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PAPER

Dynamic Channel Assignment and Reassignment for Exploiting Channel Reuse Opportunities in Ad Hoc Wireless Networks

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SUMMARY In Ad Hoc networks, communication between a pair of hosts uses channel resources, such that the channel cannot be used by the neighboring hosts. A channel used by one pair of hosts can be reused by another pair of hosts only if their communication ranges do not overlap. Channels are limited resources, accounting for why exploiting channel reuse opportunities and enhancing the channel utilization is essential to increasing system capacity. However, exploiting channel reuse opportunities may cause a co-channel interference problem. Two pairs of communicating hosts that use the same channel may gradually move toward to each other. A channel reassignment operation must be applied to these hosts to maintain their communication. This investigation presents a channel assignment protocol that enables the channel resources to be highly utilized. Following this protocol, a channel reassignment protocol is also proposed to protect the communicating hosts from co-channel interference caused by mobility. The proposed reassignment protocol efficiently reassigns a new available channel to a pair of hosts that suffers from co-channel interference. The performance of the proposed protocols is also examined. Experimental results reveal that the proposed protocols enable more hosts to communicate simultaneously and prevent their communication from failing.

key words: *channel assignment, channel reassignment, co-channel interference, ad hoc networks*

1. Introduction

Technological advances have ushered in the demand for high quality communications and consumer expectations to be able to communicate anywhere at any time. The Personal Communication System provides one-hop communication in which the base station participates importantly in communication among mobile hosts. However, in some regions, a base station may not be established due to high cost, low utilization, or poor performance. In situations such as war or natural disasters, a base station is hard to establish but is easily destroyed. Without supporting base station or access point, a MANET (Mobile Ad Hoc wireless Network) includes low-cost mobile hosts with high mobility, and enables mobile users to communicate with each other.

Communication between a pair of hosts uses channel resources, causing the channel unable to use by neighboring host. A channel used by one pair of hosts, say $\{a, b\}$, can be reused by another pair of hosts, say $\{c, d\}$, only if their communication ranges do not overlap. Channels are limited resources, so exploiting channel reuse opportunities and enhancing the channel utilization is the key technique for increasing the system's capacity. However, exploiting channel reuse opportunities may cause the problem of co-channel interference. Consider a situation in which host a gradually moves toward host c. As hosts a falls into the communication range of host c, their communication signals interfere with each other. At this moment, if the host pair $\{a, b\}$ can rapidly switch to a new communication channel, then the communication of these two pairs can be maintained without breakage.

In [1], [8], [12]–[14], channel assignment protocols were presented to provide channel for new calls inside the congested base stations. The protocols improve channel utilization by borrowing an available channel from a neighboring station. Previous studies [5], [7], [13] have used *Ad Hoc* stations to direct the new call from the congested base station to the neighboring base station. These studies utilize the set of available channels that are centrally controlled by a cellular-based system. In [10], [16]–[18], a code assignment algorithm is presented to schedule a set of codes for a number of stations in a packet radio network. The assignment of the code guarantees that the hidden terminal problem [2], [4], [6] can be prevented while the number of assigned codes is minimal. In *Ad Hoc* networks, a set of single-channel MAC protocols [20]–[25] is proposed to create a contention-free communication link. Although the RTS/CTS reservation mechanism [29] and IEEE 802.11 protocols [15], [30] provide collision-avoidance, most functions are defined in a single code environment. In the case of a single code, the system performance declines as the number of communicating hosts increases. Multiple channel access protocols [15], [26],

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[27] are proposed to extend the flexibility of assigning a single code and reduce the occurrence of collision and contention. Providing multiple channel access can increase the bandwidth resources, reduce the normalized propagation delay [27], [28], and thus guarantee that the QoS requirement is met. However, a further investigation of channel assignment and reassignment problems is required since very little multi-channel research [27]–[29] addresses mobility.

Exploiting channel reuse opportunities improves the network capacity and utilizes better channel resources, but raises the co-channel interference problem. Previous studies [3], [9], [15] use adaptive power-control mechanisms to avoid the co-channel interference. Reducing the power can reduce the coverage transmission range and thus eliminate the co-channel interference phenomenon, but create the communication breakage problem since the received signal is relatively weak. As two pairs of communicating hosts gradually move toward each other, co-channel interference increases. Power control techniques help a little to mitigate co-channel interference if the received signal is weaker than the signal-to-noise radio (SNR) value. The reassignment of a new channel to an interfered host greatly helps to prevent communicative hosts from being affected by co-channel interference. However, reassigning a new channel, say *ch*, to the interfered hosts pair, say $\{a,\ b\}$, may again introduce new co-channel interference between $\{a,\ b\}$ and its neighboring pair which is currently using the new channel *ch* for communication. Therefore, in the worst case, improper channel reassignment causes co-channel interference to propagate over the entire *Ad Hoc* networks.

This study investigates the channel assignment and reassignment problems in *Ad Hoc* networks. A channel assignment protocol is presented to exploit channel reuse opportunities. The number of communicating pairs of mobile devices is guaranteed to be maximized. A channel reassignment protocol is also proposed to eliminate the co-channel interference, when two pairs of communicating hosts gradually move close to each other. The proposed channel reassignment protocol dynamically reassigns a new channel to one pair of hosts that are suffering from the co-channel interference problem. The reassignment of a new channel is not only effective with a low overhead but also reduces the range of propagation of co-channel interference. Experimental studies reveal that the proposed channel assignment and reassignment protocols improve the capacity of *Ad Hoc* network and effectively reduce the breakage rate of communication.

The rest of this paper is organized as follows. Section 2 presents definitions and basic concepts of the proposed protocols. Section 3 illustrates the design of cache table in each mobile host and elucidates the channel assignment protocol. Section 4 proposes the channel reassignment protocol. Section 5 examines the improvement in performance associated with the proposed protocols. Section 6 draws conclusions.

2. Definitions and Basic Concepts

In a Mobile Ad Hoc NETwork (MANET), a pair of hosts can directly communicate with each other if their distance is smaller than the communication range. Communication between a pair of hosts will occupy a channel resource, causing the channel unable to be used by neighboring hosts. A channel that is used by one pair of hosts can be reused by another pair of hosts, only if their communication ranges do not overlap. In Fig. 1, a square node represents a host. A connecting link between the two hosts indicates that they are within the communicative range. Any mobile host is either in the idle state or the communication state. The gray-colored square nodes are in the communication state. A symbol on a node represents the *ID* of a host, whereas the number on a link specifies the channel that is occupied by the pair of hosts connected by the link. For example, hosts a and b are in a communication state and use channel 1 for communication. Hosts c, d and h are in the communicative range of host a. The following set of definitions is used in illustrating the operation of the proposed protocol.

Definition: *Neighbor*(x) and *Neighbor*(X)
Neighbor(x) represents the set of hosts located in communicative range of host x. Let X be the set of hosts $x_1,\ x_2,\ldots,x_n$. *Neighbor*(X) denotes the union of sets *Neighbor*(x_1), *Neighbor*$(x_2),\ldots,$ and *Neighbor*(x_n). That is,

$$\mathit{Neighbor}(X)=\bigcup_{i=1}^{n}\mathit{Neighbor}(\chi_i)$$

where $X=\{x_1,\ x_2,\ \ldots,\ x_n\}$. □

For example, in Fig. 1, *Neighbor*(a) $=\{b,\ c,\ d,\ h\}$ and *Neighbor*$(\{a,\ b\})=\{c,\ d,\ h\}$.

Definition: *One-hop Communication Com*(a,b,j)
Com(a,b,j) represents the communication between a pair of hosts a and b over channel j. □

For example, in Fig. 1, communication performed by hosts a and b is represented by *Com*$(a,\ b,\ 1)$.

For simplicity of presentation of the communication state of a MANET, the communication of a pair of hosts $\{a,\ b\}$ on channel j is represented by a circle numbered j and labeled *Com*$(a,\ b,\ j)$ in the graph.

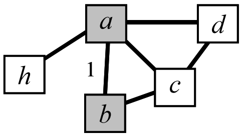


Fig. 1 An example of Ad Hoc networks. Hosts a and b communicate on channel 1.

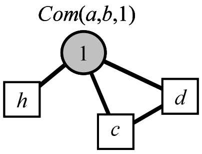


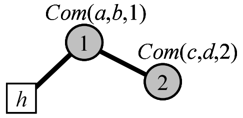
Fig. 2 An equivalent communication graph to Fig. 1.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
···	···	···	···

Fig. 3 *Neighboring Communication Table* (*NCT*).

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
{*a*, *b*}	1	null	1

(a) *NCT* of host *h*.



(b) Hosts *c* and *d* ask for communication on channel 2.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
{*a*, *b*}	1	2	2

(c) The contents fo host *h* in Fig. 4(b).

Fig. 4 The cache contents of host *h*.

Figure 2 is equivalent to Fig. 1.

Definition: *Host*(*Com*)
Host is a function that extracts the communicating hosts of a communication *Com*. For example $Host(Com(a, b, j))=\{a, b\}$. □

Definition: *Channel*(*Com*)
Channel is a function that extracts the occupied channel of a communication *Com*. For example $Channel(Com(a, b, j))=\{j\}$. □

Definition: *Interference Hosts IH*($Com1$, $Com2$) and *Interference Channel IC*($Com1$, $Com2$)
Two communications $Com1(x, y, j)$ and $Com2(x', y', j)$ interfere with each other if the communication range of one host, say x, of $Com1$ overlaps the communication rang of another host, say x', of $Com2$. The *Interference Hosts IH* is defined as the set of hosts that interfere with each other. That is, *Interference Hosts*$=\{x, x'\}$. The channel j, which is used by *Interference Hosts*, is defined as *Interference Channel IC*. □

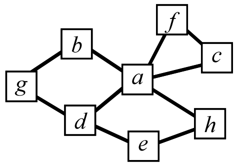
Examples and the cache structure of each host are introduced below to illustrate the basic concepts of the proposed protocol. Two pairs of hosts that use a common channel for communication and move close to each other will interfere with each other. At this moment, one of the pair requires a mechanism for reselecting a channel. Each mobile host maintains a *Neighboring Communication Table* (*NCT*) in its cache, which records the neighbors' channel usage information, to determine efficiently which channel is selected.

The information stored in *NCT* includes the *ID* of the neighboring hosts; the channel occupied by the one-hop and two-hop neighbors, and the cost of those channels. Figure 3 demonstrates the *NCT* of each mobile host. Each row in Fig. 3 records a neighbor's communication information. The *Neighbor* field records the *ID* of every neighbor, including idle and communicating neighbors. The *Nchannel* field records the channel that is occupied by the neighbor and *Nnchannel* records the channel that is occupied by the neighbor's neighbor (that is, the two-hop neighbor). If the neighbor is in the communication state, then the *Nchannel* field records the occupied channel otherwise; *Nchannel* has a *null* value.

The *Cost* field records the cost of reassigning a new channel to the neighbor. Let two communications $Com1(x, y, j)$ and $Com2(x', y', j)$ interfere with each other and $IH=\{x, x'\}$. Hosts x and x' will check the cost of assigning a new channel to itself, exchange the cost evaluation information and then determine which of x and x' is assigned a new channel to minimize the cost. If no channel is available for the interference hosts, the new channel should be selected from those channels that are currently being used by neighbors. However, this change may cause another co-channel interference problem for, say, neighbor z, since neighbor host z must be reassigned a new channel which may be currently used by a neighbor of z. An inappropriate switch in the new channel will cause that the co-channel interference to propagate over the MANET. The *Cost* field records the number of neighbors whose channels must change. This field helps the interference hosts to evaluate the cost of updating a new channel that is currently being used by their neighbors.

Consider the communication graph shown in Fig. 2. The set of neighbors of host h use channel 1 for communication is $\{a, b\}$. Figure 4(a) shows the cache table of host h. The *Nnchannel* field has a null value since the neighbors of hosts a and b are in an idle state. The *Cost* field has value one because 'one' pair of hosts $\{a, b\}$ must be reassigned a new channel, assuming that host h seeks to use the same channel as hosts $\{a, b\}$. At this moment, assume that hosts c and d hopes to communicate with each other. They choose channel 2 for communication and transmit this information to neighbors. The communication graph will be updated as shown in Fig. 4(b). On receiving this information, host h updates its cache table, as shown in Fig. 4(c). The contents of cache represent that two neighbors, a and b, communicate over channel *Nchannel*=1. If host h asks to use channel 1 for communication, in the worst case, 'two' pairs of hosts will update their channel. Therefore, the *Cost* field has a value 2. The situation is detailed below.

Consider host h, which hopes to communicate with another host. It checks the cache table and selects a proper channel. If host h determines to use channel 1 for communication, hosts $\{a, b\}$ will change their communication channel to avoid co-channel interference with host h. In the worst case, hosts $\{a, b\}$ select channel 2 as their new channel. Hosts $\{c, d\}$ again update their communication channel to avoid co-channel interference with hosts $\{a, b\}$. Therefore, in the worst case, the use of channel 1 by host h causes two pairs of hosts to update their channels, implying that the cost value, for the use of channel 1 as the communication channel of host h, will be 2, as shown in Fig. 4(c). Notably, only those hosts that wish to create a new communication need to transmit channel information, guaranteeing that the amount of control packet can be restricted.



(a) The original communication state diagram.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
a	null	null	0
e	null	null	0
g	null	null	0

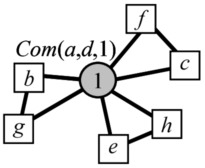
(b) *NCT* stored in host d.

Id	*Channel*

(c) Format of *Communication Notification Message (CNM)*.

Neighbor ID	*Channel*	*Total Cost*

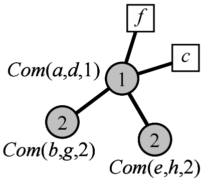
(d) Fromat of *Communication State Information (CSI)*.



(e) Hosts a and d create a communication link $Com(a, d, 1)$.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
$\{a, d\}$	1	null	1
g	null	null	0

(f) *NCT* stored in host b.



(g) Communication state diagram. Host pairs $\{b, g\}$ and $\{e, h\}$ create the communication link.

Fig. 5 An example for illustrating the channel assignment process.

3. Channel Assignment Protocol

This section proposes examples to illustrate the basic operation of the proposed channel assignment protocol. A channel assignment protocol for enhancing the channel utilization is then presented.

Figure 5 presents an example to illustrate the communication process and the contents of cache table of hosts that establish new communications. In this example, three channels, 1, 2, and 3, are assumed provided by system. In Fig. 5(a), hosts a, b, c, d, e, f, g and h are in the idle state. Host d has neighbors a, e and g, and its cache table is shown in Fig. 5(b), in which *Nchannel* and *Nnchannel* fields have a *null* value because hosts a, e and g are in the idle state.

The following example clarifies how hosts a and d execute the channel assignment protocol to assign a common channel for communicating with each other.

Step 1: Host d sends a *communication request message*(CRM) to host a. On receiving the message, host a replies with a *communication approved message*(CAM) to host d.

Step 2: When host d receives the *CAM* message, it exchanges with host a the information stored in cache table, including *neighbor ID*, *Nchannel*, and *Cost* fields.

Step 3: Hosts a and d simultaneously compare the received message with the information stored in their *NCT* tables, and add the two-hop information to their tables. Hosts a and d thus have identical tables.

Step 4: Hosts a and d select the minimum *Cost* value for communication. In this case, the cost of channels 1, 2, and 3 are equal. To enhance the channel utilization, the smallest channel will be selected. Thus, hosts a and d select channel 1 for communication and then send a *communication notification message*(CNM) and *communication state Information*(CSI) to their neighbors b, c, e, f, g and h. Figures 5(c) and (d) show the format of the *CNM* and *CSI* messages, respectively.

Step 5: Hosts b, c, e, f, g and h integrate the received *CNM* and *CSI* messages into their *NCT* tables. The operation of integration will be discussed later.

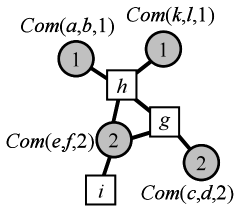
Step 6: Any neighbor of hosts a or d in the communication state also transmits the integrated *CSI* information to its neighbors. In this case, however, since all the neighbors of hosts a and d are in the idle state, this step is omitted.

Figure 5(e) plots the communication state graph. Figure 5(f) presents the contents of host b, after it has integrated *CNM* and *CSI* information in its table.

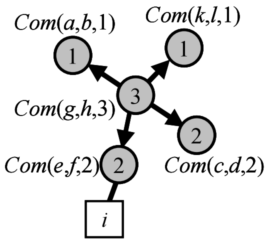
Let X represent a pair of hosts that want to establish a communication link. Both execute the specified steps to establish the communication link so that all hosts in *Neighbor*(X) have X's communicative information, including *CNM* and *CSI*. A subset of *Neighbor*(X), say Y, that consists of hosts in communication state will include the received *CNM* and *CSI* in their *NCT,* recalculate the *CNM* and *CSI*, and then send the recalculated communicative information to *Neighbor*(Y). Hereafter, when two communicative pairs detect an interference, they use the collected communicative information to execute the channel reassignment protocol efficiently; one pair of hosts will be reassigned a new channel with the least cost for communication before the communication breakages. The detailed operation of channel reassignment protocol will be addressed in the next section. Each host collects the two-hop neighbors' communicative information in its *NCT* table so that the lowest cost of each channel can be efficiently derived since the lowest cost for each communicative host changes when a new communication link is established. Executing the specified steps, host pairs $\{b, g\}$ and $\{e, h\}$ will create communication links as depicted in Fig. 5(g).

The *Cost* value of the channel that is currently used by neighbors is recorded in each host's *NCT*. The *Cost* value is the estimate of cost of assigning or reassigning a new channel. An inaccurate estimate of *Cost* increases the number of hosts that participate in the channel reassignment operations, causing neighbors recursively to execute the channel reassignment operations. An example is presented below to illustrate the evaluation of *Cost*.

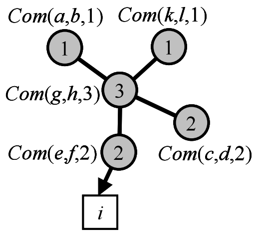
Consider Fig. 6(a). Hosts h and g hope to establish a communication link. Assume that there are 3 channels, 1, 2, and 3, provided by system. Figures 7(a) and 7(b) present *NCT* tables stored in hosts h and g, respectively. By executing Steps 2 and 3 described above, hosts h and g exchange their information and include it into their *NCT* tables. Figure 7(c) shows the resultant table of host h. As shown in Fig. 6(b), hosts h and g then select channel 3 to establish a communication link since channel 3 has lower *Cost* value in the *NCT*. When executing Step 4, hosts h and g transmit the communicative policy *CNM*=*Com*(g, h, 3) and the important information *CSI* of their tables to their neighbors a, b, c, d, e, f, k and l. Figure 7(d) shows the *CSI* information transmitted by hosts h and g.



(a) Communication state diagram before hosts $\{g, h\}$ constructing a communication link.



(b) Hosts $\{g, h\}$ select channel 3 for communication and send CNM to neighbors.



(c) Hosts $\{e, f\}$ transmit CSI information to neighbors.

Fig. 6 An example for illustrating the evaluation of *Cost* value.

On receiving the *CNM* and *CSI* information, neighbors of hosts $\{g, h\}$ integrate the received information into their tables, as described under Step 5. An example is presented to illustrate the information combination operation performed by hosts e and f, which are in the communication state. As shown in Fig. 6(b), hosts $\{e, f\}$ receive the *CNM* and *CSI* from hosts $\{g, h\}$. Hosts $\{e, f\}$ add the information "hosts $\{g, h\}$ communicate on channel 3" to their tables, as shown in Fig. 7(e). The *Cost* value of row one in Fig. 7(e) is calculated from the *CSI.* In the transmitted *CSI* information, two channels, 1 and 2, are used by the neighbors of $\{g, h\}$, as shown in Fig. 7(d). Let s represent the sum of all *Cost* values that the corresponding channel value in *CSI* is one. Hosts $\{e, f\}$ put the value (*Nnchannel*=1, *Cost*=s+1) to row one in their tables. In the worst case, if hosts $\{e, f\}$ use channel 3 as their new channel when interference occurs, s+1 pairs of hosts must switch their communication channels, because hosts $\{g, h\}$, which use channel 3 for communication, must change their channel to channel 1 to prevent co-channel interference with hosts $\{e, f\}$. However, s neighboring pairs use channel 1 for communication. The s pairs of hosts must also change their communication channel to prevent co-channel interference with hosts $\{g, h\}$. Thus, the use of channel 3 for channel reassignment in $\{e, f\}$ will cause s+1 pairs to update their channels. The s+1 pairs are $\{g, h\}$ and those neighboring pairs that use channel 1 for communication. Thus, the first row

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
g	null	null	0
{*a*,*b*}	1	null	1
{*e*,*f*}	2	null	1
{*k*,*l*}	1	null	1

(a) *NCT* of host h.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
h	null	null	0
{*c*,*d*}	2	null	1
{*e*,*f*}	2	null	1

(b) *NCT* of host g.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
{*a*,*b*}	1	null	1
{*c*,*d*}	2	null	1
{*e*,*f*}	2	null	1
{*k*,*l*}	1	null	1

(c) *NCT* of host h after information exchange of hosts g and h.

Neighbor	*Channel*	*Cost*
{*a*,*b*}	1	1
{*c*,*d*}	2	1
{*e*,*f*}	2	1
{*k*,*l*}	1	1

(d) *CSI* information transmitted by hosts g and h.

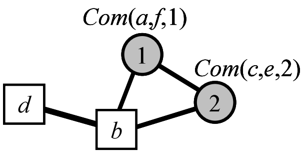
Neighbor	*Nchannel*	*Nnchannel*	*Cost*
i	null	null	0
{*g*,*h*}	3		

(e) *NCT* stored in hosts $\{e, f\}$.

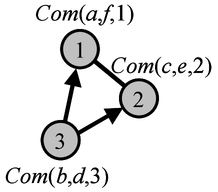
Neighbor	*Nchannel*	*Nnchannel*	*Cost*
i	null	null	0
{*g*,*h*}	3	1	3
		2	2

(f) *NCT* of hosts $\{e, f\}$ after computing the *Cost* value.

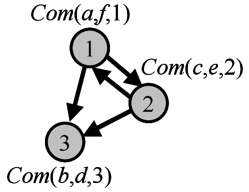
Fig. 7 An example for illustrating the *Cost* evaluation.



(a) An example of communication state diagram.



(b) Hosts $\{b, d\}$ communicate on channel 3.



(c) Information exchange among three pairs of hosts.

Fig. 8 An example of cycle existing in communication state diagram.

of the table for $\{e,\ f\}$ has values <*Neighbor*=$\{g,\ h\}$, *Nchannel*=3, *Nnchannel*=1, *Cost*=s+1=3>, as shown in Fig. 7(f). Similarly, the second row in the table for $\{e,\ f\}$ has values <*Neighbor*=$\{g,\ h\}$, *Nchannel*=3, *Nnchannel*=2, *Cost*=2>, as shown in Fig. 7(f).

After recalculating their tables, hosts $\{e,\ f\}$ create a new *CSI*, according to the contents of their tables, and transmit it to their neighbors, as described in Step 6. The *CSI* message includes value <*Neighbor ID*=$\{g,\ h\}$, *Channel*=3, *Cost*=3>, where the *Cost* value is determined from the maximum *Cost* of the costs in row <*Neighbor*=$\{g,\ h\}$>. As soon as host i receives the *CSI* information from hosts $\{e,\ f\}$, it updates its table by a calculation similar to that described above. In the cache table of host i, the *Cost* value of a specific channel *ch* represents the number of communicative pairs that must update their channels when *ch* is selected as a new channel for use by host i.

The previous example, presented to show the calculation of *Cost*, includes no cycle. If cycles are evident in the communication state diagram, then *Cost* value may be over valued. An example of a valid calculation of *Cost* is presented here. Consider the communication state diagram shown in Fig. 8(a). Host pairs $\{a,\ f\}$ and $\{c,\ e\}$ use channels 1 and 2, respectively, for communication. Figures 9(a), 9(b) and 9(c) presents tables stored in hosts b, $\{a,\ f\}$ and $\{c,\ e\}$ respectively. Hosts $\{b,\ d\}$ hope to establish a communication link. After executing Steps 1, 2, and 3 as described above, hosts $\{b,\ d\}$ select channel 3 for communication. The resultant table of host b is the same as the table shown in Fig. 9(a).

In executing Step 4, hosts $\{b,\ d\}$ transmit *CNM*=*Com*(b, d, 3) and *CSI* information, as shown in Fig. 9(d), to their neighbors $\{a,\ f\}$ and $\{c,\ e\}$. On receiving the *CNM* message, hosts $\{a,\ f\}$ update their tables by <*Neighbor*=(b, d), *Nchannel*=3>. Then, hosts $\{a,\ f\}$ update their tables with the received *CSI* information. Hosts $\{a,\ f\}$ ignore this row information of *CSI* and do nothing since <*Neighbor ID*=$\{a,\ f\}$> in the first row of *CSI* is the same as the *ID* of these hosts. The second row of *CSI* information, <*Neighbor ID*=$\{c,e\}$>, however, appears in their tables, indicating

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
$\{a,f\}$	1	2	2
$\{c,e\}$	2	1	2
d	null	null	0

(a) The *NCT* stored in host b.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
$\{c,e\}$	2	null	1
b	null	null	0

(b) The *NCT* of hosts $\{a, f\}$.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
$\{a,f\}$	1	null	1
b	null	null	0

(c) The *NCT* of hosts $\{c, e\}$.

Neighbor	*Channel*	*Cost*
$\{a,f\}$	1	2
$\{c,e\}$	2	2

(d) The contents of *CSI* transferred by hosts $\{b, d\}$ due to their communication.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
$\{c,e\}$	2	3	2
$\{b,d\}$	3	2	2

(e) The *NCT* of hosts $\{a, f\}$. The *Cost* value has been evaluated.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
$\{a,f\}$	1	3	2
$\{b,d\}$	3	1	2

(f) The *NCT* of hosts $\{c, e\}$. The *Cost* value has been evaluated.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
$\{a,f\}$	1	2	2
$\{c,e\}$	2	1	2

(g) The *NCT* of hosts $\{b, d\}$. Hosts $\{b, d\}$ have created a communication.

Fig. 9 An example of *Cost* evaluation for a communication state diagram that contains cycle.

that the receivers $\{a, f\}$ and the senders $\{b, d\}$ have common neighbor hosts $\{c, e\}$, such that the three pairs $\{a, f\}$, $\{b, d\}$ and $\{e, f\}$ constitute a cycle. Since every host has the same *Cost*=2 in a cycle, hosts $\{a, f\}$ update their table with <*Neighbor*=$\{b, d\}$, *Nchannel*=3, *Nnchannel*=2, *Cost*=2>, indicating that if hosts $\{a, f\}$ select channel 3 as their new channel, then hosts $\{b, d\}$ must change their channel to prevent the co-channel from interfering with hosts $\{a, f\}$. In the worst case, hosts $\{b, d\}$ will select channel 2 as their new communication channel, causing hosts $\{c, e\}$ again to update their communication channel. In total, hosts $\{a, f\}$ update the communication channel to channel 3, causing two pairs, hosts $\{b, d\}$ and $\{c, e\}$, to change their channels. Consequently, the *Cost* of channel 3 is 2. Figure 9(e) presents the new *NCT* table of hosts $\{a, f\}$. Hosts $\{a, f\}$ then transmit the *CSI* to neighbors $\{b, d\}$ and $\{c, e\}$, as described in Step 6 above. Similarly, hosts $\{c, e\}$ and $\{b, d\}$ update their tables, as shown in Figs. 9(f) and 9(g), respectively.

A formal channel assignment protocol is presented below.

The Protocol for Channel Assignment

Assume that hosts $\{a, b\}$ seek to establish a communication link.

1. Host a sends a *CRM* request to host b. If host b agrees to communicate with host a, it replies to host a with a *Communication Approved Message* (*CAM*).
2. On receiving *CAM*, hosts $\{a, b\}$ exchange their information, including *Neighbor ID*, *Nchannel*, *Nnchannel* and *Cost*.
3. Hosts $\{a, b\}$ complement each other's information, renew their *NCT* table, and then select an available channel that is not being used. If no channel is available, then hosts $\{a, b\}$ select a channel with minimal *Cost* for communication.
4. Hosts $\{a, b\}$ transmit the *CAM* and *CSI* information to neighbors so that all their neighbors know the communication state of $\{a, b\}$.
5. On receiving the *CNM* and *CSI* information, each neighbor x of $\{a, b\}$ executes the following operations.
    - (a) Let *Neighbor*=y be the value shared by the *NCT* and *CSI* tables. Set *Nchannel*=c for the row that corresponds to *Neighbor*=y in *NCT*, where c is the *Channel* value of the row that corresponds to *Neighbor*=y in *CSI*.
    - (b) Remove those rows of *CSI* that satisfy *Neighbor*=x.
    - (c) Sum the *Cost* values of *CSI* with the same *Channel* values. For each row (*Channel*=i, *Cost*=j) in *CSI*, perform the following operations on *NCT*:

```
For those rows for which Neighbor=(a, b) apply,
    If (Nnchannel=i)
        Set Cost=j
    else
        Insert a row with value (Neighbor=(a, b), Nchannel = Channel(Com(a, b)), Nnchannel=i, Cost=j)
```

6. If x is in the communication state, it generates *CSI*

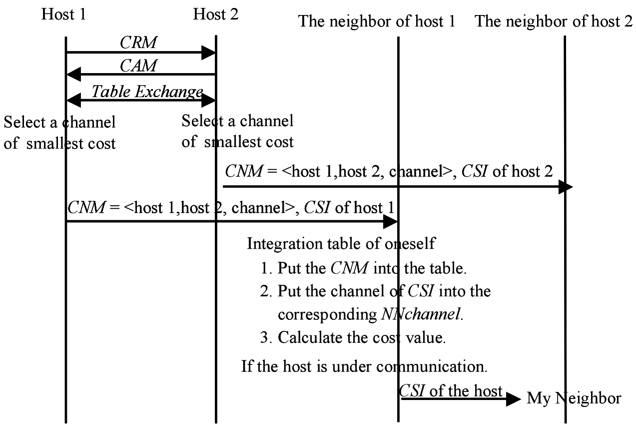


Fig. 10 Protocol for host's creating a new communication.

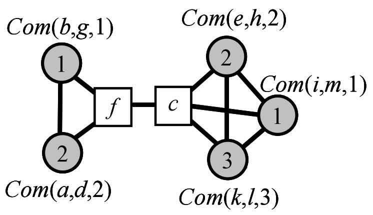
information, according to the new table, and then transmits this information to its neighbors.

Figure 10 presents the message flow of the channel assignment protocol. The presented channel assignment protocol fully exploits the channel reuse opportunities and maintains the evaluated *Cost* to reallocate the channels. Information stored in the *NCT* table is also referenced by the channel reassignment protocol, which is presented in the following section.

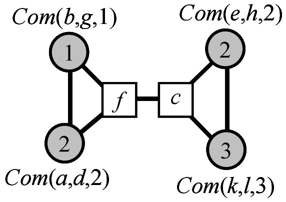
4. Channel Reassignment Protocol

In the previous section, each mobile host maintains a *NCT* table that includes neighbors, the channel used by neighbors, and the *Cost* of that channel. In establishing a communication link, a host selects an available channel that is not used by a neighbor. If no channel is available, the host refers to its table and selects a channel with minimal *Cost*. As soon as a new communication link has been built up, the *CNM* and *CSI* information should be transmitted to those neighbors that are currently in the communication state to maintain up-to-date communication information. This section introduces a channel reassignment protocol to increase the capacity of *Ad Hoc* networks. Two types of opportunities that apply the channel reassignment scheme increase the network capacity.

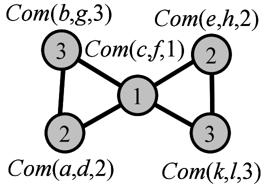
4.1 Type 1: Creating a New Communication Link



(a) No channel is available for hosts c.



(b) Communication state diagram before hosts $\{c, f\}$ creating a communication link.



(c) Communication state diagram while hosts $\{c, f\}$ creating a new communication.

Fig. 11 An example of creating a new communication by hosts $\{c, f\}$.

In *Ad Hoc* networks, communication channels are limited resources. Two hosts can not create a communication link if no channel is available. Reassigning a channel to some hosts can increase the communication capacity and balance the utilization of each channel. Assume that an *Ad Hoc* network system has three channels, 1, 2 and 3. As shown in Fig. 11(a), neighboring pairs $\{b, g\}$ and $\{a, d\}$ to host f use channels 1 and 2 for communication, respectively. Neighboring pairs $\{e, h\}$, $\{k, l\}$, and $\{i, m\}$ use channels 2, 3, 1 for communication, respectively. Channel 3 is the only channel available to host f. No channel is available to host c. As shown in Fig. 11(b), as soon as hosts $\{i, m\}$ finish communicating, channel 1 becomes available to host c. At that moment, hosts $\{c, f\}$ seek to establish a communication link but share no channel for communication. Selecting either channel 1 or 3 for communication of $\{c, f\}$ would create co-channel interference with at least one neighbor that is using that channel for communication, causing the communicating neighbor to reassign its channel. Accordingly, selecting the channel that causes the fewest hosts to change their communication channels is a basic requirement of reducing the number of hosts whose channels must be reassigned.

As discusses in the preceding section, hosts $\{c, f\}$ execute Steps 1, 2 and 3 of the channel assignment protocol to create a communication link. Figures 12(a) and 12(b) show the *NCT* tables of hosts c and f, respectively. No common channel is available to hosts c and f. Hosts c and f will examine the <*Nchannel*, *Cost*> fields of their table and select the channel from *Nchannel* column that has minimal *Cost*. Since all channels are used and have the same *Cost*, hosts $\{c, f\}$ select a channel that appears less frequently in the table to reduce the probability of co-channel interference. Thus, hosts $\{c, f\}$ select channel 1 over which to establish a communication link. On receiving the *CNM* and *CSI*

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
c	null	null	0
{*b*,*g*}	1	2	2
{*a*,*d*}	2	1	2
{*e*,*h*}	2	3	2
{*k*,*l*}	3	2	2

(a) *NCT* fo host *f*.

Neighbor	*Nchannel*	*Nnchannel*	*Cost*
f	null	null	0
{*e*,*h*}	2	3	2
{*k*,*l*}	3	2	2
{*b*,*g*}	1	2	2
{*a*,*d*}	2	1	2

(b) *NCT* of host *c*.

Fig. 12 *NCT* of hosts $\{c, f\}$ while they create a new communication.

information sent by hosts $\{c,\ f\}$, hosts $\{b,\ g\}$ will execute the channel reassignment protocol, which is described below.

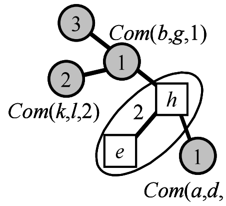
4.2 Type 2: Mobility

In the first case, channel reassignment is required because no channel is available for hosts to create a new communication link. Those neighbors with co-channel interference must execute the channel reassignment protocol to obtain a minimal *Cost* channel to establish a new communication link. Another reason for executing the channel reassignment protocol is that two pairs of hosts that are communicating over a single channel are slowly moving toward each other so that co-channel interference occurs.

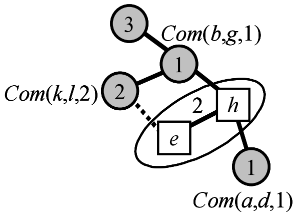
Both types use the *NCT* table to execute the channel reassignment protocol. This section elucidates a channel reassignment protocol to answer the following two questions.

(1) Which host pair should reassign a channel?
(2) Which channel is a candidate for the new channel?

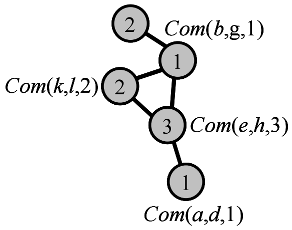
In Fig. 13(a), hosts e and h are communicating over channel 2. Hosts k and l are using the same common channel for communication. In Fig. 13(b), a dashed line connects hosts $\{e, h\}$ and $\{k,l\}$ as hosts e and l move toward each other to represent that the interference between these two pairs is arisen gradually. Two pairs $\{e, h\}$ and $\{k,l\}$ check their tables and determine a candidate channel for channel reassignment since each host maintains an information table. Each pair creates and transmits a Communication Interference Message (*CIM*) packet, as shown in Fig. 14, to another pair. On receiving the other pair's *CIM* packet, host pair $\{e,\ l\}$ compares the *Cost* of the received channel and its candidate channel and determines that pair $\{e,\ h\}$ executes the channel reassignment operation. Finally, as shown in Fig. 13(c), hosts $\{e,\ h\}$ use channel 3 for communication. After executing channel reassignment, hosts $\{e,\ h\}$ create a *CNM* packet to notify their neighbors of their changed communication channel. On receiving the *CNM* packet, neighbors of hosts $\{e,\ h\}$ update their information table and the channel reassignment protocol is complete.



(a) Hosts $\{e, h\}$ communication without interference.



(b) Host e interferes with $Com(k, l, 2)$ due to mobility.



(c) The communication state diagram after executing the channel reassignment protocol.

Fig. 13 An example for executing channel reassignment owing to mobility.

My ID	*Candidate channel*	*Cost*

Fig. 14 Format of *CIM*.

The proposed channel reassignment protocol determines a minimal *Cost* channel for communicative pairs with co-channel interference. Communication can thus be maintained. The channel reassignment protocol is detailed below.

4.3 The Protocol for Channel Reassignment

Assume that two pairs of hosts, a and b, experience co-channel interference on channel c.

Step 1: Host pairs a and b check their *NCT* tables; select a minimal channel, say c_a and c_b respectively, as candidate channels for the new channels, and send a *Communication Interference Message*

(CIM) to each other. Let the CIM sent by pair a be (a, c_a, $Cost_a$) and the CIM sent by pair b be (b, c_b, $Cost_b$)

Step 2: On receiving the *CIM* packet, a host pair compares the received *CIM* with the *CIM* it sent.

If the partial order ($Cost_a$, c_a, a) < ($Cost_b$, c_b, b) then,

Pair a executes the channel reassignment process and changes a new channel c_a for communication.

Else

Pair b executes the channel reassignment process and determines a new channel c_b for communication.

Endif

Step 3: After the channel reassignment process is executed, the reassigned pair sends a *CNM* packet to its neighbors.

Step 4: All neighbors that receive the *CNM* packet will update their *NCT* tables.

Step 5: If the channel reassignment process creates co-channel interference among neighbors, these neighbors will execute operations similar to those involved in the channel assignment protocol.

If no common channel is available over which a pair of hosts can communicate, the proposed channel reassignment protocol reassigns the allocated channel so that the common channel can be released to establish a new communication, increasing the network capacity and effectively exploiting channel reuse opportunities. For those hosts that are suffering from co-channel interference, the proposed channel reassignment protocol reassigns a channel with minimal *Cost*, to prevent the communication from breaking.

5. Performance Study

This section considers the performance of the proposed channel assignment and reassignment protocols, with respect to the extent of channel reuse, the success rate and cost of executing channel reassignment and the frequency of communication breaks. The simulation environment is as follows. The size of the MANET region is 1000*1000 basic units, and the number of hosts is set at a constant 500. The connected pairs are randomly selected and the number varies, including 25, 50, 75, 100, 125, 175 and 200. Host mobility is maintained between from 5units/hr to 100units/hr. Figure 15 compares the success rate of channel assignment. The number of channels provided by an *Ad Hoc* system is two, three or four. The proposed channel assignment protocol is compared to *random assignment*, which randomly assigns an available channel to establish new communication.

The success rate of channel assignment is generally proportional to the number of channels provided. The proposed channel assignment protocol always selects a smallest channel from the set of available channels, exploiting channel reuse opportunities and thus increasing the success rate of channel assignment. Figure 15 shows this effect, where the success rate of the proposed channel assignment protocol exceeds that of random assignment. Figure 16 plots the success rate of channel reassignment. The number of channels provided by the system is set to 2, 3 and 4. The number of opportunities to apply channel reassignment increases as the number of channels provided by the system declines. Many connection pairs exploit many opportunities for channel reuse, making the successfully reassignment of a reused channel difficult when the co-channel interference occurs. Figure 16 shows that the success rate decreases as the number of connection pairs increases.

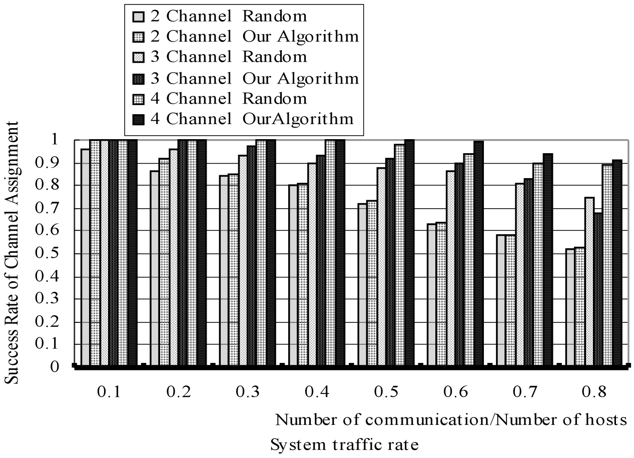


Fig. 15 Performance evaluation of successful rate.

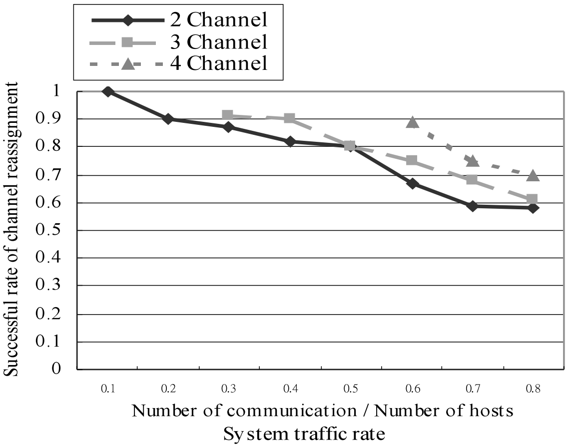


Fig. 16 The successful rate of channel.

Figure 17 shows the channel utilization. The proposed channel assignment protocol outperforms random assignment with respect to channel utilization. This is because the proposed protocol exploits the channel reuse opportunities, causing a single channel to be

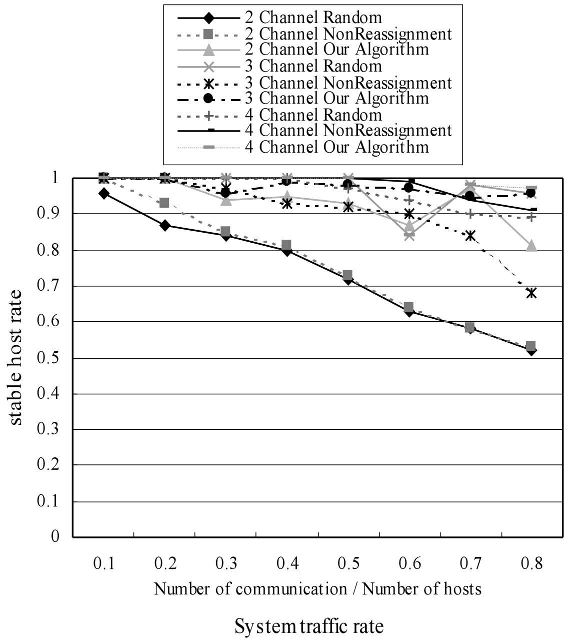


Fig. 17 The measurement of channel utilization.

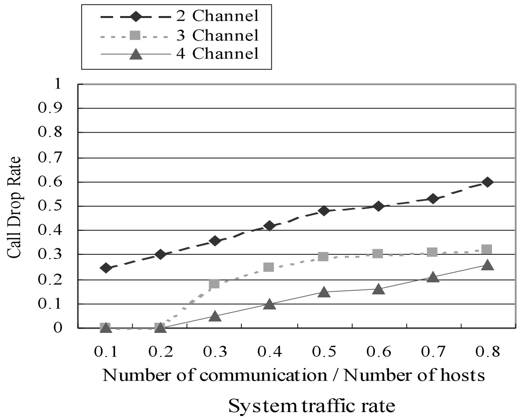


Fig. 18 Communication breakage rate due to mobility.

utilized simultaneously for communication by different pairs.

Two communicating pairs of hosts that use the same channel and gradually move toward each other will undergo co-channel interference with each other. When the co-channel interference occurs, the communication will fail if no pair of hosts undergoes channel reassignment. However, applying the channel reassignment protocol to one of the two pairs in a timely manner will prevent the communication from breakage. Figures 18, 19 and 20 show the effect of mobility on communication breakage. The communication breakage rate decreases as the number of available channels provided by system increases. As shown in Fig. 18, if only two available channels are provided by system, the communication breakage rate is high. Figure 19 plots the success rate of channel reassignment when co-channel interference occurs among two communicating pairs. The success rate of channel reassignment increases with the number of available channels, if the mobile hosts have a constant degree of mobility. Figure 20 shows the effect of the degree of mobility. When the communicating hosts move fast, the channel of minimal cost cannot be found before the communication breaks, causing a high rate of communication breakage.

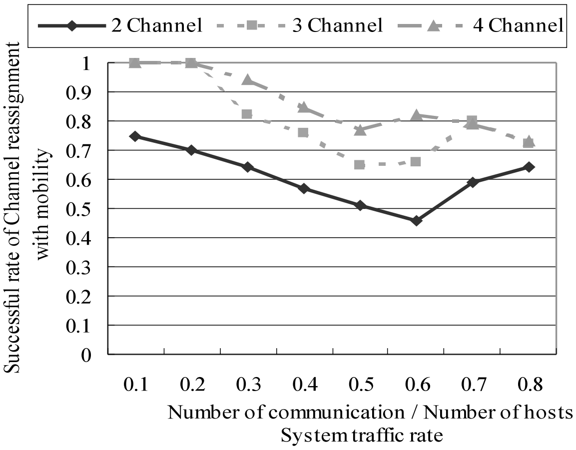


Fig. 19 Successful rate of executing channel reassignment. The co-channel interference is arisen from mobility.

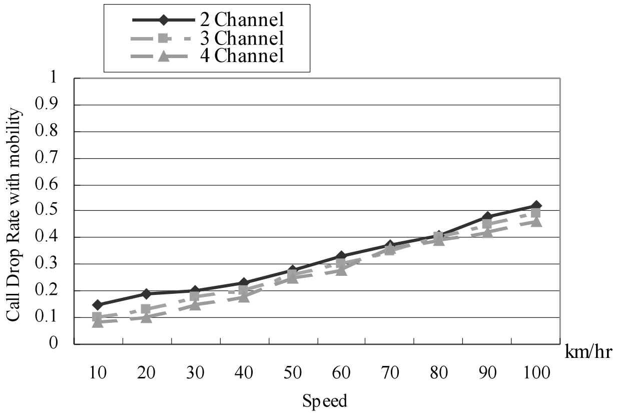


Fig. 20 The effect of speed on communication breakage rate.

Figure 21 shows the overhead associated with the control packet when executing channel assignment and reassignment. The maintenance of *NCT* in each host generates control packets for transmitting *CSI* and *CNM* messages when a new communication is established. The channel assignment and reassignment protocols generally create more control packets than does random assignment.

The *NCT* maintains the lowest cost channel for each host so that the optimal channel can be assigned for the new communication link or reassigned to a communication that is suffering from co-channel interference. The proposed channel assignment and reassign-

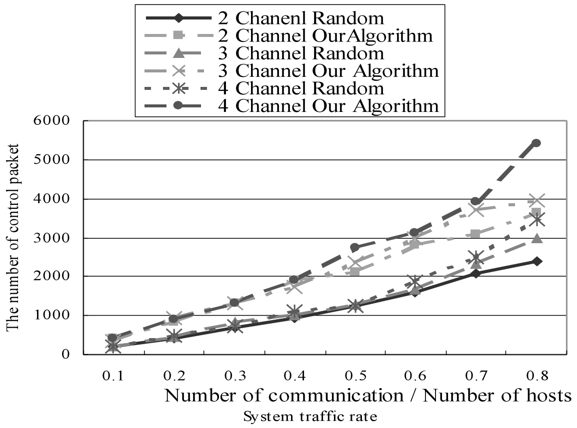


Fig. 21 The effect of the number control packet on the number of communication pairs.

ment protocols not only exploit channel reuse opportunities but also eliminate the effect of co-channel interference, and thus reduce the communication breakage rate.

6. Conclusions

This investigation presents a channel assignment protocol for exploiting channel reuse opportunities, increasing system capacity, and maintaining the lowest-cost channel information. The proposed channel assignment protocol evaluates the cost associated with each channel and stores the communication state of communicating neighbors in each host's *NCT* table. Frequent reuse of channel resource increases the system capacity but introduces co-channel interference when two pairs of hosts that use a single channel gradually move toward each other. Based on the *NCT*, a channel reassignment protocol is proposed to prevent the communication from breaking. By applying the proposed channel reassignment protocol, one of the two pairs is reassigned a lowest-cost channel in time to eliminate co-channel interference. The proposed protocols increase the system capacity, reduce the rate of communication breakage, and thus improve the performance of *Ad Hoc* networks.

Acknowledgement

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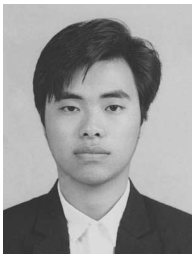

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