A Contention-free Data Transmission in Asymmetric Wireless Multi-hop Access Networks

Ryugo Nishii†, Tatsuji Munaka†, Masaki Bandai‡ and Takashi Watanabe†

†Information Technology R & D Center, Mitsubishi Electric Corp.
5-1-1 Ofuna, Kamakura, Kanagawa, 247–8501 Japan
‡Faculty of Information, Shizuoka University
3-5-1, Johoku, Hamamatsu-Shi, Shizuoka, 432-8011

ABSTRACT

The performance of wireless access network is often limited by the communication range between the access point and stations, due to long distance and shadowing. Wireless multi-hop access network is a cost-effective solution to this problem as it expands the coverage area without the need for additional access point. Unfortunately, the throughput of the network declines rapidly as the number of multi-hops increases. In this paper, we present an Asymmetric Wireless Multi-hop Access Network (AWiMA Net) based on 802.11 network. AWiMA Net divides data transmission into up-link and down-link to eliminate contention. Down-link data are transmitted in single hop, and the up-link data are transmitted in multi-hop with RTS/CTS handshaking procedure. Our proposed results in throughput increase, compared with a conventional wireless multi-hop access network. Our experimented results confirm the designed improvement.

Keywords: Asymmetric Wireless Multihop Network, IEEE802.11 DCF, RTS/CTS, contention-free control

1 INTRODUCTION

Wireless LAN systems have been evolving in performance and coming into wide use. Wireless access networks using wireless LAN are getting popular in recent years. Users can get many services like mail services, Web services, and VoIP services by wideband communication network in the area. A wireless access network consists of stations and an access point (AP), which is a fixed infrastructure connected to the Internet. However, there exist some stations which cannot be covered by the AP. They cannot get signals correctly, due to far from the service area in physical distance. Others are in the shade of buildings and structures, even though they are located within the service area of the AP. The area of this kind is called a dead spot. Usually radio signal of a station is not strong enough to reach long distance, to save its battery power consumption. AP signal is also the same as station’s, and service area is limited.

A wireless multi-hop access network is a solution for this problem without installing another new AP. This expands coverage range of an AP cost effectively. It helps every station to reach an AP with multi-hop. But it has a problem that the more multi-hops stations are connected to an AP, the less throughput of the network becomes.

In this paper, we propose an Asymmetric Wireless Multi-hop Access Network (AWiMA Net) based on IEEE802.11 to solve the problem. This network expands the communication range of an AP. Data transmission between an AP and stations is divided into up-link and down-link period to avoid data transmission congestion. Down-link data is transmitted directly with single hop, and communication is under the AP’s control. This transmission period control helps the AP and stations to reduce RTS-CTS-Data-ACK handshake procedure. AWiMA Net solves throughput degradation which is a result of congestion of RTS-CTS-Data-ACK handshake procedure in the wireless multi-hop access network using IEEE802.11 DCF.

2 RELATED WORKS

Many proposals on wireless multi-hop access networks using wireless LAN have been published, as mobile devices spreads in recent years. In wireless multi-hop access network, radio communication media are used to establish the link between arbitrary adjacent stations. IEEE802.11 is a media access protocol based on CSMA/CA and is often used as the wireless multi-hop access network. CSMA/CA takes RTS/CTS procedure to avoid hidden node problem in wireless multi-hop access network. It is known that link throughput decreases by NAV blocking problem, and data delay time becomes longer as the traffic increases when the hidden node exists [1]. Moreover, Xu [2] showed that it is impossible to achieve enough throughput in the IEEE802.11 DCF wireless multi-hop network even if stations do not move. Harada [3], Hirakawa [4], Ray [5], Bharghavan [6] [7] proposed the improvements based on RTS/CTS to this problem. However, it is necessary to take the handshake procedure named RTS-CTS-Data-ACK for the IEEE802.11 DCF for multi-hop communication collision avoidance. Therefore it is difficult to improve throughput and data delay time in wireless multi-hop networks. In another approach for the throughput improvement, Selavkennedy [8] proposed the frame bursting method that APs and stations continuously transmit data. However, the model in this method assumes single hop communication, and does not provide a solution in wireless multi-hop access network.
3 ASYMMETRIC WIRELESS MULTI-HOP ACCESS NETWORK

Fig. 1 shows the proposed AWiMA Net. This network has the following features: 1) Communication range of the AP is longer than stations. 2) The AP sends data effectively to each station with single hop. 3) Data transmission is divided into up-link and down-link to avoid congestion. 4) Under the contention-free control, the network reduces RTS-CTS-Data-ACK procedure. 5) Stations in the dead spot are connected to the network via a border station.

This network increases communication range of the AP and expands network coverage. The transmission power of APs is higher and therefore their range is longer than stations, and down-link data is transmitted directly and effectively with single hop. Stations send up-link data with normal multi-hop. Down-link data directly to an arbitrary station might cause the collision with the up-link data transfer, because the AP cannot sense carrier of every station. The signal range of the stations is shorter than that of the AP. In order to avoid signal collision, communication in the network is under the contention-free transmission control by the AP. Data transmission between the AP and the stations is divided into up-link and down-link period to avoid data transmission congestion. In the wireless multi-hop access network, up-link data transmission intermingles with down-link, and this mixture causes data transmission congestion. In AWiMA Net, the AP controls up-link and down-link period by issuing control frames to all stations. This makes the network throughput increase effectively, avoiding data transmission congestion. The AP reduces RTS-CTS-Data-ACK procedure in down-link, because no station tries to send data in this period. A border station forwards data to a station at the dead spot as a relay.

4 ROUTING ALGORITHM

4.1 Zone Definition

Based on their communication with AP, we introduce four types of Zone of station position which helps stations to recognize a border station. A station in Zone 1 and the AP communicate each other with single hop. STA1, STA6, STA8 and STA11 in Fig. 1 are in Zone 1. A station in Zone 2 gets data from the AP with single hop, but the station can not reach the AP directly. A station in Zone 2 has to send data with multi-hop. STA2, STA3, STA5, STA9 and STA10 are in Zone 2. Neither the AP nor a station in Zone 3 can send data directly, but the station can communicate with another station in Zone 1 or Zone 2 directly. We call the station of this kind a border station. STA3 and STA6 are border stations. STA4 and STA7 are in Zone 3. Neither the AP nor a station in Zone 4 can reach each other directly. The station cannot find out its border station, due to far from Zone 1 and Zone 2. STA12 is in Zone 4. The radius in Fig. 1 does not necessarily indicate physical distance. It shows communication capability of each station with the AP. STA7 is in the dead spot and can communicate with the AP in two hops.

1. Basic definitions
   - A set of all stations including AP : N
   - Maximum transmission range from k towards l : RT(k, l)
     - station k : transmitter k ∈ N
     - station l : receiver l ∈ N
   - Station k can transmit a data in the direction of l within the distance of RT(k, l)
   - Distance between two station k and l : d(k, l)
   - Station set without AP : N_STA = N – {AP}

2. Properties
   - d(k, l) = d(l, k) for ∀ k, l ∈ N
   - RT(k, l) = RT(l, k) for ∀ k, l ∈ N_STA
   - RT(AP, k) > RT(k, AP) for ∀ k ∈ N_STA
   - RT(k, l) = RT(k, n) for ∀ k ∈ N_STA, ∀ l, n ∈ N
   - Station k can transmit a signal to station l, and station l can detect and decode the signal, iff d(k, l) ≤ RT(k, l) for ∀ k, l ∈ N

3. Zone
   - Station set in Zone 1:
     N_Z1 = {n | n ∈ N_STA, d(AP, n) ≤ RT(AP, n) ∧ d(n, AP) ≤ RT(n, AP)}
   - Station set in Zone 2:
     N_Z2 = {n | n ∈ N_STA – N_Z1, RT(n, AP) < d(AP, n) ≤ RT(AP, n)}
5.1 Data Transmission Period

Data transmission in up-link period is executed in normal multi-hop mode. An AP reduces its transmitted power level to normal one which is same as station’s to avoid signal collision with stations. Routing and Zone recognition should be done in this period to avoid collision with the AP signal. In down-link period, wireless signal of the AP is in long range and can reach each station in Zone 1 and Zone 2. The AP sends data to stations in this period. It transmits data directly to the station. The amount of down-link data is much more than up-link one, so this contributes the network throughput to increase efficiently. Towards Zone 3 station, the AP sends data via a border station, which forwards data for Zone 3 station. All the stations are prohibited to send data in this period, except transmission under the AP control.

5.2 Data Transmission Scheduling Control Frames

AWiMA Net controls up-link period and down-link one by several types of control frames. We introduce three new type of control frames, NUL, NDL and RTSR, which are transmitted at the beginning of each period in the long range mode of the AP signal (Fig. 2, Fig. 3).

- NUL (Notify STA of Up-Link period) notifies STA of the beginning of the up-link period. After stations receive NUL, they start up-link data transmission. The duration field (DF) in NUL indicates the time for the up-link period timer, denoted by \( T_{mr,NUL} \).
- NDL (Notify STA of Down-Link period) notifies STA of the beginning of the down-link period. Down-link period consists of several sub-down-link periods in which an AP sends data to the grouped stations on the same up-link route. The time for the period timer \( T_{mr,NDL} \) is also described in DF of the frame.
- RTSR (notify Request To Send with Route) notifies the beginning of the down-link data delivery to stations, that is a sub down-link period described above. An AP selects stations located in the same up-link route for down-link data delivery, and sets the furthest station address on the route into the receiver address field in RTSR frame. When a station receives RTSR frame, it does not need to send back CTS to the AP, because there is no interfered factor. After RTSR, the AP begins sending data sequentially to the station whose number of hops is the least on the selected route. The data delivery to the furthest station, which address is put in receiver address field in RTSR, is executed at the end of this sub down-link period.

5.3 Cycle Time of Up-Link and Down-Link

The cycle time which consists of up-link and down-link is fixed in AWiMA Net. The longer period is efficient for the
The AP assigns adequate down-link time to amount of down-link data but cannot predict how much up-link data comes. At the beginning of each period the AP knows depends on applications in the network. Must separate an amount of data into several down-links and data delay. However it is less efficient for the AP, because it must separate an amount of data into several down-links and must change transmission direction frequently. But long down-link period, and no station tries to send RTS. Therefore, the AP can through issuing NUL to Zone 3 stations.

Here, we need to make sure all stations receive NUL and NDL successfully. If they cannot get the control frames, collisions may occur between the AP and the stations. To avoid the collision, all the stations in Zone 1 and Zone 2 set each timer for $T_{mr\text{-}NUL}$ of DF in NUL frame when they receive NUL. The station in Zone 3 also sets timer for $T_{mr\text{-}NUL} - \Delta T_{Up}$.

In case that the station detects a expired time event, it changes its own status from up-link period to down-link one by itself, and refrains from sending data. If the up-link data transmission period becomes the end while the stations still have data to be sent, the stations pause transmitting data and wait NDL. In order to make all the stations keep this, $T_{mr\text{-}NUL}$ should be $\Delta T$ shorter than up-link period $T_{n\text{-}Up}$. Here, stations take $\Delta T$ to execute RTS-CTS-Data-ACK procedure. They resume data transmission in next up-link period.

### 5.5 Down-Link Data Transmission

All stations are notified at the beginning of down-link period by receiving NDL from an AP. Stations in Zone 3 cannot get NDL directly. A border station forwards NDL to Zone 3 stations. The down-link period in Zone 3 is $\Delta T_{Down}$ shorter, which the border station takes to forward NDL to Zone 3 stations. When the border station forwards NUL, receiver address field in NUL is filled with $\Delta T_{Up}$, which is the time from receiving NUL of the AP through issuing NUL to Zone 3 stations.

In down-link data delivery, data delay time is minimized by sending data to Zone 2 stations with one hop and reducing control frames such as RTS, CTS and ACK. The AP is an only node allowed to send data to the stations during the period, and no station tries to send RTS. Therefore, the AP can continuously send data without carrier sensing and RTS/CTS

$T_{up\text{-}DF} = T_{app} - T_{n\text{-}Down}$

$T_{Down} \leq T_{app}$

$T_{Down} = \sum_{i=1}^{k} T_{group i}$

$T_{group i} = T_{data} \times (N_{a i} + N_{b i}) + N_{RTSR i} \times T_{RTSR} + Num_{Hops i} \times T_{ACK}$

Where,

- $T_{up\text{-}DF}$: time of n-th up-link.
- $T_{Down}$: time of n-th down-link.
- $T_{app}$: fixed cycle time, and application depended.
- $k$: the number of groups for down-link data delivery during $T_{Down}$
- $T_{data}$: Data transmitting time
- $N_{a i}$: the number of data packets for stations which expect to receive data in the i-th group
- $N_{b i}$: the number of data packets for stations in Zone 3 in the i-th group
- $N_{RTSR i}$: the number of issued RTSR. Normally, it is 1. If Zone 3 station exists, it is 2. They are issued by the AP and by a border station.
- $T_{RTSR}$: RTSR transmitting time
- $Num_{Hops i}$: the number of hops between the AP and the furthest station in the i-th group
- $T_{ACK}$: ACK transmitting time
- $T_{group i}$: time for down-link data transmission in group i
1. Dividing stations into groups
   An AP divides stations which are expecting to receive data from it, into several groups. Each group consists of stations that are located on the same route to the AP. The AP keeps routes which were attached to data from the source stations. If the station, to which the AP is going to send data, is the only one on the route to the AP, it forms its own group. After data delivery, all ACKs of the stations in the group will be merged into one ACK and sent back to the AP.

2. Data delivery to a group
   (a) Sending RTSR
      The AP notifies all stations in Zone 1 and Zone 2 the beginning of the data delivery by sending RTSR. The AP specifies the station which is located in the furthest, in order with large number of hops to the AP, on the selected route. And it fills the receiver address field of RTSR frame with the selected station address. Each station checks whether it is the border station of the furthest address station. If so, it gets border station mode for the furthest station in Zone 3. The AP also keeps all the routes from the source stations, it knows whether the furthest station is in Zone 3 or not. No station sends back CTS to the AP after receiving RTSR. The AP puts DF for $T_{group}$ which is the down-link data delivery time for the group. Stations which receive RTSR set and start their timer for DF of RTSR.

   (b) Data delivery with ACK pending demand
      Firstly, the AP selects a station whose number of hops is the smallest on the route, and sends data to it with ACK pending demand. When the station receives data with this demand, it sets ACK pending flag in itself and does not send back the ACK immediately. In order to distinguish the operation of this sort from that of normal data frame, we newly define a subtype for data frame. We denote this data frame as Data_w/A (Data with ACK, subtype 1010, hereafter) in Fig. 4. Data_w/A has quite the same content as the normal data frame except the subtype demanding ACK pending. If the station pending ACK does not receive ACK from further station within the timer, it sends its own ACK to the AP, to inform the AP of its data completion.

3. Data transmission in a normal data frame
   The AP finally transmits data to the station which is located at the furthest on the route using normal data frame. If the furthest station is in Zone 3, the AP transmits data with Data_w/b (Data with ACK pending for a border station, subtype 1011) frame shown in Fig. 4. The border station is ready to forward packets to the Zone 3 station in this transmission process by checking the receiver address field in the former RTSR. The AP sends data to the border station as well as Data_w/A frame. The border station forwards data to the Zone 3 station. This data transmission is also as well as normal data transmission.

   When the furthest station receives data completely, it sends back the ACK to the nearest station on the route to the AP. The sender address field of this ACK is filled with this station address. The station turns on the first bit of DF which indicates the data reception flag. DF in the ACK frame is used as a data reception completion flag in each station. When the source station sends data to the AP, it attaches the route with data, and each station on the way to the AP keeps the route in its cache. Each station knows its corresponding bit in DF. If a station receives data completely, it sets one in its data reception completion flag. A station which fails in receiving data sets zero there. Each bit is allocated to a station in order far from the AP in the route. The station received ACK sets its corresponding flag bit in DF,
merging ACKs, and sends the updated one to the next station towards the AP. This ACK combing process is repeated until the ACK reaches the AP. The AP knows which station receives the data completely by confirming the corresponding bit in DF in the received ACK. If the corresponding ACK flag is not turned on, the AP knows the station which failed to get data and tries to retransmit the data frame in the next down-link period.

5.6 Example of Down-link Data Delivery

In this example, STA2 in Zone 2 and STA4 in Zone3 are expecting to receive data from the AP in Fig. 1. The route is STA4, STA3, STA2, STA1, the AP. And STA3 is the border station for STA4. The down-link sequence of control and data frame transmission is shown in Fig. 5.

1. Data request by a station in up-link period
   After establishing a route to the AP, STA2 and STA4 make requests to the AP through relay stations in up-link period. STA4 issues RTS to the nearest station STA3. STA3 replies CTS to STA4. After receiving CTS, STA4 sends data and its Zone flag with the route to the AP, and waits ACK from STA3. This procedure is the same as IEEE 802.11 RTS-CTS-Data-ACK procedure. After STA3 receiving the request, it takes the same procedure as STA4. STA3 makes request to STA2 as well. When the AP finally receives the request, it keeps the source station STA4 ID, the route and its Zone flag. Each station on the way to the AP also keeps them as well. During up-link period, STA2 sends its request to the AP. According to the route and Zone flag attached, the AP can get to know that STA3 is the border station for STA4.

2. Down-link data transmission
   The AP has DataX to STA2 and DataY to STA4 in this example. The AP issues RTSR, whose receiver address field is set STA4. Border station STA3 checks the receiver address in RTSR, and knows that it has to work as a relay for STA4 in this process, and STA3 forwards RTSR to STA4. The AP sets STA2 address in the receiver address field into Data_w/A frame, and sends DataX at first directly without expecting CTS. STA2 checks the subtype in the data frame, and knows ACK pending mode and it does not send back the ACK. Then the AP sends next Data Y to STA3 with Data_w/b frame without expecting CTS. After receiving data, STA3 forwards it to STA4 with normal data frame. When STA4 receives the data completely, it sets the flag (0x8000) in DF of ACK, and sends ACK to STA3 which is on the way to the AP. STA3 does not alter the data reception completion flag, which is the 2nd bit in DF of received ACK, and the DF in the frame is still 0x8000. It sends ACK to STA2. STA2 alters the DF into 0xA000, which indicates it has received data completely, and sends ACK to STA1. STA1 forwards ACK to the AP without any update. The AP checks each data reception completion flag in the DF. It knows that 0xA000 in DF means STA2 and STA4 received data completely.

6 EVALUATION BY SIMULATION

Using network simulator QualNet, we compare normal multi-hop and AWiMA Net. In the simulation total station number is fifty, and ten stations are located in Zone 3.

The objective of the proposal is to improve network throughput and delay time. They are defined as follows:

- Throughput : data reception ratio, during elapsed time from request to an AP by a station to data reception by itself (kbps)
- Delay time : elapsed time until completing data reception (second)

In the simulator stations issue data request to the AP periodically, every fixed interval time, and receives data. We call a station which issues data request to AP as an active station. Simulator selects active stations randomly from fifty stations in the simulation model. Parameters in the application are given in Table 1.

6.1 Throughput of multi-hop network

Fig. 6 shows throughput of multi-hop based on IEEE 802.11 DCF. Each active station issues data request every 25 msec. As number of multi-hop increases, network throughput decreases sharply. Even though number of active stations is ten, throughput of two hops drops to less than one-third of one hop. In the case of five hops, each throughput falls around 2 kbps. According to these results, we confirmed that multi-hop based on 802.11 DCF had a problem, which more hops causes less throughput sharply.

6.2 Effects of cycle time and interval time

The throughput of respective stations depends on cycle time of the AP and interval time of stations. Fig. 7 shows network throughput at several fixed interval times, as cycle time of the

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<th>Table 1: Simulation parameters</th>
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<td>size of upload packet</td>
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<tr>
<td>size of download packet</td>
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<tr>
<td>Simulator</td>
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<td>Simulator execution</td>
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<td>MAC</td>
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<td>The number of terminals</td>
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<td>Commu. distance of stations</td>
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<td>Commu. distance of AP in 802.11 DCF</td>
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<td>Commu. distance of AP in AWiMA net</td>
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AP increases. Here, throughput is an average of all active stations when from ten to fifty stations are selected randomly. As cycle time gets longer, throughput at each interval time decreases. It takes longer time for the stations to get down-link data from data request by itself, and the AP has to wait to send data to a station until down-link period. In three interval times, 25 msec has better performance. The throughput depends on cycle time, interval time, data packet size, and number of stations. In the evaluation 25 msec interval time is adequate under the condition that data packet is 1000byte, cycle time is 25 msec, and number of stations is 30.

### 6.3 Throughput and number of stations

Fig. 8 shows throughput vs. number of active stations in change of interval time in proposed method and in 802.11 DCF based multi-hop network. Fig. 9 shows delay time vs. number of active stations under the same condition. As number of active stations increase, throughput in 802.11 DCF based multi-hop network sharply falls. Throughput in proposed method decreases, but it keeps several times performance against 802.11 DCF based multi-hop network. Especially proposed method with 25 msec interval time keeps the throughput even though number of active stations increase. Fig. 9 shows that delay time of 802.11 DCF based multi-hop network grows larger as active stations increase. However delay time of proposed method is improved.

### 6.4 Impact of number of hops

Fig. 10 shows throughput vs. hopping number when cycle time and interval time are set as 25 msec. Stations within four hops, which are located in Zone1 or Zone 2, get data in one hop from the AP, so its throughput depends on time for data request to reach the AP in up-link period. Throughput of proposed method decreases as hopping number increases, but average throughput still keeps 25 kbps in four hops. Stations in five hops are located in Zone 3, and they communicate with the AP via a border station. And its average throughput is 16 kbps. Compared with 802.11 DCF based multi-hop network in Fig. 6, proposed method keeps some throughput even in more than three hops. We confirm that proposed method
works for the station at the dead spot.

7 CONCLUSIONS

Wireless multi-hop access network based on IEEE 802.11 DCF enables users to connect to the network easily and fairly, but throughput drops sharply as the number of multi-hop increases. We proposed data transmission method with contention-free control which divides data transmission into up-link and down-link to prevent throughput decreasing. We show that AWiMA Net is efficient in multi-hop transmission when cycle time and interval time are set properly.

REFERENCES