A Relay-Aided Media Access (RAMA) Protocol in Multirate Wireless Networks

Shihong Zou, *Member, IEEE*, Bo Li, *Senior Member, IEEE*, Haitao Wu, *Member, IEEE*, Qian Zhang, *Senior Member, IEEE*, Wenwu Zhu, *Senior Member, IEEE*, and Shiduan Cheng, *Member, IEEE*

***Abstract*—The IEEE 802.11 standard inherently supports multiple data rates at the physical layer. Various rate adaptation mechanisms have been proposed to exploit this multirate capability by automatically adapting the transmission rate to best utilize the wireless spectrum. This study is primarily motivated by the observation that in a wireless network, a multihop high-rate path can potentially achieve better throughput and delay than using a single-hop low-rate path for transmission. Specifically, this paper introduces a relay-aided media access (RAMA) protocol by taking advantage of the existence of such multihop high-rate links. This is demonstrated by replacing one low-rate link with two high-rate links using a relay node. One of the key novelties in the proposed RAMA protocol is that the transmission from the immediate relay node to the destination node is free of contention. Results from analysis and simulations show that RAMA can significantly improve performances in terms of both throughput and delay.**

***Index Terms*—IEEE 802.11, media access control (MAC), multirate transmission, wireless networks.**

I. Introduction

IEEE 802.11 [1] based wireless LAN (WLAN) has been one of the primary enablers of wireless access to the Internet. The fundamental restriction of IEEE 802.11 WLAN is its limited coverage area. Recently, there have been considerable efforts in expanding WLAN to multihop ad hoc networks. In the original IEEE 802.11 protocol, all transmissions take place using a single base rate, typically 2 Mb/s. IEEE 802.11a and 802.11b offer multirate capability at the physical layer. When the signal-to-noise ratio (SNR) is sufficiently high, higher data rates can be explored directly from the fundamental properties of wireless communications. With this multirate enhancement, transmissions can take place at a number of rates according to channel conditions. The set of possible data rates that IEEE 802.11a supports is 6, 9, 12, 18, ..., 54 Mb/s, and the set that IEEE 802.11b supports is 1, 2, 5.5, and 11 Mb/s.

Given this multirate capability at the physical layer, media access control (MAC) layer mechanisms are required to exploit this capability. The autorate fallback (ARF) protocol [2] was the first mechanism that utilized multirate at the MAC layer. A receiver-based autorate (RBAR) protocol was proposed in [3]. Under autorate adaptation mechanisms, when the sender and receiver are far away from each other, or there are obstacles between them, they have to rely on low-rate link for transmission due to the potentially serious signal attenuation. When one node captures the channel for a long time using the low bit rate, it penalizes other nodes in the coverage area that can use higher rate [4]. This is because the basic carrier sense multiple access with collision avoidance (CSMA/CA) access method used in the IEEE 802.11 protocol guarantees an equally long-term channel access probability to all nodes. Sadeghi *et al.* [5] proposed an opportunistic autorate (OAR) protocol to improve the performance of high-rate nodes.

The signal attenuation on a wireless link typically varies as d^n for $2 \leq n < 6$, where d is the distance between the sender and the receiver. When there are obstacles in the line-of-sight, the wireless signal deteriorates more seriously [6]. The key observation that leads to the development of our proposed relay-aided media access (RAMA) protocol is the following: when there is a node located between the sender and the receiver, its rate to the sender and receiver is usually much higher than the rate from the sender to the receiver due to the shorter distance or without line-of-sight obstacles. In such an environment, if the immediate node can be used as a relay node, the transmission can potentially be significantly improved. The key challenge is that the existing protocols cannot directly make use of such relays. In a WLAN, each node contacts with the access point (AP) directly even when it is far away from the AP or there are obstacles in between. In wireless ad hoc networks, the low-rate links are often used for a pair of far away nodes under the typical minimum hop routing protocols such as dynamic source routing (DSR) [7] and ad hoc on demand distance vector (AODV) [8]. Although several multirate-aware routing protocols [9]–[11] have been proposed, none of those explicitly address this issue.

In this paper, we introduce the RAMA protocol, which is an enhanced protocol for multirate IEEE 802.11 to be used

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S. Zou and S. Cheng are with the State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications, Beijing 100876, China (e-mail: zoush@bupt.edu.cn; chsd@bupt.edu.cn).

B. Li and Q. Zhang are with the Department of Computer Science, Hong Kong University of Science and Technology, Kowloon, Hong Kong (e-mail: bli@cs.ust.hk; qzhang@cs.ust.hk).

H. Wu is with Microsoft Research Asia, Beijing 100080, China (e-mail: hwu@microsoft.com).

W. Zhu is with Intel Research, Beijing, China (e-mail: wenwu.zhu@intel.com).

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in general wireless networks. The fundamental idea of the RAMA protocol is to fully exploit the relay effect to improve the performance of low-rate transmission whenever feasible. Whenever there exists an intermediate node between the low-rate sender and receiver, the sender can utilize the intermediate node to relay its frames to the receiver after gaining access to the channel, in which a low-rate link is replaced by two much higher rate links. One of the key novelties in the RAMA protocol is that the transmission from the relay node to the destination is free of contention. Theoretical analysis and extensive simulation results show that the RAMA protocol can significantly improve the throughput and delay performance.

The rest of this paper is organized as follows: In Section II, we review IEEE 802.11 and related works. In Section III, we introduce the motivation of the RAMA protocol. In Section IV, the RAMA protocol is proposed. Simulation results and analyses are presented in Section V. Section VI concludes this paper.

II. Background and Related Works

A. Basic Mechanisms in IEEE 802.11

Distributed coordination function (DCF) supports asynchronous data transfer on the best effort basis. It is the basic access method of the IEEE 802.11 protocol and is also frequently used in the MAC protocol in ad hoc networks. As specified in the standard, DCF must be supported by all the hosts in a basic service set (BSS). The DCF protocol is based on CSMA/CA. In DCF, carrier sense is performed both at the physical layer, referred to as physical carrier sensing, and at the MAC layer, known as virtual carrier sensing. The objective of CA is to avoid cases wherein all the hosts transmit data immediately after the medium has been sensed idle for Distributed coordination function InterFrame Space (DIFS), thus preventing collision to occur. CA is implemented by a backoff procedure. DCF demands a host to start a backoff procedure right after the host transmits a message, or when a host wants to transmit but the medium is busy and the previous backoff has been done. To perform a backoff, a counter is first set to an integer randomly selected from its current contention window. When the medium is detected to be idle for a slot (a fixed period), the counter is decreased by one. Only when the counter reaches zero can the host transmit data.

There are two techniques used for packet transmission in DCF. The default technique is a two-way handshaking mechanism, also known as basic access method. A positive MAC acknowledgment is transmitted by the destination to confirm each successful packet transmission. The other optional technique used in DCF is a four-way handshaking mechanism, which uses the RTS/CTS technique to reserve the medium before data transmission. This technique has been introduced to reduce the performance degradation due to hidden terminal problem. The RTS/CTS access mechanism is shown in Fig. 1.

Since a node may overhear many different potentially overlapping reservation requests, it needs a means by which it can efficiently manage them. This is the purpose for the mainte-

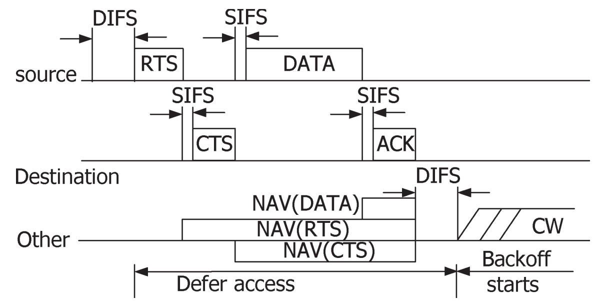

Fig. 1. RTS/CTS access mechanism in DCF.

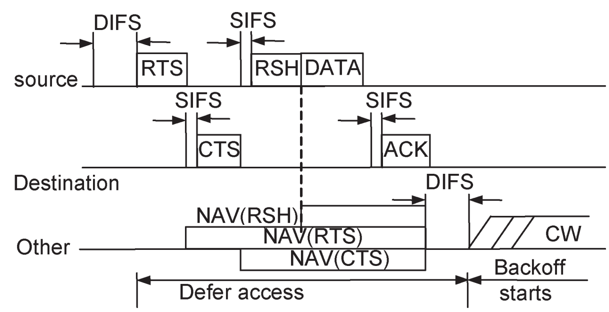

Fig. 2. NAV set by other nodes in RBAR.

nance of a structure called the network allocation vector (NAV) [1]. NAV is a data structure that stores the aggregate duration of times that the medium is presumed to be "busy" based on the reservation requests that have been received. Maintenance of the NAV in DCF is straightforward since reservations are not allowed to change. But this is no longer true in RBAR [3] and our protocol RAMA since the reservation can be changed due to multirate enhancement.

B. Related Works

Kamerman and Monteban [2] proposed the ARF protocol. With ARF, the sender attempts to use higher transmission rates after consecutive transmission successes and reverts to lower rates after failures. Under most channel conditions, ARF provides better performance over the pure single-rate IEEE 802.11.

Holland *et al.* [3] proposed the RBAR protocol. The key idea in RBAR is for receivers to select the appropriate rate for the DATA frame during the RTS/CTS frame exchange. The receiver uses the physical layer analysis of the received RTS message to determine the maximum possible transmission rate for a particular bit error rate. The receiver inserts this rate into a special field of the CTS message to inform the sender. As the RTS is sent shortly before data transmission, the estimation of the channel condition is quite accurate so that RBAR yields significant throughput gains compared to ARF. A new subheader termed reservation subheader (RSH) is inserted preceding data transfer as illustrated in Fig. 2. With the RSH message, overhearing nodes can modify their NAV values to the new potentially decreased transmission time. To implement the above mechanism, RBAR modifies the formats of RTS/CTS

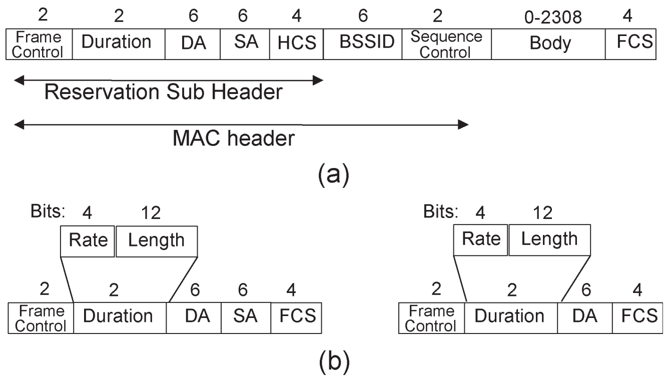

Fig. 3. MAC frame formats used in RBAR protocol.

and DATA frame illustrated in Fig. 3. In addition, RBAR must keep a list of $\langle \mathrm{src}, \mathrm{dst}, \mathrm{NAV} \rangle$ to acquire the right NAV when reservation is changed due to multirate.

Sadeghi *et al.* [5] proposed an OAR protocol to improve the performance of high-rate nodes. The key idea in OAR is to opportunistically exploit high-quality channels when they occur via transmission of multiple back-to-back packets. In particular, when the multirate MAC indicates that the channel quality allows transmission beyond the base rate, OAR grants channel access for multiple packet transmissions in proportion to the ratio of the achievable data rate over the base rate. However, OAR does not improve the performance of low-rate nodes.

Lee *et al.* [12] proposed a multihop WLAN architecture to enhance the performance and extend the wireless coverage. This scheme was designed for WLAN with AP. Although it was claimed to be a MAC layer scheme, it is actually a routing layer scheme, and channel contention can be increased as one hop simply being replaced by two hops. A complication was introduced as the relay nodes must obtain access to the channel for both itself and the nodes it served for. One of the fundamental advantages in our proposed RAMA protocol is the contention-free characteristics in the transmission from the relay to the receiver. The relay node only performs relaying and forwarding after the sender obtains the access, which does not affect the channel access of the relay node itself. This turns out to be one of the most significant factors for performance improvement.

Multirate-aware routing protocols in multihop ad hoc networks have been proposed in [9]–[11]. The routing protocols capture the multirate, but they do not overcome the problem that a low-rate link can still be selected due to the on-demand characteristic of these routing protocols (this will be further discussed in Section III-B). Relying on the multihop routing to deal with this problem is not only cumbersome but also far less effective since the underlying MAC protocol still encounters multiple collisions.

III. Motivation

In DCF, each node must transmit with the same power. Wireless signal strength attenuates proportionally with d^n $(2 \leq n < 6)$, where d denotes the distance between the sender and receiver. The available rate is determined by the SNR at the receiver. Therefore, with the help of a node located between the sender and receiver, a lower rate link can be replaced by two higher rate links. In the following, we first demonstrate quantitatively that using relay nodes reduces the transmission time with high probability. Then, we point out that it is inevitable to use low-rate links in current wireless networks (including both WLAN and wireless ad hoc networks) even if such relays exist.

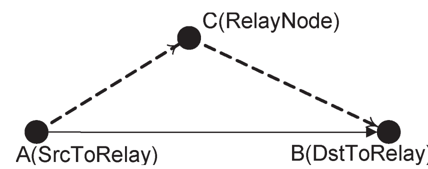

Fig. 4. Reference scenario of RAMA.

A. Existence of Relay Nodes

First, we define the following notations: Let L be the length of the DATA frame (including payload and MAC header). For any link A$->$B, let d_{AB}, R_{AB}, and T_{AB} denote the distance between A and B, the rate A can use to reach B, and the time needed to transmit the DATA frame, respectively. In DCF, $T_{\mathrm{AB}} = L/R_{\mathrm{AB}} + T_{\mathrm{overhead}}$, where T_{overhead} is the time to transmit the physical layer header.

As stated in the Shannon formula, we have

$$R = W \log(1 + \mathrm{SNR}) \tag{1}$$

where R is the rate that can be achieved, and W is the bandwidth and SNR is the signal to noise ratio. We use the following wireless propagation model [6]:

$$P_r = K \frac{P_t}{d^n} \tag{2}$$

where $P_r P_t$ are the power received and transmitted with, respectively, d as the distance between the sender and receiver, and K is the constant. Note that our goal to use the relay is to reduce the transmission time. Therefore, referring to Fig. 4, we define the relay condition as

$$T_{\mathrm{AC}} + T_{\mathrm{CB}} + \mathrm{SIFS} < T_{\mathrm{AB}} \tag{3}$$

where SIFS stands for short interframe space that is defined in IEEE 802.11 and is used here for the relay to transform from receiving state to transmitting state. The relay condition (3) can also be expressed as

$$L/R_{\mathrm{AC}} + L/R_{CB} + T_{\mathrm{overhead}} + \mathrm{SIFS} < L/R_{AB}. \tag{4}$$

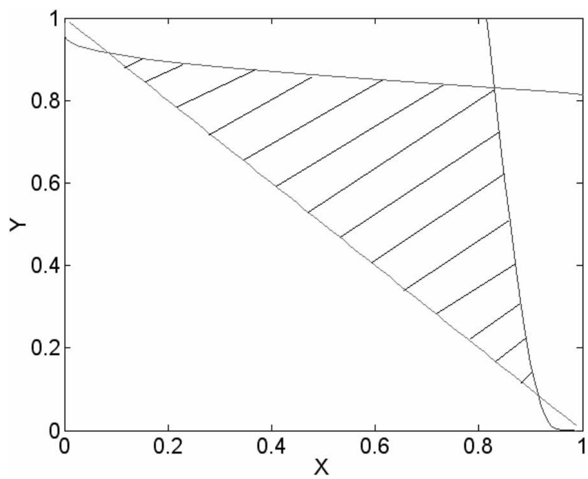

Fig. 5. Theoretical probability.

TABLE I
TYPICAL RANGES AT DIFFERENT RATES (BER $< 10^{-5}$)

Range (meters)	11Mbps	5.5Mbps	2Mbps	1Mbps
Open	160m	270m	400m	550m
Semi-open	50m	70m	90m	115m
Closed	25m	35m	40m	50m

Letting $x = d_{AC}/d_{AB}$ and $y = d_{CB}/d_{AB}$, we can obtain the following inequalities from (1), (2), and (4):

$$\begin{cases} \frac{L}{W \log(1+\mathrm{SNR}/x^n)} + \frac{L}{W \log(1+\mathrm{SNR}/y^n)} \\ \quad +T_{\text{overhead}} + \mathrm{SIFS} < \frac{L}{W \log(1+\mathrm{SNR})} \\ x + y > 1 \end{cases}$$

where SNR denotes the signal-to-nose ratio when A transmits to B, the SNR of AC is SNR/x^n, and the SNR of CB is SNR/y^n.

We solve the inequalities with $n = 4$ and $\mathrm{SNR} = 10$ given in Fig. 5. The area enclosed by $x = 1$, $y = 1$, and $x + y = 1$ is the intersection of the two circles, whose radii are d_{AB} and the origins are A and B, respectively. The shadow area is where the relay condition can be satisfied. Fig. 5 theoretically shows that the probability for such a relay to exist is very high. In addition, when direct transmission between SrcToRelay and DstToRelay suffers serious attenuation due to obstacles in the line-of-sight, the probability and gain can be higher.

Table I shows the characteristic of the popular industry wireless card at open environment, semi-open environment, and closed environment, respectively. Fig. 6 shows the probability that such relays exist according to the closed environment parameters shown in Table I (under open and semi-open environments, the probability that such relays exist can be lower due to the slower attenuation of wireless signal). In Fig. 6, if there are nodes (such as C and C′) at the intersection of the two circles, the relay can help. If C or C′ acts as relay, the transmission time will reduce to nearly half for the DATA from A to B.

As discussed in Section II, under the original IEEE 802.11 DCF, when A is communicating with B at low rate, the intermediate node (C) can only listen silently. If A utilizes C as relay to reach B after A and B gain the channel by exchanging RTS/CTS, the media access of C itself will not be affected. On the other hand, if C acts as a relay node, the transmission time for the same frame from source (A) to destination (B) will be greatly reduced.

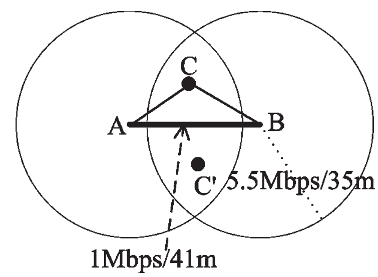

Fig. 6. Probability based on industry parameter.

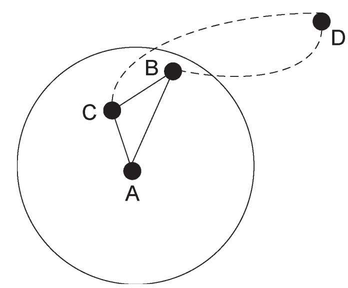

Fig. 7. The Fault of on-demand routing protocols.

B. Low-Rate Links in the Current Protocols

In WLAN with AP, each node must contact with the AP directly even when it is far away from the AP or there are obstacles between them. The transmission can potentially suffer serious performance degradation due to the long occupation of the low-rate transmission, even if there are possible relay nodes in between.

In wireless ad hoc networks, since the bandwidth and energy are scarce, on-demand routing protocols are generally applied due to their low overhead. During the route discovery procedure, when a node receives a Route REQuest (RREQ), it first checks to determine whether it has received an RREQ with the same originator address and RREQ ID. If this has been received, it simply discards the newly received RREQ. Referring to Fig. 7, assuming B and C are in the receiving range of A, A is the origin of the RREQ, C is the relay node that satisfies the relay condition, and for some destination D, the optimal route is $A- > C- > B- > \cdots - > D$. With on-demand routing protocol, when A broadcasts its RREQ for D, B and C will receive it at the same time. Hereafter, even if C rebroadcasts RREQ before B does, node B only simply discards the RREQ from C. Therefore, it is impossible for on-demand routing protocols to find the optimal route $A- > C- > B$. Instead, the low-rate link $A- > B$ is likely to be used in the final route. This seems to be an inherent nature of the on-demand routing protocols, which cannot be overcome by routing metrics.

IV. RAMA Protocol

The RAMA protocol works as follows: Referring to Fig. 4, when node C finds that A is communicating with B at low bit rate and the relay condition is satisfied, which can be accomplished by overhearing RTS/CTS/DATA/ACK, it produces an invitation frame and sends it according to DCF. After A receives the invitation from C, A will record it in its Relay List defined in Table III. Other relay candidates such as C$'$ in Fig. 6 will cancel their invitation for AB after hearing the invitation from C. Next time A sends data packets to B, it will use C as a relay node. As to node C, when it receives the relayed frame from A, it forwards that immediately after SIFS. Since SIFS has the highest priority in DCF, this assures that the forwarding by node C is free of contention. Therefore, RAMA is mainly composed of two parts: one is the invitation trigger and the other is transmission. RAMA can be designed on top of any automatic rate adaptation protocol. We describe RAMA in the context of RBAR.

In the following, we first describe the invitation trigger procedure and the relay transmission procedure, and then we analyze the overhead due to invitation frame. Finally, the performance comparison between RAMA and DCF when facing hidden terminals and the energy efficiency of RAMA is analyzed.

A. Invitation Trigger

RAMA can coexist with current DCF-based multirate wireless networks. If a node is RAMA capable, it must send RTS/CTS with MoreFrag in the Frame Control field set to 1, which is used only in DATA frames for fragmentation in DCF [1]. The conditions for RelayNode(C) to trigger the invitation are as follows:

1) The low-rate communication pairs are both RAMA capable, determined by the RTS/CTS they exchanged.
2) The size of DATA frame SrcToRelay(A) sent to DstToRelay(B) is greater than RTSthreshold, which is a constant defined in [1]. For DATA frames less than RTSthreshold bytes, the gain is less evident, so the relay need not be activated.
3) The relay condition $L/R_{\mathrm{AC}} + L/R_{\mathrm{CB}} + T_{\mathrm{overhead}} + \mathrm{SIFS} > L/R_{\mathrm{AB}}$ is satisfied. When RelayNode(C) hears the DATA of SrcToRelay(A), C can estimate the rate from A to C (R_{AC}) and obtain the rate of A$->$B (R_{AB}) from the physical layer header of DATA. When C hears the ACK of B, C can estimate the rate to B (R_{CB}). We assume that the channel gain between the two nodes is the same in both directions. So after a complete RTS/CTS/DATA/ACK, RelayNode(C) can make the decision whether to invite.
4) The DATA frame is followed immediately by an ACK frame, which prevents some other nodes to invite the link from SrcToRelay to RelayNode (such as the link from A to C in Fig. 4). In RAMA, only one relay is allowed for one transmission because more than one relay unnecessarily complicates the transmission.
5) The source of the DATA frame and the destination of the ACK frame must be the same to avoid some other node to invite the link from RelayNode to DstToRelay (such as the link from C to B in Fig. 4).

2	2	6	6	6	6	1	1	4
Frame Control	Duration	RA	TA	SrcToRelay	DstToRelay	Rate1	Rate2	FCS

Fig. 8. Format of invitation frame.

TABLE II
SERVE TABLE IN RELAY NODE

<SrcToRelay, DstToRelay>	T1	T2	BI	Rate	State

If the invitation is collided by other frames, RelayNode need not retransmit it since another invitation will be triggered when the low-rate communication happens again. Therefore, the invitation is sent as a broadcast. And the invitation is sent at the basic data rate so that all other possible RelayNodes (such as C$'$ in Fig. 6) can hear. Fig. 8 shows the format of invitation frame, which is a new subtype of control frame. Frame Control, Duration, RA, TA, and FCS fields are the same as specified in IEEE 802.11. RA is filled by broadcast address. TA is the MAC address of RelayNode(C). SrcToRelay(A) and DstToRelay(B) are the low-rate communication pair to be relayed. Rate1 and Rate2 fields indicate the rates from SrcToRelay to RelayNode and the rate from RelayNode to DstToRleay, respectively.

In order to handle the hidden terminal problem, an intermediate node should not casually send an invitation. In the RAMA protocol, we propose a backoff algorithm to deal with this problem. To perform the backoff algorithm, each node maintains a Serve Table as shown in Table II. There are six fields for each entry in the Serve Table. The field $\langle \mathrm{SrcToRelay}, \mathrm{DstToRelay} \rangle$ denotes the low-rate communication pair that RelayNode wants to aid. The field T1 records the time when $\langle \mathrm{SrcToRelay}, \mathrm{DstToRelay} \rangle$ communicated at low rate. The field T2 records the time when RelayNode sent an invitation or was used as a relay recently. The field BI denotes the backoff interval. The field Rate is the rate for RelayNode to reach DstToRelay, which is used when RelayNode forwards the relay to DstToRelay. The last field State denotes whether this entry is valid: 1 for valid and 0 for invalid. The key idea of the backoff algorithm is as follows:

1) A node is not allowed to send an invitation during BI time after it sends out an invitation or acts as relay for the pair.
2) The initial value of BI is set to a constant value INITIAL_INTERVAL. A node doubles the value of the corresponding BI when it sends out invitation and finds that the pair of nodes still communicates with low rate. The State field of the corresponding entry is set to be 0 when BI exceeds a constant MAX_INTERVAL, and so the node will not send invitation for this pair any more.

The invitation procedure works as follows:

1) If an invitation is triggered for $\langle \mathrm{A}, \mathrm{B} \rangle$ at some time t1, C first checks its Serve Table to see whether the

entry for $\langle A, B\rangle$ already exists and executes the following pseudocode, where R_{CB} is the estimated rate from C to B:

```
if (the entry ⟨A, B⟩ does not exist) {
   Create an entry for ⟨A, B⟩;
   T1 = T2 = t1; BI = INITIAL_INTERVAL;
   Rate = R_CB; State = 1;
        Set up an invitation frame and insert it in the front
          of the queue;
}else{
   Rate = R_CB;
   if (T2 + BI > t1 or State = 0) {
      T1 = t1;
      }else{
      BI = 2 * BI;
      if (BI > MAX_INTERVAL) {
         State = 0;
         exit;
      }else{
         T1 = T2 = t1;
         Set up an invitation frame and insert it in the front
           of the queue;
      {
      {
{
```

2) When A uses C as relay to reach B at another time t2, C updates T2 to be t2 and sets BI = INITIAL_INTERVAL.
3) When C hears some other node such as C' sending invitation for this pair, C will delete the invitation frame from its queue and delete the corresponding entry from its Serve Table.
4) Any entry in the table with state $= 0$ and $T1 +$ MAX_INTERVAL $< t_{now}$ will be deleted, where t_{now} denotes the current time.

B. Relay for Transmission

For SrcToRelay to utilize RelayNode, it must record the content of the invitation from RelayNode in the Relay List, which is defined in Table III. The DstToRelay field is the node address that SrcToRelay can utilize to reach RelayNode. The RelayNode field is the address of the relay node. Rate1 and Rate2 are the rates from SrcToRelay to RelayNode and the rate from RelayNode to DstToRelay, respectively, which can be extracted from the content of the invitation frame. When SrcToRelay has a packet to a destination, it first exchanges RTS/CTS with the destination as in the original DCF. Then, after the RTS/CTS exchange, it checks the Relay List to see if there is an entry corresponding to the destination. If there is one and the relay condition is still satisfied (since the wireless channel may change with time), it transmits the DATA frame to RelayNode using relaying. If an ACK frame is received from DstToRelay for the DATA frame that is transmitted through RelayNode, SrcToRelay will update the Create_Time of the corresponding entry for the DstToRelay. The stale entry will be flashed periodically.

TABLE III
RELAY LIST IN SrcToRelay

DstToRelay	RelayNode	Rate1	Rate2	Create_Time

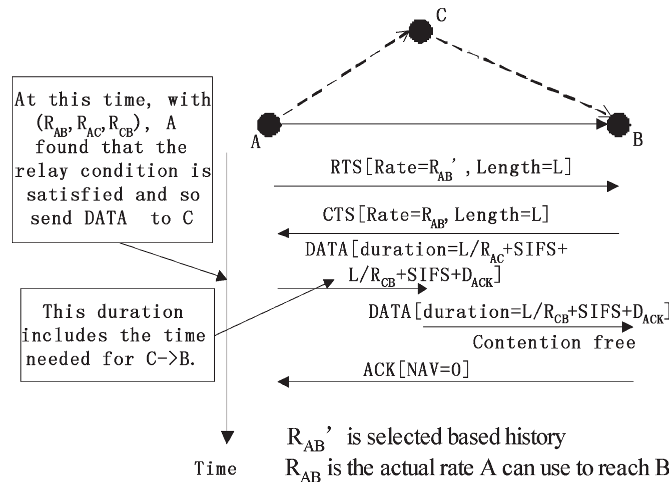

Fig. 9. Detailed procedure for RAMA to transmit packet.

Note that in the RAMA protocol, it is up to SrcToRelay to decide whether to exploit RelayNode when SrcToRelay obtains access to the channel. So when the relay condition is not satisfied due to the time variance of the wireless channel, or there are potential hidden terminals (discussed in Section IV-D), SrcToRelay can still choose not to use the RelayNode. Also, it is impossible for RelayNode to mount a denial of service attack to SrcToRelay.

The detailed procedure for SrcToRelay(A) to send data through RelayNode(C) to DstToRelay(B) is illustrated in Fig. 9. A sends RTS to B, and B returns CTS. After receiving B's CTS, A knows the rate between AB (R_{AB}), and A already has the rates of AC and CB (R_{AC}, R_{CB}). So at this time, A can decide whether to use C as relay according to the relay condition. If A decides to use C as relay, A will directly transmit the DATA to C. Relay node C, which is overhearing all the time and receives a DATA frame immediately after some other's RTS/CTS exchange, can make a decision whether the DATA frame is sent to it for relaying. After receiving the DATA frame, C will transmit the DATA to B (which is the destination of last RTS) in SIFS. B, who is still waiting for A's DATA, finds that a DATA frame is received in the duration of the RTS just received. So B can decide that this DATA is sent from a relay node, and the original source is the source of the RTS just received, namely A. After receiving DATA, B sends ACK to A for acknowledgement. So in RAMA, the RTS/CTS are exchanged as in the original DCF, but the DATA frame is sent through RelayNode. The reliability of transmission is still ensured by SrcToRelay and DstToRelay. RelayNode is not involved for the retransmission of the frame being relayed, which is preserved by end-to-end.

In a multirate protocol, the duration fields of the frames must be selected carefully, or unfairness or performance degradation may happen when other nodes are set with an incorrect NAV. In the RAMA protocol, the duration fields include the rate field,

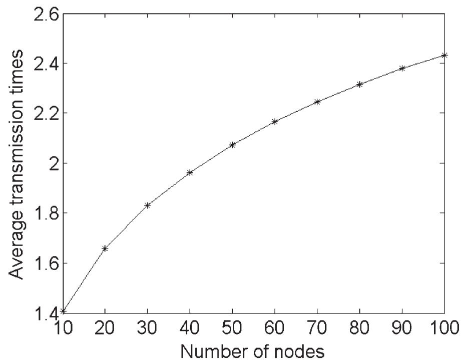

Fig. 10. Average transmission times for a packet.

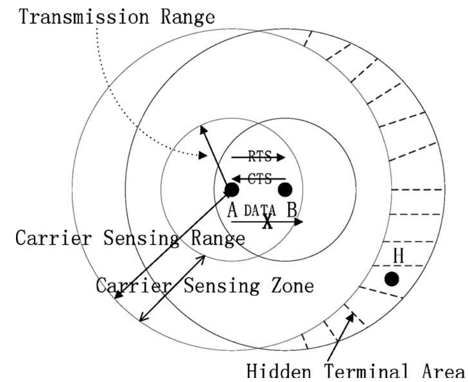

Fig. 11. Hidden terminal area.

the length field in the RTS/CTS frame, and the duration field in the other frames. We next describe the correct setting of these fields in the RAMA protocol.

For the RTS sent by A, the rate field is set with the latest rate used for B. For the CTS sent by B, the rate field is set with the available rate at current time, the same as that in RBAR. For the DATA sent by A to C, the duration field is set as $\mathrm{L/R_{AC}} + \mathrm{SIFS} + \mathrm{L/R_{CB}} + \mathrm{SIFS} + \mathrm{D_{ACK}}$ for the DATA sent by C to B, and the duration field is set as $\mathrm{L/R_{CB}} + \mathrm{SIFS} + \mathrm{D_{ACK}}$, where $\mathrm{D_{ACK}}$ is the transmission time of ACK. For the ACK sent by B, the duration is set to 0, which is the same as in DCF. The rate and length fields in the RTS/CTS frame may set an incorrect NAV to other nodes, but the DATA sent by A, C, and the ACK sent by B have the correct value. So for each node, it must maintain a list of the end times of each tentative reservation indexed by their corresponding sender. The actual NAV is the largest entry in the list. When receiving a frame whose sender is already in the list, the corresponding entry is updated and the actual NAV is updated with the largest entry in the list.

C. Invitation Overhead Analysis

In the RAMA protocol, only one correct reception of the invitation frame is needed for one low-rate link. We use the same approximation as in [17]. At each transmission attempt, regardless of the number of retransmissions suffered, each packet collides with the constant and independent probability p. Let n be the maximum possible number of invitation transmissions for one low-rate link. n is equal to or less than the number of relay candidates since two invitations may collide. Therefore, the average times of the invitation transmission for a low-rate link is

$$\phi(n,p) = (1-p) + 2p(1-p) + \cdots + np^{n-1}(1-p). \quad (5)$$

From (5), we obtain

$$\phi(n,p) = 1 - np^n + \frac{p-p^n}{1-p}. \quad (6)$$

Letting $n = 7$ (7 is also used as the maximum retransmission times in DCF) and with the numerical solution of p in [17], we show the average transmission times in Fig. 10. From Fig. 10, we can obtain that the average cost for the invitation is less than 2.5 frames (short control frames), which is acceptable given that there are usually multiple packets for transmission in one link.

D. Hidden Terminal Analysis

Because relay node C does not need to send any control frame (RTS/CTS), the transmission from A to C may be corrupted by the existence of potential hidden terminal(s). In this section, the performance comparison between RAMA and DCF when facing hidden terminals is analyzed.

We use the terms transmission range, carrier sensing range, and carrier sensing zone defined in [13], and define the term hidden terminal area. These terms are illustrated in Fig. 11.

- Transmission range: When a node is within transmission range of a sender, it can receive and correctly decode packets.
- Carrier sensing range: The carrier sensing range is typically larger than the transmission range, for instance, it can be twice as large as the transmission range [2].
- Carrier sensing zone: When a node is within the carrier sensing zone, it can sense the signal but cannot decode it correctly. In another word, the carrier sensing zone is the carrier sensing range minus the transmission range.
- Hidden terminal area: The nodes in the carrier sensing zone of the receiver but not in the carrier sensing range of the sender are the hidden terminals [14]. These nodes cannot set the NAV correctly since they cannot sense the transmission of the sender and cannot decode the CTS sent by the receiver correctly. When the receiver is receiving the DATA frame, it may be corrupted by the transmission of these hidden terminals. We denote this area as the hidden terminal area.

Since the RTS/CTS exchange in the RAMA protocol is essentially same as that in the original 802.11 DCF, we do not explicitly consider the hidden terminal problem already addressed for DCF in [15]. Instead, we consider the hidden terminals located in the hidden terminal area.

To compare the performance between RAMA and DCF, we adopt the same tractable model used in [15] to analyze the impact of hidden terminals. The assumptions are as follows:

- Nodes are uniformly distributed in the network area.
- Nodes in a unit area collectively form a Poisson source with an aggregate mean rate of λ requests per second.

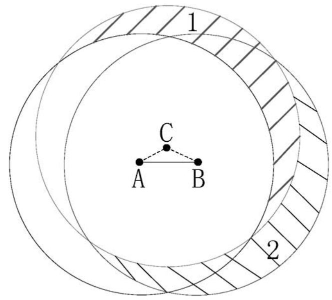

Fig. 12. Different hidden terminal areas when relay is introduced.

Referring to Fig. 12, let a, a_1, and a_2 be the hidden terminal area when A$->$B, A$->$C, and C$->$B, respectively; t, t_1, and t_2 be the transmission times for DATA when A$->$B, A$->$C, and C$->$B, respectively; and p_1 and p_2 be the probability to transmit the DATA frame successfully with RAMA and DCF, respectively. We have $a_1 < a$ and $a_2 < a$ because $d_{AC} < d_{AB}$ and $d_{CB} < d_{AB}$, and $t_1 + t_2 < t$ from the relay condition.

So, $p_1 = e^{-a_1 \lambda t_1} \times e^{-a_2 \lambda t_2}$ and $p_2 = e^{-a \lambda t}$.

Therefore, we can obtain that $p_1 > p_2$, which implies that in the presence of hidden terminals, the probability of successful DATA transmission in the RAMA protocol is higher than that under DCF. Since the only difference between RAMA and DCF is the DATA transmission, the performance of RAMA with hidden terminals is no worse than DCF, although the relay node is not protected by control frames.

This simple analysis illustrates the fact that under the general hidden terminal scenario, RAMA performs no worse than DCF. For special cases that there are hidden terminals located at the hidden terminal area of A$->$C but not at the hidden terminal area of A$->$B, we take the following measures to explicitly prevent using C as relay.

- If A has sent DATA to C for relaying but does not hear any transmission after SIFS, then A treats the transmission as failure, which could potentially be caused by the hidden terminal. In order not to use C as relay in the subsequent transmission, A deletes the entry corresponding to C in the Relay List.
- As for relay node C, it should not invite when overhearing that A $-$ B is communicating at low rate again. This is done by the backoff mechanism in the invitation procedure.

E. Energy Efficiency of RAMA

Assuming that the energy consumed in the computation can be omitted compared with the communication energy consumed, we can then analyze the energy consumption of RAMA. We only need to compare the energy consumption during DATA transmission since other procedures are the same with DCF. Let P_t, P_r, and P_i denote the transmitting power, receiving power, and idling power of the wireless card, respectively. Given three nodes A, B, and C in the network, for one DATA frame to be transmitted through relay, the total energy consumption is $(P_t + P_r + P_i)t_1 + (P_t + P_r + P_i)t_2$. If the DATA frame is transmitted by the original DCF, the total energy consumption is $(P_t + P_r + P_i)t$, which is greater than $(P_t + P_r + P_i)(t_1 + t_2)$. Therefore, with RAMA, the total energy consumption is less than that of DCF.

In addition, referring to Fig. 12, when C does relay, spatial reuse is reduced because of the additional carrier sensing area caused by C's transmission. However, since C is located at the intersection between the high-rate range of A and B, the additional carrier sensing area is small compared with the total carrier sensing area of the sender and receiver. Through numerical calculation, we can get that the upper bound of increased sensing area is less than 10% of the total sensing area. This is also verified by the simulation results.

TABLE IV
IMPORTANT PARAMETERS

Parameter	Value
Frequency	2.4GHz
Range for 11M	125m
Range for 5.5M	175m
Range for 2M	200m
Range for 1M	250m
Carrier Sensing Range	550m
INITIAL_INTERVAL	2s
MAX_INTERVAL	128s
RTS Threshold	100bytes
Packet Size	1500bytes

V. SIMULATION RESULTS AND ANALYSIS

In this section, we use NS-2 to evaluate the performance of RAMA and RBAR. We carry out simulations in WLAN, a scenario with hidden terminal and multihop scenarios.

First, we simulated a WLAN environment wherein all nodes are in each other's transmission range. The network area is 250 m $\times$ 250 m. For static scenario, we vary the number of nodes from 20 to 60, and the number of flows is 10. For mobile scenario, there are 40 nodes and 20 flows, and we adopt the random waypoint model with pause time 0 s. All the nodes are randomly distributed. All reported results are averaged over ten runs of 50-s simulations. When user datagram protocol (UDP) is used as the transport protocol, each flow generates packets at a constant bit rate. The packet generation interval is 0.04 s, which saturates the WLAN. When using transmission control protocol (TCP), the version we used is Tahoe. The other important parameters of simulation are listed in Table IV. Different transmission ranges at different rates are set proportional as in Table I. As specified in IEEE 802.11, all control frames and physical layer headers are sent at a basic rate of 1 Mb/s.

The throughput reported is the aggregate throughput of ten flows (20 flows for mobile scenario). The delay reported is the MAC layer delay, which excludes the queuing delay.

The results under a static scenario are shown in Figs. 13–16. We can see that RAMA has significant improvement over RBAR in terms of both throughput and delay regardless of what transport protocol is used. Furthermore, we can see that the improvement does not vary much with the number of nodes. That is to say, there are sufficient numbers of RelayNodes to be exploited when there are even only 20 nodes in a 250 m $\times$ 250 m network area. This can be easily satisfied in reality. Due to the

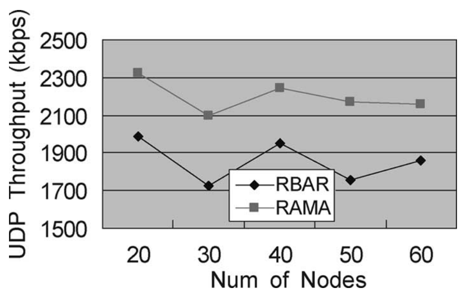

Fig. 13. UDP throughput under static scenario.

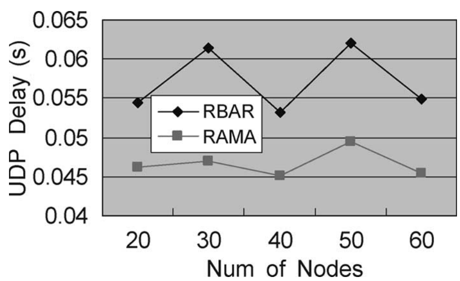

Fig. 14. UDP delay under static scenario.

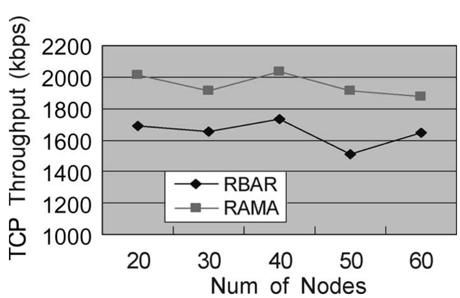

Fig. 15. TCP throughput under static scenario.

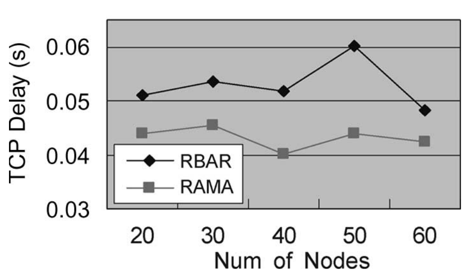

Fig. 16. TCP delay under static scenario.

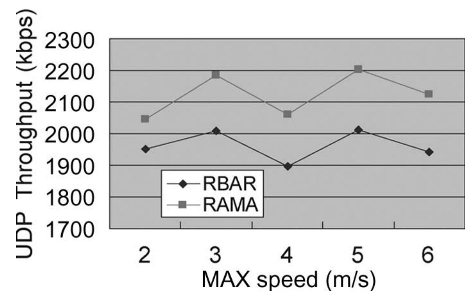

Fig. 17. UDP throughput under mobile scenario.

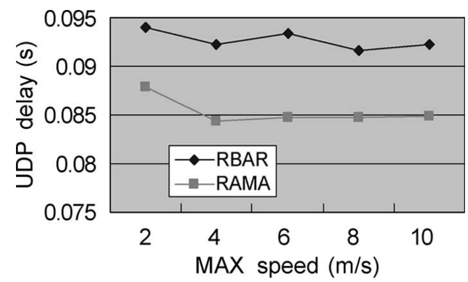

Fig. 18. UDP delay under mobile scenario.

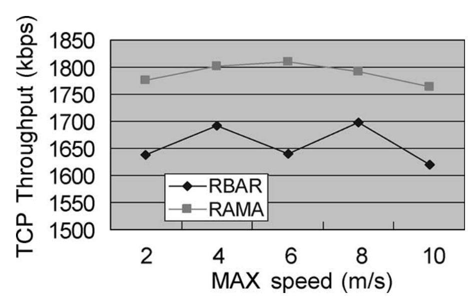

Fig. 19. TCP throughput under mobile scenario.

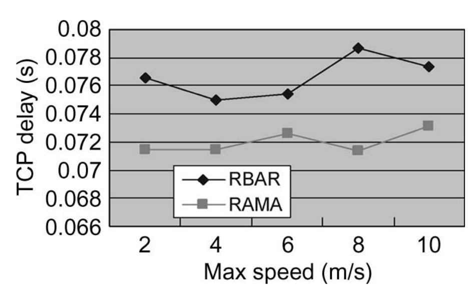

Fig. 20. TCP delay under mobile scenario.

flow control in TCP, the network is not saturated, and so the TCP throughput is less than the UDP throughput, and the TCP delay is also shorter.

Under a mobile scenario, the maximum speed of mobility is varied from 2 to 10 m/s. The simulation results are presented in Figs. 17–20. We can observe that RAMA still outperforms RBAR, but the improvement is a bit less than that under the static scenario. There are two reasons. One is that the nodes tend to move to the center of the network under the random waypoint model [16], and the number of low-rate links is reduced. The other reason is that the relay node moves away from the sender or the receiver, but the sender's Relay List has not been refreshed. This will cause one transmission failure. After that, the sender will refresh its Relay List, i.e., delete the corresponding entry.

Second, we did simulations to compare the performance of RAMA and RBAR when facing hidden terminals. The scenario we used to evaluate the impact of the hidden terminal is given in Fig. 21, where H is in the hidden terminal areas of $\mathrm{A}- > \mathrm{C}$ and $\mathrm{A}- > \mathrm{B}$, and D is out of the carrier sensing zone of B and C. A always has packets to send to B. The traffic from H to D forms a Poisson source with arrival interval from 0.05 to 0.5 s. The throughputs of $\mathrm{A}- > \mathrm{B}$ when using UDP and TCP are shown in Figs. 22 and 23, respectively. Results confirm that RAMA performs significantly better than RBAR.

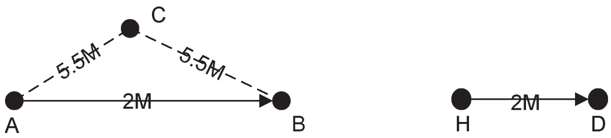

Fig. 21. Hidden terminal scenario.

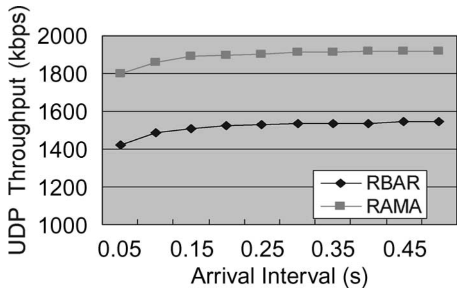

Fig. 22. UDP throughput with HT.

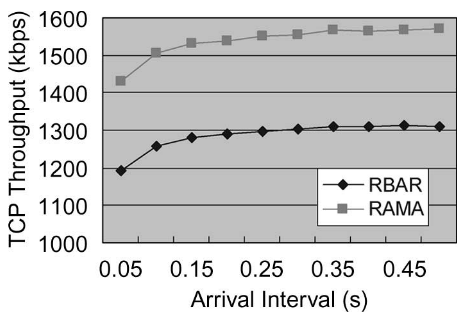

Fig. 23. TCP throughput with HT.

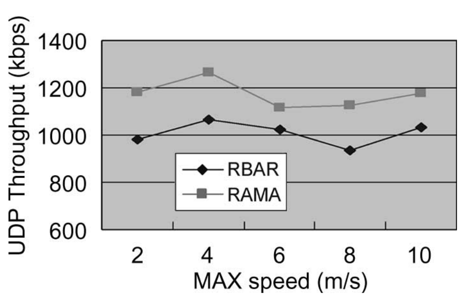

Fig. 24. UDP throughput under multihop scenario.

Third, we evaluated the performance of RAMA under a multihop scenario, wherein 50 nodes are randomly distributed in a rectangle area of 1000 m $\times$ 400 m. There are ten constant bit rate (CBR) flows, and the packet generation interval of CBR is 0.015 s. The simulation result is given in Fig. 24. We can see that in the multihop scenario, the performance of RAMA is also better than that of RBAR.

VI. Conclusion

In this paper, we exploited the use of multihop and multirate to improve the performance of wireless networks. We propose a novel random access protocol called RAMA protocol, in which by taking advantage of the existence of multihop high-rate links, it can significantly improve the performance in terms of both throughput and delay for low-rate transmissions. One possible avenue for further study is to conduct more formal theoretical analysis of the RAMA protocol under the general network configuration.

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Shihong Zou (S'01–M'04) received the B.S. degree in computer engineering from the Nanjing University of Posts and Telecommunications, Nanjing, China, in 1999, and the Ph.D. degree in communication and information systems from the Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 2004.

He is currently an Associate Professor at the State Key Laboratory of Networking and Switching Technology, BUPT. His research interests include IP quality-of-service, WLAN, mobile *ad hoc* networks, wireless sensor networks, and network security.

Bo Li (S'90–M'92–SM'99) received the B.Eng. (*summa cum laude*) and M.Eng. degrees in computer science from Tsinghua University, Beijing, China, in 1987 and 1989, respectively, and the Ph.D. degree in electrical and computer engineering from the University of Massachusetts, Amherst, in 1993.

Between 1993 and 1996, he was with the IBM Networking System Division, Research Triangle Park, NC, where he worked on high-performance routers and asynchronous transfer mode switches. Since 1996, he has been with the Department of Computer Science, Hong Kong University of Science and Technology, Hong Kong. Since 1999, he has also been an Adjunct Researcher at Microsoft Research Asia, Beijing, China. He has published 80 journal papers and holds several patents. His current research interests are on adaptive video multicast, peer-to-peer streaming, resource management in mobile wireless systems, across layer design in multihop wireless networks, content distribution, and replication.

Dr. Li has been on the Editorial Board of IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, IEEE TRANSACTIONS ON MOBILE COMPUTING, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, *ACM/Kluwer Journal of Wireless Networks*, *IEEE Journal of Selected Areas in Communications—Wireless Communications Series*, *ACM Mobile Computing and Communications Review*, *Elsevier Ad Hoc Networks*, *SPIE/Kluwer Optical Networking Magazine*, and *KICS/IEEE Journal of Communications and Networks*. He served as a Guest Editor for *IEEE Communications Magazine Special Issue on Active, Programmable, and Mobile Code Networking* (April 2000), *ACM Performance Evaluation Review Special Issue on Mobile Computing* (December 2000), *SPIE/Kluwer Optical Networks Magazine Special Issue in Wavelength Routed Networks: Architecture, Protocols and Experiments* (January/February 2002), IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS *Special Issue on Protocols for Next Generation Optical WDM Networks* (October 2000), *Special Issue on Recent Advances in Service-Overlay Network* (January 2004), *Special Issue on Quality of Service Delivery in Variable Topology Networks* (September 2004), *ACM/Kluwer Mobile Networks and Applications Special Issue on Energy Constraints and Lifetime Performance in Wireless Sensor Networks* (2nd Quarter of 2005). In addition, since 1996, he has been involved in organizing over 40 conferences, especially IEEE INFOCOM. He was the Co-TPC Chair for IEEE INFOCOM 2004. He received the Oversea Outstanding Young Scientist Investigator Award from the Natural Science Foundation of China in 2004.

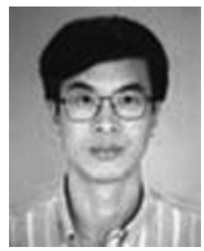
Haitao Wu (M'06) was born in 1976. He received the B.S. degree in telecommunications engineering and the Ph.D. degree in telecommunications and information system from the Beijing University of Posts and Telecommunications, Beijing, China, in 1998 and 2003, respectively.

He is currently an Associate Researcher at the Wireless Networking Group, Microsoft Research Asia, Beijing. His research interests are quality-of-service, TCP/IP, P2P, and wireless networks.

Qian Zhang (M'00–SM'04) received the B.S., M.S., and Ph.D. degrees from Wuhan University, Wuhan, China, in 1994, 1996, and 1999, respectively, all in computer science.

In September 2005, she was an Associate Professor at the Hong Kong University of Science and Technology. In July 1999, she was the Research Manager of the Wireless and Networking Group, Microsoft Research, Asia, Beijing, China. She also participated in many activities in the IETF Robust Header Compression (ROHC) WG Group for TCP/IP header compression. She has published more than 100 refereed papers in international leading journals and key conferences in the areas of wireless/Internet multimedia networking, wireless communications and networking, and overlay networking. She is the inventor of about 30 pending patents. Her current research interests are in the areas of wireless communications, IP networking, multimedia, P2P overlay, and wireless security.

Dr. Zhang is a member of the Visual Signal Processing and Communication Technical Committee and the Multimedia System and Application Technical Committee of the IEEE Circuits and Systems Society. She is the Associate Editor for IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGIES and IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS. She also served as Guest Editor for special issue on wireless video in *IEEE Wireless Communication Magazine*. She is the Chair of QoSIG of the Multimedia Communication Technical Committee of the IEEE Communications Society. She received the TR 100 (MIT Technology Review) World's Top Young Innovator Award. She also received the Best Asia Pacific (AP) Young Researcher Award elected by IEEE Communication Society in 2004. She received the Best Paper Award from Multimedia Technical Committee of the IEEE Communication Society.



Wenwu Zhu (S'91–M'96–SM'01) received the B.E. and M.E. degrees from the National University of Science and Technology, Wuhan, China, in 1985 and 1988, respectively, the M.S. degree from the Illinois Institute of Technology, Chicago, in 1993, and the Ph.D. degree from the Polytechnic University, Brooklyn, NY, in 1996, all in electrical engineering.

From 1988 to 1990, he was with the Graduate School, University of Science and Technology of China, and the Chinese Academy of Sciences (Institute of Electronics), Beijing, China. From 1996 to 1999, he was a member of technical staff at Bell Laboratories, Lucent Technologies, Murray Hill, NJ. Prior to September 2004, he was as the Research Manager of the wireless and networking group and the Area Manager of the wireless, networking and systems with Microsoft Research Asia, Beijing. He is currently the Director of the Intel Communication Technology Laboratory, Beijing. He has published over 200 refereed papers in the areas of wireless/Internet multimedia delivery and wireless communications and networking. He participated in the IETF ROHC WG on robust TCP/IP header compression over wireless links. He is co-inventor of over 20 patents. His current research interest is in the area of wireless communication and networking and wireless/Internet multimedia communication and networking.

Dr. Zhu is a member of Eta Kappa Nu, Multimedia System and Application Technical Committee and Life Science Committee in IEEE Circuits and Systems Society, and Multimedia Communication Technical Committee in IEEE Communications Society. He has been on various editorial boards of IEEE journals such as Guest Editor for the PROCEEDINGS OF THE IEEE and IEEE JOURNAL OF SELECTED AREAS IN COMMUNICATIONS (JSAC), Associate Editor for the IEEE TRANSACTIONS ON MOBILE COMPUTING, IEEE TRANSACTIONS ON MULTIMEDIA, IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY. He currently serves as the Chairman of IEEE Circuits and System Society Beijing Chapter and the Secretary of Visual Signal Processing and Communication Technical Committee. He received the Best Paper Award in IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY in 2001. He also received the Best Paper Award in the multimedia communication area in ComSoc 2005 for his paper published on IEEE JSAC 2003.

Shiduan Cheng (M'98) received the degree in communication engineering from the Beijing University of Posts and Telecommunications (BUPT), Beijing, China, in 1963.

Since 1963, she has been with BUPT. From 1984 to 1987 and in 1994, she was a Visiting Scholar with Alcatel Bell, Belgium, where she was involved in R&D work on integrated services digital network (ISDN) and broadband ISDN networks and systems. In 1987, she was the Vice Dean of the Computer Department, BUPT. From 1992 to 1999, she was the Director of The National Key Laboratory of Switching Technology and Telecommunication Networks, BUPT, and the Head of the Switching and Networking Expert Group in the 863 program, a national high-tech R&D plan organized by The Ministry of Science and Technology of China. She is currently the Vise Director of the Standing Committee of Science, BUPT. She has published more than 100 papers and several books in the field of telecommunications. Her research interests cover ISDN, asynchronous transfer mode, TCP/IP, switching software, protocol engineering, traffic engineering, network performance, quality-of-service (QoS), security, and survivability. She is currently working on QoS control, measurement, and management for the next-generation Internet.