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Assigning channels by link directionality in a medium access control protocol for IEEE 802.11 *ad hoc* networks

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Abstract: This study attempts to exploit the potential of link directionality to increase the achievable capacities of *ad hoc* networks. When an IEEE 802.11 *ad hoc* network achieves capacity C by using a single channel, the targeted capacity by using two channels should be $2C$. However, most of the dual-channel 802.11 protocols proposed in the literature appear only to be able to achieve less than 60% of the $2C$ targeted capacity. The authors thus propose a link-directionality-based dual-channel medium access control protocol in an attempt to double the capacities of networks using the single-channel IEEE 802.11 protocol. The main idea is to assign channels according to link directionality to allow a link to transmit simultaneously within the carrier-sensing region of another link provided that these transmissions do not interfere with each other. Simulations show that our proposed scheme can achieve more than 85% of our targeted capacities, $0.85 \times 2C = 1.7C$, in large-scale random topologies. In lattice and irregular topologies, the throughput is boosted up to $2.83C$ and $2.13C$, respectively. An approach for capacity analysis is also introduced to determine the throughput improvements that can be achieved by our proposed protocol. We believe using link directionality for channel allocations is a key step that yields significant potential for multiplying the capacity of *ad hoc* networks.

1 Introduction

When a wireless network uses more channel resources, it should be expected to achieve a proportionally higher network capacity. If an IEEE 802.11 *ad hoc* network achieves capacity C by using a single channel, the targeted capacity by using n channels should be therefore nC. However, most of the multi-channel 802.11 protocols proposed in the literature simply compared their performance with the original single-channel 802.11 protocol, without considering the additional channel resources used. In fact, most of them (e.g. [1–3]) only appear to be able to achieve less than 60% of the targeted capacities nC. This inefficiency can be attributed to three reasons: (i) an additional control channel is used to allocate transmission channels, (ii) the overhead incurred by the information added to the frame headers and (iii) the transmissions of request-to-send (RTS)/DATA and the receptions of clear-to-send (CTS)/acknowledgment (ACK) by a node are assigned to the same channel that limit the potential for simultaneous transmissions (details will be explained in Sections 2 and 3). In this paper, we attempt to achieve the targeted capacity $2C$ of a two-channel system. Our proposed protocol does not require (i) and (ii). In addition, we propose to transmit RTS/DATA and CTS/ACK of a link in separated channels to scale the capacity better.

There are many proposed multi-channel protocols for 802.11 *ad hoc* networks in the literature. Mo *et al.* [4] compared these protocols and classified them into four categories: (i) dedicated control channel, (ii) common hopping, (iii) split phase and (iv) multiple rendezvous. Our proposed protocol does not belong to these categories. Instead, our scheme assigns transmission channels based on link directionalities.

Wu *et al.* [5]and Tseng *et al.* [6] proposed to use a control channel to exchange RTS/CTS frames which contain the channel information. Then, nodes use the agreed data channels to send DATA and ACK frames. These protocols require a separate control channel which does not carry data packets. This significantly increases the overhead incurred by the protocol. For example, if three channels are used, the targeted capacity would be $3C$. One of the three channels, however, is assigned as the control channel and this wastes one-third of the data transmission capacity.

Chen *et al.* [7] and So and Vaidya [8] proposed to split the transmission time into two phases: (i) control phase and (ii) data phase. During the control phase, all nodes switch to the control channel and allocate the transmission channels for the next data phase. These protocols require synchronisation between nodes which is difficult to achieve in distributed *ad hoc* networks. In addition, during the control phase, no data can be transmitted in other data channels. This, again, wastes the communications resource.

Another approach is to use frequency hopping [9]. Nodes use pre-assigned hopping patterns to switch channels for transmitting RTS/CTS frames until agreements are made between nodes. Then, they will use the concurred channels for data transmission. As mentioned in [4], these protocols may incur significant overheads because of the frequent channel switching.

Compared to the above protocols, our proposed scheme does not need (i) a dedicated control channel, (ii) synchronisations between distributed nodes and (iii) the channel hopping of radio transceivers. This helps to minimise the overhead incurred by the protocol.

The preliminary results of this research have been published in [10], which introduced the protocol and presented some pilot simulation results. That paper forms the foundation of this journal paper. After discussing the theoretical concept with experts in the field in IEEE GlobeCom'06 in San Francisco, we have worked on the feedback and addressed the issues raised in the conference. Therefore comparing with the conference paper, this journal paper:

1. provides further details of the proposed protocol, particularly using algorithm ii (randomly assigned transmission channels) to decide the channel of a transmitter with an empty SimTable (simultaneous transmission table);

2. discusses the impact of exposed-node problem;

3. conducts further simulations for random topologies with various numbers of links. This provides further justifications of the throughput improvements achieved by the proposed scheme;

4. introduces an approach for capacity analysis which can evaluate the improvements obtained by the proposed scheme.

2 The concept

There are two access modes for the 802.11 protocol: (a) basic access mode and (b) RTS/CTS access mode. This paper assumes the use of (b). With the RTS/CTS access mode, the protocol uses short RTS and CTS messages to notify other nodes within the virtual carrier-sensing range VCSRange to update their network allocation vector (NAV). The NAV includes the duration time of the ongoing transmission. Thus, no other nodes within the VCSRange can begin transmissions before the NAV expires. This prevents simultaneous transmissions that may lead to collisions. Fig. 1*a* shows an example. Under the 802.11 protocol with RTS/CTS access mode, none of the links B, C or D can transmit at the same time with link A. This is because R_A has to receive the DATA frame from T_A, while T_A has to wait for the ACK from R_A. Any other simultaneous transmissions within the VCSRange region of R_A and T_A in the same channel will lead to collision of the transmission between R_A and T_A. To avoid such collision, the RTS of T_A and the CTS of R_A forewarns links B, C and D not to transmit before link A transmits its DATA frame.

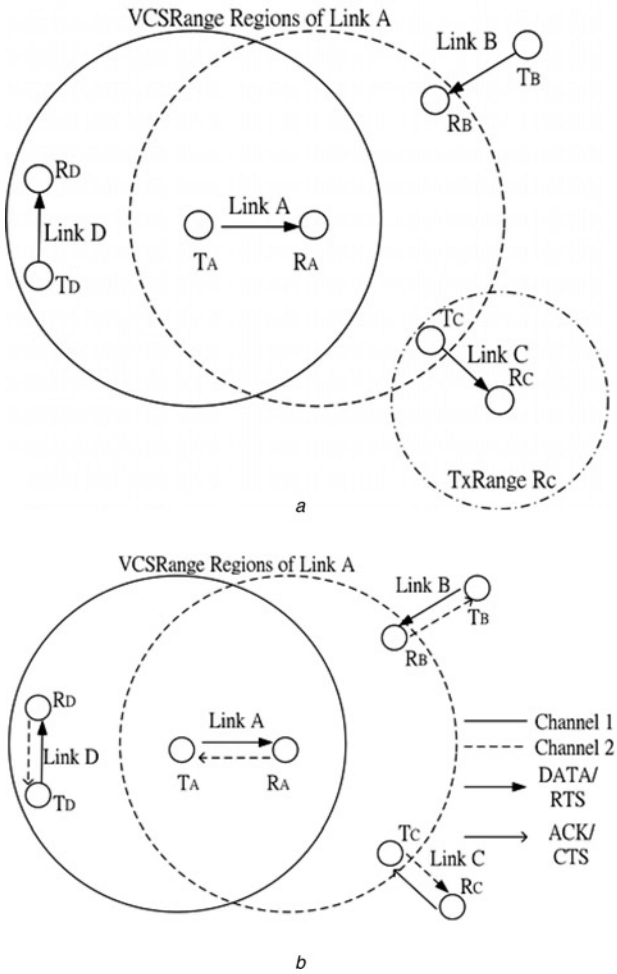

Figure 1 *A network topology using*
a Original 802.11
b Our proposed scheme

To overcome the above situation, we can split the transmissions between two nodes of a link into two channels based on their directionalities. Let us consider the case where there are two channels, s and t. Nodes transmit RTS and DATA in one channel (e.g. channel s) as they are in the same direction (from T_A to R_A), whereas CTS and ACK are transmitted in another channel (e.g. channel t). We now assume reciprocity for the receive and transmit channels. This can be claimed as valid since the channel is pseudo-stationary over the time period of the protocol and the terminals possess reciprocal receive/transmit antenna systems.

These channels are assigned dynamically based on the directionality, network topology and who else are transmitting in the neighbourhood. RTS and DATA can be transmitted in either channel s or t, and thus CTS and ACK will be sent in the other channel (t or s). The main idea is to allow the simultaneous transmission of another link i within the VCSRange region of R_A and T_A provided that the transmissions of link i do not interfere with the receptions of the ACK on T_A or the DATA on R_A. There are two possible cases:

Case 1: the transmissions of link i within the VCSRange use a different channel, and thus these do not affect the reception of $R_A(T_A)$ in another channel.

Case 2: the transmissions of link i use the same channel as the reception of $R_A(T_A)$ but those transmissions are far enough from $R_A(T_A)$.

For Case 2, let d_{TA-RA} be the distance between T_A and R_A, d_{TB-RA} be the distance between T_B and R_A and assume the capture threshold (CPThreshold) is set to be 10 dB [11, 12], which is the same as the default setting of the NS-2 simulator [13]. From [14], in a two-ray propagation model, assuming noise is negligible, if the signal-to-interference ratio at R_A is larger than the CPThreshold, R_A can capture the signal from T_A when T_B is transmitting. That is

$$\begin{aligned} &\mathrm{SIR} = (d_{TB-RA}/d_{TA-RA})^4 > \mathrm{CPThreshold} \\ &d_{TB-RA} > 1.78 \times d_{TA-RA} \end{aligned} \tag{1}$$

In our simulations, the transmission range (TxRange) is set to be 250 m. whereas VCSRange is 550 m by assigning the data rate for sending DATA/ACK at 12 Mbps (OFDM, QPSK) and the basic rate for transmitting RTS/CTS at 2 Mbps (DSSS, DQPSK). In the worst case that T_A and R_A are separated by the maximum TxRange (250 m), R_A can capture the signal from T_A if T_B is located at more than 1.78×250 m = 445 m away from R_A. If T_B cannot receive the CTS from R_A, T_B must be far enough so that its signal cannot interfere with the reception of signal from T_A at R_A. In next section, our proposed medium access control (MAC) protocol will utilise this property to assign transmission channels for links.

Fig. 1*b* shows the same scenario as Fig. 1*a* with the channel assignments based on Cases 1 and 2. Assuming link A is using channel 1 to transmit RTS and DATA from T_A to R_A and another independent channel 2 to send CTS and ACK from R_A to T_A. For link B to transmit simultaneously with link A, we can assign channel 1 for the transmission of RTS and DATA from T_B to R_B. This will not lead to collisions on link A because the signal from T_B is much weaker than the signal from T_A when they reach R_A (Case 2). R_B can then use channel 2 to transmit CTS and ACK. This, again, will not incur collisions on R_A because R_B is using another independent channel for transmissions (Case 1). Similarly, for link C, T_C can use channel 2 to transmit RTS and DATA, whereas R_C can use channel 1 to reply CTS and ACK. For link D, since both T_D and R_D are within the VCSRange of link A, links A and D cannot transmit at the same time and thus they have to take turns to transmit.

3 Proposed MAC protocol

In this section, we describe a MAC protocol to achieve the channel assignments as explained in Section 2. The protocol assigns the transmission channels of each link based on the availabilities of the receptions of RTS and CTS from other links. The protocol is modified from the original 802.11 MAC protocol and it attempts to seek opportunities for simultaneous transmissions. Assume that all nodes use the same power for transmissions and each node has two receivers and one transmitter. The two receivers are monitoring both channels at the same time. In addition, the receivers and transmitters do not need the ability to transmit and receive concurrently. In this section, we first outline the basic concept of our protocol. Then, we describe the algorithms required for our protocol.

3.1 Basic concept

The main purpose of the protocol is to identify the transmission channel which does not interfere with the transmissions of nearby links based on the RTS/CTS frames received from neighbourhoods. Note that a node can receive the DATA frames successfully from another node when they are within the TxRange. When a node is within the VCSRange but outside the TxRange of another node, it can still receive and decode the RTS/CTS frames but not the DATA frames since RTS/CTS are set to be transmitted at 2 Mbps data rate, while DATA frames are sent at a higher data rate at 12 Mbps. Therefore RTS/CTS frames can reach a longer range than DATA frames. The protocol utilises the availability of RTS/CTS frames to decide whether a simultaneous transmission will interfere with nearby transmissions with the same channel. Consider two links, i and j, which are within the VCSRange but outside the TxRange of each other. When a node (e.g. T_i) of link i receives the RTS$_j$ but not the CTS$_j$ of another link j, it will assign its RTS$_i$ to the same channel as that of RTS$_j$. Thus, link $i_{T->R}$ can transmit simultaneously with

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$j_{T->R}$ because receiver R_j is located far enough away from the transmitter T_i (as explained in Case 2 in Section 2) and T_j is receiving CTS or ACK in another channel (Case 1 in Section 2). In other words, T_i knows that its RTS$_i$ or DATA$_i$ transmitted on the assigned channel will not corrupt the reception at T_j and R_j, and so it is safe for T_i to transmit its RTS$_i$ and DATA$_i$. Similarly, when a node (e.g. T_i) of link i receives the CTS$_j$ but not the RTS$_j$ of another link j, it will assign its RTS$_i$ to the same channel as that of CTS$_j$. If a node can receive both the CTS$_j$ and RTS$_j$ of another link j, it will fall back to the original 802.11 protocol and will resume transmissions only after the NAV expires. In this case, links i and j have to take turns to transmit.

3.2 *Algorithms of our protocol*

To assign channels for simultaneous transmission links, the protocol requires the algorithms below. The first algorithm identifies possible channels for simultaneous transmissions based on the received RTS/CTS frames from nearby links; the second algorithm chooses channels when RTS/CTS information are unavailable.

3.2.1 Constructions of simultaneous transmission tables: Our proposed MAC protocol constructs a simultaneous transmission table (SimTable) in each node based on the receptions of RTS and CTS from other links. Each entry in the table corresponds to the channel number used. Each node attempts to seek opportunities for simultaneous transmissions according to the sensed signals and the records of its SimTable. Table 1 shows an example of the SimTable of node T_A of link A in Fig. 2. In the topology of Fig. 2, let us say link B begins the transmission first. T_A receives the CTS from R_B and then updates its SimTable$_{TA}$ (as shown in Table 1) with a new record (the first row). The CTSChannel field is set to channel 2. Since T_A cannot receive the RTS from T_B, the RTSChannel field remains null. According to SimTable$_{TA}$, T_A realises that it can transmit simultaneously with R_B in channel 2 without interfering with reception at T_B as T_B is far enough from T_A. Similarly, T_A receives the RTS from T_C and then updates its SimTable$_{TA}$ with another record (the second row). The RTSChannel field is set to channel 2. Since T_A cannot receive the CTS from R_C, the CTSChannel field remains null. T_A thus recognises that it can transmit concurrently with T_C in channel 2 without intruding R_C. When T_A has a packet to transmit, it examines its SimTable$_{TA}$. If simultaneous transmissions are allowed, T_A will transmit an RTS to R_A. Otherwise, it will wait for the expiration of NAV and then resume the transmission process.

Table 1 SimTable of node T_A in Fig. 2

Index	From	To	RTSChannel	CTSChannel
1	T_B	R_B	null	2
2	T_C	R_C	2	null
3	T_D	R_D	1	2

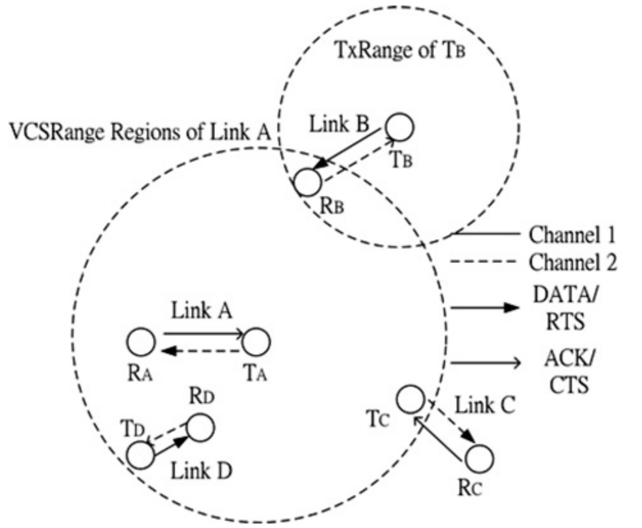

Figure 2 *A network topology using our proposed channel assignment scheme*

Consider link D in Fig. 2. T_D sends RTS to R_D and R_D replies CTS back to T_D. T_A receives both the RTS$_D$ and CTS$_D$ of link D. Thus, the RTSChannel and CTSChannel fields of the record (the third row in Table 1) are set to 1 and 2, respectively. So, in this case, link A cannot transmit at the same time with link D and they must take turn to transmit.

The reader may consider the case when link A begins the transmission before link B, so that R_B senses the signal from T_A before the signal from T_B and cannot receive packets from T_B. A so-called 're-start' mode chip [11, 15] set is required to eliminate this issue. When the receiver R_B is in the mid of receiving a signal from T_A, another signal from T_B with sufficiently large power margin arrives (more than 10 dB stronger since T_B is much closer to T_A as shown in Fig. 2), R_B will switch to receive the signal from T_B. This feature will also be used to eliminate the hidden-node problem in Section 4.

3.2.2 Randomly assigned transmission channels: When a transmitter of a link does not receive RTS/CTS signals from its nearby links for channel allocations, it will just randomly pick up one of the two channels for sending its RTS to the receiver of the link. If it can receive the CTS replied from the receiver, it will retain the channel for transmissions. Otherwise, it will swap to the other channel for a retransmission. This algorithm allows a node to identify the suitable transmission channel to avoid collisions when RTS/CTS information is unavailable. Fig. 3 shows an example when a receiver R_2 is in silence for later transmissions. Assume T_1 is transmitting DATA to R_1 on channel 1 when T_2 begins its transmissions to R_2. T_2 cannot identify the available channel for simultaneous

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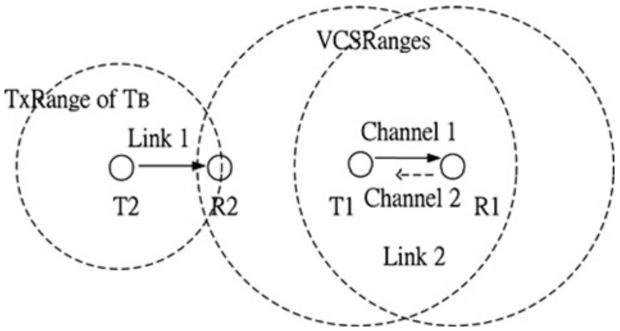

Figure 3 *Choosing transmission channels with algorithm ii of our protocol*

transmissions since T_2 cannot receive the RTS and CTS from link 1. T_2 will then randomly pick one of the two channels for sending RTS to R_2. For example, channel 1 is chosen, RTS_2 will collide with $DATA_1$ at R_2. Thus, R_2 will not reply a CTS back to T_2. When the timer of T_2 expires, it will switch to another channel (channel 2) for a retransmission. In this case, R_2 can now receive RTS_2 successfully and will reply a CTS_2 to R_2 in channel 1. Link 2 will then retain these channel assignments for ongoing transmissions. Note that here the exponential backoff will not be triggered unless and until the second attempt also fails to obtain a response from R_2.

4 Exposed-node and hidden-node problems

Exposed-node and hidden-node problems in wireless networks have been studied extensively. With the original 802.11 protocol, only one of links 1 and 2 in Fig. 4*a* can transmit data at one time because of the exposed-node problem. When node 2 transmits a frame to node 1, node 3 senses the transmission since node 2 is within the carrier-sensing range of node 3. Node 3 then declares the channel as busy and defers its transmission. This prevents the collision of the ACK replied by node 1 with the DATA transmitted by node 3. However, it also limits the achievable capacity of the network. With our proposed protocol as shown in Fig. 4*b*, nodes 2 and 3 are assigned to transmit with channel 1, whereas nodes 1 and 4 will reply ACKs in channel 2. In this way, the ACK replied by node 1 will not collide with the DATA sent by node 3 at node 2 since they are transmitted in different channels. Links 1 and 2 therefore can transmit simultaneously.

Fig. 5*a* shows a hidden-node scenario with the original 802.11 protocol. When node 3 sends a frame to node 4, node 2 senses the channel to be busy, whereas node 1 senses the channel to be idle, since node 3 is inside the carrier-sensing range of node 2 but outside that of node 1. Once node 1 senses the channel as idle, it may count down its back-off contention window until zero and transmit a frame to node 2. If the transmission from node 4 is still in progress, node 2 will continue to sense the

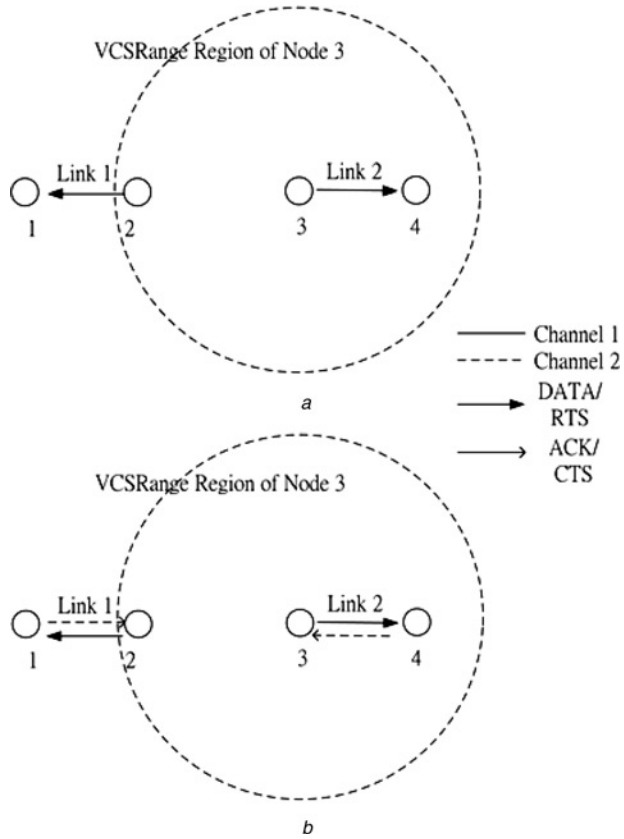

Figure 4 *Exposed-node problem*

a In original 802.11 protocol
b Does not exist in our proposed MAC protocol

channel as busy, and it will not receive the frame from node 1. As a result, node 2 will not return an ACK to node 1. Node 1 may then time out and double the contention window size for retransmission later.

Meanwhile, node 3 transmits the frame successfully and is not aware of the collision at node 2. When transmitting the next frame, node 3 will use the minimum contention window size. The hidden-node scenario favours node 3, and the chance of collision at node 2 cannot be reduced even though node 1 backs off before the next retry.

The RTS/CTS mechanism in 802.11 is designed to solve the hidden node problem. However, using RTS/CTS in *ad hoc* networks does not eliminate the hidden node problem [16]. The effectiveness of RTS/CTS mechanism is based on the assumption that transmissions by mutually hidden nodes are to a common receiver. Before the transmission of a hidden node begins, the receiver will forewarn other hidden nodes to prevent them from transmitting. This assumption may not hold in an *ad hoc* network.

In our proposed MAC protocol, the above hidden-node scenario does not exist thanks to the channel assignment property of the protocol. If node 3 uses channel 2 to send RTS/DATA to node 4, node 1 will use channel 1 to

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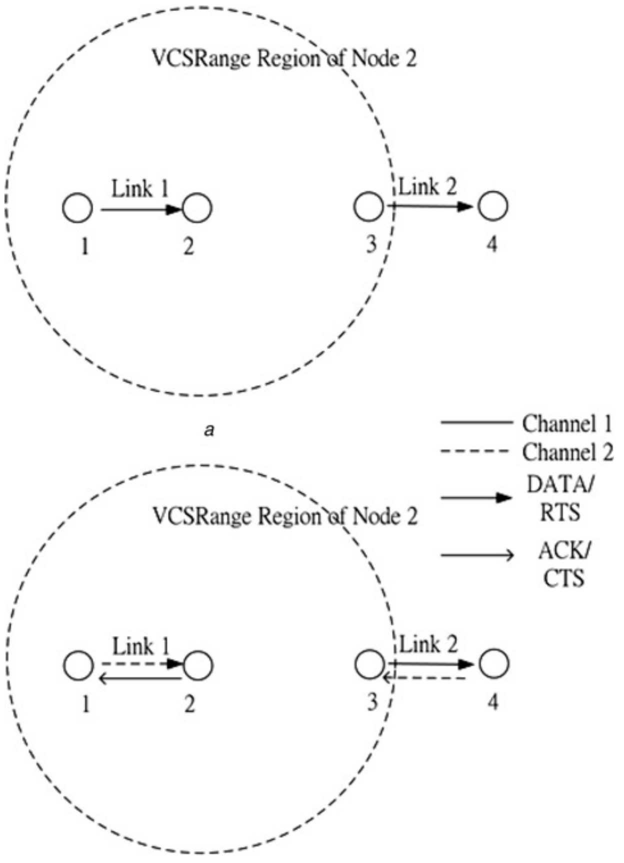

Figure 5 *Hidden-node problem*

a In original 802.11 protocol
b Does not exist in our proposed MAC protocol

transmit RTS/DATA to node 2 (as shown in Fig. 5*b*). Since the transmissions are in independent channels, both nodes 2 and 4 can receive the signals successfully.

Beside the above scenario, there is a 'hidden-node' scenario specific to our proposed protocol. Consider Fig. 6. Since nodes 3 and 4 are within the VCSRange of node 2, node 2 can receive both the RTS and CTS of link 2. Thus, links 1 and 2 must take turn to transmit. However, node 1 cannot receive the RTS and CTS from link 2 as nodes 3 and 4 are outside the VCSRange of node 1. In this way, node 1 may send RTS to node 2. If the transmission of link 2 is still in progress, node 2 will not reply CTS to node 1. Thus, node 1 may time out and double its contention window for retransmission. This will induce an unfairness problem between links 1 and 2. From the protocol's point of view, only one of links 1 and 2 is allowed to transmit at each time. In a simulation with two links as shown in Fig. 6, link 2 obtains four times throughput as that of link 1. Although the overall capacity achieved by links 1 and 2 remains the same as allowed by the protocol, link 2 occupies most of the share of the channel bandwidth. Similar to the conventional hidden-node problem in the literature, the 'hidden-node' scenario specific to our proposed protocol induces unfairness among links.

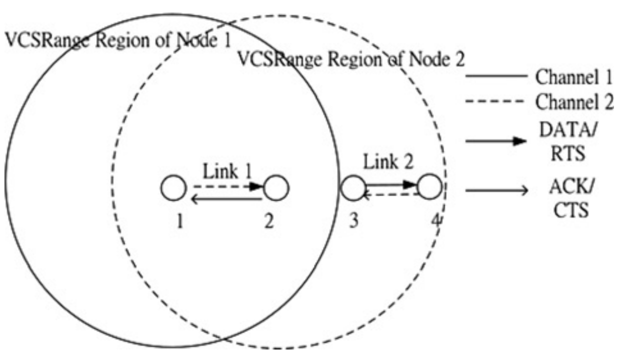

Figure 6 *Hidden-node problem in our proposed protocol*

Many solutions (e.g. [8, 15, 17]) have been proposed in the literature to solve the hidden-node problem. A possible solution for this unfairness problem is to use a so-called 're-start mode' chip set and extend the VCSRange to sufficiently large in order to cover all potential interfering nodes by the RTS/CTS mechanism. Jiang and Liew [15] show that the hidden-node problem of original 802.11 networks can be avoided when restart mode is enabled and the carrier-sensing range is sufficiently large. In particular, Jiang and Liew [15] proves two conditions that can guarantee a hidden-node-free operation in a general network: (i) restart mode and (ii) a lower-bound requirement on the carrier-sensing range. In our case, with the 're-start mode', if the receiver is in the midst of receiving a signal, another signal with sufficiently large power margin arrives (say, 10 dB stronger), the receiver will switch to receive the new signal. In Fig. 6, if we set the *VCSRange* to 700 m and retain the TxRange to 250 m, node 4 will be at least 450 m away from node 2. The signal from node 1 at node 2 will then be at least 10 dB stronger than the signal from node 4. Thus, node 2 can always capture the frames from node 1 successfully.

5 Simulation results

We have implemented our proposed MAC protocol in the NS-2 [13] simulator. For fair comparisons, we use the settings of original 802.11 protocol in NS-2 such that VCSRange = 550 m and TxRange = 250 m by assigning the data rate (for sending DATA/ACK) at 12 Mbps (OFDM, QPSK) and the basic rate (for transmitting RTS/CTS) at 2 Mbps (DSSS, DQPSK) as listed in Tables 2 and 3. In our simulations, all data sources are

Table 2 System parameters assumed

virtual carrier-sensing range (VCSRange)	550 m
transmission range (TxRange)	250 m
capture threshold (CPThreshold)	10 dB

Table 3 System parameters assumed in our MAC protocol

packet payload (DATA)	1460 bytes
UDP/IP header	20 bytes
MAC header	28 bytes
PHY header	24 bytes
ACK size	14 bytes
RTS size	20 bytes
CTS size	14 bytes
data rate (DATA/ACK)	12 Mbps
basic rate (RTS/CTS)	2 Mbps
PHY header bit rate	1 Mbps
slot time σ	20 μs
SIFS	10 μs
DIFS	50 μs
$CW_{\min}$	32
$CW_{\max}$	1024
CW_{average}	310 μs
retransmission limit	7

saturated UDP traffic stream with fixed packet size of 1460 bytes.

5.1 A lattice topology

Fig. 7 shows 12 links in an 8 × 3 lattice topology. As shown in Fig. 9*a*, using the original single-channel 802.11 protocol results in 19.93 Mbps total network throughput, thus the targeted capacity for using dual channels is by definition 19.93 Mbps × 2 = 39.86 Mbps. With our proposed scheme, a total network throughput of 56.50 Mbps is achieved, which is 142% of the targeted capacity. In other words, our protocol improves the capacity by 183%. This shows our proposed protocol can doubles the network capacity by using only two channels.

With the single-channel scheme, links at the edges of the network topology experience less interference than those in the centre. For example, node 11 of link 6 can sense the transmissions of four neighbour nodes 3, 10 and 19, whereas node 7 of link 4 can only sense the transmissions of two neighbour nodes 6 and 15. This induces an unfair capacity allocation in the network, particularly with links 4, 5 and 8 obtaining higher capacities than links 2, 6 and 11.

With our proposed scheme for channel assignments as shown in Fig. 7, simultaneous transmissions of links can be achieved by resolving these channel conflicts. Assume node 11 uses channel 2 to transmit RTS/DATA to node 12. Since nodes 3, 10 and 19 are within the VCSRange of node 11, they can receive the RTS but not the CTS of link 6. Nodes 3, 10 and 19 then assign their transmission channels to channel 2. As they are far enough from node 12, nodes 3, 10, 11 and 19 can transmit simultaneously without interfering the reception of signals at node 12. However, when using the original 802.11 protocol, once link 6 is transmitting, links 2, 5 and 10 cannot transmit because they can receive the RTS from node 11 of link 6. Any simultaneous transmissions from links 2, 5 and 10 will lead to collisions on link 6. Our proposed protocol significantly boosts the network capacity by allowing simultaneous transmissions.

5.2 Irregular topology

Fig. 8 shows another example of an irregular topology with channel assignments. Our proposed scheme obtains total network throughput at 31.49 Mbps, which is 106% of the

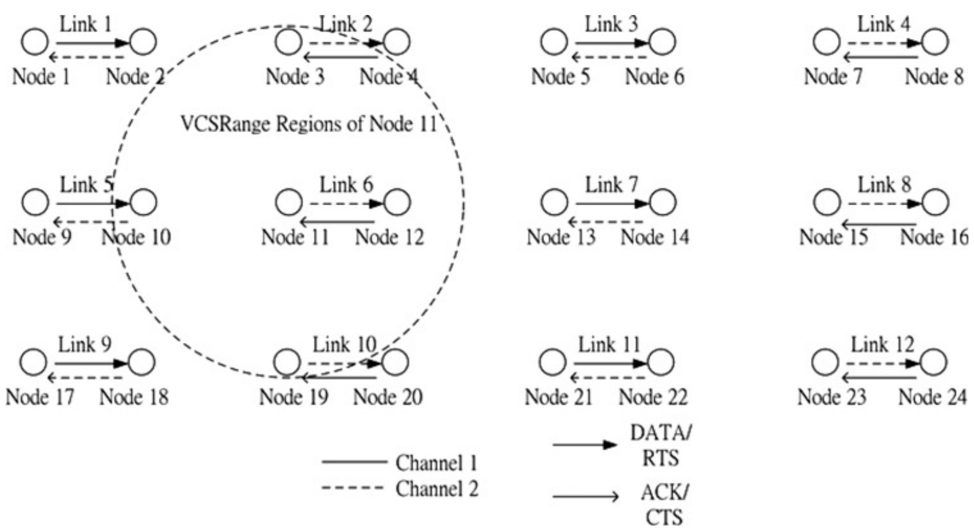

Figure 7 *Twelve links in a lattice topology using our proposed scheme*

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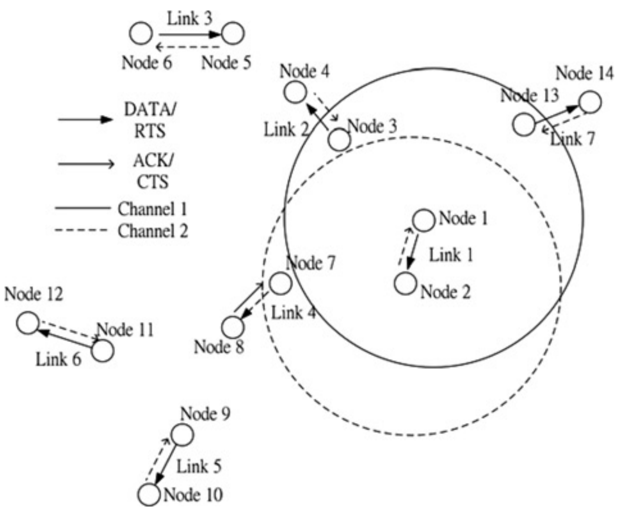

Figure 8 *Seven links in an irregular network topology using our proposed scheme*

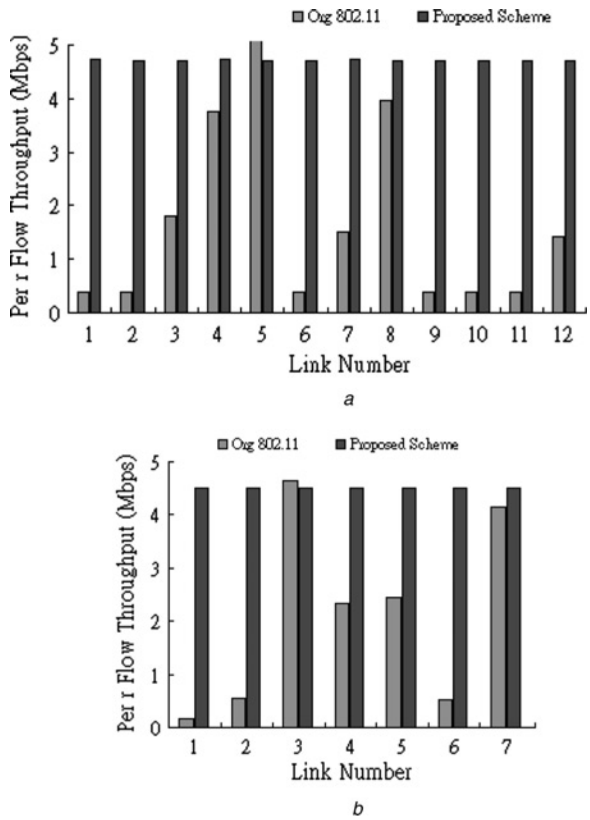

Figure 9 *Per-link throughput of the networks of*

a Fig. 7 and
b Fig. 8 with the original 802.11 protocol and our proposed MAC protocol

targeted capacity (14.81 Mbps × 2 = 29.62 Mbps). In other words, our protocol improves the capacity by 113%.

With the single-channel scheme, links 3 and 7 achieve the highest capacity since they are at the edge of the topology with less neighbour links and experience less interference. On the other hand, link 1 in the middle of the topology has to compete with links 2, 4 and 7 which results in the lowest link throughput.

With the proposed scheme, node 1 is assigned to use channel 1 for transmissions and thus nodes 3 and 13 can receive signal with channel 2. This can resolve the channel conflicts for simultaneous transmissions. Similarly, since node 2 of link 1 is receiving signal at channel 1, node 7 of link 4 then uses channel 2 for transmissions to prevent interference at node 2. In this way, our proposed protocol significantly boosts the network capacity by allowing simultaneous transmissions. In addition to the capacity enhancement, our proposed protocol also achieves a fairer bandwidth allocation in both the lattice and irregular topologies (as shown in Fig. 9*b*).

5.3 Random topologies

Fig. 10 shows the total throughputs of random topologies with n links. In each random network, n single-hop links are randomly placed inside a 3000 m × 3000 m square. In all cases, as shown in Fig. 11, the capacity improvements achieve more than 70%. The throughput improvements, however, are highly dependent on the network topologies. In the best case when $n = 70$, our protocol boosts the total network throughput by 104%.

The throughput improvements, in fact, depend on the network topologies. As mentioned in Section 1, if a

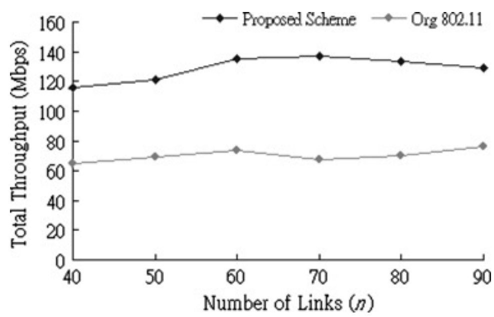

Figure 10 *Total throughputs of random networks with n single-hop links*

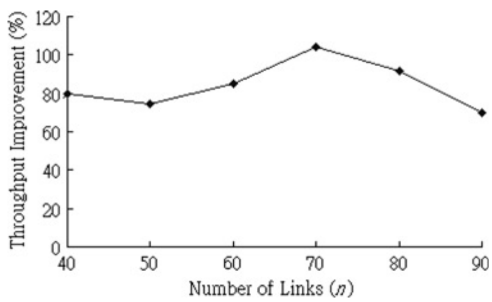

Figure 11 *Throughput improvements by using our proposed protocol in random networks with n single-hop links*

single-channel protocol can achieve capacity C, using n channels should achieve nC. However, most of the proposed protocols (e.g. [1–3]) in the literature only appear to be able to achieve less than 60% of this targeted capacity. This paper aims to reach the $2C$ capacity target by the proposed dual-channel protocol. In some cases, for example, the lattice topology, the irregular topology and the random topology with 70 links in the network as shown above, the targets are met. To achieve the $2C$ target for other topologies, a power exchange algorithm was introduced in [18], which can be implemented with the proposed protocol to further increase the achievable network throughput. We refer the interested reader to [18] for details.

6 An approach for capacity analysis

In the previous section, we have mentioned the network topologies can impact the throughput improvements achieved by the proposed protocol. This section introduces an approach for capacity analysis to demonstrate the throughput advantage that can be obtained by the proposed protocol. It includes the following steps:

1. Converting the network topology into a link interference graph; In a link interference graph, each directional link is represented by an arrow-shape directional vertex as shown in Fig. 12*b*. Therefore vertex F1 represents the DATA/RTS traffic from node T1 to node R1, whereas vertex B1 represents the reverse ACK/CTS traffic from node R1 to node T1. When the transmitter of a vertex is within the VCSRange of the receiver of another vertex, an interference edge is drawn between these two vertices. For example, node $T2$ is within the VCSRange of node $R1$, thus there is an interference edge between verteces $F2$ and $F1$. The same approach is applied to the rest of the network in Fig. 12*a* to convert the network topology into the link interference graph in Fig. 12*b*.

2. Colouring the link interference graph with two channels (colours); A colouring algorithm is applied to the link interference graph with two colours (channels) and the colouring results can then be used for channel assignments. The colouring algorithm is modified from the 'degree of saturation' (DSATUR) algorithm in [19]. First, the 'degree of saturation' is defined as the number of differently coloured neighbours of a vertex. The algorithm consists of the following steps:

a. Initialise the degrees of saturation of all vertices to 0.

b. Select the uncoloured vertex of highest degree of saturation. If more than one vertex have the same degree of saturation, choose the one with the highest number of uncoloured neighbours.

c. If the chosen vertex is connected to other vertices coloured with one of the two colours (say colour 1), colour the chosen

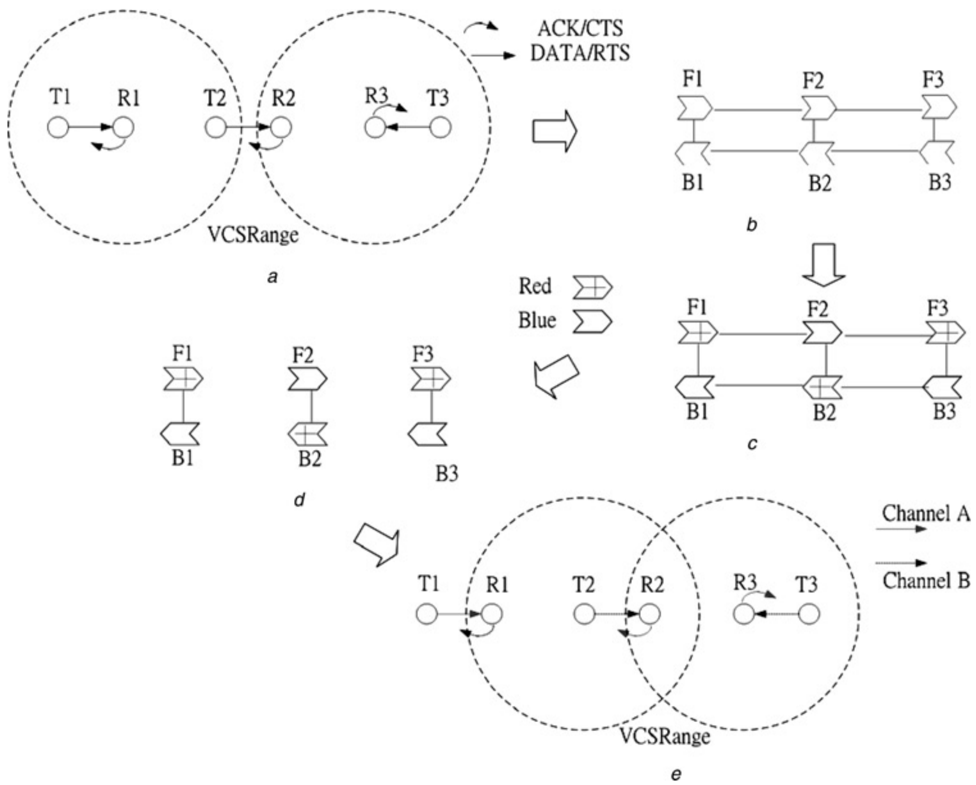

Figure 12 *Using the approach for capacity analysis to determine the achievable throughput by assigning channels with link directionalities*

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vertex with another colour (say colour 2). Otherwise, randomly pick one of the two colours for the chosen vertex.

d. Update the degrees of saturation of the uncoloured vertices connected to the chosen vertex.

Steps b–d are repeated until all vertices are coloured.

Fig. 12*c* shows the result of the colouring algorithm. Since there is an interference edge between vertices *F*2 and *F*1, simultaneous transmissions with the same channel will cause collisions. Therefore red colour (channel A) is applied to *F*1, whereas blue colour (channel B) is applied to *F*2. Vertices *F*2 and *F*1 can now transmit successfully at the same time.

3. Eliminating interference edges; After colouring the link interference graph, interference edges connecting vertices with different colours can be eliminated as shown in Fig. 12*d*. Two links without interference edges connecting between them can now transmit simultaneously with the channel assignments.

The above approach can then be used to determine the achievable throughput improvements by the proposed dual-channel protocol. In Fig. 12*a*, with a single-channel protocol, links 1 and 3 can transmit at the same time since they are far apart. However, they have to take turn with link 2. Otherwise, collisions will occur. Therefore the network capacity is 1.5. In Figs. 12*d* and *e*, with the channel assignments, links 1–23 can transmit concurrently without interfering each other. This significantly increases the network throughput to 3 which is a double of that of the single-channel scheme. As mentioned above, the throughput improvement depends on the network topology. In densely packed networks, the improvement may not be sufficient enough to achieve the $2C$ target. Therefore this approach allows us to determine if link directionality should be used in a given network. To further increase the network throughput, other enhancement schemes can be implemented with the proposed protocol (e.g. the power exchange algorithm in [18]).

7 Conclusion

This paper has presented an approach with the aim of doubling the network capacity of 802.11 *ad hoc* networks by using a link-directionality-based MAC protocol. We have shown that our proposed scheme can boost the network capacities of single channel IEEE 802.11 *ad hoc* networks by 183% in a lattice topology, 113% in an irregular topology and more than 70% in large-scale random network topologies. Splitting the transmission and reception channels of each node of links allows nodes using the same reception channel to be packed closer to each other since their transmissions are in another independent channel. We believe our proposed scheme has the potential to outperform other multi-channel protocols in terms of capacity per channel resource.

8 References

[1] ZHAI H., WANG J., FANG Y., WU D.: 'A dual-channel MAC protocol for mobile ad hoc networks'. Proc. IEEE GLOBECOM Workshop'04, Dallas, USA, 29 November–3 December 2004, pp. 27–32

[2] CHOI N., SEOK Y., CHOI Y.: 'Multi-channel MAC protocol for mobile ad hoc networks'. Proc. IEEE VTC'03-Fall, Orlando, USA, 6–9 October 2003, vol. 2, pp. 1379–1382

[3] BAIOCCHI A., TODINI A., VALLETTA A.: 'Why a multichannel protocol can boost IEEE 802.11 performance'. Proc. ACM MSWiM'04, Venice, Italy, 4–6 October 2004, pp. 143–148

[4] MO J., SO H.W., WALRAND J.: 'Comparison of multi-channel MAC protocols'. Proc. ACM MSWiM'05, Montreal, Canada, 10–13 October 2005, pp. 209–218

[5] WU S., LIN C., TSENG Y., SHEU J.: 'A new multi-channel mac protocol with on demand channel assignment for multi-hop mobile ad-hoc networks'. Proc. IEEE I-SPAN'00, Dallas, USA, 7–9 December 2000, pp. 232–237

[6] TSENG Y., WU S., LIN C., SHEU J.: 'A multi-channel MAC protocol with power control for multi-hop mobile ad-hoc networks'. Proc. IEEE Distributed Computing Systems Workshop'01, Phoenix, USA, 16–19 April 2001, pp. 419–424

[7] CHEN J., SHEU S., YANG C.: 'A new multichannel access protocol for IEEE 802.11 Ad Hoc Wireless LANs'. Proc. IEEE PIMRC'03, Beijing, China, 7–10 September 2003, vol. 3, pp. 2291–2296

[8] SO J., VAIDYA N.: 'Multi-channel MAC for ad hoc networks: handling multi-channel hidden terminals using a single transceiver'. Proc. ACM MobiHoc'04, Tokyo, Japan, 24–26 May 2004, pp. 222–233

[9] TZAMALOUKAS A., GARCIA-LUNA-ACEVES J.J.: 'A receiver-initiated collision-avoidance protocol for multi-channel networks'. Proc. IEEE InfoCom'01, Anchorage, USA, 22–26 April 2001, vol. 1, pp. 189–198

[10] NG P.C., LIEW S.C.: 'Throughput analysis of IEEE802.11 multi-hop Ad Hoc networks', *IEEE/ACM Trans. Netw.*, 2007, **15**, (2), pp. 309–322

[11] GAO Y., CHIU D., LUI J.: 'Determining the end-to-end throughput capacity in multi-hop networks: methodology and applications'. Proc. ACM SIGMetrics/Performance'06, Saint Malo, France, 26–30 June 2006, pp. 39–50

[12] 'The Network Simulator – ns2', http://www.isi.edu/nsnam/ns

[13] RAPPAPORT T.: 'Wireless communications: principles and practice' (Prentice-Hall, Englewood Cliffs, NJ, 2002)

[14] XU K., GERLA M., BAE S.: 'How effective is the IEEE 802.11 RTS/CTS handshake in Ad Hoc networks?'. Proc. IEEE GLOBECOM '02, Taipei, Taiwan, 17–21 November 2002, vol. 1, pp. 17–21

[15] JIANG L., LIEW S.C.: 'Removing hidden Nodes in IEEE 802.11 wireless networks'. Proc. IEEE VTC'05-Fall, Dallas, USA, 25–28 September 2005, vol. 2, pp. 1127–1131

[16] FULLMER C.L., GARCIA-LUNA-ACEVES J.J.: 'Complete single-channel solutions to hidden terminal problems in wireless LANs'. Proc. IEEE ICC'97, Montreal, Canada, 8–12 June 1997, vol. 2, pp. 575–579

[17] NG P.C., EDWARDS D., LIEW S.C.: 'Doubling capacity by a link-directionality-based dual channel MAC protocol for IEEE 802.11 ad-hoc networks'. IEEE GlobeCom'06, San Francisco, USA, November 2006, pp. 1–5

[18] NG P.C., EDWARDS D., LIEW S.C.: 'A link-directionality-based dual channel MAC protocol with a power exchange algorithm for IEEE 802.11 ad-hoc networks'. IEEE PIMRC'06, Helsinki, Finland, September 2006, pp. 1–5

[19] RIIHIJARVI J., PETROVA M., MAHONEN P.: 'Frequency allocation for WLANs using graph colouring techniques'. IEEE WONS'05, St. Moritz, Switzerland, January 2005, pp. 216–222

IET Commun., 2009, Vol. 3, Iss. 11, pp. 1736–1746
doi: 10.1049/iet-com.2008.0522