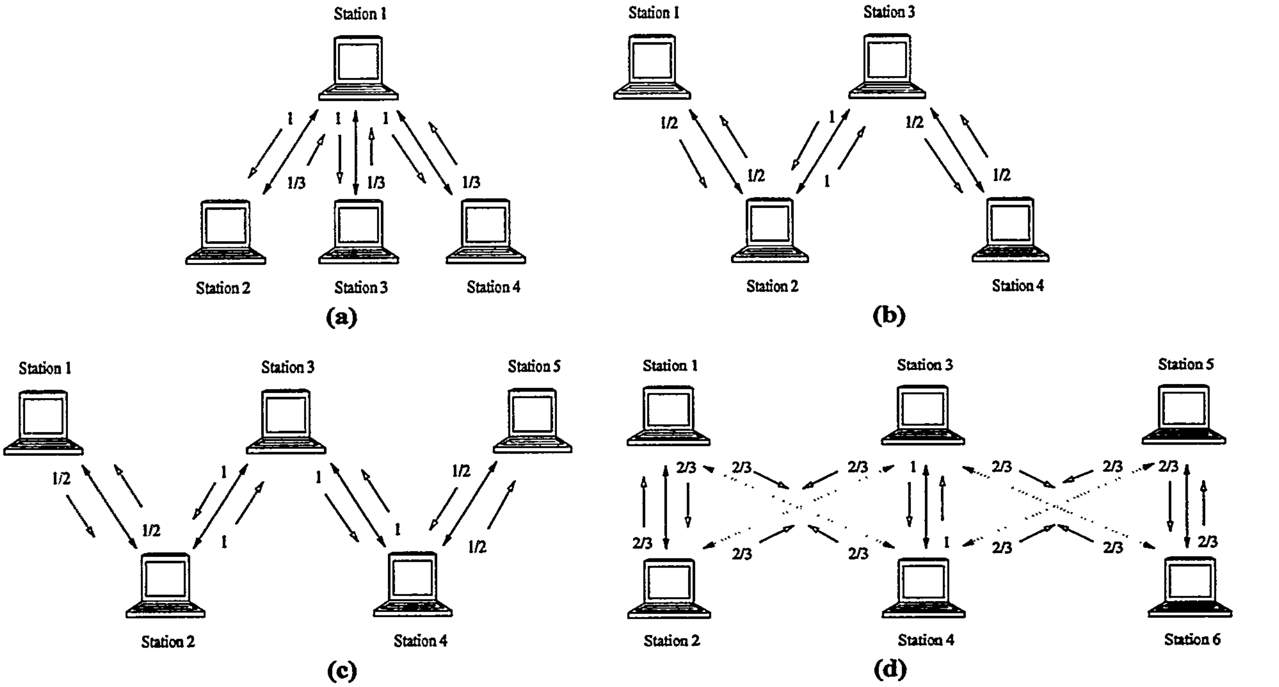

Figure 5: Wireless network configurations and link access probabilities for the connection-based method, (a) client-server scenario, (b) 4-station scenario, (c) 5-station scenario, (d) 6-station scenario.

The simulation parameters are given as follows: The wireless channel is capable of transmitting at 4 Mbps. Stations are within 10 meters of each other, giving a maximum propagation delay of approximately 3.33 nsec. The packet length is 2 Kbytes. The transmitting window size is 8 packets. The slot size is 900 μsec. Note that one slot time is enough to cover the RTS frame and the preamble of the CTS frame. The processing and transmission time of RTS/CTS/EOB/EOBC packets is 1.984 msec. The sum of the transmission time of an ACK packet and the processing time of a received packet is 872 μsec. A burst transmission (8 packets) takes approximately 45 slots. Since we focus on how stations gain access to the channel, which is directly related with the contention period, we simulate the scenarios in a noise-free setting. Therefore, if a station reserves the channel successfully, it sends exactly 8 packets. In the time-based media access method, we assume that the stations broadcast the information on the average contention period and the link traffic descriptor L_{ij} in every 5K slots, which is approximately 4.5 sec. Increasing the frequency of broadcast will decrease the bandwidth efficiency. Simulation run time is one million slots (15 network minutes).

The link access probabilities for the connection-based media access method are shown in Figure 5. Stations that have more connections have higher link access probabilities than stations with fewer connections. Stations with more logical links are referred to as *inner stations*. In other words, inner stations have more visible stations. Stations with fewer logical links are referred to as *edge stations*. Since inner stations are usually the most congested or blocked in practice, our connection-based method gives higher priority to the inner stations and lower priority to the edge stations.

Link access probabilities for the time-based media access method are simulated. The results are given in Figure 6. The link access probabilities of the 4-station scenario are not shown because the 5-station scenario covers a similar network topology. Note that Link_{ij} represents transmission from station i to station j. According to the time-based method, links have higher link access probabilities if they have longer contention periods, and they have smaller link access probabilities if they have smaller contention periods. The link access probabilities for the client-server scenario are given in Figure 6(a). In this scenario, since stations 2, 3 and 4 are similar stations, the link access probability of each station converges to the same probability. The link access probabilities for the 5-station scenario are given in Figure 6(b). According to the topology, Link_{12} and Link_{54} are similar as are Link_{21} and Link_{45}. Thus, the link access probability converges to 0.4 for both Link_{12} and Link_{54}, and the probability converges 0.7 for both Link_{21} and Link_{45}. The link access probability is 1 for the rest of the links. The 6-station scenario is simulated in two different ways; using solid diagonal links and dashed diagonal links. Stations that are connected with dashed diagonal links can hear each other, but they don't have any packets to send to each other. Stations that are connected with solid diagonal links have data packets for each other as well as they hear each other. Link access probabilities for the 6-station scenario with dashed diagonal links are given in Figure 6(c), and the 6-station scenario with solid diagonal links are given in Figure 6(d). Since changing the types of the diagonal links does not have any impact on the number of connections, the link access probabilities for the connection-based method are not changed. However, the link access probabilities for the time-based method are changed as are the average contention periods. In the 6-station scenario with dashed diagonal links, Link_{12}, Link_{21}, Link_{56}, and Link_{65} are similar links so that they have similar access probabilities. Link_{34} and Link_{43} are also similar to each other. As seen from the 6-station scenario with solid diagonal links, a group of similar links are converging to the same link access probability. Note that link access probabilities make some oscillations in the beginning

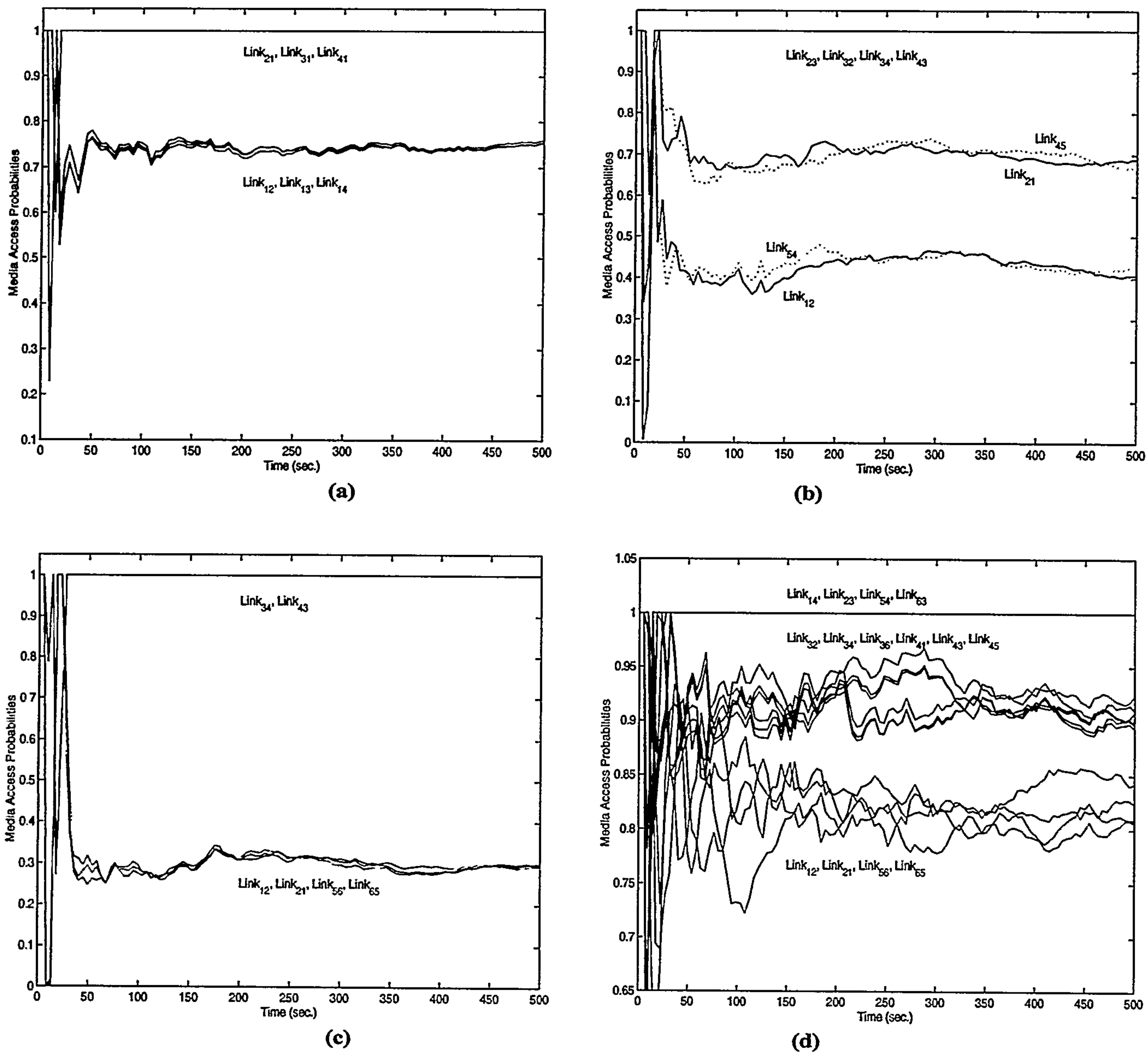

Figure 6: Link access probabilities using the time-based method for the given topologies, (a) client-server scenario, (b) 5-station scenario, (c) 6-station with dashed diagonal links, (d) 6-station scenario with solid diagonal links, where Link_{ij} represents the link from station i to station j and $\gamma = 2$.

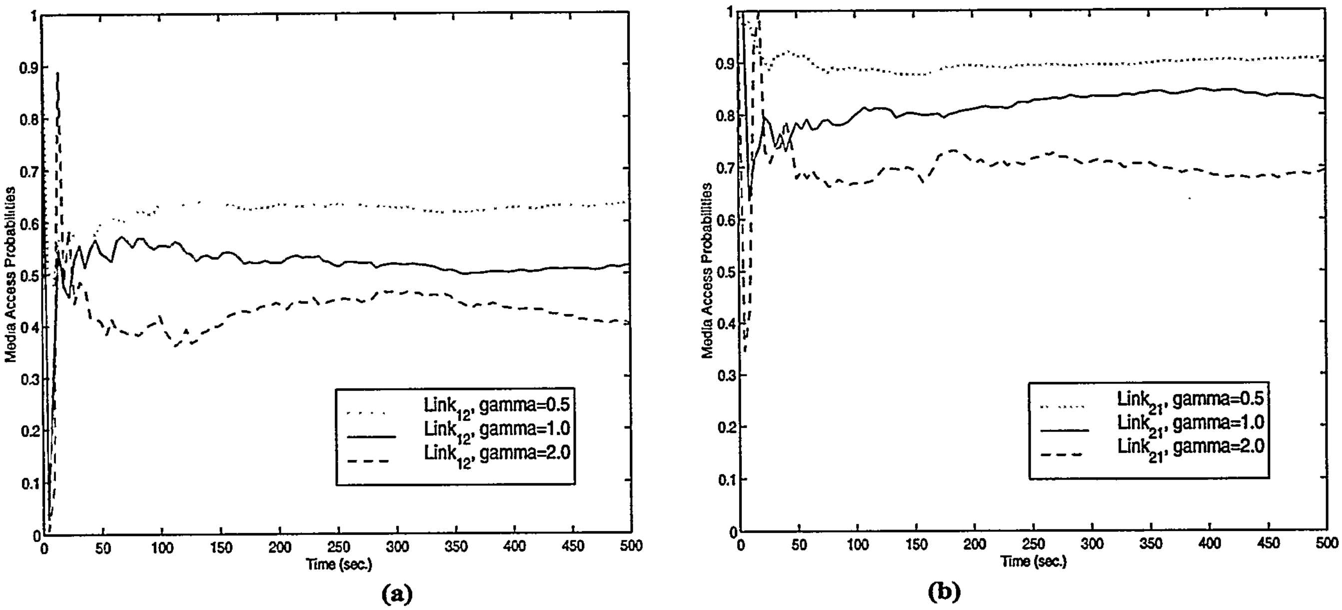

Figure 7: Impact of the weight factor γ on link access probabilities for 5-station scenario, (a) $Link_{12}$, (b) $Link_{21}$.

stage before converging to a limit. Since the 6-station scenario with solid diagonal links has large amount of active links, the oscillation stage is longer. In the time-based method, the weight factor γ has an impact on the link access probability. The impact for the 5-station scenario is shown in Figure 7. Figure 7(a)-(b) show the link access probability of $Link_{12}$ and $Link_{21}$ for various γ values, respectively. According to the 5-station scenario, $Link_{12}$ and $Link_{54}$ dominate the wireless medium since stations 1 and 5 could transmit data simultaneously. Consequently, the inner stations can not find a chance to reserve the channel, such as $Link_{21}$, and so on. To increase the throughput of inner stations, the time-based method gives higher link access probability to $Link_{21}$ than $Link_{12}$. In this way, stations with longer contention periods have a change to reserve the media. As seen from the figure, an increase in the weight factor γ always decreases the link access probabilities of the links.

In the following subsections, we investigate the performance in terms of throughput for the network topologies given in Figure 5. The experimental results show the throughput of the configurations using AIR specifications without any algorithm (original), with the window-exchange algorithm (Win-exc) only, the connection-based balanced media access method (CB-fair) only, both the connection-based method and the window-exchange algorithm (CB-fair+WE), and both the time-based method and the window-exchange algorithm (TB-fair+WE) for various γ values.

A *fairness index* (FI) is introduced to show the degree of effectiveness of the algorithms. FI is defined as the ratio of the maximum link throughput and the minimum link throughput. FI=1 represents the ideal fairness in the network. It means every link has the same throughput. If FI $\gg$ 1, it means the links can not equally gain access into the medium.

4.1 Throughput of the Client-Server Scenario

The results of the client-server scenario are given in Table 1. According to the results, the network without any algorithm is reasonably fair since all links have similar chances to reserve the channel. The probability of collision of two clients at the server station is higher than the probability of collision of a client and the server station. Collisions results in larger back-off window sizes. Thus, implementing only the window-exchange algorithm increases the throughput of the clients by decreasing their back-off window sizes. The time-based media access method with the window-exchange algorithm also increases the throughput of the clients. However, implementing both the window exchange algorithm and the connection-based access method increases the throughput of the server station. Implementing only the connection-based media access method also increases the throughput of the server, but it can not provide a fair access by itself. Implementing both the window exchange algorithm and the connection-based access method provides a fair network access among the other algorithms, but the network without any algorithm has already the most fair network access conditions. It can be seen easily by the help of the fairness index. FI is 1.18 (=0.5470/0.4627) for the client-sevrer configuration without any algorithm. It is 1.37 (=0.5761/0.4202) if both the window exchange algorithm and the connection-based method is implemented. It may be suggested that the algorithms can be turned off if there is a client-server application. Since the server is the only station that has a knowledge of the client-server application, it instructs the clients to turn off the algorithms. The total throughputs are %74.67 (2.9868 Mbps), %75.52 (3.0209 Mbps), %74.45 (2.9779 Mbps) and %75.38 (3.0151 Mbps) for the original network, the network with the window-exchange algorithm, with both the connection-based method and the window-exchange algorithm, and with both the time based method ($\gamma = 2$) and the window-exchange algorithm, respectively.

4.2 Throughput of the 4-station Scenario

In some topologies, inner stations may sometimes dominate the wireless medium. Consequently, edge stations suffer, as described in Section 2. When edge stations suffer, the window-exchange

Algorithms	Tx:1 → 2	Tx:2 → 1	Tx: 1 → 3	Tx:3 → 1	Tx:1 → 4	Tx: 4 → 1	FI
Original	0.5065	0.4627	0.4892	0.4803	0.5011	0.5470	1.18
Win-exc	0.3687	0.6516	0.3472	0.6390	0.3654	0.6490	1.88
CB-fair	0.6906	0.2637	0.6883	0.3152	0.7034	0.2838	2.67
CB-fair+WE	0.5761	0.4202	0.5640	0.4216	0.5681	0.4279	1.37
$\gamma = 1/2$-TB fair+WE	0.3261	0.6779	0.3262	0.6734	0.3360	0.6776	2.08
$\gamma = 1$-TB fair+WE	0.3124	0.7020	0.3140	0.6893	0.3083	0.6905	2.28
$\gamma = 2$-TB fair+WE	0.2824	0.7040	0.2879	0.7151	0.2956	0.7301	2.59

Table 1: Link throughput (Mbps) for the client-server scenario where the offered load → ∞.

Algorithms	Tx:1 → 2	Tx:2 → 1	Tx:2 → 3	Tx:3 → 2	Tx:3 → 4	Tx:4 → 3	FI
Original	0.1568	0.6712	0.6733	0.6865	0.6878	0.1657	4.38
Win-exc	0.5588	0.5145	0.5177	0.5107	0.4978	0.5179	1.12
CB-fair	0.0984	0.6744	0.6865	0.7119	0.7011	0.1015	7.23
CB-fair+WE	0.4694	0.5256	0.5281	0.5422	0.5192	0.4560	1.19
$\gamma = 1/2$-TB fair+WE	0.5991	0.4811	0.4937	0.4840	0.4861	0.5773	1.25
$\gamma = 1$-TB fair+WE	0.6454	0.4641	0.4696	0.4612	0.4638	0.6116	1.40
$\gamma = 2$-TB fair+WE	0.6808	0.4459	0.4437	0.4600	0.4236	0.6518	1.61

Table 2: Link throughput (Mbps) for the 4-station scenario where the offered load → ∞.

algorithm is able to improve the performance of edge stations adequately. The 4-station scenario has the above described impact. The results of the 4-station scenario are shown in Table 2. The simulation results of the network without any algorithm show that $Link_{12}$ and $Link_{43}$ have the lowest throughput, whereas the other links have similar throughput. FI is 4.38 (0.6878/0.1568) for the network without any algorithm. At this point, implementing only the window-exchange algorithm increases the throughput of $Link_{12}$ from 0.1568 Mbps to 0.5588 Mbps. Now, FI becomes 1.12 (=0.5588/0.4978). This is the best FI value among the results of the network with the other algorithms. Since the connection-based method gives higher priority to the inner stations, it increases the throughput of the inner stations, and decreases the throughput of the edge stations. Thus, if we implement only the connection-based method, it worsens the fairness in the the network. FI becomes 7.23 (=0.7119/0.0984). Implementing both the window-exchange algorithm and the connection-based method also provides a fair network access. In this case, FI becomes 1.19 (=0.5422/0.4560). The time-based method ($\gamma = 1/2$) with the window-exchange algorithm also provides a fair access where FI is 1.25 (=0.5991/0.4811). The total throughput of the network where both the window-exchange algorithm and the connection-based method is implemented, is %76 (3.04 Mbps). It is exactly same as the total throughput of the network without any algorithm. Using only the window-exchange algorithm increases total throughput slightly, which is %78 (3.12 Mbps).

4.3 Throughput of the 5-station Scenario

In some cases, edge stations dominate the network, consequently, inner stations can not find any chance to reserve the channel, such as the 5-station scenario. The results are given in Table 3. The network without any algorithm has a fairness index of 23.79 (=1.9530/0.0821) which shows that there is a link ($Link_{54}$) in the network that can transmit 23.79 times more than another link ($Link_{23}$). The reason of this unfair network access is the presence of more than one simultaneous communication. Using only the window-exchange algorithm can not solve the problem, where FI becomes 15.10 (=1.9726/0.1306). Using both the connection-based method and the window-exchange algorithm, we improve the performance of the inner stations. In this case, FI becomes 4.07 (=1.1948/0.2933). The best fair network access is achieved by using the time-based method ($\gamma = 2$) with the window-exchange algorithm where FI becomes 3.15 (=1.0353/0.3288). There is an interesting phenomenon such that while the window-exchange algorithm increases the throughputs of the outer links, it decreases the throughputs of the inner links. The impact of the connection-based method is vice versa. Using both algorithms simultaneously smoothes the impact. As discussed in Section 2.1, edge stations do not realize the transmission if its neighbor station is in non-participant mode. In this case, edge stations back off with larger back-off window sizes. Thus, the throughput of the edge stations decreases. However, the window-exchange algorithm increases the throughputs of the edge stations by minimizing their back-off window sizes. Since the connection-based method gives a higher probability to inner links and lower probability to lower links, it decreases the throughputs of the edge stations. In this scenario, the total throughput of the original network is 4.89 Mbps which is a result of having two simultaneous communications in the network. Note that the channel capacity is 4 Mbps. The network with the window-exchange algorithm gives a total throughput of 5.14 Mbps. The network with both the connection-based method and the window-exchange algorithm results in a total throughput of 4.39 Mbps.

Algorithms	Tx: 1 → 2	Tx: 2 → 1	Tx: 2 → 3	Tx: 3 → 2	Tx: 3 → 4	Tx: 4 → 3	Tx: 4 → 5	Tx: 5 → 4	FI
Original	1.9508	0.1200	0.0821	0.2865	0.2870	0.0871	0.1213	1.9530	23.79
Win-exc	1.9664	0.3133	0.1609	0.1306	0.1340	0.1574	0.3048	1.9726	15.10
CB-fair	0.3387	0.2317	0.2294	0.8508	0.8614	0.2291	0.2434	0.3341	3.76
CB-fair+WE	1.1948	0.3880	0.2974	0.3133	0.3217	0.2933	0.3896	1.1929	4.07
$\gamma = 1/2$-TB fair+WE	1.3704	0.4188	0.2774	0.2473	0.2438	0.2696	0.3958	1.3761	5.64
$\gamma = 1$-TB fair+WE	1.1917	0.4226	0.3112	0.2760	0.3080	0.3035	0.4142	1.1949	4.33
$\gamma = 2$-TB fair+WE	1.0347	0.4223	0.3374	0.3339	0.3288	0.3369	0.4302	1.0353	3.15

Table 3: Link throughput (Mbps) for the 5-station scenario where offered load → ∞.

Algorithms	Tx:1 → 2	Tx:2 → 1	Tx: 3 → 4	Tx:4 → 3	Tx:5 → 6	Tx: 6 → 5	FI
Original	1.4111	1.4491	0.0668	0.0250	1.4392	1.4208	57.96
Win-exc	1.3982	1.4070	0.0932	0.0888	1.4023	1.4022	15.84
CB-fair	1.3765	1.3267	0.0950	0.1135	1.3879	1.3926	14.66
CB-fair+WE	1.3047	1.3075	0.1704	0.1707	1.3034	1.3066	7.67
$\gamma = 1/2$-TB fair+WE	1.2309	1.2277	0.2323	0.2339	1.2313	1.2290	5.30
$\gamma = 1$-TB fair+WE	1.0904	1.0930	0.3581	0.3533	1.0940	1.0921	3.10
$\gamma = 2$-TB fair+WE	0.9554	0.9493	0.4819	0.4787	0.9501	0.9516	2.00

Table 4: Link throughput (Mbps) for the 6-station scenario with dashed diagonal links where the offered load → ∞.

4.4 Throughput of the 6-station Scenario with Dashed Diagonal Links

The 6-station scenario with dashed diagonal links is a typical example of a network with distributed network load. Simulation results are given in Table 4. As seen from the table, the throughputs of the links between stations 3 and 4 are very low. Thus, the network without any algorithm has a very poor fair network access where FI is 57.96 (=1.4491/0.0250). Using both the window-exchange algorithm and the connection-based method, the network access is improved to a certain limit where FI is 7.67 (=1.3075/0.1704). However, the time-based method with the window-exchange algorithm has better impact when there is a distributed network load. The time-based method for $\gamma = 2$ with the window-exchange algorithm eliminates the problem significantly where FI is 2.00 (=0.9554/0.4787).

4.5 Throughput of the 6-station Scenario with Solid Diagonal Links

The 6-station scenario with solid diagonal links is an example of blocked edge stations like the 4-station scenario. Simulation results are given in Table 5. As seen from the table, the links of the stations 1, 2, 5 and 6 have less throughput than the links of the stations 3 and 4. The network without any algorithm has a fairness index of 4.55 (=0.4062/0.0893). Using only the window-exchange algorithm, FI becomes 1.71 (=0.3603/0.2110). As we discussed in Section 4.2, using only the connection-based method worsens the fair access where FI is 5.92 (=0.4190/0.0708). Using both the connection-based method and the window-exchange algorithm, FI becomes 1.46 (=0.3220/0.2205). This configuration provides the best FI value, which leads to the most fair network access. Using the time-based method also leads to the fair network conditions. Using the algorithms also increases the total network throughput. The total throughput of the network without any algorithm is 3.22 Mbps. The total throughputs achieved by using only the window-exchange algorithm, the time-based method for $\gamma = 1$ with the window-exchange algorithm, and both the connection-based method and the window-exchange algorithm are 3.74 Mbps, 3.73 Mbps and 3.61 Mbps, respectively. In this scenario, the algorithms not only provide a fair access in the network, but also increase the total network throughput.

5 Conclusions

In recent years, CSMA-based MAC protocols have been designed to control the media and to provide a fair and robust wireless network. However, those protocols do not provide a fair network. In this paper, balanced media access methods have been proposed for wireless networks to solve the fairness problem. The proposed methods, which are based on p-persistent CSMA protocols, are generally applicable to all MAC protocols. Two different balanced media access methods were introduced: a connection-based and a time-based method. The proposed methods are based on the exchange of information about the number of connections or the average contention period, respectively. Each station is responsible of broadcasting the related information to the stations within its communication reach. Using the received information, each station calculates a link access probability for its individual link. Stations access the medium using the calculated probability, like

Algorithms	Tx: 1 → 2	Tx: 2 → 1	Tx: 1 → 4	Tx: 2 → 3	Tx: 3 → 2	Tx: 3 → 4	Tx: 3 → 6	FI
Original	0.1174	0.1127	0.0893	0.0928	0.3983	0.4021	0.4062	-
Win-exc	0.3472	0.3529	0.2600	0.2621	0.2186	0.2150	0.2186	-
CB-fair	0.0867	0.0909	0.0786	0.0778	0.4146	0.4123	0.4190	-
CB-fair+WE	0.3220	0.3191	0.2461	0.2543	0.2224	0.2319	0.2262	-
$\gamma = 1/2$-TB fair+WE	0.3505	0.3622	0.2570	0.2605	0.2139	0.2097	0.2212	-
$\gamma = 1$-TB fair+WE	0.3555	0.3454	0.2659	0.2710	0.2100	0.2214	0.2119	-
$\gamma = 2$-TB fair+WE	0.3447	0.3470	0.2795	0.2656	0.2160	0.2069	0.2160	-
Algorithms *(cont.ed)*	Tx: 4 → 1	Tx: 4 → 3	Tx: 4 → 5	Tx: 5 → 4	Tx: 6 → 3	Tx: 5 → 6	Tx: 6 → 5	FI
Original	0.3944	0.4020	0.3913	0.0912	0.0948	0.1151	0.1148	4.55
Win-exc	0.2167	0.2110	0.2209	0.2570	0.2560	0.3603	0.3404	1.71
CB-fair	0.4168	0.4117	0.4143	0.0708	0.0731	0.0849	0.0826	5.92
CB-fair+WE	0.2240	0.2275	0.2205	0.2391	0.2381	0.3195	0.3188	1.46
$\gamma = 1/2$-TB fair+WE	0.2087	0.2212	0.2109	0.2473	0.2546	0.3583	0.3537	1.74
$\gamma = 1$-TB fair+WE	0.2174	0.2158	0.2062	0.2620	0.2506	0.3443	0.3548	1.72
$\gamma = 2$-TB fair+WE	0.2090	0.2189	0.2088	0.2635	0.2544	0.3443	0.3412	1.68

Table 5: Link throughput (Mbps) for the 6-station scenario with solid diagonal links where the offered load $\rightarrow \infty$.

the p-persistent protocol. In the connection-based method, the information is broadcasted whenever stations realize the change in the network topology. In the time-based method, it is broadcasted in a periodic basis. The connection-based method doesn't have any overhead which is occurred in the time-based method because of the periodic information exchange. The performance of the time-based method is better when the network load differs from link to link, such as the 6-station scenario with dashed diagonal links. The results show that none of the algorithm always provide the best fair access in every scenario. According to the scenarios, sometimes the network without any algorithm gives the best results, sometimes the window-exchange algorithm, and mostly the balanced media access methods. Although it does not always achieve the best fair access, the connection-based method with the window-exchange algorithm always achieves a very reasonable fair access, which is close to the the results of the best configuration. It also provides the best fair access in the 6-station scenario with solid diagonal links. The time-based method with the window-exchange algorithm provides the best fair network access in two scenarios (the 5-station scenario and the 6-station scenario with dashed diagonal links) out of five. However, it introduce a periodic information exchange, and the weight factor γ needs to be estimated for each scenario. As a result, the balanced media access methods with the window-exchange algorithm significantly eliminate the fairness problem that exists in the wireless MAC protocols. The future research work is to develop a method to estimate the traffic demand in the connection-based method and calculate the weight factor based on the network configurations in the time-based method. The other future work is to simulate the algorithms for different offered loads to show the impact of the algorithms, such as operating the stations on an ON/OFF basis.

References

[1] I. Millar and M. Naghshineh, "Advanced Infrared (AIR) IrMAC Draft Protocol Specification," *IrDA draft proposal for Advanced Infrared standard by IBM/HP Version 0.2*, July 1997.

[2] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: A Media Access Protocol for Wireless LAN's," *Proc. of ACM SIGCOMM '94*, pp. 212-224, 1994.

[3] P. Karn, "MACA - A New Channel Access Method for Packet Radio," *ARRL/CRRL Amateur Radio 9th Computer Networking Conference*, pp. 134-140, Sept. 22, 1990.

[4] C. L. Fullmer and J. J. Garcia-Luna-Aceves, "Floor Acquisition Multiple Access (FAMA) for Packet-Radio Networks," *Proc. of ACM SIGCOMM'95*, ACM, 1995.

[5] P802.11, D3 - Unapproved Draft 3: Wireless LAN Medium Access control (MAC) and Physical Specifications, IEEE, January 1996.

[6] L. Kleinrock and F. A. Tobagi, "Packet switching in radio channels: Part I - carrier sense multiple access modes and their throughput-delay characteristics," *IEEE Trans. Commun.*, Vol. COM-23, No. 12, pp. 1400-1416, 1975.

[7] K.-C. Chen, "Medium Access Control of Wireless LANs for Mobile Computing," *IEEE Network*, Vol. 8, No. 5, pp.50-63, 1994.

[8] B. P. Crow, I. Widjaja, J. G. Kim, and P. T. Sakai, "IEEE 802.11 Wireless Local Area Networks," *IEEE Comm. Mag.*, pp.116-126, Sept. 1997.