Published in IET Communications
Received on 17th May 2009
Revised on 27th August 2009
doi: 10.1049/iet-com.2009.0318

ISSN 1751-8628

AMNP: *ad hoc* multichannel negotiation protocol with broadcast solutions for multi-hop mobile wireless networks

J. Chen

Department of Computer Science and Information Engineering, Chang Gung University, Kweishan, Taoyuan, Taiwan
E-mail: jhchen@mail.cgu.edu.tw

Abstract: A multi-hop mobile *ad hoc* network (MANET) is generally configured as a peer-to-peer network with no centralised hubs or controllers that coordinate channel resources. Nodes in a MANET usually equip one single transceiver for data transmissions. However, the single transceiver architecture will cause a difficulty of being implemented in multichannel environment if the network transmission capacity would be improved by adopting parallel multichannel access. To solve this thorny problem, this study presents a distributed medium access control (MAC) layer protocol called *ad hoc* multichannel negotiation protocol (AMNP) for multichannel transmissions in the multi-hop MANET. Additionally, two problems, the multichannel hidden terminal problem and the multichannel broadcast transmission problem, caused by single transceiver operations in the multichannel environment, which have not been revealed in academia, is presented and solved in this study. Finally, an enhanced AMNP with channel scheduling (AMNP/s) scheme is introduced to improve the channel utilisation. The author show, via simulations, that AMNP/s provides a higher throughput compared to its single-channel counterpart by promoting simultaneous transmissions in different channels. Simulation results also show that AMNP/s derives higher performance than other multichannel transmission schemes that use multiple transceivers.

1 Introduction

In the recent years, the proliferation of portable and laptop computers has led to LAN technology being required to support wireless connectivity. One of the essential issues is about the medium access control (MAC) protocol and how to utilise radio spectrum efficiently to resolve potential contentions and collisions among mobile nodes (or hosts) [1, 2]. Existing works have dedicated to using multiple channels [3–7] to increase the capacity of wireless communications. Recently, researchers have focused on providing high-capacity transmission and resource allocation efficiently in mobile *ad hoc* networks (MANETs) [8, 9].

With a selected modulation scheme, high-capacity wireless networks can be realised 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 will be addressed in this paper, has been adopted by IEEE 802.11 wireless local area networks (WLANs) [10–12]. In the direct sequence spread spectrum (DSSS) specification, the 83.5 MHz radio spectrum is divided into 14 channels, some of them can be used simultaneously and independently. In order to avoid the electromagnetic wave interference, only three available channels in total are utilised concurrently for data transmission. Owing to the popularity of one single transceiver, however, the standard only defines the MAC operations for single-channel mode. Consequently, many bandwidths will be inevitably wasted. One way to improve this drawback is to upgrade all mobile nodes to equip with multiple transceivers [5–7]. Nevertheless, from the viewpoint of the cost effectiveness and implementation complexity, it is worth enhancing the standard MAC protocol to support multichannel access by using one single transceiver.

Several papers have proposed possible solutions on this matter by adopting multiple transceivers to achieve this goal [5–7]. Nasipuri *et al.* [6] proposed a multichannel carrier sense multiple access protocol for multi-hop MANETs. In such case, if there are N channels, the protocol assumes that each node can listen to all N channels concurrently. This implies that each node requires least N transceivers for data transmissions, which is very expensive and the protocol will be bounded by the number of transceivers.

In [7], Wu *et al.* proposed a so-called dynamic channel assignment (DCA) scheme where one transceiver is fixed to a dedicated control channel for contention and the other one is tunable among other channels for data transmissions. When a node receives a request-to-send (RTS) control frame from a sender in the control channel, it will scan all channels except the control channel and choose the first detected idle channel to inform the sender to transmit data; this approach increases both the implementation complexity and the prime cost and is impractical to present WLAN adapters. Furthermore, Chen *et al.* [4] and Chen and Sheu [13] have proposed a multichannel access protocol by using single transceiver, however, it can only be applied in the one-hop basic service set (BSS) of WLAN environment and needs an AP to coordinate the multichannel transmission. In a similar attempt to address this issue, Chen and Chen [14] and So and Vaidya [15] proposed protocols that use one transceiver to achieve multichannel transmissions. So and Vaidya [15] designed the protocol based on *ad hoc* traffic indication messages (ATIM), which is the power saving mechanism used in the IEEE 802.11 MAC protocol, to deal with multichannel negotiations and reservations. Using this mechanism, however, will cause additional bandwidth to be wasted in the ATIM window and beacon operations. In addition, both protocols do not address an important issue in designing a new MAC protocol; a method to broadcast transmissions in their multichannel environment is not mentioned.

On the contrary of the above methods, we propose using a decentralised contention and reservation based *ad hoc* multichannel negotiation protocol (AMNP) for supporting multichannel transmissions over MANETs in which each mobile node is equipped with one single transceiver. The AMNP has five unique characteristics: (i) AMNP is a fully distributed and interactive multichannel transmission protocol, which means that no centralised coordinator, such as AP, is needed in this protocol; (ii) by adopting AMNP, mobile nodes can communicate with each other simultaneously in the multichannel and multi-hop MANET scenario; (iii) AMNP employs a multichannel RTS/clear-to-send (MRTS/MCTS) mechanism to lower the collision or interruption probabilities caused by the multichannel hidden terminal problem [6] or nodes' mobility, and thus further enhances the performance of wireless transmissions; (iv) the broadcast problem caused by using one transceiver in a multichannel environment is solved in AMNP and (v) AMNP can be combined with the channel reservation, channel scheduling, and broadcasting scheme (the combined protocol is named as AMNP/s) to enhance the performance (i.e. the channel utilisation) of the original AMNP protocol.

The remainder of this paper is organised as follows. In Section 2, we point out some problems and challenges during the designing of a distributed multichannel reservation protocol by using single transceiver in multihop MANETs. Section 3 describes AMNP and the enhanced version AMNP/s in detail. The processes and results of a series of stimulations we preformed to evaluate the effectiveness of the proposed AMNP and AMNP/s is presented in Section 4. Finally, we give conclusions and possible future works in Section 5.

2 Problem statements

2.1 Single transceiver constraint

The MAC protocol of IEEE 802.11 DCF [10] is designed for sharing a single-channel between nodes. Most of the present wireless device of mobile nodes are equipped with one half-duplex transceiver to transmit or to receive data. The transceiver can operate on multiple channels dynamically, but it can only transmit or receive from one channel at a time. This implies that a node cannot communicate with other nodes when it is listening on a different channel from these nodes. Many articles [5–7] propose potential solutions for multichannel transmission by adopting multiple transceivers to achieve this goal. However, these solutions may not be applicable for wireless equipments with one transceiver and operating on multiple channels. Moreover, a single-channel MAC protocol such as IEEE 802.11 DCF will be no longer suitable for the multichannel environment where nodes may dynamically switch channels.

2.2 Multichannel hidden terminal problem

The hidden terminal problem [16] is one of the most important issues in MANETs. This problem is caused by hidden terminals (nodes), which are nodes that cannot hear the radio signal from the sender node and may disturb an ongoing data transmission. Although the IEEE 802.11 standard provides RTS/CTS control frames to conquer the hidden terminal problem, nodes may still collide with other nodes unwittingly in the multichannel environment, since they only equip with one transceiver and could not perceive the statuses of other channels [15]. This is a severe problem when designing a multichannel protocol with the constraint of using only one transceiver. Besides, MANETs are generally configured as peer-to-peer networks with no centralised hubs or controllers to coordinate resource allocation. In other words, a mobile node should have sufficient channel statuses within its and the expected receiver's radio covering area before its data transmission in order to avoid unexpected collisions.

doi: 10.1049/iet-com.2009.0318

2.3 Broadcast in multichannel

Broadcasting a message to all nodes in a network is an important activity in multi-hop MANETs [17–21]. In single-channel environment, it is 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 on other channels currently. This problem should be examined at a further note.

3 *Ad hoc* multichannel negotiation protocol

3.1 Data transmissions

In general, if all mobile nodes are equally allocated to all available channels, the collision probability of each attempted request would be minimised accordingly. Based on the MAC protocol of IEEE 802.11, the sender and the receiver should perform a four way handshaking mechanism: RTS/clear-to-send (RTS/CTS), data, and acknowledgment (ACK) when they have data to transmit in the same channel. If mobile nodes equip with only one transceiver, some nodes will never communicate with each other at the same time. As a result, few data frames will be transmitted in the multichannel environment. If we assign mobile nodes to access channels dynamically, a complicated and distributed channel scheduling mechanism has to be provided for MANETs. It will be more difficult in the MANET.

Instead of employing such complicated scheme, AMNP allocates a dedicated contention or broadcast channel for all mobile nodes to contend. The remaining channels are served as data channels permanently. Fig. 1 illustrates the channel usage of AMNP in which channels $C_1 - C_{n-1}$ represent data channels, and channel C_0 alternatively represents the role of the dedicated contention channel or broadcast channel dynamically. Since there is no stationary node for supporting centralised multichannel control in MANETs, the distributed negotiation protocol, which can provide *ad hoc* multichannel transmission, is needed. To solve the above-mentioned problems, we employ the concept of IEEE 802.11 RTS/CTS handshaking mechanism to fulfil the multichannel negotiation and transmission mechanism in multi-hop MANETs. We name the RTS/CTS mechanism as MRTS/MCTS in the AMNP. Unlike IEEE 802.11 RTS/CTS mechanism, we need more information to indicate the usage of other data channels.

A mobile node has to first complete a MRTS/MCTS handshaking in the contention channel to acquire the access right of the expected data channel if it has a packet to transmit. The purpose of the MRTS control frame is to inform its direct receiver and neighbours the preselected data channel to indicate a virtual carrier sensing delay named network allocation vector (NAV); this will prevent the exposed and hidden node problems in the preselected channel. Likewise, the MRTS also carries the newest status information of data channels to notify other mobile nodes within its transmitting range for information updating.

The frame format of MRTS is shown in Fig. 2*a* where the frame control, receiver address, transmitter address and frame check sequence fields are the same as the description in the IEEE 802.11 standard [10]. In order to be compatible with the IEEE 802.11 standard, we use the reserved value Type = 01 and Subtype = 0011 as indicated in the frame control field to represent the MRTS control frame. The original duration field is eliminated since the channel C_0 is for contention and broadcast use only. Therefore the NAV will not be used in C_0 when contending for the channel access. 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 that the sender prefers to transmit data with the receiver. The preferred channel (selected) is not compulsory for the receiver depending on the availability of the channel on the receiver's side.

The CUI field length is one octet long and the content of CUI indicates the status of the usage in each channel. Each bit field of CUI represents each corresponding channel in prior order and is called bit map. The left side bit of the

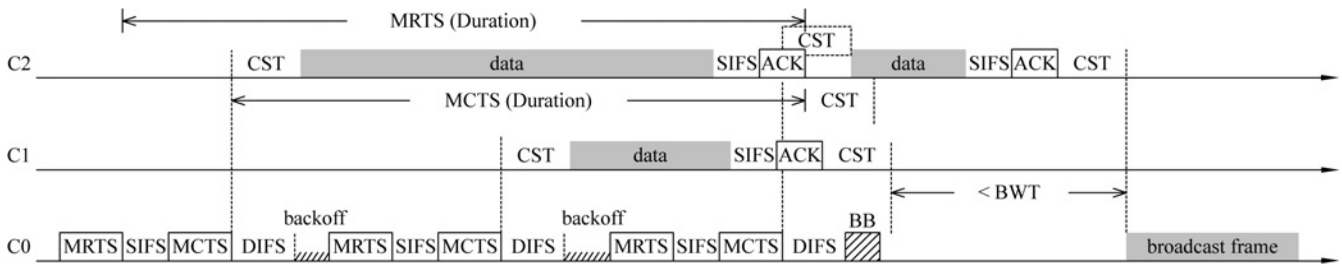

Figure 1 *Illustration of proposed AMNP, which C_0 represents the contention/reservation channel and C_1 and C_2 represent the data channels*

The identifier BB represents the broadcast beacon, the BWT represents the broadcast waited time and the CST is the channel switching/settling time, respectively

doi: 10.1049/iet-com.2009.0318

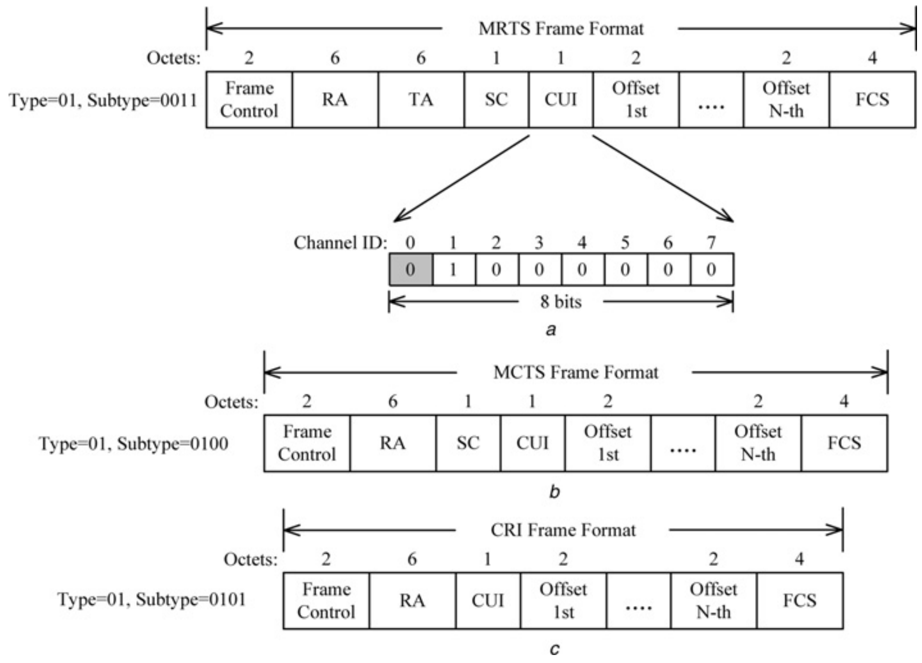

Figure 2 *Formats of the MRTS, MCTS and CRI control frames*

CUI indicates a broadcast transmission. The bit will be set to 0 if the corresponding data channel is not in use; the bit will be set to 1, if the corresponding data channel is in use. The following Offset fields are variable depending on the content of CUI field. For example, as shown in Fig. 2, the second bit (channel ID = 1) of CUI is set 1, which signifies that only the first data channel is in currently use and the free time of the first data channel would be the ending time of its transmitted MRTS pluses the value of the Offset. The unit of Offset field is measured in microsecond (μs).

When a node has received a MRTS frame, it will first 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. The preselected channel cannot be granted otherwise. The receiver then reselects another available channel according to the status of channel usage of the sender. The reselection rules are that if the sender has another free data channel and the channel is also available in the receiver's side, the re-selection commences. Otherwise, the receiver will compare all data channels and select one earliest free channel in both sides. The channel information of both sides is considered in order to prevent the multichannel hidden terminal 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 final usage status of data channels including the agreed selected data channel information. If the SC is the same as the sender, the handshaking is finished. Otherwise, the agreed SC will be different from the preselected channel indicated by the sender; the sender will issue a channel renewal information (CRI) control frame, shown in Fig. 2*c*, to make the neighbours around the sender to cancel the previous data channel NAV. Since the control frame is a new frame, we use the Type = 01 and Subtype = 0101 to indicate the CRI control frame.

A node needs to spend an extra channel switching/settling time (CST) when it switches 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 224 μs long [10]. This time varies from the physical medium dependent entity. Consequently, the corresponding offset field of the MRTS control frame will be SIFS + MCTS + CST + L_D + SIFS + ACK, where SIFS is the short inter frame space and L_D represents the data length in microsecond. In order to avoid other nodes from interrupting transmissions on other channels, nodes that intend to transmit frames must persistently monitor the control channel until the node hears either an MRTS or CRI control frame issued by other nodes. The restriction is to ensure that each sender synchronises to the latest channel information around its radius area before its transmission. Note that the nodes can only contend the data channel access right if they have heard an MRTS or CRI; the MCTS is excluded because of the broadcast transmission. This will be discussed again in the next subsection. We also note that the nodes should update the channel information if they hear an MCTS. Moreover, if a node has a frame to send but it does not listen to an MRTS or CRI after coming back from a data channel transmission or being in the initial stage (e.g. just power on), this node might suspects all data

doi: 10.1049/iet-com.2009.0318

channels to be free after waiting for a time period over a maximum transmissible frame length (2312 octets specified in the standard). The maximum waiting time will be the physical layer convergence procedure (PLCP) header + MAC_header + $L_D \simeq 192 + 136 + 9248 = 9576$ µs with a 2 Mb/s transmission rate.

Taking Fig. 3 for example, assume there are five mobile nodes in the *ad hoc* network. Nodes *c* and *d* are the exposed terminals of nodes *a* and *b*, and node *e* is the hidden terminal of node *b*. Initially, node *e* finishes its back-off count down and then sends an MRTS frame to request the channel 1 for data transmission. The receiver node *d* approves the request since channel 1 is also available in the side of node *d*. After the negotiation of nodes *d* and *e*, node *a* finishes its back-off count down and sends an MRTS to node *b* to ask channel 1 for data transmission. Since channel 1 has been reserved by nodes *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, which is 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 send a CRI to refresh the reservation information (to node *c* in this example). Finally, two transmissions are simultaneously permitted in the *ad hoc* network and the communication capacity of the network is increased.

3.2 Broadcast transmissions

The broadcast operation is an important activity in *ad hoc* networks since, for instance, it needs broadcasting to achieve routing information exchanges [22, 23], address resolution protocol and message advertisement and so on. These broadcast activities can be achieved by either adopting multiple unicast transmissions [20, 21] in network layer or via broadcast mechanism in data link layer [17, 24]. The latter approach will save network bandwidth more efficiently. However, under the

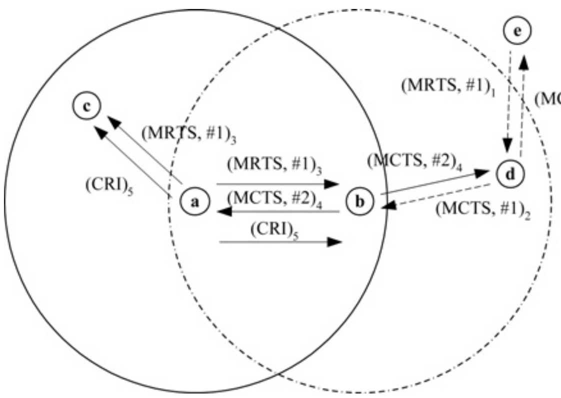

Figure 3 *Example of geographic topology in multihop MANET scenario*

constraint of the sole transceiver and the multichannel environment, it is hard to broadcast a frame to all neighbours especially since nodes can transmit or receive data in different channels. To conquer this problem, AMNP uses a designated control frame named broadcast beacon (BB) to announce to its neighbouring nodes of an upcoming broadcast transmission. We use the reserved value Type = 00 and Subtype = 0111 to denote the BB control frame. The frame format of the BB is shown in Fig. 4, where the CUI is equal to the CUI field of the MRTS and MCTS control frames except the first bit (bit 0).

When a node has a broadcast frame to transmit, it first checks whether there are some transmission pairs ongoing in data channels simultaneously. If there is no transmission proceeding in data channels, this node, after finishing its back-off countdown, will transmit its broadcast data on the contention channel directly. Otherwise, it will send a BB to its neighbouring nodes for announcement of the broadcast transmission. All nodes, which has now received the BB, will stay in the contention channel and wait for the broadcast waiting time (BWT) duration to receive the broadcast frame even though they may have made a successful reservation. The broadcast transmission is performed in the contention channel in order to let all neighbouring nodes be able to receive it. To ensure that all neighbouring nodes can receive the broadcast frame, the broadcast transmission should be performed when the entire neighbouring nodes are in the contention channel. To do so, the broadcast transmission will be delayed until the neighbouring nodes, which are now transmitting data in data channels, have returned to the contention channel. Although this scheme can guarantee all neighbouring nodes to receive the broadcast frame, the channel resource will inevitably be wasted. Taking Fig. 5, for example, the BB is issued when channels C_1 and C_2 have ongoing transmissions. The channel will be blocked and wasted if the broadcast frame is delayed until all transmissions are finished.

To avoid this drawback, we let the broadcast frame be transmitted immediately after a SIFS interval follows the BB frame. As a result, mobile nodes, which have received the BB, will receive the broadcast frame immediately after the SIFS interval. Several problems remain by adopting this immediate transmission of the broadcast frame after a SIFS interval. We demonstrate the following four cases, shown in Fig. 6, to describe the broadcast problems caused by this scheme in the multichannel environment.

BB Frame Format

Octets:	2	6	6	1	2		2	4
	Frame Control	RA	TA	CUI	Offset 1st	....	Offset N-th	FCS

Figure 4 *Format of the BB control frame*

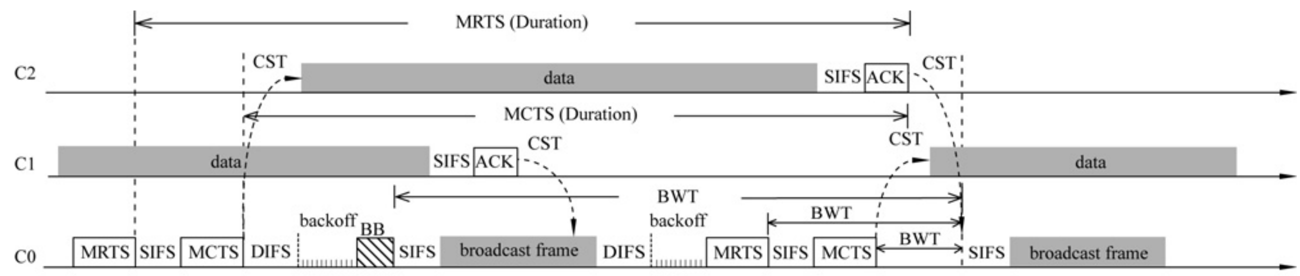

Figure 5 *Illustration of the identifier BB represents the broadcast beacon and the BWT represents the broadcast waiting time*

Case 1: At a finished transmission where the sender and the receiver will return to the contention channel during the time period of the beginning of the BB and before the broadcast frame.

Case 2: When a new coming node, which may move in from the outside of the sender's transmission range or just power on in the sender's transmission range, arrives during the time period of the beginning of the BB and before the broadcast frame.

Case 3: At a finished transmission where the sender and the receiver will return to the contention channel in the broadcast frame.

Case 4: At a finished transmission where the sender and the receiver will return to the contention channel after the broadcast frame.

In case 1, the nodes will receive the broadcast frame without missing it since they return to content channel before the broadcast frame and can be synchronised by the PLCP preamble of the broadcast frame to receive it. In case 2, nodes may not receive the broadcast frame depending on its facility capabilities, that is, the physical response time and the ready time and so on. Likewise, in cases 3 and 4, they will miss the broadcast frame if no second broadcast transmission is permitted. To solve these problems, we let the broadcast frame to be transmitted twice at a time, if transmissions are still performing on data channels as the BB is issued. On the contrary, the broadcast frame will be transmitted only once if there are no transmissions on data channels.

If the double broadcast transmission is performed, the BWT is calculated to indicate when the second broadcast will be transmitted. The BWT is recorded in the first Offset field of the BB control frame, and the first bit of the CUI field is set to 1. The duration of the BWT is calculated as the time that the latest free channel time among current transmissions plus the CST. For example, as shown in Fig. 5, the BWT is equal to the latest free time (C_2 in this example) plus the CST. To avoid wasting unnecessary channel, nodes that received the broadcast frame can proceed to reserve the channel by MRTS/MCTS handshaking if they have frames to transmit. Notice that the second broadcast will be delayed by a SIFS following an MRTS/MCTS handshaking if the last handshake time MRTS + SIFS + MCTS exceeds the ending time of the BWT. If the MRTS is performed, the first bit (bit 0) of the CUI is set 1 (in the broadcast indication) to notify nodes, which are in cases 3 and 4, of the second broadcast frame. Please also note that the first Offset field (the NAV in the C_0) of the MRTS or CRI indicates the remaining time of the BWT (refer to Fig. 5), since the NAV is decreased as time goes on.

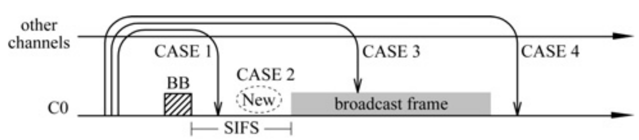

Figure 6 *Problems of broadcast in multichannel environment*

According to the scheme, cases 3 and 4 can be solved by either receiving the MRTS or CRI to obtain the time of the broadcast retransmission, or by waiting until receiving the broadcast retransmission since nodes cannot do anything until receive an MRTS or CRI. To avoid nodes, in cases 3 and 4, switching to other channels because of the new handshaking proceeded by other nodes, which do not belong to cases 3 and 4, we limit these nodes to stay in C_0 until receiving the second broadcast frame. However, some special cases may lead to the following situation: for example, some nodes outside of the radius of the broadcast sender nodes (which are in cases 3 and 4) make the reservations with these nodes before they listen to an MRTS or CRI. This problem is similar the issue called reliable broadcast transmission in the single-channel environment [17, 24–26]. We leave this for future work since it is beyond the scope of this paper.

We also note that AMNP does not allow nested or intersected broadcast transmissions to avoid broadcast confusion. That is, no other broadcast transmissions will be permitted before the finishing of a previous broadcast transmission. This is because that some nodes may miss the new broadcast frame if the nested or intersected broadcast is allowed since nodes may switch to other channels after receiving the first broadcast frame.

doi: 10.1049/iet-com.2009.0318

3.3 Channel utilisation improvement

The throughput of systems can be improved if the degree of channel utilisation is further increased. A simple way to increase the degree of channel utilisation is to adopt channel scheduling scheme. Without losing the simplicity of AMNP, we use the first-release-first-reserve strategy to schedule all reservations. We named the AMNP with scheduling scheme as AMNP/s. The scheduling policies of AMNP/s are as follows. If there are available free channels, then randomly select one channel to reserve. If there is no available channel for reservation, the sender chooses the first will-be-released channel to reserve the needed transmission interval. The reservation is not the final solution since this reservation may not be allowed in the receiver's side. If the reserved time of the SC is not allowed in the receiver's side, the receiver will select the second best channel (both available in the sender's and receiver's side) for reservation by comparing the CUI indicated in the MRTS frame with its channel status.

After comparing the CUI with its channel status, the receiver will reply an MCTS to the sender immediately. If the replied SC field of the MCTS is the same as the SC field of the original MRTS, the reservation is successful. Otherwise, the sender will update the new information and retransmit an MRTS to its neighbours for updating the new reservation.

However, the channel scheduling scheme will cause some problems if we want to transmit the broadcast frame. As we mentioned above, nodes receiving the BB will stay in the contention channel even if they have made reservations on other channels. This enforcement of the rule will cause nodes to miss the reserved transmission time. To resolve this problem, an amendment of the AMNP to fit the AMNP/s is given. If successful reservations are made before the BB and the scheduled reservation are during or exceeding the duration of the broadcast transmission, as shown in Fig. 7 on channels C_1 and C_2, all scheduled reservations will be delayed for a SIFS + L_B spontaneously, where L_B represents the length of the broadcast frame in microsecond. The extended time is indicated in the Offset fields of the BB for renewing the information of channels to neighbouring nodes.

Table 1 System parameters in simulations

Parameter	Normal value
simulation area	300 m × 300 m
transmission range	100 m
transmission rate	2 Mb/s
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 (136 μs)
mean frame length	512 octets
broadcast frame length	128 octets
aCWmin	31 slots
aCWmax	1023 slots
channel switching time	224 μs

4 Simulation model and results

4.1 Simulation model

The simulation model follows the IEEE 802.11b standard using the DSSS system at the physical layer with the long PLCP protocol data unit format (192 bits). Poisson distribution is used to determine the number of MAC service data unit (MSDU) arrivals. The lengths of the MSDUs are decided by the exponential distribution function. Most of the parameters are from the IEEE standard and listed in Table 1. The transmit-to-receive (Tx-to-Rx) turnaround time should be less than 10 μs, including the power-down ramp as specified in the IEEE 802.11 Standard [10]. The Rx-to-Tx turnaround time should be measured by the MAC/PHY interface, and should be less than 5 μs. The channel switching/settling time is 224 μs as defined in the standard.

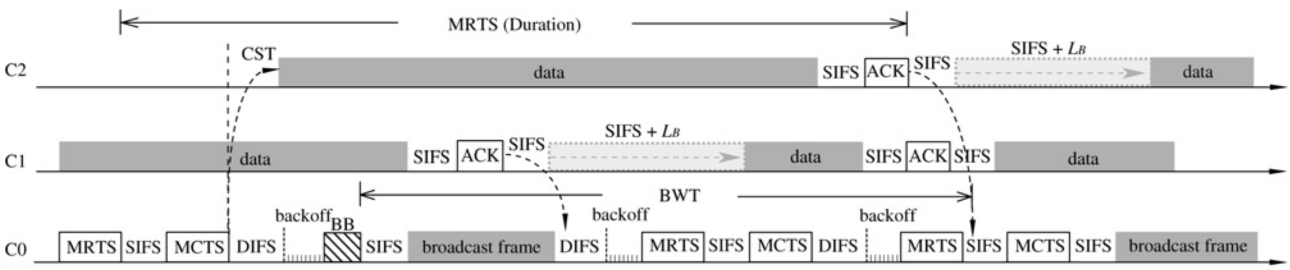

Figure 7 *Illustration of broadcast transmissions in AMNP/s*

In all simulations, we consider one contention channel and several data channels. For example, if the number of channels is 5, there are one contention channel and four data channels. The simulation scenario is considered as a multi-hop network. We vary the traffic loads by increasing the data arrival rate per node to observe the performance of each protocol. Each simulation runs at least over 10 000 000 slots time (600 s), and each data point represents an average of at least ten runs with identical traffic models, but different in randomly generated scenarios. Several assumptions are made to reduce the complexity of the simulation model: all nodes support the 2 Mb/s data rate and all data and control frames are sent at 2 Mb/s; the air propagation delay is neglected and the channel is considered as error free. There is no interference from nearby channels and all nodes are active (not in power-saving mode) throughout all simulations.

The mobility model uses the random waypoint model [27] in a rectangular field. We vary the pause time which affects the relative speeds of the mobiles. Each mobile node starts from a random location to a random destination with a randomly chosen speed (uniformly distributed between 0 and 94 m/s). (Note that this is a fairly high speed for an *ad hoc* network, comparable to traffic speeds inside a city.)

To evaluate the performance of AMNP/s, we compare our scheme with IEEE 802.11 [10] and the DCA protocol [7]. We use two metrics to evaluate the performance of the proposed AMNP/s.

- *Aggregate throughput over all flows in the network:* The throughput is measured in Mb/s. Theoretically, a multichannel MAC protocol will improve the total throughput by a factor of N over a single-channel MAC protocol given that N data channels are available. This throughput can be achieved if every node has N transceivers. However, with one transceiver per node, the ideal throughput cannot be achieved because of the overhead required for negotiating channels and avoiding the hidden terminal problem.

- *Average MAC delay over all flows in the network:* Average frame delay is the duration between the time when the frame reaches the first position of the queue in data link layer and the time that the receiver has received the frame successfully in the data link layer. Therefore the MAC delay is the sum of MAC operations including back-off countdown, channel negotiation and transmission delay. The queue size is assumed infinite with no frame dropped in the queue.

4.2 Simulation results

The first set of experiments compares the throughput of different schemes, for example, IEEE 802.11, AMNP, DCA and AMNP/s, by varying the traffic load. The number of channels is set to be 3. The curve labelled as 'DCA/cost' refers to the viewpoint of cost efficiency since DCA scheme adopts two transceivers. All nodes of this experiment are set to be immovable. The throughput is measured by calculating all successful transmitting data excluding the PHY and MAC header over total simulation time. The experiment purpose is to only observe the scheme performance without any broadcast frame generation.

The network sizes are 27, 54 and 108 nodes as shown in Figs. 8*a*, *b* and *c*, respectively. As shown in Fig. 8, the aggregated throughput of all schemes increases following the increment of the network load. The IEEE 802.11 protocol (labelled as 802.11 for short) first saturates its upper bound threshold when network load is light since IEEE 802.11 protocol only operates on one channel. On the contrary, other schemes such as the DCA, AMNP and AMNP/s, their throughput significantly increases following the increment of network load continuously. This is because of that these schemes use more than one channel for data transmissions. As the graphs show, AMNP performs significantly better

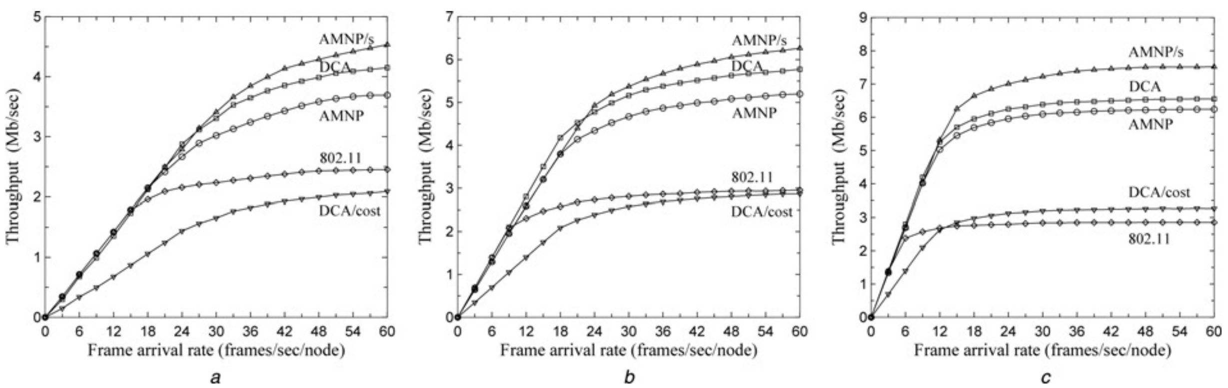

Figure 8 *Throughput against frame arrival rate derived by IEEE 802.11, AMNP, DCA, DCA/cost and AMNP/s under different number of nodes*

a 27 nodes
b 54 nodes
c 108 nodes

doi: 10.1049/iet-com.2009.0318

than IEEE 802.11 in heavy traffic load but less than the DCA scheme. This is because DCA uses one transceiver for data contention and another transceiver for data transmission on other channels. That is, DCA does not need the extra CST overhead for channel switching and it outperforms than AMNP. However, the gap lessens when the network density increases (from 27 to 108 nodes) since the degree of parallel processing by nodes increases. Moreover, by adopting the channel scheduling strategy, AMNP/s can gain 10–20% more throughput than DCA, especially when the network load is heavy, or the network density is large. Although the improvement of AMNP/s over DCA may not be dramatic, it is important because AMNP/s achieves this throughput by using only one transceiver per node. This implies that the throughput increment by multichannel transmission can be achieved by AMNP/s using a single transceiver per node. Moreover, by looking at the viewpoint of cost benefit, as shown in the curves labelled DCA/cost, the performance of per transceiver is not as efficient as AMNP and AMNP/s.

Fig. 9 shows the MAC delay of AMNP/s, DCA and IEEE 802.11. We can see that IEEE 802.11 get higher MAC delay because of the fact that it operates on one channel, a frame will suffer a longer delay to access the channel as the network load becomes heavier. On the contrary, AMNP/s and DCA both can switch data transmissions to data channels after making successful handshakes and thus reduce the longer MAC delay. DCA has lower MAC delay than AMNP/s as the number of channels increases. This is because that DCA gets the benefit from using two transceivers, so once a successful handshake is made by another transceiver, the transmission can be performed in the data channel without extra CST. 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.

In the following experiments, we investigate the effect of broadcast transmissions using the AMNP/s, DCA and

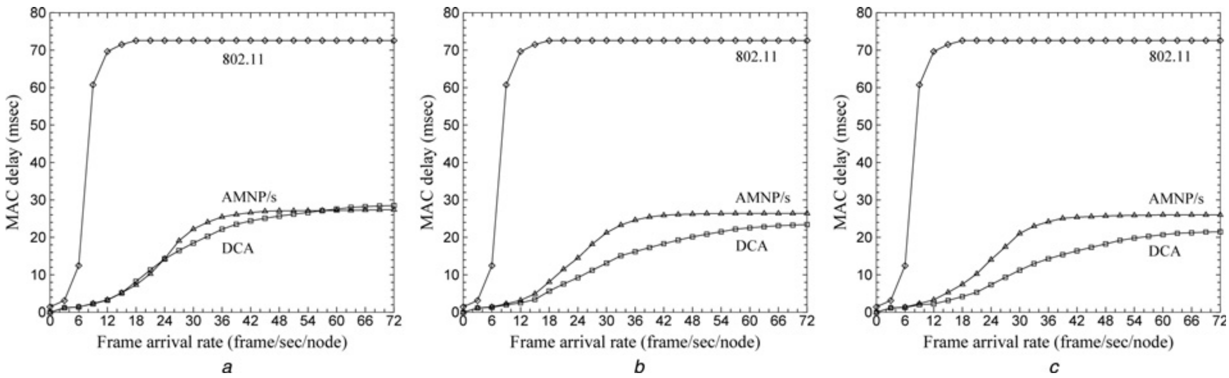

Figure 9 *MAC delay against frame arrival rate under different number of channels, where subgraphs a, b and c are 54 nodes*

a Three channels
b Five channels
c Seven channels

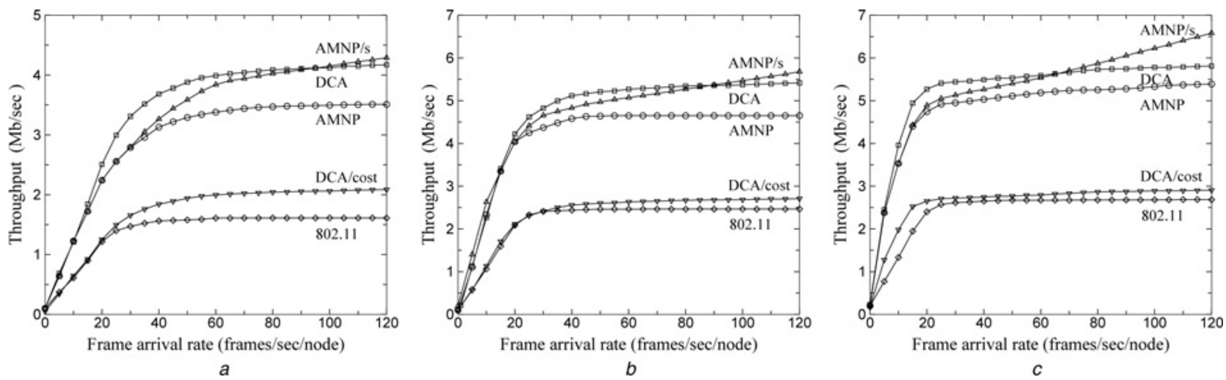

Figure 10 *Throughput against frame arrival rate derived by IEEE 802.11, AMNP, DCA and AMNP/s under different number of nodes*

a 27 nodes
b 54 nodes
c 108 nodes

IEEE 802.11 schemes, respectively. First, each node has a fixed broadcast frame arrival rate at 12 frames/s and all arrived data including unicast and broadcast frames are served in a first-in-first-out manner. We also double the unicast frame arrival rate to 120 frames/s on each node, comparing to the previous experiment, to observe the effect on throughput when the network load is under saturation. First, in all densities, the throughput of each scheme increases when the network load is not heavy. The IEEE 802.11 first saturates its throughput in every scenario and gets lower throughput than its unicast counterpart because of the impact of broadcast transmissions. The throughput of AMNP/s and DCA are also affected by the broadcast transmissions. However, the throughput is still double than IEEE 802.11 since they use two extra channels. Moreover, when the network load is heavy and network density is large (see Fig. 10*c*), AMNP/s gets about 6.53 Mb/s throughput and it is more than DCA's 5.81 Mb/s when the network load is 120 frames/s per node. This is because that more data frames can be scheduled and thus more throughput will be obtained. DCA's throughput is bounded since the broadcast is performed in the contention channel, and other channels are idle when broadcast is transmitting. This result indicates that AMNP/s can deal effectively with broadcast transmissions in the multichannel system under the one-transceiver constrain.

As discussed in previous sections, the broadcast transmission is an another major problem when design a new MAC protocol. AMNP/s uses the BB control frame and double broadcast transmission mechanism to conquer the multichannel broadcast problem. However, the AMNP/s cannot prevent nodes which miss the BB control frame and still not receiving any MRTS or CRI frame during the BWT from being handshaking by other nodes who are hidden terminals to the broadcast sender. These hidden terminals have the possibility to send the MRTS control frame to these nodes meantime. This is another broadcast problem called reliable broadcast transmission problem. This problem can be investigated in the future.

5 Conclusion

A multi-hop MANET consists of mobile devices with limited power and communication capacity. The multi-hop MANET transmission capacity can be improved by adopting parallel multichannel access schemes. This paper address the problem of designing a distributed multichannel MAC protocol when mobile devices only equip one single transceiver. The key challenge in the design process is coping with the new multi-hop, multichannel hidden terminal problem and the multichannel broadcast problem due to that mobile nodes cannot listen to all channels simultaneously. In this paper, we propose new MRTS and MCTS handshaking messages to conquer the multichannel hidden terminal problem. As the population of a MANET gets high, simulation results show that AMNP/s achieves throughput as well as the dual-transceiver scheme does and even gets better when traffic load is heavy. Additionally, we propose the BB control frame to conquer the multichannel broadcast problem, so that broadcast frames can be successfully transmitted in the scenario. Since the mechanism inherits from IEEE 802.11 standard, it is fully compatible with the standard. These results encourage MANET designers to realise the multichannel transmission by adopting one transceiver in multi-hop MANETs for throughput enhancement.

6 Acknowledgments

This work was supported in part by the National Science Council, Taiwan, under Contract NSC97-2221-E-182-035-MY2 and the High Speed and Intelligence Center (HSIC), Chang Gung University, Taiwan.

7 References

[1] KHAYATZADEH MAHANI A., NADERI M., CASETTI C., CHIASSERINI C.F.: 'MAC-layer channel utilization enhancements for wireless mesh networks', *IET Commun.*, 2009, **3**, (5), pp. 794–807

[2] XU S., PAPAVASSILLIOU S., NARAYANAN S.: 'Layer-2 multi-hop IEEE 802.11 architecture: design and performance analysis', *IEE Proc. Commun.*, 2004, **151**, (5), pp. 460–466

[3] AJMONE-MARSAN M., ROFFINELLA D.: 'Multichannel local area network protocols', *IEEE J. Sel. Areas Commun.*, 1983, **1**, pp. 885–897

[4] CHEN J., PANG A.-C., SHEU S.-T., TSENG H.-W.: 'High performance wireless switch protocol for IEEE 802.11 wireless networks', *ACM/Springer Mob. Netw. Appl. (MONET)*, 2005, **10**, (5), pp. 741–751

[5] JAIN N., DAS S.R., NASIPURI A.: 'A multichannel CSMA MAC protocol with receiver-based channel selection for multihop wireless networks'. Proc. IEEE ICCCN 2001, Scottsdale, AZ, May 2001, pp. 432–439

[6] NASIPURI A., ZHUANG J., DAS S.R.: 'A multichannel CSMA MAC protocol for multihop wireless networks'. Proc. IEEE WCNC'99, Piscataway, NJ, 1999, vol. 3, pp. 1402–1406

[7] WU S.-L., LIN C.-Y., TSENG Y.-C., SHEU J.-L.: 'A multi-channel MAC protocol with power control for multi-hop mobile *ad hoc* networks', *Comput. J.*, 2002, **45**, (1), pp. 101–110

[8] CHOU H.-Z., WANG S.-C., KUO S.Y., CHEN I.-Y., YUAN S.-Y.: 'Randomised and distributed methods for reliable peer-to-peer data communication in wireless *ad hoc* networks', *IET Commun.*, 2007, **1**, (5), pp. 915–923

[9] MAHASUKHON P., SHARIF H., HEMPEL M., ZHOU T., WANG W., CHEN H.-H.: 'IEEE 802.11b based *ad hoc* networking and its

doi: 10.1049/iet-com.2009.0318

performance in mobile channels', *IET Commun.*, 2009, **3**, (5), pp. 689–699

[10] IEEE 802.11 Working Group: 'Part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications'. ANSI/IEEE Std 802.11, September 1999

[11] KARAMAD E., ASHTIANI F.: 'Performance analysis of IEEE 802.11 DCF and 802.11e EDCA based on queueing networks', *IET Commun.*, 2009, **3**, (5), pp. 871–881

[12] O'HARA B., PETRICK A.: 'The IEEE 802.11 handbook: a designer's companion' (IEEE Press, 1999)

[13] CHEN J., SHEU S.-T.: 'Distributed multichannel MAC protocol for IEEE 802.11 *ad hoc* wireless LANs', *Comput. Commun.*, 2005, **28**, (9), pp. 1000–1013

[14] CHEN J., CHEN Y.-D.: 'AMNP: *ad hoc* multichannel negotiation protocol for multihop mobile wireless networks'. Proc. IEEE ICC'2004, Paris, France, June 2004

[15] SO J., VAIDYA N.H.: 'Multi-channel MAC for *ad hoc* networks: handling multi-channel hidden terminals using a single transceiver'. Proc. ACM MobiHoc 2004, Tokyo, Japan, May 2004, pp. 222–233

[16] TOBAGI F.A., KLEINROCK L.: 'Packet switching in radio channels: part II-the hidden terminal problem in carrier sense multiple-access and the busy-tone solution', *IEEE Trans. Commun.*, 1975, **COM-23**, (12), pp. 1417–1433

[17] CHEN J., SHEU S.-T.: 'A reliable broadcast/multicast MAC protocol for multi-hop mobile *ad hoc* networks', *IEICE Trans. Commun.*, 2006, **E89-B**, (3), pp. 867–878

[18] CHLAMTAC I., KUTTEN S.: 'On broadcasting in radio networks – problem analysis and protocol design', *IEEE Trans. Commun.*, 1985, **COM-33**, (12), pp. 1240–1246

[19] GÁLLEGO J.R., CANALES M., HERNÁNDEZ-SOLANA A., VALDOVINOS A.: 'Analysis and modelling of broadcast services for TDMA wireless *ad hoc* networks', *Electron. Lett.*, 2007, **43**, (6), pp. 350–351

[20] LOU W., WU J.: 'On reducing broadcast redundancy in *ad hoc* wireless networks', *IEEE Trans. Mob. Comput.*, 2002, **1**, (2), pp. 111–122

[21] TSENG Y.-C., NI S.-Y., CHEN Y.-S., SHEU J.-P.: 'The broadcast storm problem in a mobile *ad hoc* network', *ACM/Kluwer Wirel. Netw.*, 2002, **8**, (2–3), pp. 153–167

[22] PERKINS C.E., ROYER E.M.: '*Ad-hoc* on-demand distance vector routing'. Proc. Second IEEE Workshop Mobile Computing Systems and Applications (IEEE WMCSA'99), New Orleans, LA, February 1999, pp. 90–100

[23] ROYER E.M., TOH C.K.: 'A review of current routing protocols for *ad hoc* mobile wireless networks', *IEEE Pers. Commun.*, 1999, **6**, (2), pp. 46–55

[24] CHEN J., HUANG M.: 'A broadcast engagement ACK mechanism for reliable broadcast transmission in mobile *ad hoc* networks', *IEICE Trans. Commun.*, 2005, **E88-B**, (9), pp. 3570–3578

[25] LOU W., WU J.: 'A reliable broadcast algorithm with selected acknowledgements in mobile *ad hoc* networks'. Proc. IEEE GLOBECOM'03, San Francisco, CA, December 2003, vol. 6, pp. 3536–3541

[26] TANG K., GERLA M.: 'MAC reliable broadcast in *ad hoc* networks'. Proc. IEEE MILCOM'01, Washington, DC, October 2001, vol. 2, pp. 1008–1013

[27] BROCH J., MALTZ D.A., JOHNSON D.B., *ET AL.*: 'A performance comparison of multihop wireless *ad hoc* network routing protocols'. Proc. ACM/IEEE MOBICOM'98, October 1998, pp. 85–97