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An efficient MAC protocol for multi-channel mobile *ad hoc* networks based on location information

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SUMMARY

This paper considers the *channel assignment* problem in a multi-channel MANET environment. We propose a scheme called *GRID*, by which a mobile host can easily determine which channel to use based on its current location. In fact, following the GSM style, our GRID spends no communication cost to allocate channels to mobile hosts since channel assignment is purely determined by hosts' physical locations. We show that this can improve the *channel reuse* ratio. We then propose a multi-channel MAC protocol, which integrates GRID. Our protocol is characterized by the following features: (i) it follows an 'on-demand' style to access the medium and thus a mobile host will occupy a channel only when necessary, (ii) the number of channels required is independent of the network topology, and (iii) no form of clock synchronization is required. On the other hand, most existing protocols assign channels to a host statically even if it has no intention to transmit [*IEEE/ACM Trans. Networks* 1995; **3**(4):441–449; 1993; **1**(6): 668–677; *IEEE J. Selected Areas Commun.* 1999; **17**(8):1345–1352], require a number of channels which is a function of the maximum connectivity [*IEEE/ACM Trans. Networks* 1995; **3**(4):441–449; 1993; **1**(6): 668–677; *Proceedings of IEEE MILCOM'97, November 1997*; *IEEE J. Selected Areas Commun.* 1999; **17**(8):1345–1352], or necessitate a clock synchronization among all hosts in the MANET [*IEEE J. Selected Areas Commun.* 1999; **17**(8):1345–1352; *Proceedings of IEEE INFOCOM'99*, October 1999]. Through simulations, we demonstrate the advantages of our protocol. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: channel management; communication protocol; location-aware protocols; medium access control (MAC); mobile *ad hoc* network (MANET); mobile computing; wireless communication

1. INTRODUCTION

A *mobile ad hoc network* (*MANET*) is formed by a cluster of mobile hosts without the infrastructure of base stations. Two mobile hosts can communicate with each other indirectly in

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a multi-hop manner. Since no base station is required, one of its main advantages is that it can be rapidly deployed. The applications of MANETs appear in places where pre-deployment of network infrastructure is difficult or unavailable (e.g. fleets in oceans, armies in march, natural disasters, battle fields, festival field grounds, and historic sites).

A *medium access control* (MAC) protocol is responsible for resolving the communication contention and collision among hosts. Many MAC protocols have been proposed for wireless networks [1–6], which assume a common channel shared by mobile hosts. We call such protocols *single-channel MAC protocols*. The widely accepted standard IEEE 802.11 [7] follows such model. One common problem with such protocols is that the network performance will degrade quickly as the number of mobile hosts increases, due to higher contention/collision.

One approach to relieving the contention/collision problem is to utilize multiple channels. The idea of using separate control and data channels was first proposed in Reference [8]. We thus define a *multi-channel MAC protocol* as one which allows mobile hosts to dynamically access more than one channel in a MANET environment. Using multiple channels has several advantages. First, while the maximum throughput of a single-channel MAC protocol will be limited by the bandwidth of the channel, the throughput may be increased immediately if a host is allowed to utilize multiple channels. Second, as shown in References [9, 10], using multiple channels will experience less *normalized propagation delay* per channel than its single-channel counterpart, where the normalized propagation delay is defined to be the ratio of the propagation time over the packet transmission time. Therefore, this reduces the probability of collisions. Third, QoS routing may be supported [11].

Here, we use ‘channel’ upon a logical level. Physically, a channel can be a frequency band (under FDMA), or an orthogonal code (under CDMA). How to access multiple channels is thus technology-dependent. Disregard of the transmission technology, we categorize mobile hosts’ channel access capability as follows:

- *Single-transceiver*: A mobile host can only access one channel at a time. The transceiver can be simplex or duplex. Note that this is not necessarily equivalent to the single-channel model, because the transceiver is still capable of switching from one channel to another.
- *Multiple-transceiver*: Each transceiver could be simplex or duplex. A mobile host can access multiple channels simultaneously.

In this paper, we propose a new multi-channel MAC protocol for a MANET in which each mobile host is equipped with a positioning device, such as GPS. A multi-channel MAC typically needs to address two issues: *channel assignment* and *medium access*. The former is to choose proper channels to send/receive for hosts, while the latter is to resolve the contention/collision problem when using a particular channel. These two issues are sometimes addressed separately, but eventually one has to integrate them to provide a total solution. Our channel assignment, called *GRID*, is characterized by two features: (i) it exploits location information by partitioning the physical area into a number of squares called *grids*, and (ii) it does not need to transmit any message to assign channels to mobile hosts since channel assignment is purely determined by a host’s physical location. Several channel assignment schemes have been proposed earlier [10, 12–15], but none of them try to exploit the location information. Our medium access protocol is characterized by the following features: (i) it follows an ‘on-demand’ style to access the medium and thus a mobile host will occupy a channel only when necessary, (ii) the number of channels required is independent of the network topology, and (iii) no form of clock synchronization is required. On the other hand, most existing protocols assign channels to a host statically even if it

Table I. Comparison of channel assignment schemes (n is the number of hosts, and m is the maximum network degree).

Scheme	Assignment	No. channels	Info. collected	Loc.-aware	Assgn. cost	Transceivers
[16, 17, 29–31]	Static	deg.-dep.	Global	No	$O(n^k),\ k \geq 2$	1
[14]	Static	deg.-dep.	None	No	0	m
[12]	Dynamic	deg.-dep.	2-hop	No	$O(n^3)$	2
[10]	Dynamic	deg.-indep.	None	No	0	m
[15]	Dynamic	deg.-indep.	None	No	$O(n)$	1
Ours	Dynamic	deg.-indep.	None	Yes	0	2

has no intention to transmit [14, 16, 17], require a number of channels which is a function of the maximum connectivity [12, 14, 16, 17], or necessitate a clock synchronization among all hosts in the MANET [14, 15]. A centralized scheme is proposed in a recent work [18]. Similar to hexagonal cellular systems, all channel assignment in a cell is controlled and allocated by the cell leader located at this cell. Since a cellular structure is assumed, location information is needed by each station. Contrary to Reference [18], our GRID scheme is fully distributed and no traffic overhead is incurred for channel allocation. A detailed review will be given in Section 2.1. For an overview, Table I gives a comparison on existing and our protocols.

Since a MANET should operate in a physical area, it is very natural to exploit location information in such an environment. Indeed, location information has been exploited in several issues in MANET (e.g. routing [19–26], broadcasting [27], and power saving [28]), but not in channel assignment. Global System for Mobile Communications (GSM) is an instance which uses location information to exploit channel reuse, but MANET has quite different features—there is no base station, and thus channel assignment has to be done more dynamically in an in-band manner. Since the concept of 'channel reuse' is highly related to the area where a channel is used, exploiting location information, as we do in this work, on channel assignment could effectively solve this problem.

Outdoor positioning can be solved satisfactorily by global positioning systems (GPS) or differential GPS (DGPS). Both the price drop of GPS and the recent discontinuation of Selective Availability (SA) motivate us to conduct this research. However, for indoor positioning there is no satisfactory solution at this point.

The rest of this paper is organized as follows. Section 2 discusses some existing channel assignment schemes and our GRID scheme. Section 3 presents our MAC protocol by integrating the GRID assignment. Analysis and simulations are in Section 4. Conclusions will be drawn in Section 5.

2. CHANNEL ASSIGNMENT

As mentioned earlier, a multi-channel MAC needs to address two issues: channel assignment and medium access. In this section, we will consider the channel assignment problem. We will first review some existing protocols, which are all non-location-aware. Then we will present our location-aware channel assignment.

2.1. Non-location-aware schemes

In this section, we review some channel assignment schemes that do not utilize the location information of mobile hosts. These schemes can be further divided to *static* and *dynamic*. The simplest static approach is to assign channels to mobile hosts when the system is first set up. For instance, channel i can be statically assigned to those hosts with IDs such that $i = \text{ID} \bmod n$ (supposing that we number channels as $0, 1, \ldots, n-1$).

A scheme based on *Latin square* is proposed in Reference [14], which assumes a TDMA-over-FDMA technology. Each channel is divided into fixed-length frames. Each host is statically assigned to a time slot in each frame belonging to a frequency band. Since TDMA is used, clock synchronization among all hosts is necessary. Furthermore, each host has to be equipped with a number of transceivers equal to the number of frequency bands, so this approach is quite costly. Also, this scheme needs to know in advance the maximum number of mobile hosts as well as the maximum degree of the topology formed by the MANET.

The schemes in References [16, 17, 29–31] are for channel assignment in the traditional packet radio network. Partial or even complete network topology has to be collected to perform channel assignment. These approaches can basically be classified as static, although some can handle dynamic failure of base stations. Since these schemes are not designed for MANET, which is typically characterized by high host mobility, they do not fit our need.

A protocol based on dynamic channel assignment is in Reference [12]. It is assumed that the channel assigned to a host must be different from those of its two-hop neighbours. To maintain this condition, a large amount of update messages will be sent whenever a host determines any change on channel assignment in its two-hop neighbours. This is inefficient in a highly mobile system. Further, this protocol is 'degree-dependent' in the sense that it dictates a number of channels equal to an order of the square of the maximum degree of the MANET. So the protocol is inappropriate for a crowded environment.

A 'degree-independent' protocol called *multichannel-CSMA* protocol is proposed in Reference [10]. Suppose that there are n channels. The protocol imposes that each mobile host must have n receivers which concurrently listen on all n channels. Also, there is only one transmitter which will hop from channel to channel and, if necessary, will send on any detected idle channel. Again, this protocol has high hardware cost. Further, since no RTS/CTS is used, the hidden-terminal problem may easily occur. A hop-reservation MAC protocol based on very-slow frequency-hopping spread spectrum is proposed in Reference [15]. Its channel assignment employs RTS/CTS dialogue to reserve a channel. The protocol is also degree-independent but requires clock synchronization among all mobile hosts, which is difficult when the network is dispersed in a large area.

Recently, Wu *et al.* [32] propose a new protocol, called *Dynamic Channel Assignment* (*DCA*), which possesses the following characters: (i) it follows an 'on-demand' style to access the medium and thus a mobile host will occupy a channel only when necessary, (ii) the number of channels required is independent of the network topology, and (iii) no form of clock synchronization is required. DCA uses one dedicated channel for control packets, and other channels for data. The purpose of the control channel is to assign data channels to mobile hosts or schedule the use of data channels among hosts' while data channels are used to transmit data packets and acknowledgements. Reference [33] combines DCA and power control to further improve channel reuse. However, because there is no location information, DCA cannot maintain an efficient channel reuse pattern.

In Table I, we summarize and compare existing schemes with our yet-to-be-presented GRID scheme.

2.2. Our location-aware channel assignment: GRID

Next, we introduce our location-aware channel assignment scheme. The MANET environment is the same, except that each mobile host must be installed with a positioning device, such as GPS receiver. So our protocol is more appropriate for outdoor environment. As will be seen later, our approach will assign a channel to a host once the host knows its current location. As a result, in addition to the positioning cost, there is no communication cost for our channel assignment (no message will be sent for this purpose).

We will refer to our scheme as GRID. The MANET is assumed to operate in a pre-defined geographic area. The area is partitioned into 2D logical grids as illustrated in Figure 1. Each grid is a square of size $d \times d$. Grids are numbered (x, y) following the conventional xy-co-ordinate. To be location-aware, a mobile host must be able to determine its current grid co-ordinate. Thus, each mobile host must know how to map a physical location to the corresponding grid co-ordinate.

Our channel assignment works as follows. We assume that the system is given a fixed number, n, of channels. For each grid, we will assign a channel to it. When a mobile host is located at a grid, say (x, y), it will use the channel assigned to grid (x, y) for transmission. One can easily observe that if we assign the same channel to two neighbouring grids, then there will be high chance that the transmission activities on these two neighbouring grids will contend, or even interfere, with each other. Thus, we should assign the same channel to grids that are spatially separated by some distance, but will exploit the largest frequency reuse.

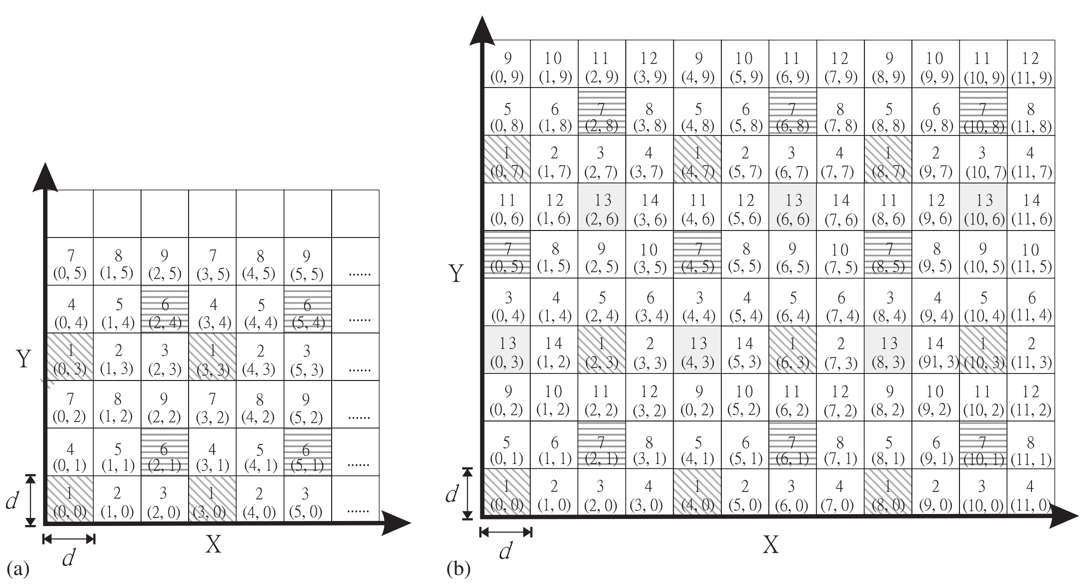


Figure 1. Assigning channels to grids in a band-by-band manner: (a) $n = 9$; and (b) $n = 14$. In each grid, the number on the top is the channel number, while those on the bottom are the grid co-ordinate. Here, we number channels from 1 to n.

The above formulation turns out to be similar to the channel arrangement in the GSM system. In the following, we propose a way to assign channels to grids. Let $m = \lceil \sqrt{n} \rceil$. We first partition the grids vertically into a number of *bands* such that each band contains m columns of grids. Then, for each band, we sequentially assign the n channels to each row of grids, in a row-by-row manner. In Figure 1, we illustrate this assignment when $n = 9$ and 14. It can readily be seen that when n is a square of some integer, each channel will be regularly separated in the area.

2.2.1. Grid size vs transmission range. Let r be the transmission range of an antenna. Suppose the value of r is fixed. In this section, we discuss an important design issue: the relationship between r and the side length of grids, d. Below, we discuss several possibilities. For simplicity, let us assume that $m = \sqrt{n}$ is an integer.

- $d \gg r$: This means many hosts will stay in a grid and thus contend with each other on one channel. When $d = \infty$, this degenerates to the case of one single channel.
- $d > 2r/(m-1)$: This is the case where the transmission activities from two hosts choosing the same channel will never interfere with each other. As illustrated in Figure 2(a), hosts A and B (both choosing the same channel) are located in the nearest possible locations, but their signals will not overlap in any location.
- $d = 2r/m$: This is the case where the transmission activities from two hosts which choose the same channel and which are each located in the centre of a grid will not interfere with each other. This is illustrated in Figure 2(b).
- $d = r/m$: This represents the minimal value of d such that two hosts (located at the grid centres) using the same channel will not hear each other. This is illustrated in Figure 2(c). By simple calculus, we can find that each receiver of these two hosts will have a probability of 0.396 being interfered by the signals from the other sender. The value is the ratio of the intersection area that is covered by both hosts A and B to the area that is covered by either host A or host B.
- $d \approx 0$: This means that the grid size is infinitely small. This degenerates to the case where a mobile host will randomly choose a channel to transmit its packets, and thus little channel reuse can be exploited.

The above analysis has indicated some tradeoffs. This concept will be captured by the ratio r/d. If the ratio is too large, then the chance of co-channel interference will be high. On the other hand, if the ratio is too small, although co-channel interference can be reduced, the channel reuse will be reduced too since a channel will be unavailable in many locations. Thus, we need to

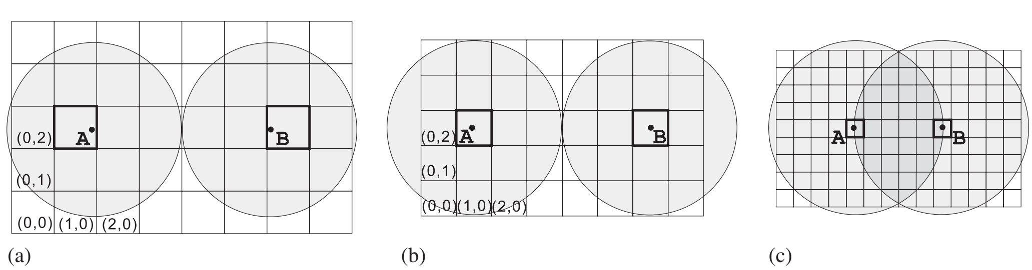


Figure 2. The effect of r/d ratio on channel co-interference when $n = 25$.

carefully adjust the r/d ratio for the best network performance. This will be further investigated through simulations in Section 4.2.

2.2.2. Some experiments on the r/d ratio. At this point, it deserves to be predicted, under ideal situations, how much benefit our location-aware channel assignment can offer over a non-location-aware one. We developed a simple simulation without concerning the details of medium access, such as collision, timing, etc. (this will be explored in Section 4). We simulated an area of size 1000×1000. On this area, we randomly generated a sender A and then randomly generated a receiver B in the circle of radius $r = 100$ centred at A. A transmitted using a channel selected by two methods: (i) a static one based on host ID (referred to as SCA, static channel assignment), and (ii) our GRID approach. We then repeated this process to generate more sender–receiver pairs. However, for each pair generated, we tested whether this transmission will interfere any earlier ongoing pairs. If so, the current pair will be deleted; otherwise, it will be granted.

Through this ideal experiment, we intend to observe how many more sender–receiver pairs can be generated in the physical area by GRID than SCA. This will verify whether GRID has a better channel reuse. Another important issue we would like to explore here is: what is best ratio r/d to maximize channel reuse?

Figure 3 shows our first experimental results. The x-axis is the number of sender–receiver pairs generated. The y-axis shows the number of pairs that fail and thus are deleted. For our GRID, we tested different r/d ratios. Figure 3(a) uses a total number of $n = 36$ channels, and Figure 3(b) uses $n = 81$. Indeed, some r/d ratios are better than SCA, while some are worse. In Figure 3(a), we see that the r/d ratios 2.5, 3.0, and 3.5 will outperform SCA, while in Figure 3(b), the r/d ratios 4.0, 4.5, and 5.0 will outperform SCA.

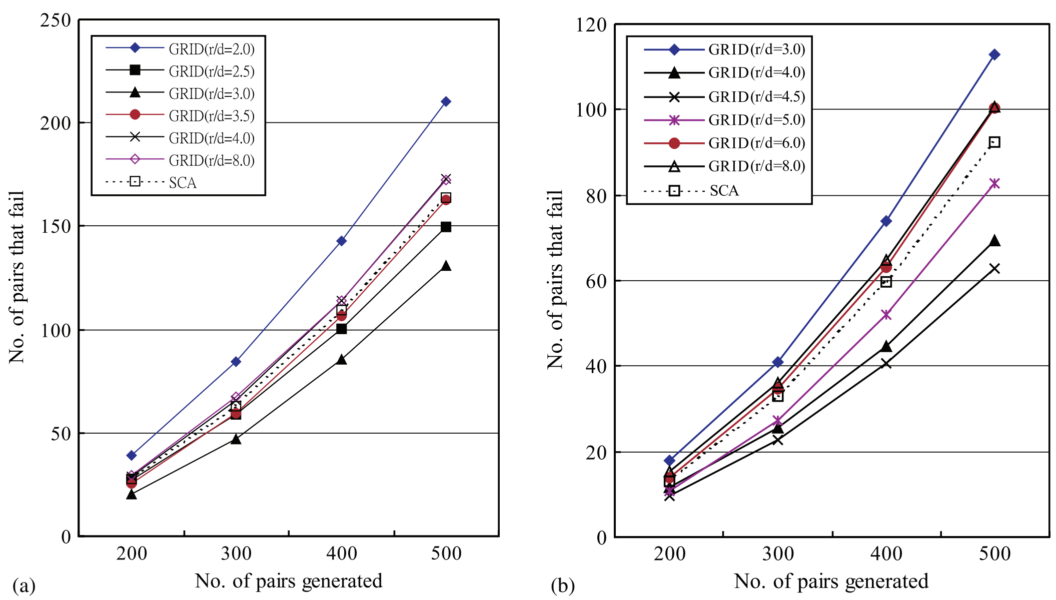
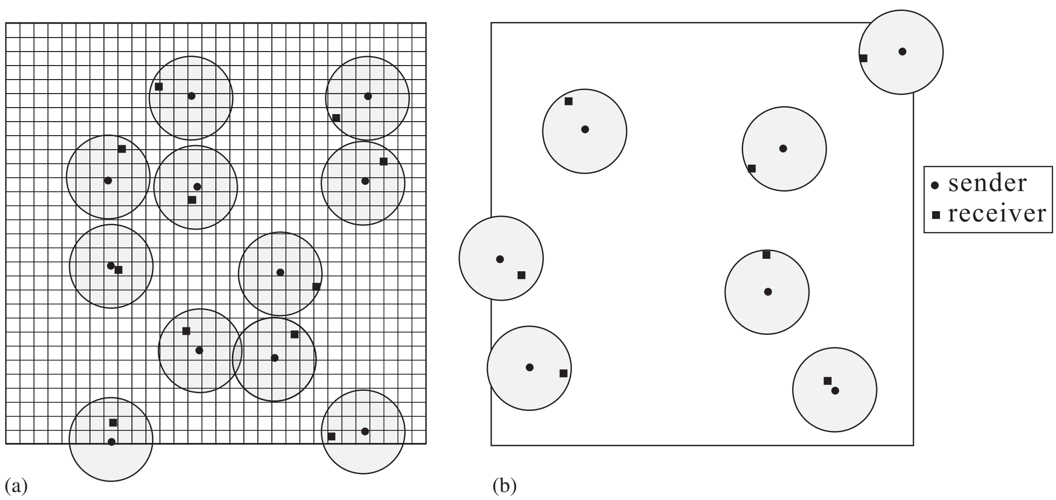


Figure 3. Tests of blocked sender-receiver pairs at different r/d ratios: (a) $n = 36$; and (b) $n = 81$.

We conclude from the above experiments that when $r/d \approx \sqrt{n}/2$, our GRID will perform well. The reason is as follows. Let us consider any channel. At this ratio, it is more likely that we can place most circles (which represent transmission activities of this channel) in a physical area, while incurring the least overlapping among circles (which represents co-channel interference). This is how our GRID can offer better channel reuse. Figure 4 shows a snapshot in our experiment when $n = 36$ and $r/d = 3.0$ on the use of channel 1. Clearly, the placement of circles by GRID is denser and more regular than that of SCA.

In Figure 5, we further vary the value of n to observe the trend. In this figure, we have picked the best r/d ratio for each n. The number of sender–receiver pairs generated is 2000. As can be seen, the best ratios are all very close to $\sqrt{n}/2$, as we have predicted. Also, with more channels, there are less pairs being blocked by both GRID and SCA. But the gain of GRID over SCA will enlarge as a larger n is used.



(a) (b)

Figure 4. A snapshot of our experiment in Figure 3 when $n = 36$ and $r/d = 3.0$: (a) GRID; and (b) SCA. The snapshots are taken on a 1000 × 1000 area, and each circle means a sender–receiver pair.

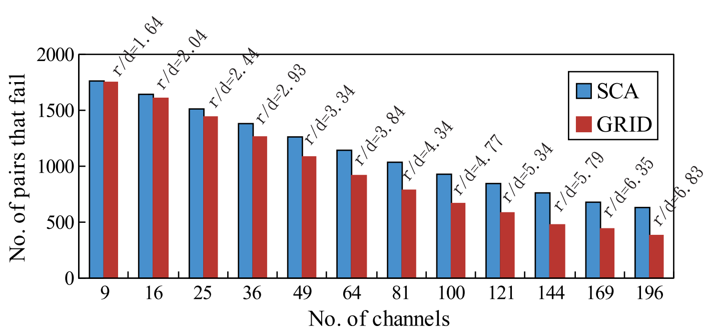


Figure 5. Tests of blocked sender–receiver pairs at various n's.

3. THE MAC PROTOCOL

This section presents the medium access part of our protocol by integrating the channel assignment part in the previous section. The channel model is as follows. The overall bandwidth is divided into one control channel and n data channels $D_1, D_2, \ldots, D_n$. Each channel, including control and data ones, is of the same bandwidth. The purpose of data channels is to transmit data packets and acknowledgements. Control channel serves in many important management purposes: (i) to synchronize the use of data channels among hosts, (ii) to broadcast beacons periodically, and (iii) to search for routes. Note that beacons can help mobile hosts to discover which hosts are currently neighbours. Hosts can always communicate with others through the control channel, but they can only communicate with each other through a data channel if they switch to the same one. Route discovery and routing functions are beyond the scope of this paper and will not be elaborated, but can be supported by the control channel.

In our protocol, the channel assignment should be done in advance. We think that the organization, e.g. city governments or corporations, should take the responsibility of channel allocation if it wants to use GRID in its district such that the best performance can be got. It is something like that FCC regulates the use of radio spectrum to satisfy the communications needs without interference.

Each mobile host is equipped with two half-duplex transceivers:

- *Control transceiver*: This transceiver will operate on the control channel to exchange control packets with other mobile hosts and to obtain rights to access data channels.
- *Data transceiver*: This transceiver will dynamically operate on one of the data channels, according to our channel assignment, to transmit data packets and acknowledgements.

Each mobile host X maintains the following data structure.

- CUL[ ]: This is called the *channel usage list*. Each list entry CUL[i] keeps records of how and when a host neighbouring to X uses a channel. CUL[i] has three fields:
  - — CUL[i].*host*: a neighbour host of X.
  - — CUL[i].*ch*: a data channel used by CUL[i].*host*.
  - — CUL[i].*rel_time*: when channel CUL[i].*ch* will be released by CUL[i].*host*.

Note that this CUL is distributedly maintained by each mobile host and thus may not contain the precise information.

The main idea of our protocol is as follows. For a mobile host A to communicate with host B, A will send a RTS (request-to-send) to B. This RTS will also carry the channel number that A intends to use in its subsequent transmission. Then B will match this request with its in CUL[ ] and, if granted, reply a CTS (clear-to-send) to A. All these will happen on the control channel. Similar to the IEEE 802.11 [7], the purpose of the RTS/CTS dialogue is to warn the neighbourhood of A and B not to interfere their subsequent transmission, except that a host is still allowed to use the channels different from that indicated in the RTS and CTS packets. Finally, transmission of a data packet will occur on the data channel.

The complete protocol is shown below. Table II lists the variables/constants used in our presentation.

1. On a mobile host A having a data packet to send to host B, it first checks whether the following two conditions are true:

Table II. Meanings of variables and constants used in our protocol.

T_{SIFS}	Length of short inter-frame spacing
T_{DIFS}	Length of distributed inter-frame spacing
T_{RTS}	Time to transmit a RTS
T_{CTS}	Time to transmit a CTS
T_{curr}	The current clock of a mobile host
T_{ACK}	Time to transmit an ACK
$\mathrm{NAV}_{\mathrm{RTS}}$	Network allocation vector on receiving a RTS
$\mathrm{NAV}_{\mathrm{CTS}}$	Network allocation vector on receiving a CTS
L_{d}	Length of a data packet
L_{c}	Length of a control packet (RTS/CTS)
B_{d}	Bandwidth of a data channel
B_{c}	Bandwidth of a control channel
τ	Maximal propagation delay

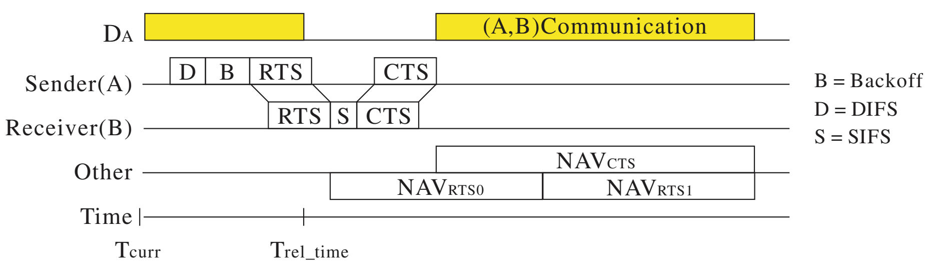


Figure 6. Timing to determine whether a channel will be free after a successful exchange of RTS and CTS packets.

(a) B is not equal to any CUL[i].*host* such that

$$\mathrm{CUL}[i].\mathrm{rel\_time} > T_{\mathrm{curr}} + (T_{\mathrm{DIFS}} + T_{\mathrm{RTS}} + T_{\mathrm{SIFS}} + T_{\mathrm{CTS}})$$

If so, this means B will still be busy (in using data channel CUL[i].*ch*) after a successful exchange of RTS and CTS packets.

(b) Suppose A determines that its current data channel is D_A. Then for each $i = 1..n$

$$(D_A = \mathrm{CUL}[i].\mathrm{ch}) \Rightarrow (\mathrm{CUL}[i].\mathrm{rel\_time} \leqslant T_{\mathrm{curr}} + (T_{\mathrm{DIFS}} + T_{\mathrm{RTS}} + T_{\mathrm{SIFS}} + T_{\mathrm{CTS}}))$$

If so, this means A's data channel is either not currently being used by any of its neighbours, or currently being occupied by some neighbour(s) but will be released after a successful exchange of RTS and CTS packets. (Figure 6 shows how the above timing is calculated.)

If the above two conditions are true, proceed to step 2; otherwise, A must wait at step 1 until these conditions become true.

2. Then A can send a RTS(D_A, L_{d}) to B, where L_{d} is the length of the yet-to-be-sent data packet. Also, following the IEEE 802.11 style, A can send this RTS only if there is no carrier on the control channel in a T_{DIFS} plus a random backoff time period. Otherwise, it has to go back to step 1.

3. On a host B receiving the RTS(D_A, L_d) from A, it has to check whether the following condition is true for each $i = 1..n$:

$$(D_A = \text{CUL}[i].\text{ch}) \Rightarrow (\text{CUL}[i].\text{rel\_time} \leqslant T_{\text{curr}} + (T_{\text{SIFS}} + T_{\text{CTS}}))$$

If so, D_A is either not currently being used by any of its neighbours, or currently being used by some neighbour(s) but will be released after a successful transmission of a CTS packet. Then B replies a CTS($D_A, \text{NAV}_{\text{CTS}}$) to A, where

$$\text{NAV}_{\text{CTS}} = L_d/B_d + T_{\text{ACK}} + 2\tau$$

Then B tunes its data transceiver to D_A. Otherwise, B replies a CTS(T_{est}) to A, where T_{est} is the estimated time that B's data channel D_A will change minus the time for an exchange of a CTS packet

$$T_{\text{est}} = \max\{\forall i \ni \text{CUL}[i].\text{ch} = D_A, \text{CUL}[i].\text{rel\_time}\} - T_{\text{curr}} - T_{\text{SIFS}} - T_{\text{CTS}}$$

4. On an irrelevant host $C \neq B$ receiving A's RTS(D_A, L_d), it has to inhibit itself from using the control channel for a period

$$\text{NAV}_{\text{RTS0}} = T_{\text{SIFS}} + T_{\text{CTS}} + \tau$$

This is to avoid C from interrupting the RTS → CTS dialogue between A and B. Then, C senses channel D_A for a period of τ to determine whether this communication is successful or not. If so, it appends an entry CUL[k] to its CUL such that

$$\text{CUL}[k].\text{host} = A$$

$$\text{CUL}[k].\text{ch} = D_A$$

$$\text{CUL}[k].\text{rel\_time} = T_{\text{curr}} + \text{NAV}_{\text{RTS1}}$$

where

$$\text{NAV}_{\text{RTS1}} = T_{\text{curr}} + L_d/B_d + T_{\text{ACK}} + \tau$$

5. Host A, after sending its RTS, will wait for B's CTS with a timeout period of $T_{\text{SIFS}} + T_{\text{CTS}} + 2\tau$. If no CTS is received, A will retry until the maximum number of retries is reached.
6. On host A receiving B's CTS($D_A, \text{NAV}_{\text{CTS}}$), it performs the following steps:
   (a) Append an entry CUL[k] to its CUL such that

$$\text{CUL}[k].\text{host} = B$$

$$\text{CUL}[k].\text{ch} = D_A$$

$$\text{CUL}[k].\text{rel\_time} = T_{\text{curr}} + \text{NAV}_{\text{CTS}}$$

   (b) Send its DATA packet to B on the data channel D_A.
   On the other hand, if A receives B's CTS(T_{est}), it has to wait for a time period T_{est} and go back to step 1.
7. On an irrelevant host $C \neq A$ receiving B's CTS($D_A, \text{NAV}_{\text{CTS}}$), C updates its CUL. This is the same as step 6(a) except that

$$\text{CUL}[k].\text{rel\_time} = T_{\text{curr}} + \text{NAV}_{\text{CTS}} + \tau$$

On the other hand, if C receives B's CTS(T_{est}), it ignores this packet.

8. On B completely receiving A's data packet, B replies an ACK on D_A.

To summarize, our protocol relies on the control channel to negotiate the transmissions among hosts using the same data channel. Also, note that although our protocol will send timing information in packets, these are only relative time intervals. No absolute time is sent. So there is no need of clock synchronization in our protocol.

4. ANALYSIS AND SIMULATION RESULTS

4.1. Arrangement of control and data channels

One concern in our protocol is: Can the control channel efficiently distribute the communication jobs to data channels? For example, in Figure 7, we show an example with 5 channels, one for control and four for data. For simplicity, let us assume that the lengths of all control packets (RTS, and CTS) are L_c, and lengths of all data packets $L_d = 6L_c$. Then Figure 7 shows a scenario that the control channel can only utilize three data channels D_1, D_2, and D_3. Channel D_4 may never be used because the control channel can serve at most three data channels. Although L_d is typically larger than L_c by an order of at least tens or hundreds, it still deserves to analyse this issue to understand the limitation.

The above example shows that how to arrange the control and data channels is a critical issue. In the following, we consider two bandwidth models.

- *Fixed-channel-bandwidth*: Each channel (data and control) has a fixed bandwidth. Thus, with more channels, the network can potentially use more bandwidth.
- *Fixed-total-bandwidth*: The total bandwidth offered to the network is fixed. Thus, with more channels, each channel will have less bandwidth.

We comment that the first model may reflect the situation in CDMA, where each code has the same bandwidth, and we may utilize multiple codes to increase the actual bandwidth of the network. On the other hand, the second model may reflect the situation in FDMA, where the total bandwidth is fixed, and our job is to determine an appropriate number of channels to best utilize the given bandwidth.

We will show how to arrange the control and data channels under these models so as to well utilize a given bandwidth. Let us consider the fixed-channel-bandwidth model first. Apparently, since the control channel can arrange a data packet by sending 2 control packets of total length $2L_c$, the maximum number of data channels should be limited by

$$n \leqslant \frac{L_d}{2 \times L_c} \tag{1}$$

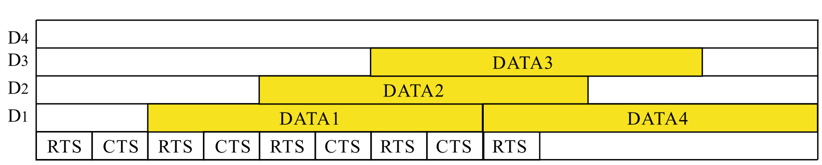


Figure 7. An example that the control channel is fully loaded and the data channel D_4 is not utilized.

Also, consider the utilization U of the total given bandwidth. Since the control channel is actually not used for transmitting data packets, we have

$$U \leqslant \frac{n}{n+1} \tag{2}$$

From Equations (1) and (2), we derive that

$$\frac{U}{1-U} \leqslant n \leqslant \frac{L_d}{2 \times L_c} \Rightarrow U \leqslant \frac{L_d}{2 \times L_c + L_d} \tag{3}$$

The above inequality implies that the maximum utilization is a function of the lengths of control and data packets. Thus, decreasing the length of control packets or increasing the length of data packets will improve the utilization. Since the maximum utilization is only dependent on L_d and L_c, it will be unwise to unlimitedly increase the number of data channels.

Next, we consider the fixed-total-bandwidth model. Suppose that we are given a fixed bandwidth. The problem is: how to assign the bandwidth to the control and data channels to achieve the best utilization. Also, how many data channels (n) will be most efficient? Let the bandwidth of the control channel be B_c, and that of each data channel B_d. Again, the number of data channels should be limited by the assignment capability of the control channel:

$$n \leqslant \frac{L_d/B_d}{2 \times L_c/B_c} \tag{4}$$

Similarly, the utilization U must satisfy

$$U \leqslant \frac{n \times B_d}{n \times B_d + B_c} \tag{5}$$

Combining Equations (4) and (5) gives

$$\frac{UB_c}{B_d - UB_d} \leqslant n \leqslant \frac{L_d B_c}{2 \times L_c B_d} \Rightarrow U \leqslant \frac{L_d}{2 \times L_c + L_d} \tag{6}$$

Interestingly, this gives the same conclusion as that in the fixed-channel-bandwidth model. The bandwidths B_c and B_d have disappeared in the above inequality, and the maximum utilization is still only a function of the lengths of control and data packets. Thus, decreasing the length of control packets or increasing the length of data packets may improve the utilization. To understand how to arrange the bandwidth, we replace the maximum utilization into Equation (5), which gives

$$\frac{L_d}{2 \times L_c + L_d} = \frac{n \times B_d}{n \times B_d + B_c} \Rightarrow \frac{B_c}{nB_d} = \frac{2L_c}{L_d} \tag{7}$$

Thus, to achieve the best utilization, the ratio of the control bandwidth to the data bandwidth should be $2L_c/L_d$. Furthermore, since the maximum utilization is independent of the value of n, theoretically once the above ratio ($2L_c/L_d$) is used, it does not matter how many data channels that we divide the data bandwidth into. (Thus, one can even adjust the value of n according to the number of mobile hosts or host density.)

Finally, we comment on several minor things in the above analysis. First, if the control packets are of different lengths, the $2L_c$ can simply be replaced by the total length of RTS, and CTS. Second, the L_d has included the length of ACK packets. So the real data packet length should be L_d minus the length of an ACK packet. Last, we did not consider protocol factors (such as propagation delay, SIFS, DIFS, collisions of control and data packets, backoffs, etc.) in the analysis and hence the bandwidth considered above is not 'effective' bandwidth. In reality, these factors will certainly affect the performance. In the next section, we will explore this through simulations.

4.2. *Experimental results*

We have implemented a simulator to evaluate the performance of our GRID protocol. We mainly used the SCA protocol as a reference for comparison. SCA only differs from our GRID in its channel assignment strategy. Specifically, in SCA, the overall bandwidth is still divided into one control channel and n data channels. But each host is statically assigned to only one data channel. To use its data channel, a host must go through a RTS/CTS exchange with its intending receiver before using the data channel. Since both SCA and GRID use the same channel model and medium access approach, we believe that the experiment can give a clear indication how much more channel reuse that GRID can offer. Also, whenever appropriate, we will include the performance of IEEE 802.11, which is based on a single-channel model, to demonstrate the benefit of using multiple channels.

The parameters used in our experiments are: physical area $= 1000 \times 1000$, transmission range $r = 200$, hosts $= 400$, DIFS $= 50$ μs, SIFS $= 10$ μs, backoff slot time $= 20$ μs, control packet length $L_c = 100$ bits. A data packet length L_d is a multiple of L_c. Packets arrived at each mobile host in an Poisson distribution with arrival rate λ packet/s. For each packet arrived at a host, we randomly chose a host at the former's neighbourhood as its receiver. Both of the earlier bandwidth models are used. If the fixed-channel-bandwidth model is assumed, each channel's bandwidth is 1 Mbps/s. If the fixed-total-bandwidth model is assumed, the total bandwidth is 1 Mbps/s. In the following, we make observations from four aspects.

(A) *Effect of the* r/d *ratios*: In this experiment, we change the r/d ratio to observe the effect. We use $n = 16$ data channels and $L_d/L_c = 200$. Figure 8 shows the network throughput under different loads under the fixed-channel-bandwidth model. We can see that both SCA and GRID have similar throughput curves. When $r/d = 0.5, 1.0$, and 1.5, our GRID protocol is worse than the SCA protocol. When $r/d \geqslant 2.0$, our GRID will outperform SCA. At $r/d = 3.5$, GRID will deliver the highest throughput, which is about 25% more than the highest throughput of SCA.

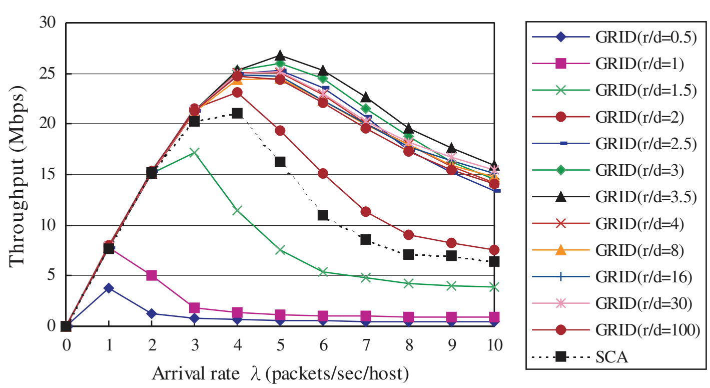


Figure 8. Arrival rate vs throughput under the fixed-channel-bandwidth model at different r/d ratios with $n = 16$.

After $r/d > 3.5$, GRID will saturate and degrade slightly, but still outperform SCA. It is worth to mentioning that according to our earlier ideal analysis in Section 2, the best performance of GRID will appear when $r/d = \sqrt{n}/2 = 2$. This ratio is somewhat smaller than the ratio 3.5 that we obtain here. We believe that this is because in this experiment we have taken timing factors (such as different packet arrival time and different backoff intervals) into consideration, while in Section 2 we have disregarded this factor. Thus, different sender–receiver pairs may be time-differentiated, and thus more pairs may coexist. In fact, this is a favourable result to GRID because a higher r/d ratio means more signal overlapping, and thus higher channel reuse.

Figure 9 shows the similar experiment under the fixed-total-bandwidth model. Again, the best r/d ratio appears at around 2.5–4. The trend is similar to that of the fixed-channel bandwidth model. Also, as a reference point, this figure contains the performance of IEEE 802.11.

(B) *Effect of the number of channels*: In this experiment, we still use $L_d/L_c = 200$, but vary the number of channels n, to observe its effect. Figure 10 shows the result under the fixed-channel-bandwidth model. Note that in this figure we have picked the best r/d ratio (through experiments) for each given n for our GRID protocol. We see that both SCA's and GRID's throughputs will increase as more data channels are used. This is quite reasonable because under the fixed-channel-bandwidth model, a larger n means more total bandwidth being provided. As n enlarges, the gap between GRID and SCA will increase slightly.

Figure 11 shows the same simulation under fixed-total-bandwidth model. The trend is similar. One important observation is that the best performance for both SCA and GRID will appear at around $n = 4$ data channels. With more channels, the throughput will degrade significantly. Also, as comparing GRID and SCA, we see that when n is too large (e.g. $n = 49$), The gap between GRID and SCA will decrease significantly. This may due to two reasons: either the control channel is overloaded, or the control channel has not been fully loaded but there are too few mobile hosts to fully utilize these data channels.

(C) *Effect of the L_d/L_c ratios*: As discussed earlier, the performance of GRID will be limited by the use of the control channel. One way to increase performance is to increase the data packet length in order to reduce the load on the control channel. To understand this issue, observe

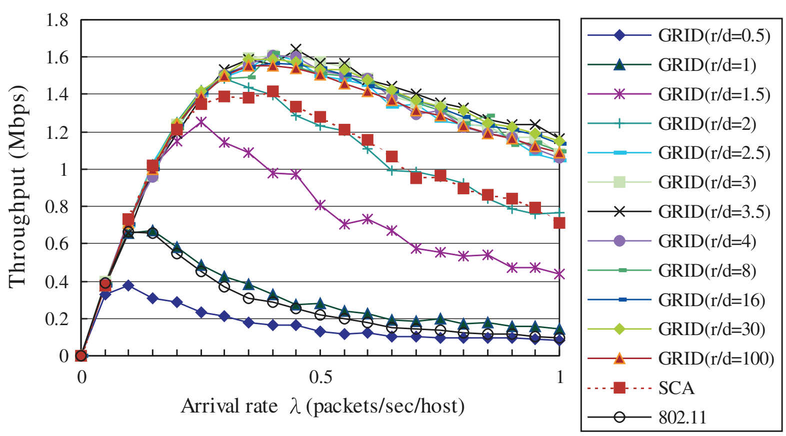


Figure 9. Arrival rate vs throughput under the fixed-total-bandwidth model at different r/d ratios with $n = 16$.

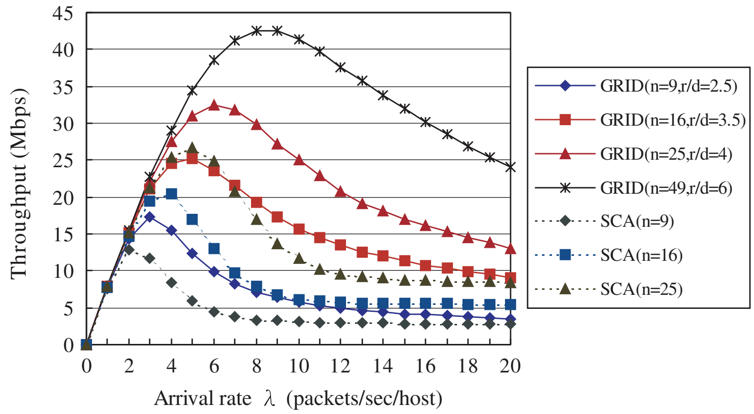


Figure 10. Arrival rate vs throughput under the fixed-channel-bandwidth model with different numbers of data channels.

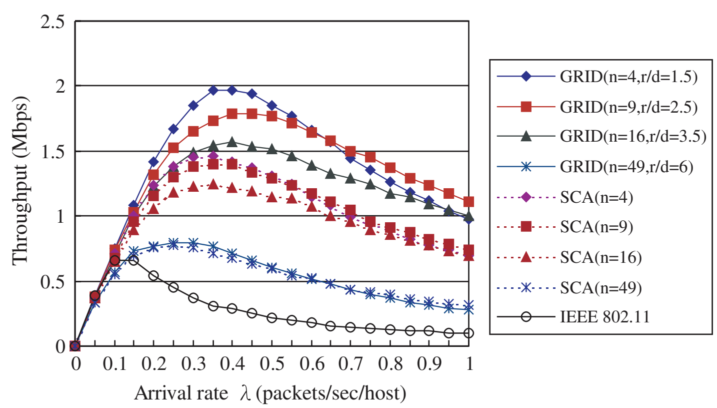


Figure 11. Arrival rate vs throughput under the fixed-total-bandwidth model with different numbers of data channels.

Figure 12(a), which assumes $L_d/L_c = 50$ and the number of hosts = 1600 under the fixed-channel-bandwidth model. Comparing the curves in this figure, we see that there is a large performance improvement between using $n = 9$ channels and $n = 25$ channels. However, the improvement reduces significantly from using $n = 25$ to using $n = 49$ channels. When using $n = 100$ channels, the gain relative to using $n = 49$ is very limited (note that under the fixed-channel-bandwidth model, this means much bandwidth being wasted). To resolve this problem, in Figure 12(b), we increase L_d/L_c to 200. Now the improvements all enlarged. This has justified our argument. As a result, given an n, one has to wisely adjust the ratio L_d/L_c so as to get the best throughput.

(D) *Effect of transmission error rates*: In the previous experiment, we have made a strong assumption: the transmission is error-free. To take this into consideration, we further assume a

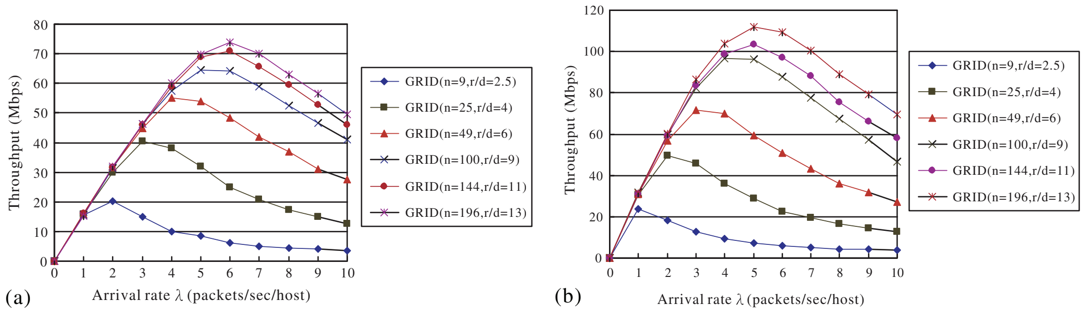


Figure 12. Arrival rate vs throughput under the fixed-channel-bandwidth model at different numbers of data channels: (a) $L_d/L_c = 50$; and (b) $L_d/L_c = 200$.

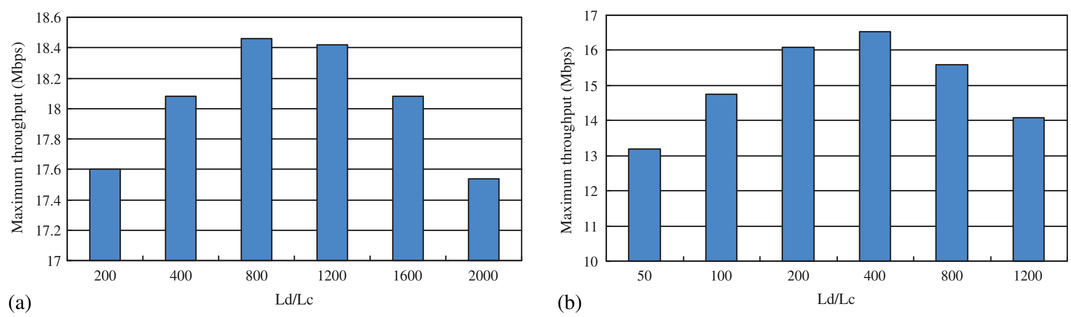


Figure 13. Ratio L_d/L_c vs maximum throughput under the fixed-channel-bandwidth model with $n = 9$: (a) bit error rate $= 10^{-6}$; and (b) bit error rate $= 5 \times 10^{-6}$.

bit error rate during transmission. Under the fixed-channel-bandwidth model with $n = 9$ channels, Figures 13(a) and (b) show our simulation results under the transmission bit error rates of 10^{-6} and 5×10^{-6}, respectively. Under an error rate of 10^{-6}, $L_d/L_c = 800$ has the best maximum throughput. With a larger error rate of 5×10^{-6}, the best maximum throughput will appear at the smaller ratio $L_d/L_c = 400$.

5. CONCLUSIONS

We have developed a new MAC protocol for a multi-channel MANET. Our channel assignment is characterized by location awareness capability and it incurs no communication cost to conduct the assignment. This is a significant breakthrough compared to existing protocols which require clock synchronization and/or which dictate a number of channels which is a function of the network degree. Our simulation results have also indicated that it is worthwhile to consider using multiple channels under both the fixed-channel-bandwidth model and the fixed-total-bandwidth model.

In this paper, we focus on the scenario where hosts are randomly deployed. In such an environment, GRID is a simple yet efficient solution. For larger areas where users have geographical locality, the GRID-B proposed in Reference [34] tries to explore channel borrowing to make an efficient use of channels. However, due to its channel relocation behaviour, GRID-B involves higher complexity. The purpose of this paper is to develop a light-weight MAC protocol that is suitable for an *ad hoc* environment.

We believe that there are many open research problems from this work. In our simulations, we have used a number of data channels (n) which is a square of some integer. Other values of n deserve investigation. In practice, the best r/d ratio may change due to many factors, such as system load, which also deserves studies. While GPS is widely available, indoor positioning is still an open issue. Since our work relies on physical locations to assign channels, for indoor environment pre-assignment of channels to each location may be necessary.

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