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Replica Allocation in Ad Hoc Networks Considering the Stability of Radio Links

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In ad hoc networks, a collection of mobile hosts dynamically form a temporary network without using any existing network infrastructure or centralized administration. Since disconnection occurs frequently, data accessibility in ad hoc networks is usually lower than that in the conventional fixed networks. To improve the data accessibility, we have proposed a few methods of replicating data items on mobile hosts by considering the data access frequencies from mobile hosts to each data item and the network topology. In this paper, we consider the stability of radio links among mobile hosts to enhance our previously proposed methods. We show that the newly proposed methods are more efficient by simulation results.

1. Introduction

With the advances in wireless communication and miniaturization of computers, the mobile computing environment is becoming a more common platform. In such environments, users carry portable computers or personal digital assistants called mobile hosts with them when they move from one place to another. This has led to a new concept, the *ad hoc networks*, where two or more mobile hosts can form a temporary network when they are together, without using any existing network infrastructure or centralized administration. In ad hoc networks, mobile hosts act as routers themselves, keeping information on routes to reach other mobile hosts, and they help to forward data packets sent from one mobile host to another. At present, ad hoc networks are actively used in military affairs and sensor networks but other applications are expected to be built in the near future.

As mobile hosts move freely in ad hoc networks, disconnections often occur. This causes data between two separated networks to become inaccessible to each other. For example, in **Fig. 1**, when disconnection happens between two hosts, data item D_1 becomes inaccessible to those mobile hosts on the right side while data item D_2 becomes inaccessible to those mobile hosts on the left side. To improve data accessibility, data replication is the most promising solution. In the above example, a replica of data item D_1 may be replicated at one of the mobile hosts on the right side, while D_2 on the left side, to improve data accessibility.

Most conventional works on ad hoc networks, which have been done in various research projects such as IETF (Internet Engineering Task Force), have proposed routing protocols to support communications among mobile hosts connected to each other by one-hop/multihop links[1),9)~11),13)~15)]. Such routing protocols are useful for applications in which mobile hosts directly communicate with each other, e.g., video conference systems. However, in ad hoc networks, there may also be many applications in which mobile hosts access data held by other mobile hosts. A good example is when a research project team constructs an ad hoc network and the team members refer to data obtained by other members for efficiency. Recently, ad hoc networks have attracted much attention as an infrastructure of next-generation computer environments, e.g., wearable computing environments and sensor networks. Therefore, it will be more and more important to improve data accessibility in ad hoc networks.

We have proposed several methods for effective data replication in our previous work[6),7)]. Several conventional works such as Refs. 8), 12) address some issues about data replication in mobile computing networks but to our best knowledge, there is no research work on improving data accessibility in ad hoc networks before us.

In this paper, we introduce the concept of the stability of radio links into our previous work. Previously, to raise the data accessibility

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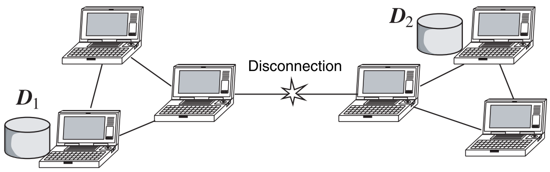

Fig. 1 Disconnection in ad hoc networks.

of mobile hosts, different replicas are allocated on connected mobile hosts wherever possible. However, when mobile hosts are connected by unstable radio links, meaning that they are going to be disconnected soon, it is inefficient to allocate different replicas on them as they cannot share those replicas after they are disconnected. Therefore, in this new approach, the unstable radio links are ignored when replicating data. In such a way, we diminish the danger of depending on replicas at hosts that will soon become inaccessible. As a result, traffic to allocate replicas is reduced and data accessibility may be increased.

The remainder of this paper is organized as follows. In Section 2, we explain the system model. The details of our proposed algorithm are explained in Section 3. We show our simulation results in Section 4. Finally we conclude this paper in Section 5.

2. System Model

We assume an environment as follows:

- In the system, every mobile host is assigned a unique host identifier. The set of all mobile hosts in the system is denoted by $\boldsymbol{M} = \{M_1, M_2, \cdots, M_m\}$, where m is the total number of mobile hosts and $M_i (1 \leq i \leq m)$ is the host identifier.
- The mobile hosts move according to the "random waypoint model" which is used in many related works[1),10),15)]. In this model, each host initially pauses for a rest period. It then selects a random destination and a random speed and moves to that destination with that speed. This process repeats where all the hosts alternately pause and move to a new location. Each mobile host knows its destination, speed and rest time, and can find out its current location with Global Positioning System (GPS).
- Data is handled in units of data items, each assigned a unique data identifier. The set of all data items is denoted by $\boldsymbol{D} = \{D_1, D_2, \cdots, D_n\}$, where n is the total number of data items and $D_i (1 \leq i \leq n)$ is the data identifier. All data items are of the same size, and the original of each item is held by a particular mobile host in the system.
- Each mobile host contains additional memory space to replicate C data items on top of the space to store the original data items it holds.
- The data items are not updated. This assumption is made for the purpose of simplicity. In the real world, this situation is possible where new data is inserted but old data is not updated; for example, weather information.
- The access frequencies to data items from each mobile host are known and they do not change.

In our approach, data items to be replicated at each mobile host are determined periodically at a certain interval. We call this the *relocation period* and represent it with T. After the data items to be replicated are determined, the mobile hosts try to access these data items to create the replicas. If they are not able to access certain requested data items, they may retain the old replicas they were holding before the relocation period until they are able to access the requested data items. In this case, the old replicas with the highest access frequencies are selected.

Mobile hosts access data items in accordance to their access frequencies to the data items. The access is considered successful if the mobile host itself or one of its connected mobile hosts (either by one-hop or multi-hop radio links) holds the original or replica of the requested data item. Otherwise the access is considered failed.

3. Data Replication Methods

In Ref. 6), we have proposed three data replication methods as follows:

(1) SAF (Static Access Frequency) method: At each mobile host, data items with the highest data access frequencies are replicated.

(2) DAFN (Dynamic Access Frequency and Neighborhood) method: After applying the SAF method, replicas of every pair of neighboring mobile hosts are compared to eliminate duplication.

(3) DCG (Dynamic Connectivity based Grouping) method: Unlike DAFN that only considers replicas held by neighbor-

ing hosts, DCG takes into account the whole network topology to allow more variety of data items to be shared by connected mobile hosts in the network.

All the above three methods were evaluated, where in general DCG gives the highest data accessibility while SAF gives the lowest traffic. In this paper, we enhance the DAFN and DCG methods to increase the data accessibility and reduce the traffic. We take into account the stability of radio links between any two mobile hosts.

In ad hoc networks, two mobile hosts can be connected directly to each other by a radio link. This link is disconnected when they move further away from each other making the distance between them longer than the possible communication range. By comparing the movements of two connected neighboring mobile hosts, the time at which they will be disconnected can be estimated. Using current time as 0, we describe the disconnection time of two mobile hosts M_i and M_j as t_{ij}. t_{ij} is calculated only within the time where the status of the mobile hosts are known from the random waypoint model. There are three possible cases.

(1) Both mobile hosts are resting. The shorter remaining rest time becomes t_{ij}.

(2) Both mobile hosts are moving. From the current location, destination point and movement speed, the time when their distance becomes larger than the communication range becomes t_{ij}. t_{ij} should be smaller than the arrival times of both mobile hosts at their destination.

(3) One mobile host is resting while one moving. Similarly, the time when their distance becomes larger than the communication range becomes t_{ij}, which should be smaller than the remaining rest time and the arrival time.

We represent the stability of the radio link between these two hosts with B_{ij} which is calculated with the following equation using the relocation period T:

$$B_{ij} = \begin{cases} 1 & t_{ij} \geq T \\ \dfrac{t_{ij}}{T} & otherwise. \end{cases} \quad (1)$$

The value of B_{ij} indicates the proportion of connection time to the relocation period T. We say that a radio link with a larger B_{ij} is more stable than one with a smaller B_{ij}.

Using the concept of this stability, we propose three enhanced methods as follows:

(1) DAFN-S1 (DAFN — Stability of radio links, method 1)

(2) DAFN-S2 (DAFN — Stability of radio links, method 2)

(3) DCG-S1 (DCG — Stability of radio links, method 1)

In these methods, using the value of B_{ij}, we evaluate the stability of radio links among mobile hosts. When the radio links between hosts are unstable, it implies that the hosts are going to be disconnected in a short period of time and thus the period of time they can share replicas with each other is limited. Therefore, it is inefficient to eliminate duplicate replicas among the hosts as it causes unnecessary traffic that does not contribute to the improvement of data accessibility. Further, there is a danger of depending on replicas at hosts that will soon become inaccessible. By ignoring the unstable radio links, unnecessary traffic to allocate replicas is eliminated and data accessibility is expected to increase.

We describe the methods in detail below.

3.1 DAFN-S1

DAFN-S1 basically adopts the algorithm of DAFN, except that the stability of radio links between mobile hosts are taken into account when eliminating duplicate replicas between the hosts. The algorithm of DAFN-S1 is as follows:

(1) At every relocation period, each mobile host broadcasts its host identifier. After all mobile hosts have completed the broadcasts, every host should know all the other connected mobile hosts and their identifiers.

(2) Each mobile host preliminary determines the data items to be replicated based on the SAF method, where at each mobile host, data items with the highest data access frequencies are replicated. Each mobile host exchanges with all its neighboring hosts information on data items held, the access frequencies to those data items and the current movements.

(3) In each set of connected mobile hosts, starting from the mobile host with the lowest suffix (i_0) of host identifier (M_{i_0}), the following procedure is repeated in the order of breadth first search. For each connected neighboring host M_j of M_i ($i < j$), M_i calculates B_{ij}. If $B_{ij} \geq x$ where x represents a threshold value, the following steps are performed. When there is a duplication of a data item (orig-

Table 1 Access frequencies to data items.

Data	Mobile host					Group		
	M_1	M_2	M_3	M_4	M_5	G_1	G_2	G_3
D_1	0.65	0.25	0.17	0.22	0.31	0.90	0.39	0.31
D_2	0.44	0.62	0.41	0.40	0.42	1.06	0.63	0.11
D_3	0.20	0.47	0.50	0.18	0.23	0.67	0.68	0.23
D_4	0.10	0.53	0.67	0.60	0.09	0.63	1.27	0.09
D_5	0.51	0.28	0.72	0.58	0.71	0.79	1.30	0.71
D_6	0.08	0.38	0.43	0.33	0.26	0.46	0.76	0.26
D_7	0.17	0.32	0.11	0.49	0.62	0.49	0.60	0.62
D_8	0.22	0.24	0.21	0.23	0.57	0.46	0.44	0.57

inal/replica) between M_i and M_j, one of them is replaced. If one of them is the original, the replica is replaced; if both of them are replicas, the one at the host whose access frequency to the data item is lower is replaced; if both are replicas and the access frequencies are the same, the one at M_i is replaced. This replica is replaced with a new replica of another data item where the access frequency is the highest at this host among all data items which are not yet replicated at both hosts. The old replicas being replaced will not be replicated again at the same mobile host for this relocation period.

In the DAFN-S1 method, we use $B_{ij} \geq x$ to evaluate the stability of radio links. A larger B_{ij} represents a more stable radio link, and the threshold value x sets the boundary between stable and unstable links. When B_{ij} is smaller than x, the radio link between M_i and M_j is simply ignored as if it does not exist.

3.2 DAFN-S2

DAFN-S2 is a variation of DAFN-S1. The difference of these two methods is that DAFN-S1 uses $B_{ij} \geq x$ to evaluate whether to consider or ignore a radio link when eliminating duplicate replicas while DAFN-S2 uses another evaluation method.

The evaluation method in DAFN-S2 is as follows. In DAFN-S2, for every pair of mobile hosts M_i and M_j, when there is a duplication of a data item between them, first a host whose replica is to be replaced is chosen with the same method as described in DAFN-S1. Let the access frequency to this data item at this host be p. This host then calculates $(1 - B_{ij}) \times p$ which represents the probability that this host will access the data item after being disconnected from the other host. If $(1 - B_{ij}) \times p \leq x$ where x represents a threshold value, this host replaces this item in the same way as described in DAFN-S1. Otherwise, the next pair of similar data items are searched and the same process is repeated.

The other steps are identical to those in DAFN-S1.

In the DAFN-S2 method, we use $(1 - B_{ij}) \times p \leq x$ as an evaluation method, where p represents the access frequency to the data item involved at the mobile host. Here, the probability of data access after disconnection, $(1 - B_{ij}) \times p$, is considered, and a lower value is preferred because the lower the value, the less chance the mobile host will access the data item after disconnection. If the probability of data access is high and the replica of the data item is eliminated, chances that this mobile host will fail to access the data item after disconnection becomes higher because it does not have a replica of the data item and it can no longer access the data item held by its disconnected neighbor. Thus, this formula helps determining and eliminating the above case.

Example:

We explain an example of executing the DAFN-S1 or DAFN-S2 method. Assume that there are five mobile hosts (M_1, M_2, $\cdots$, M_5) and M_i ($i = 1, 2, \cdots, 5$) holds the original of data item D_i. The data access frequency of each mobile host to each data item is shown in **Table 1**. **Figure 2** shows the result of executing the SAF method where at each mobile host, the data items with the highest access frequencies are selected to be replicated.

Figure 2 also shows the result of executing the DAFN-S1 or DAFN-S2 method after the SAF method where the unstable links M_1-M_3, M_2-M_3 and M_4-M_5 are ignored. Data items between neighboring hosts of stable links are compared and the replicas changed are shown in dark gray rectangulars. The comparison and replacement are held as follows:

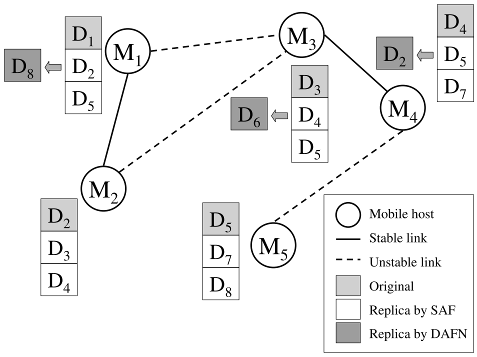

Fig. 2 Result of the SAF and DAFN-S1 or DAFN-S2 methods.

M_1-M_2: $D_2 \rightarrow D_8$ (M_1)
M_3-M_4: $D_4 \rightarrow D_6$ (M_3), $D_5 \rightarrow D_2$ (M_4)

If the original DAFN method were to be used, replicas between the pairs M_1-M_3, M_2-M_3 and M_4-M_5 will be compared and eliminated. As a result, after the disconnection, there is a possibility that M_1 and M_2 may not be able to access some data items with high access frequencies because the replicas are only held by M_3. Same thing happens for M_4 and M_5. On the whole, by using the DAFN-S1 or DAFN-S2 method instead of the DAFN method, traffic for replicating data items is expected to decrease and in certain cases, the data accessibility may increase.

3.3 DCG-S1

DCG-S1 basically adopts the algorithm of DCG, except that the stability of radio links is taken into account when grouping the mobile hosts together. The algorithm of DCG-S1 is as follows:

(1) At every relocation period, each mobile host broadcasts its host identifier. After all mobile hosts have completed the broadcasts, every host should know all the other connected mobile hosts and their identifiers. Each mobile host exchanges with all its neighboring hosts information on its current movement.

(2) In each set of connected mobile hosts, starting from the mobile host with the lowest suffix (i_0) of host identifier (M_{i_0}), an algorithm to find biconnected components is executed in which two hosts M_i and M_j are considered to be connected only when $B_{ij} \geq x$, where x is a threshold value. Then, each biconnected component is put to a group. If a mobile host belongs to more than one biconnected components, that is, it is an articulation point, it belongs to only the group of biconnected component first found in executing the algorithm.

(3) In each group, the mobile host with the lowest suffix of host identifier calculates for each data item, the summation of access frequencies of all mobile hosts in the group to the item. It then creates a list of data items sorted in the descending order of the access frequencies of the group.

(4) In the order of this list, replicas of data items are allocated until memory space of all mobile hosts in the group becomes full. Here replicas of data items which are held as originals by mobile hosts in the group are not allocated. Each replica is allocated at the host whose access frequency to the data item is the highest among hosts that have free memory space. When there exist mobile hosts with the same access frequencies, it is allocated at the mobile host with a lower suffix of host identifier.

(5) After allocating replicas of all kinds of data items, if there is still free memory space at mobile hosts in the group, replicas are allocated from the top of the list again until the memory space is full. Each replica is allocated at the host whose access frequency to the data item is the highest among all hosts that have free memory space to create it and do not hold the replica or its original. If there is no such mobile host, the replica is not allocated.

With the DCG-S1 method, a larger group of mobile hosts can share replicas with each other, thus more variety of data items can be replicated on different mobile hosts, which may make the data accessibility higher. However, compared to the DAFN-S1 and DAFN-S2 methods, since more information needs to be exchanged, this method not only takes a longer time when allocating replicas, but also causes traffic to increase.

Example:

We show an example of executing the DCG-S1 method using the same data access frequencies in Table 1. **Figure 3** shows the result of executing the DCG-S1 method. In this figure, three groups are created (shown by dotted circles). The data access frequencies of these

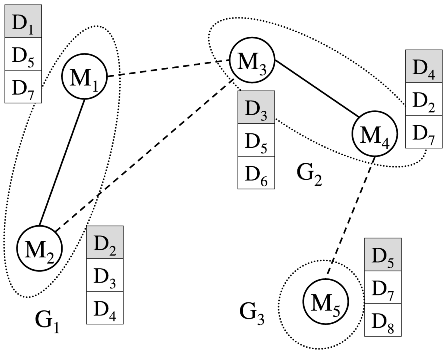

Fig. 3 Result of the DCG-S1 method.

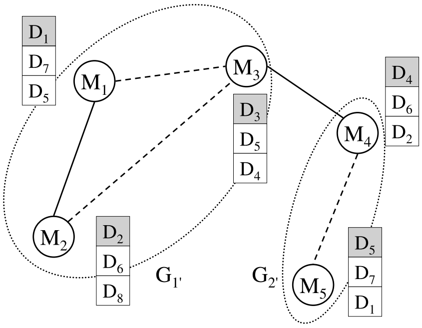

Fig. 4 Result of the DCG method.

groups are also shown in Table 1.

As a comparison, we include **Fig. 4** that shows the result of executing the DCG method. In this figure, only two groups are created. Similar to the DAFN method, when the unstable radio links are disconnected, mobile hosts can no longer access data items previously accessible. Hence, it is better not to share data items among mobile hosts that are connected by unstable radio links.

4. Performance Evaluation

4.1 Simulation Model

In our simulation, mobile hosts move around in a 50×50 space according to the random waypoint model. The rest period is a constant r. For simplicity, r is set to 0 in our simulation. The destination is selected uniformly in the 50×50 space and the movement speed is distributed uniformly between 0 and d. The radio communication range of each mobile host is fixed as a circle with the radius of R. Both the number of mobile hosts and kinds of data items in the whole network are 40 ($\boldsymbol{M} = \{M_1, \cdots, M_{40}\}$, $\boldsymbol{D} = \{D_1, \cdots, D_{40}\}$). M_i ($i = 1, \cdots, 40$) holds the original data of D_i. Each mobile host creates up to C replicas.

As for access frequency, we consider the following three patterns:

Case 1: The mobile hosts are divided into eight groups (five hosts for each group) where members in each group share the same access frequencies to data items. Specifically, mobile hosts $M_{5(i-1)+1}, \cdots, M_{5(i-1)+5}$ ($i = 1, \cdots, 8$) belong to group G_i. In each group G_i, for each of 25% of all data items $(D_{5(i-1)+1}, \cdots, D_{5(i-1)+10})$, its access frequency is determined as a positive value based on the normal distribution with mean 0.8 and standard deviation 0.05. For each of remaining data items, its access frequency is determined based on the normal distribution with mean 0.2 and standard deviation 0.05. Case 1 represents a situation where the entire system has no access skew and mobile hosts in the same group have the same access characteristics but those in different groups have different access characteristics.

Case 2: All mobile hosts share the same access frequencies. For each of 25% of all data items $(D_1, \cdots, D_{10})$, its access frequency is determined as a positive value based on the normal distribution with mean 0.8 and standard deviation 0.05. For each of remaining data items $(D_{11}, \cdots, D_{40})$, its access frequency is determined based on the normal distribution with mean 0.2 and standard deviation 0.05. Case 2 represents a situation where there is access skew and every mobile host has the same access characteristics.

Case 3: Access frequencies of the mobile hosts to 40 data items are set from 0.025 to 1 with an interval of 0.025. Specifically, the access frequency of mobile host M_i to data item D_j is determined as $0.025 \times (|i-20|+j+1)$ where $|i-20|+j+1 \leq 40$ and $0.025 \times (|i-20|+j-39)$ otherwise. Case 3 represents a situation where the entire system has no access skew but all mobile hosts have different access patterns; that is, 40 different access patterns are used for 40 mobile hosts and no two mobile hosts have the same access frequencies for the same data items.

In the proposed methods, replicas are relocated periodically based on the relocation period T. **Table 2** shows the default values of the parameters and the range they vary in the simulation experiments. In the experiments, we vary the relocation period T, the communication range R, the memory size C, and the threshold value x used in evaluating the stability of the radio links. (x is set as 0.6 for the

Table 2 Parameter configuration.

Parameter	Value	(Variation)
d (maximum speed)	1	
r (rest period)	0	
R (communication range)	4	(2 ∼ 18)
C (memory size)	5	(0 ∼ 39)
T (relocation period)	64	(32 ∼ 4096)
x (threshold value)	0.6, 0.3	(0 ∼ 1)

DAFN-S1 and DCG-S1 methods, and 0.3 for DAFN-S2 method.)

In all simulation experiments, we examine the data accessibility and the traffic of each of the three methods during 50,000 units of time and compared them with the original DAFN and DCG methods and the case in which data replication is not performed.

The data accessibility is defined as the ratio of the number of successful access requests to the total number of access requests issued during the simulation time. Here, we exclude data access from a mobile host to its own original data item.

$$\text{data accessibility} = \frac{\#\text{ of successful requests}}{\text{total }\#\text{ of issued requests}}$$

The traffic is defined as the total hop count of data transmission for allocating/relocating replicas. Here, we ignore the traffic for exchanging host identifiers, information on access frequencies, and other messages for determining the replica allocation. This is because the data volume of a data item is much larger than that of an above message.

$$\text{traffic} = \sum (\text{hop count for allocating a replica})$$

4.2 Results

We show the simulation results in this subsection.

4.2.1 Effects of Relocation Period

Figures 5 and **6** show the effects of the relocation period on data accessibility and traffic for the DAFN, DAFN-S1, DAFN-S2, DCG and DCG-S1 methods with the access frequencies of Case 1. In both graphs, the result when data replication is not performed is shown as “No replica”.

From Fig. 5, first of all, it is shown that data replication is very effective to improve the data accessibility. Each replica allocation method gives almost nine times higher data accessibility than the case without data replication.

For this case, the DCG method gives a lower data accessibility than the DAFN method. This is because the difference of access frequencies

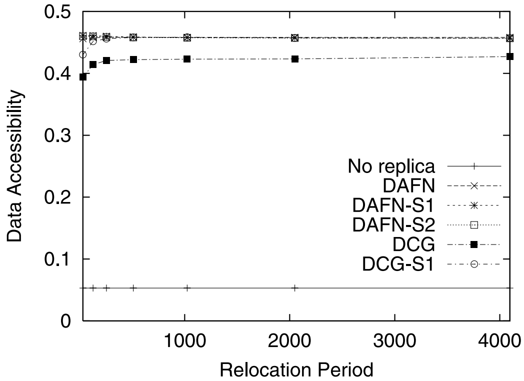

Fig. 5 Relocation period and data accessibility (Case 1).

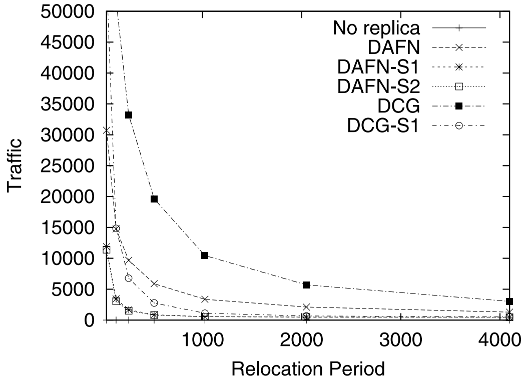

Fig. 6 Relocation period and traffic (Case 1).

is big (0.8 and 0.2), thus when mobile hosts are grouped together in the DCG method, more mobile hosts will be allocated replicas of data items with lower access frequencies. When disconnection occurs, these mobile hosts cannot access data items with high access frequencies allocated at other mobile hosts.

Although it is very hard to see due to the overlap of lines and plots in Fig. 5, both the DAFN-S1 and DAFN-S2 methods give slightly higher data accessibility than the original DAFN method when the relocation period is small (below 1000); and the DAFN-S1 and DAFN-S2 methods give almost the same data accessibility. The DCG-S1 method gives a better improvement from the DCG method compared to the DAFN methods because only mobile hosts connected by stable links are grouped together, thus data sharing becomes more effective. Except when relocation period is small, DCG-S1 gives almost the same or better data accessibility compared to the DAFN-S1 and DAFN-S2 methods.

Table 3 Breadths of confidence intervals.

(a) Data accessibility ($\times 10^{-2}$)

T	32	64	128	256	512	1024	2048	4096
No Replica	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
DAFN	0.218	0.219	0.222	0.220	0.222	0.223	0.227	0.224
DAFN-S1	0.221	0.224	0.225	0.222	0.221	0.216	0.217	0.217
DAFN-S2	0.219	0.220	0.219	0.216	0.216	0.212	0.212	0.213
DCG	0.211	0.216	0.217	0.223	0.220	0.220	0.225	0.245
DCG-S1	0.245	0.258	0.263	0.258	0.246	0.236	0.228	0.226

(b) Traffic

T	32	64	128	256	512	1024	2048	4096
No replica	0	0	0	0	0	0	0	0
DAFN	745	512	310	183	101	52	27	16
DAFN-S1	292	146	73	28	18	15	8	4
DAFN-S2	287	140	59	30	22	14	9	4
DCG	2073	1457	956	538	295	122	61	20
DCG-S1	1143	586	252	100	49	41	22	11

Figure 6 shows that the methods that consider the stability of radio links give a far lower traffic than the original methods, and the DCG-S1 method even gives a lower traffic than the DAFN method in most cases. By calculation, the traffic of the DAFN-S1, DAFN-S2, and DCG-S1 methods improves 75.6%, 76.8%, and 77.9% on average, respectively.

Now, we examine the reliability of the above simulation results. The *Batch Means Method*[3] is used to calculate breadths of 90% confidence intervals for the simulation results, where the batch size is 50,000 units of time and the number of batches is 10. **Table 3** shows the calculation results. The results show that the breadths of 90% confidence intervals are enough small to verify the simulation results in Figs. 5 and 6.

4.2.2 Effects of Memory Size

Figures 7 and **8** show the effects of the memory size on data accessibility and traffic. Figure 7 shows that data accessibility gets higher when memory size gets larger. Overall, the data accessibility is higher when the stability of radio links are taken into account even though the difference is not very big.

On the other hand, traffic increases when memory size gets larger. However, traffic decreases from a certain point. When the memory size is small, traffic is small because the number of replicas relocated is small. When the memory size is large, traffic is also small because all mobile hosts hold the replicas of most data items and thus replica relocation rarely occurs. On the whole, the traffic is much lower when the stability of radio links is taken into account.

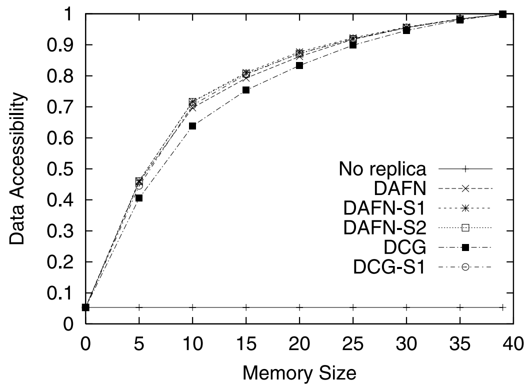

Fig. 7 Memory size and data accessibility (Case 1).

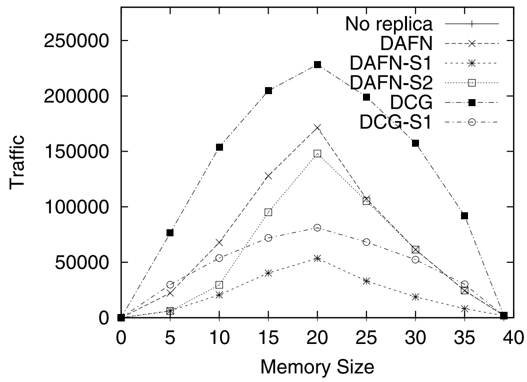

Fig. 8 Memory size and traffic (Case 1).

4.2.3 Effects of Radio Communication Range

Figures 9 and **10** show the effects of the radio communication range on data accessibility and traffic. From Fig. 9, as the radio communication range gets larger, the data accessibility also gets higher in every method. This is be-

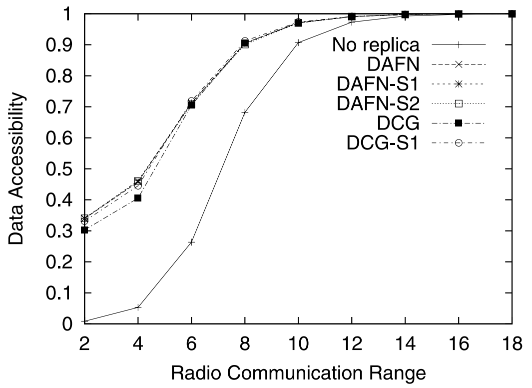

Fig. 9 Radio communication range and data accessibility (Case 1).

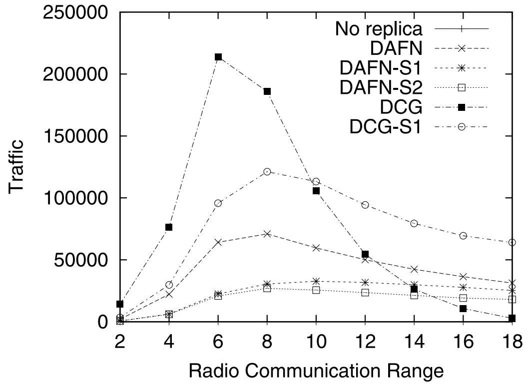

Fig. 10 Radio communication range and traffic (Case 1).

cause the number of mobile hosts connected to each other gets larger, and thus, mobile hosts can access original data items with higher probability. This is shown by the result of "No replica", where the data accessibility to original data items gets higher as the radio communication range gets larger. Of the three proposed methods, when the radio communication range is small, the DAFN-S1 and DAFN-S2 methods give higher data accessibility than the other methods. When the radio communication range is large, the DCG-S1 method gives the highest data accessibility.

From Fig. 10, when the radio communication range gets larger, the traffic also gets larger, but it becomes smaller from a certain point. When the radio communication range is small, the number of mobile hosts connected to each other is small, thus replica relocation does not cause large traffic. On the other hand, when the radio communication range is very large, the DCG methods give a smaller traffic than the

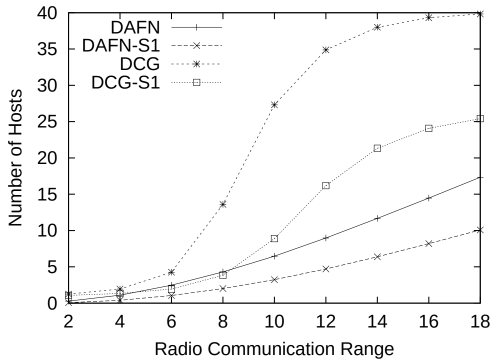

Fig. 11 Number of hosts and traffic (Case 1).

DAFN methods. Since the number of mobile hosts in a group is large in the DCG method, mobile hosts can access original data items in most cases and thus replica relocation rarely occurs.

Now, to verify above discussions for the results from Fig. 10, we examine the average numbers of neighboring hosts for one mobile host in the DAFN and DAFN-S1 methods and those of hosts in one group to which a host belong in the DCG and DCG-S1 methods. Here, the neighboring hosts that are linked by unstable links are excluded in the DAFN-S1 method. Moreover, the DAFN-S2 method are excluded in this examination since this method takes into account both the stability of radio links and access frequencies to data items when eliminating duplicate replicas and thus the number of neighboring hosts cannot be defined. **Figure 11** shows the examination results. From the results, as the radio communication range gets larger, the average number of neighboring hosts or hosts in one group gets larger in every method. The results verify our discussions for the results from Fig. 10.

4.2.4 Effects of Access Characteristics

Figure 12 shows the data accessibility for three different cases of data access frequencies for the DCG-S1 method. The data accessibility is the highest in Case 1, followed by Case 2 and Case 3. In Case 2, since all mobile hosts have the same access characteristics, it is efficient to sensitively relocate replicas with a short interval according to the changes of network topology. We omit the graph which shows the traffic here, since all three cases gives almost the same results. We also omit the results of the DAFN-S1 and DAFN-S2 methods which show the same thing.

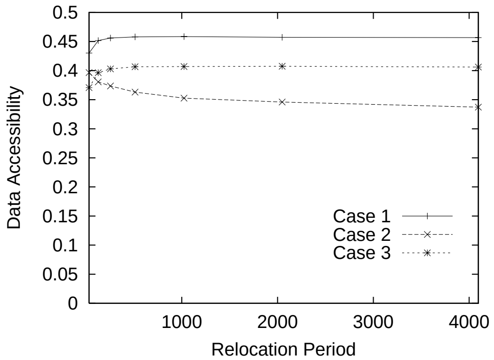

Fig. 12 Relocation period and data accessibility for three different cases of data access patterns in the DCG-S1 method.

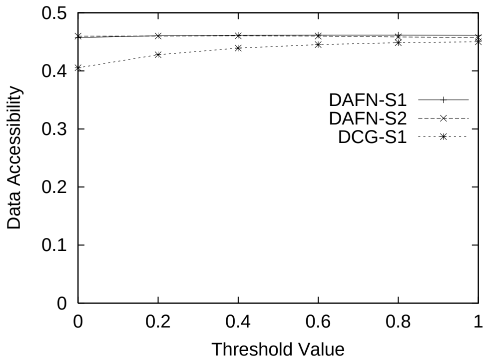

Fig. 13 Threshold value and data accessibility (Case 1).

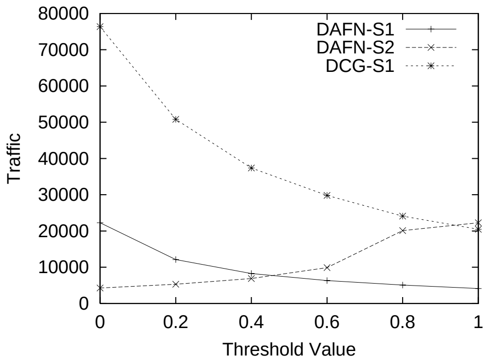

Fig. 14 Threshold value and traffic (Case 1).

4.2.5 Effects of Threshold Value x

Figures 13 and **14** show the effect of the threshold value x on data accessibility and traffic. For the DAFN-S1 or DCG-S1 method, $x = 0$ represents the original DAFN or DCG method; for the DAFN-S2 method, $x = 1$ represents the original DAFN method. For both data accessibility and traffic, the DAFN-S1 and DCG-S1 methods give a better performance when the threshold value increases, while DAFN-S2 method gives a better performance when the threshold value decreases. This proves that the newly proposed methods are effective in decreasing the traffic and increasing the data accessibility.

From the above, we can conclude that in all cases, traffic for relocation is greatly reduced. Data accessibility is also slightly increased in the above cases. Overall, the DCG method shows a greater improvement when the stability of radio links are taken into consideration.

5. Conclusions

In this paper, we have proposed a few methods for allocating replicas in ad hoc networks considering the stability of radio links. We have shown in our simulation results that the methods proposed give a better performance compared to those do not take into consideration the stability of radio links.

In this paper, we have estimated the time remaining until a radio link between two mobile hosts is disconnected from the distance between the two hosts, their movement speed, and their radio communication ranges. However, this estimation is not always precise in a real environment because there often exist some obstacles to radio communication, e.g., buildings. Therefore, as part of our future work, we plan to extend our proposed methods to consider such obstacles to radio communication. Intuitively, this is done by considering the signal strength of radio links. In the research field of ad hoc networks routing, several protocols consider the signal strength of radio links [2),4),5),16)]. These approaches could be partially applied to extend our methods.

Moreover, we will extend the proposed methods to adapt an environment where update of data items occurs. For this task, the approaches in Ref. 7) could be partially applied. We are also looking at the possibilities of using methods where mobile hosts leave behind necessary replicas before the disconnection.

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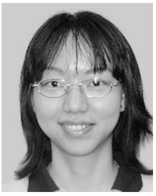

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