AMNP: Ad Hoc Multichannel Negotiation Protocol for Multihop Mobile Wireless Networks

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Abstract— **Increasing the capacity of wireless communication is an open and interesting research area which has attracted much attention. The familiar solution is dividing the radio spectrum into several independent radio channels, which can be operated and accessed simultaneously by all nodes within its radio transmitting power. All solutions of researches adopt multiple transceivers to fulfill this goal. Nevertheless, these schemes will be short of implementation and may increase the prime cost since most wireless devices only equip one transceiver. Moreover, with a few exceptions, most researchers have emphasized centralized resource allocation algorithms for cellular systems where the base station keeps track of the requirements of the various users and is thus responsible for the management of network resources. However, on the other hand, multihop mobile ad hoc networks (MANETs) are generally configured as peer-to-peer networks with no centralized hubs or controllers. Therefore, in this paper, we proposed a multichannel medium access control (MAC) protocol, named ad hoc multichannel negotiation protocol (AMNP), for multichannel transmission in distribution fashion. We address the issue of distributed resource allocation for multihop MANETs by presenting an AMNP that builds on the multichannel request-to-send/clear-to-send (MRTS/MCTS) bandwidth reservation mechanism under the constraint of single transceiver. We show via simulations that AMNP provides a higher throughput compared to its single channel counterpart by promoting simultaneous transmissions in different channels. Simulation results also show that the performance of proposed AMNP derives well than other multichannel approaches with multiple transceivers.**

I. Introduction

Advanced wireless communication technologies are extensively investigated and studied in recent years [2], [8], [14], [18]. These studies include related issues of increasing the capacity of transmission, high quality multimedia wireless transmission, quality of service (QoS) and reliability, etc. One of essential issues is medium access control (MAC), which is how to utilize radio spectrum efficiently and to resolve potential contentions and collisions among mobile nodes (or hosts). Existing works have dedicated to using multiple channels [1], [11], [15], [21] to increasing the capacity of wireless communications. These researches all focus on providing high-capacity transmission and resource allocation efficiently in wireless communication systems.

With a selected modulation scheme, high-capacity wireless networks may be realized either by assigning a single wide-band channel or by using multiple narrow-band channels that may partially overlap to each other. The latter approach, which we consider in this paper, has been adopted by IEEE 802.11 wireless local area networks (WLANs) [9], [16]. In recent years, all of the commercial developments and the basis for IEEE 802.11 standard [9] have been in the 2.4 GHz band. In the direct sequence spread spectrum (DSSS) specification, the 83.5 MHz radio spectrum are divided into 14 channels and some of them can be used simultaneously and independently. Using all frequencies to transmit data at a same location may cause electromagnetic wave interference that will decrease the transmission quality; therefore, standard suggests that at least 25 MHz or 30 MHz guard band should be maintained for any two adjacent cells. As a result, there are totally 3 available channels can be utilized concurrently for data transfer in current IEEE 802.11 WLANs. In other words, if the channel data rate is 2 Mb/sec (or 11 Mb/sec in IEEE 802.11b), the aggregated network bandwidth in WLANs will be 6 Mb/sec (or 33 Mb/sec). Unfortunately, with one transceiver constraint, the standard only defines the MAC operations for single channel mode. Intuitively, the simplest way to achieve multichannel access is to upgrade mobile nodes to equip several transceivers [11], [21]. But from the view point of cost effectiveness, it is worth to enhancing the standard MAC protocol for single transceiver to support multichannel access.

A multihop mobile ad hoc network (MANET) is constructed by several mobility handsets or laptops in a limited communication range, characterized by multihop wireless connectivity and changing network topology frequently. The communication range is around 150∼300 meters long and varies from different modulation schemes. In recent years, the proliferation of portable and laptop computers has led to LAN technology being required to support wireless connectivity. IEEE 802.11 WLANs standard defines two possible network configurations: one is the infrastructure WLAN and the other one is ad hoc network. An infrastructure WLAN connects mobile nodes to a wired network via access point (AP). Basically, the AP is a stationary node that provides mobile nodes to access the distributed systems (e.g., Internet). Contrarily, the ad hoc network is composed solely of nodes within mutual communication range of each other and they are able to communicate to each other directly. In both configurations, all adjacent mobile nodes access the same channel will form a basic service set (BSS). In a BSS, the basic distributed coordination function (DCF)

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using carrier sense multiple access with collision avoidance (CSMA/CA) mechanism is used as the basic channel access protocol to transmit asynchronous data in the contention period.

Our goal in this paper is to investigate and design a new multichannel CSMA/CA protocol for supporting multichannel transmission by using single transceiver in multi-hop MANET. We note that papers [11], [21] had proposed some possible solutions for this scenario by adopting dual transceivers to achieve this goal. In paper [21], Wu *et al.* proposed a so-called dynamic channel allocation (DCA) scheme which one transceiver is fixed in a dedicated control channel for contention and the other transceiver is tunable among other channels for data transmission. When a node receives a request-to-send (RTS) control frame from sender in the control channel, it will scan all channels except the control channel and choose the first detected idle channel to inform sender to transmit data. Nevertheless, the requirement of dual transceivers increases both the implementation complexity and implementation cost, and becomes impractical for present WLAN adapters. Besides, the paper [4] had proposed a multichannel access protocol by using single transceiver, however, it can only be applied in the one-hop BSS of WLAN environment and needs an AP to coordinate the multichannel transmission. Therefore, in this paper, we propose a contention and reservation based *ad hoc multichannel negotiation protocol* (AMNP) in distributed fashion for supporting multichannel transmission over MANETs in which each mobile node equips single transceiver.

The remainder of this paper is organized as follows. In Section II, we point out some problems and challenges when designing a distributed multichannel reservation protocol by using single transceiver in multihop MANETs. Section III describes our proposed AMNP in details. Finally, we give the conclusion and describe future work in Section V.

II. Problem Statement

A. Challenge Statements

We first describe some problems and challenges of designing a distributed contention and resource reservation protocol in multichannel multihop MANETs with the constraint on single transceiver in this section. In order to design an ad hoc multichannel negotiation protocol (AMNP), there are several critical issues needed to be solved. However, to meet these objectives, the design of AMNP faces certain challenges and constraints that are not imposed on their single channel counterparts.

- ***Single Transceiver Constraint*** — Most of present wireless devices of mobile nodes only equip one transceiver to transmit or to receive data. However, many articles [11], [15], [21] propose potential solutions for multichannel transmission by adopting multiple transceivers to achieve this goal. These solutions may not be applied or be implemented on such wireless equipments.
- ***Hidden Node Problem*** — The hidden node problem [19] is one of the most important issues in multihop MANETs. Although the IEEE 802.11 standard provides RTS/CTS control frame to conquer the hidden terminal problem, nodes may still collide with other nodes unwittingly in other channels since they only equip one transceiver and could not perceive the statuses of other channels. This is a severe problem when designing a multichannel protocol with the constraint on single transceiver. This is because that each node difficultly collects whole channel information within its two hops.
- ***Channel Information Coherence*** — Since MANETs are generally configured as peer-to-peer networks with no centralized hubs or controllers to coordinate resource allocation, it is a big challenge to design a distributed fashion of resource reservation protocol for multichannel access. This is because that a mobile node should have sufficient channel statuses within its and the expected receiver's transmitting area before it transmitting data in order to avoid unexpected collisions.
- ***Broadcast Transmission*** — Broadcasting a message to all nodes in a network is an important activity in multihop MANETs [5], [13], [17], [20]. In single channel environment, it's easy to broadcast a packet to all nodes which are within the radio transmission range of the source, since all nodes operate on the same channel. However, in multichannel environment, nodes may miss a broadcast frame when they are transmitting or receiving data in other channels in other data channels. This problem should be solved further.
- ***Mobility and Scalability*** — Since the MANET is constructed by several movable laptops, the designed multichannel MAC protocol should satisfy the requirement of mobility. For example, a mobile node should get sufficient channel statuses of the area in which it moves before it attempting to transmit data. Furthermore, the scalability that supports unlimited number of mobile node to access the medium is another important issue when designing the MAC protocol.

According to above-mentioned and indicated problem statements, we, then, propose a suitable distributed negotiation protocol for MANETs.

III. Ad Hoc Multichannel Negotiation Protocol (AMNP)

This section will describe the proposed AMNP in details. In general, if all mobile nodes are equally allocated to all available channels, the collision probability of each attempted request would be minimized accordingly. However, based on the constraint that the sender and the receiver should stay in the same channel to complete the request-to-send/clear-to-send (RTS/CTS) handshaking, the mobile node with one transceiver might exchange data with other mobile nodes which listen to the same channel. As a result, few data frames will be transmitted successfully and some nodes will never communicate with each other. If we assign mobile nodes to access channels dynamically, a complicated channel scheduler has to be provided for the distributed ad hoc WLANs. In stead

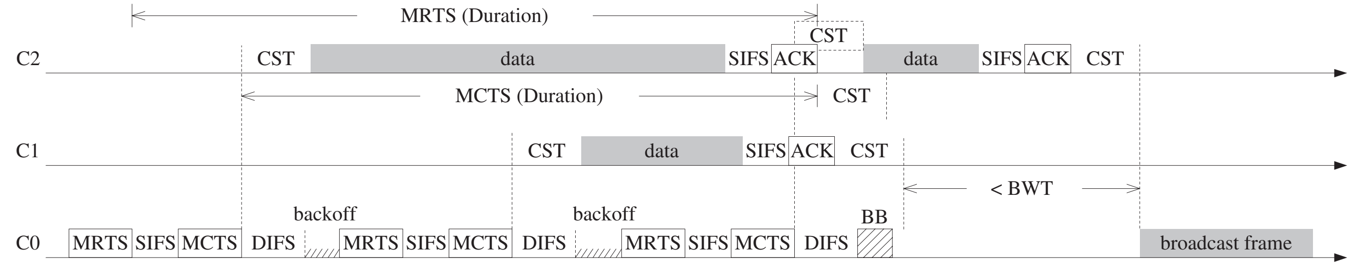

Fig. 1. An illustration of proposed AMNP, which C_0 represents the contention/reservation channel and C_1 and C_2 represent the data channels. The identifier BB represents the broadcast beacon, the BWT represents the broadcast waited time and the CST is the channel switching/settlling time, respectively.

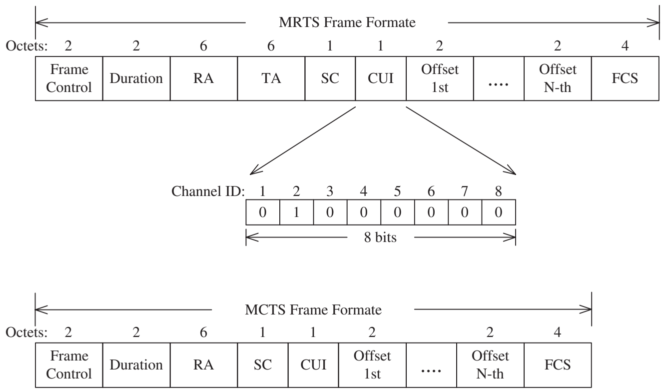

Fig. 2. The frame format of MRTS and MCTS control frame of proposed AMNP.

of employing such complicated scheme, the proposed AMNP allocates a dedicated *contention* channel for all mobile nodes to contend and the remaining channels are serving as *data* channels permanently. Fig. 1 illustrates the usage of channels of AMNP in which channels $C_1 \sim C_{n-1}$ represent data channels and channel C_0 alternatively plays the role of the dedicated contention channel or data channel dynamically.

Since, in ad hoc networks, there is no stationary node for supporting centralized multichannel control, the distributed negotiation protocol which can provide ad hoc multichannel transmission is needed. To solve above mentioned problems, we adopt the concept of IEEE 802.11 RTS/CTS handshake mechanism to fulfill multichannel transmission in multihop mobile ad hoc networks. We name the RTS/CTS as *multichannel RTS/CTS* (MRTS/MCTS). Unlike IEEE 802.11 RTS/CTS mechanism, we need more information to indicate the usage of other data channels.

First, a node attempts to issue a MRTS control frame to acquire the authorization of expected data channel when it has a frame to transmit. The purposes of MRTS control frame are used to inform its direct receiver and neighbors the preselected data channel, which it prefers to use to prevent the exposed node problem in other channels and the current channel status within its transmitting range. The frame format of MRTS is shown in Fig. 2 where the Frame Control, Duration, RA (receiver address), TA (transmitter address), and FCS (frame check sequence) fields are as same as the description in IEEE 802.11 Standard [9]. The additional fields *selected channel* (SC), *channel usage indication* (CUI), and the *n-th used channel's offset* are described as follows. The SC field indicates which channel the sender prefers to transmit data with the receiver. The CUI field length is one octet long and the content of CUI indicates the status of the usage in each data channel. Each bit field of CUI represents each corresponding data channel in prior order called *bit map*. The bit would be set 0, if the corresponding data channel is not in use. On the contrary, the bit would be set 1, if the corresponding data channel is in use. The following Offset fields are various depending on the content of CUI field. For example, shown in Fig. 2, the second bit of CUI is set 1, that is, only the second data channel is in use currently and the free time of the second data channel would be the ending time of its transmitted MRTS plus the value of the Offset. The units of Duration field and Offset field are measured in microsecond (μs).

When a node has received a MRTS frame, it will compare the SC field of the MRTS with its channel status and then check whether it can satisfy the request. If the preselected channel is also available in receiver's side, the receiver will grant the transmission request and reply the MCTS frame back to the sender immediately. Otherwise, the preselected channel can not be granted to use since the preselected data channel in receiver's side is not free. The receiver then reselects another available channel according to comparing with the status of channel usage of the sender. The reselection rules are as follows:

1) If the sender has another free data channel and the channel is also available in receiver's side. The receiver will select the common available channel to receive data frames.
2) If there is no available free channel in the side of the sender or receiver now, the receiver will compare all data channels of both sender and receiver and then select a common channel which will be earliest released.

Please note that we have to consider both sides' channel information in order to prevent the hidden node problem. After the checking process, the receiver will reply a MCTS frame back to the sender to make the final decision. The MCTS frame contains the current the usage status of data channels and the agreed selected data channel information. Note that the sender have to resend the MRTS back to the receiver in order to refresh the channel status of the sender's side.

A node will spend an extra *channel switching/setttling time* (CST) when it wishes to switch from one channel to another. The CST is defined as the time to change from one operating channel frequency to another channel frequency and is defined as 224 μs. This time varies from the physical medium dependent (PMD) entity. Therefore, the duration field of the MRTS control frame will be SIFS + MCTS + CST + data_length + SIFS + ACK where SIFS is the *short inter frame space*. In order to avoid other nodes interrupting transmissions on other channels, nodes that intend to transmit frames must persistently monitor the control channel until hear either a MRTS or a MCTS control frame issued by other nodes. This is because that the channel status is recorded in the MRTS or MCTS control frame. The data transmissions on data channels would be guaranteed that no other nodes will interrupt this communication, if it hears at least an MRTS or an MCTS before it transmitting the data.

Taking Fig. 3 for example, assuming there are 5 mobile nodes in the ad hoc network. Node c and d are the exposed terminal of node a and b, and node e is the hidden terminal of node b. Initially node e finishes its backoff count down and then sends an MRTS frame to request the channel 1 for transmitting data. The receiver node d approves the request since the channel 1 is also available in side of d. After the negotiation of node d and e, node a finishes its backoff count down and sends an MRTS to node b to ask channel 1 for transmitting data. Since channel 1 has been reserved by node d and e, the request could not be accepted. Node b compares channel statuses of node a with node b and then selects an available channel 2 in this example and sends MCTS back to node a. After receiving an MCTS from node b, node a is notified that channel 1 would not be accepted and the agreed channel is channel 2. Node a will resend an MRTS to refresh the reservation information (to node c in this example).

A. Improving the Degree of Channel Utilization

The throughput of networks can be improved further by increasing channel utilization using channel reservation scheduling scheme. We named the AMNP with scheduling scheme as AMNP/s. The scheduling policies of AMNP/s are as follows. If there is no available channel for transmission, the sender would choice the first being released channel to reserve the needed transmission interval. If the channel is the last available channel of the sender's side but not in the receiver's side, the receiver will reserve the first being released channel for transmission by sending the MCTS back to the sender. After receiving the MCTS, the sender will retransmit a MRTS to update the new reservation. Note that the contention channel C_0 would not be considered for data transmission, since this channel will be used for negotiation reservation or broadcast transmission.

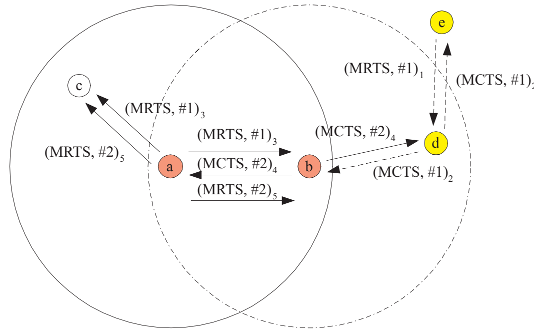

Fig. 3. The MRTS/MCTS frame formate of proposed AMNP.

B. The Broadcast in AMNP

The broadcast operation is an important activity in ad hoc networks. However, in multichannel transmission and the constraint of one transceiver, it is hard to broadcast a frame to all neighbors especially nodes transmitting in different channels. The AMNP uses a so called *broadcast beacon* (BB) technique to conquer this problem. The BB contains the time that when the broadcast frame will be transmitted. All nodes which received the BB will stay in the contention channel and wait a *broadcast waiting time* (BWT) to receive this frame even though it has made a successful reservation. The ending time of BWT is calculated as the time that the last freed channel time among current transmissions plus the CST. All the scheduled reservations will be delayed a SIFS + BWT + SIFS + broadcast_frame_length + SIFS period. The purpose of restraint is in order to broadcast all neighbors including nodes which is transmitting in other data channels.

IV. Simulation Model and Results

The simulation model follows IEEE 802.11b Standard using DSSS system at the physical layer with the long physical layer convergence protocol (PLCP) protocol data unit (PPDU) format. Poisson distribution is used to determine the number of MAC service data unit (MSDU) arrivals and the lengths of the MSDUs are decided by the exponential distribution function. Most of the parameters were taken from the standard and are listed in Table I. The Transmit-to-Receive (Tx-to-Rx) turnaround time should be less than 10μs, including the power-down ramp specified in IEEE 802.11 Standard [9] and the Rx-to-Tx turnaround time should be measured at the MAC/PHY interface, and should be less than 5μs.

In all simulations we consider one contention channel and two data channels. Each simulation runs least over 10,000,000 slot time (600 sec) and each data point represents an average of at least ten runs with identical traffic models, but different randomly generated scenarios. Several assumptions were made to reduce the complexity of the simulation model:

- All nodes support the 2 Mb/sec data rate.
- All data and control frames were sent at 2 Mb/sec.
- The propagation delay was neglected.
- The channel was error-free.
- There was no interference from nearby channels.

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TABLE I

SYSTEM PARAMETERS IN SIMULATIONS

Parameter	Normal Value
Simulation Area	300 meters $\times$ 300 meters
Transmission range	100 meters
Transmission rate	2 Mb/sec
A slot time	20 μs
SIFS	10 μs
DIFS	50 μs
MRTS frame length	variable 160 bits (80 μs)
MCTS frame length	112 bits (56 μs)
ACK frame length	112 bits (56 μs)
Preamble and PLCP header	192 bits (192 μs)
MAC header length	34 octets (136μs)
Mean frame length	512 octets
aCWmin	31 slots
aCWmax	1023 slots
Channel Switching Time	224 μs

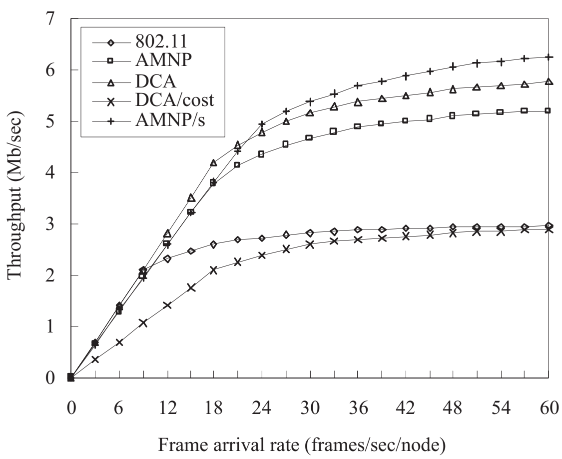

Fig. 4. The comparison of throughput derived by IEEE 802.11, AMNP, DCA, DCA/cost, and AMNP/s when number of nodes is 54 nodes.

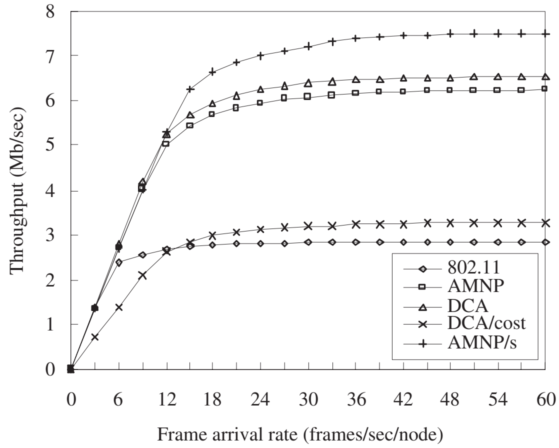

Fig. 5. The comparison of throughput derived by IEEE 802.11, AMNP, DCA, DCA/cost, and AMNP/s when number of nodes is 108 nodes.

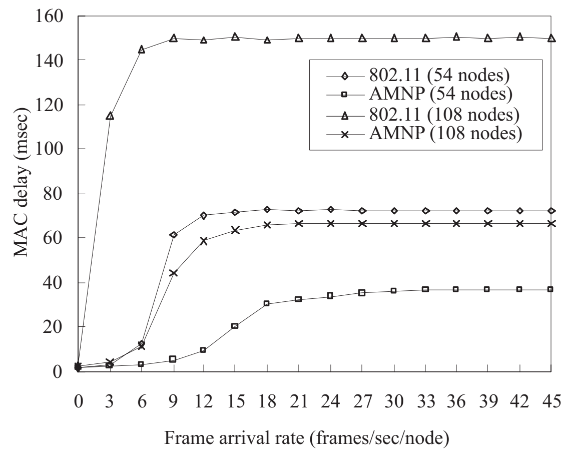

Fig. 6. The comparison of MAC delay derived by the IEEE 802.11 and AMNP under different number of nodes.

- All nodes were active (not in power-saving mode).

The mobility model uses the *random waypoint* model [3] in a rectangular field. We vary the pause time, which affects the relative speeds of the mobiles. Here, each mobile node starts its journey from a random location to a random destination with a randomly chosen speed (uniformly distributed between 0–94 m/s).[1]

A. Simulation Results

The first set of experiments uses differing numbers of nodes 54 nodes and 108 nodes and varying frame arrival rates. All nodes of this experiment are set to be immovable. The throughput is measured by calculating all successful transmitting data divided by simulation time. The throughput of all schemes, shown in Fig. 4 (54 nodes) and Fig. 5 (108 nodes), increase following the increment of frame arrival rate. IEEE 802.11 protocol first saturates its upper bound of threshold at 24 frames/sec/node. On the contrary, other schemes such as the DCA, AMNP, and AMNP/s smoothly increase following the increment of frame arrival rate continuously. This is because that the IEEE 802.11 only uses one channel for contention and transmission. Taking Fig. 4 for example, the DCA performs a 5.5 Mb/sec throughput than the maximum throughput 5.1 Mb/sec of proposed AMNP since DCA adopts two transceiver for one contention and another transmission. If we take the cost-benefit of DCA denoted as DCA/cost under consideration, the throughput of DCA/cost only performs 2.75 Mb/sec. However, the AMNP/s scheme can retrieve the shortcoming of AMNP by using one transceiver. We can see that AMNP/s could outperform DCA and gets 6.2 Mb/sec throughput. Fig. 5 also shows that the network throughput will be increased by increasing the number of nodes in the network but not in the IEEE 802.11. The proposed AMNP and AMNP/s, moreover, gets higher improvement of throughput than DCA scheme when increasing the number of channels.

In Fig. 6, we evaluate the MAC delay by comparing the IEEE 802.11 with proposed AMNP with different number of nodes under different frame arrival rate. The simulation result

[1]Note that this is a fairly high speed for an ad hoc network, comparable to traffic speeds inside a city.

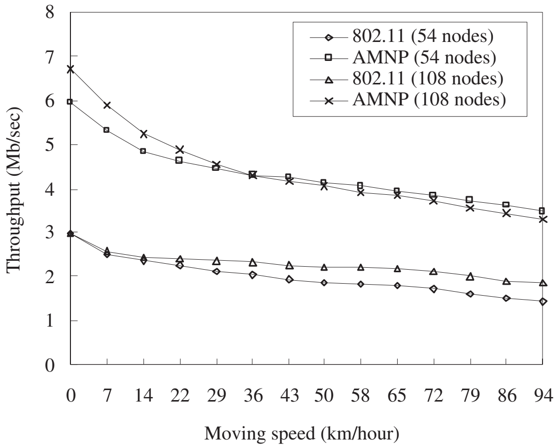

Fig. 7. The comparison of throughput derived by the IEEE 802.11 and AMNP under different number of nodes and different moving speed.

shows that the MAC delay of AMNP is lower than IEEE 802.11. This is because that we use one channel for contention and reservation and other channels for data transmissions. Note that the MAC delay of each condition will reach a value and will not increase further since the increasing of MAC delay is bounded by the number of contention nodes.

The mobility is a major property of MANETs. Therefore, we perform a set of experiments by varying the movement of mobile nodes to investigate the influence of mobility on throughput of proposed AMNP in MANETs. We set a higher frame arrival rate 37 frames/sec/node to saturate the network both on 54 and 108 nodes conditions. In Fig. 7, the throughput will degrade following the increment of mobile nodes' moving speed. At the beginning, the throughput of 108 nodes model gets higher throughput than 54 nodes model, however, by increasing the speed of mobility 108 nodes model of AMNP performs lower and lower throughput than 54 nodes model. We can see that, from the result, the AMNP could achieve twice throughput as high as the IEEE 802.11 does.

V. Conclusion

Increasing the capacity of wireless communication is an open and interesting research area which has attracted much attention. In this paper, we proposed an ad hoc multichannel negotiation protocol (AMNP) for multichannel transmission by adopting one transceiver in multihop mobile ad hoc networks (MANETs). We adopt the concept of the negotiable fashion by using MRTS/MCTS control frame to achieve this goal. Besides, we also use the broadcast beacon (BB) technique to transmit the broadcast frame in order to overcome the problem that mobile node with one transceiver would not always stay in one channel when transmit in multichannel environment. Furthermore, AMNP with scheduling scheme (AMNP/s) further promotes the network utilization of ordinary AMNP. Simulation results show that the AMNP/s can achieve higher performance than DCA scheme. The obtained results encourage us to realize multichannel transmission by adopting one transceiver in multihop MANETs.

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References

[1] M. Ajmone-Marsan and D. Roffinella, "Multichannel Local Area Network Protocols," *IEEE J. Select. Areas Commun.*, vol. 1, pp. 885–897, 1983.

[2] R. Becher, M. Dillinger, M. Haardt, and W. Mohr, "Broadband Wireless Access and Future Communication Networks," *Proc. IEEE*, vol. 89, no. 1, pp. 58–75, Jan. 2001.

[3] J. Broch *et al.*, "A Performance Comparison of Multihop Wireless Ad Hoc Network Routing Protocols," in *Proc. ACM/IEEE MOBICOM'98*, pp. 85–97, Oct. 1998.

[4] J. Chen, S.-T. Sheu, and C.-A. Yang, "A New Multichannel Access Protocol for IEEE 802.11 Ad Hoc Wireless LANs," in *Proc. IEEE PIMRC'03*, vol. 3, pp. 2203–2208, Beijing, China, Sept. 2003.

[5] I. Chlamtac and S. Kutten, "On Broadcasting in Radio Networks–Problem Analysis and Protocol Design," *IEEE Trans. Commun.*, vol. COM-33, no. 12, pp. 1240–1246, Dec. 1985.

[6] B.N. Clark, C.J. Colbourn, and D.S. Johnson, "Unit Disk Graph," *Discrete Math.*, vol. 86, pp. 165–177, 1990.

[7] C.L. Fullmer and J.J. Garcia-Luna-Aceves, "Complete Single-Channel Solutions to Hidden Terminal Problems in Wireless LANs," in *Proc. IEEE ICC'97*, vol. 2, pp. 575–579, 1997.

[8] M. Hännikäinen, T.D. Hämäläinen, M. Niemi, and J. Saarinen, "Trends in Personal Wireless Data Communications," *Comput. Commun.*, vol. 25, no. 1, pp. 84–99, Jan. 2002.

[9] IEEE 802.11 Working Group, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," ANSI/IEEE Std 802.11, Sept. 1999.

[10] —–, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band," ANSI/IEEE Std 802.11, Sept. 1999.

[11] N. Jain, S.R. Das, and A. Nasipuri, "A Multichannel CSMA MAC Protocol with Receiver-based Channel Selection for Multihop Wireless Networks," in *Proc. IEEE ICCCN 2001*, pp. 432–439, Scottsdale, Arizona, May 2001.

[12] 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, Dec. 1975.

[13] W. Lou and J. Wu, "On Reducing Broadcast Redundancy in Ad Hoc Wireless Networks," *IEEE Trans. Mobile Computing*, vol. 1, no. 2, pp. 111–122, Apr. 2002.

[14] A.F. Naguib, V. Tarokh, N. Seshadri, and A.R. Calderbank, "A Space-Time Coding Modem for High-Data-Rate Wireless Communications," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1459–1478, Oct. 1998.

[15] A. Nasipuri, J. Zhuang, and S.R. Das, "A Multichannel CSMA MAC Protocol for Multihop Wireless Networks," in *Proc. IEEE WCNC'99*, vol. 3, pp. 1402–1406, Piscataway, NJ, 1999.

[16] B. O'Hara and A. Petrick, *The IEEE 802.11 Handbook: A Designer's Companion*, IEEE press, Dec. 1999.

[17] S.-T. Sheu, Y. Tsai, and J. Chen, "A Highly Reliable Broadcast Scheme for IEEE 802.11 Multi-hop Ad Hoc Networks," in *Proc. IEEE ICC 2002*, vol. 1, pp. 610–615, New York, Apr./May 2002.

[18] —–, "MR^2RP: The Multi-Rate and Multi-Range Routing Protocol for IEEE 802.11 Ad Hoc Wireless Networks," *ACM/Kluwer Wireless Networks (WINET)*, vol. 9, no. 2, pp. 165–177, Mar. 2003.

[19] F.A. Tobagi and L. Kleinrock, "Packet Switching in Radio Channels: Part II–The Hidden Terminal Problem in Carrier Sense Multiple-Access and the Busy-Tone Solution," *IEEE Trans. Commun.*, vol. COM–23, no. 12, pp. 1417–1433, Dec. 1975.

[20] Y.-C. Tseng, S.-Y. Ni, Y.-S. Chen, and J.-P. Sheu, "The Broadcast Storm Problem in a Mobile Ad Hoc Network," *ACM/Kluwer Wireless Networks*, vol. 8, no. 2–3, pp. 153–167, Mar. 2002.

[21] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng, and J.-L. Sheu, "A Multi-channel MAC Protocol with Power Control for Multi-hop Mobile Ad Hoc Networks," *Computer Journal*, vol. 45, no. 1, pp. 101–110, Jan. 2002.