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A Perspective on Next-Generation Ad Hoc Networks

—A Proposal for an Open Community Network—

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SUMMARY The concept of wireless ad hoc networking has unique features in which neither base stations nor wired backbone networks are required and a mobile node can communicate with a partner beyond the transmission range by multihopping. In this paper, innovations and issues in ad hoc network technologies are reviewed. The concept of a general-purpose ad hoc network is identified as a step toward next-generation ad hoc network development. The concept of an open community network is then presented as a vision for general-purpose ad hoc networks. An open community network is a novel information infrastructure for local communities based on wireless multihopping technologies, which may support an advanced information-oriented society in the twenty-first century. As a case study, an experimental system using PHS (Personal Handy Phone System) is described and some research issues for developing an open community network are identified.

key words: *multihop, wireless, mobile communication, ad hoc network, community network*

1. Introduction

The number of mobile communication subscribers has continued to grow rapidly in many countries and has even exceeded that of conventional telephone subscribers in some countries. These statistics show how mobile communication fits the needs of the present society. It is of no doubt that mobile communication services will be further enhanced in the twenty-first century, which requires continuing innovations in mobile communication technologies.

In the current cellular mobile architecture, only the last hop is wireless. On the other hand, in the wireless multihop architecture, every hop is wireless and a message is carried from a source to a destination by repeating wireless hopping at intermediate nodes on a route. This technique, termed wireless multihopping, is used in so-called ad hoc networking [1]–[55]. Ad hoc networking is a technology that instantly creates a network for a specific and temporary purpose within a group. Typical ad hoc network applications include military affairs, events and disaster recovery. In short, conventional ad hoc networks are considered as specific-

purpose ad hoc networks.

It should be noted, however, that wireless multihopping is a general and promising technique and can be used for wider applications beyond conventional categories of ad hoc networks. Specifically, instead of specific-purpose ad hoc networks, a general-purpose (or universal) ad hoc network may be useful and can be a step toward next-generation ad hoc networks [47]–[49]. As an example, this technique has a high potential for realizing a novel communication environment, which cannot be properly covered by conventional cellular mobile technologies, giving rise to many challenging research issues.

In this paper we present an overview on ad hoc networks and identify a general-purpose ad hoc network as a step toward next-generation ad hoc networks. We also propose the concept of an open community network, a novel information infrastructure for local communities, as a vision of a general-purpose ad hoc network.

The rest of the paper is organized as follows: Section 2 presents an overview on ad hoc networks. Section 3 shows a concept of an open community network, where a communication port (CP) is introduced as a key element for the network. Section 4 describes a case study for developing an open community network [55]. Section 5 gives the concluding remarks.

2. Overview of Ad Hoc Networks

2.1 Background

Ad hoc networks have the following features. They do not use base stations and a wired backbone network, which are indispensable to conventional mobile communication networks. Mobile nodes directly send messages to each other using radio waves. A node can send a message to a destination node beyond the transmission range by using other nodes as relay points (wireless multihopping). That is, a node provides a router function. The name ad hoc networks was given because nodes are instantly connected to form a network in any area without depending on any infrastructure. Ad hoc networking is promising to realize a new communication environment which conventional networks cannot cover, and is a field in which rapid development is expected in the near future.

The research on ad hoc networks has a long his-

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tory. It was started in 1970s as part of the ARPA project. With the explosive growth of the Internet and mobile communication networks, research activities have been activated. Various routing and multicast protocols have been proposed in IETF MANET (working group on mobile ad hoc networks) [56]. With innovations in computer and communication technologies, ad hoc network based service development has also been activated recently. For example, applications for supervising and managing widely spread facilities, for distributing teaching materials in a classroom, and for spreading vacancy information of a parking lot to drivers in the neighborhood have been developed on ad hoc networks. A conventional ad hoc network is usually a closed network which is used in a specific user group for a specific and temporary purpose.

2.2 Next-Generation Internet and Ad Hoc Networks

Internet technologies have rapidly progressed, but it is not sufficient in terms of quality and reliability, and continuous innovation is required. Research on next-generation Internet has been activated worldwide. In the next decades, computers will be a part of all equipment in various places such as homes, offices, streets, and it is considered that these computers will be connected to the Internet (IP on Everything) [57]. Drastic innovations are required of the Internet's architecture in order to cope with such an environment. Novel concepts will also be required in mobile communication at that age and ad hoc networks may hold the key as a basis of next-generation Internet (Fig. 1). In this context, next-generation ad hoc networks may create a new paradigm in the history of mobile communication technology.

The concept of next-generation ad hoc network is not yet clear at this time. We propose the concept of a general-purpose (or universal) ad hoc network as a possible step toward next-generation ad hoc networks, while many conventional ad hoc networks are considered as rather specific-purpose ad hoc networks. A

general-purpose ad hoc network is an open network which can be used by anybody, anytime, anywhere. A general-purpose ad hoc network may be a heterogeneous network, where different nodes in terms of transmission range as well as communication technologies should be allowed. A specific-purpose ad hoc network can be formed with the support of a general-purpose ad hoc network. For example, nodes of a general-purpose ad hoc network can be used as routers for a specific-purpose ad hoc network in order to increase connectivity and reliability.

2.3 Wireless Communication Technologies

Node communication devices support either connection-less communication (packet radio) or connection-oriented communication (wireless circuit connection). For example, wireless LAN belongs to the former and PHS (Personal Handy Phone System) with the transceiver mode belongs to the latter. Bluetooth may support both types of communication. In packet radio, a packet is forwarded to all nodes in a range of transmission simultaneously. On the other hand, in wireless circuit connection, a packet is forwarded only to a connected destination node. ID discovery and connection setup are necessary before data transmission. A node may have more than one wireless circuit connection device. It is, then, possible for a node to send/receive packets with multiple partners simultaneously, resulting in the improvement in communication performance.

2.4 Node Responsibility

In an ad hoc network, a mobile node may be used as a router for relaying information, even if the node does not require it, resulting in battery consumption. Instead, it can acquire information which it needs, by employing the router function of others nodes. That is, it is a give and take relation. It is a question of whether the router function is obligatory or optional for each node. If it is not a duty, some nodes may select not to perform router function. As a result, the chance for one node to communicate with another node may decrease. That is, network connectivity may be degraded due to network partitioning. If it is a duty, however, some nodes may run out of battery power when they are used as a router.

It may be necessary to restrict the conditions for a node to exempt it from the duty of the router to avoid network partitioning. For example, a node is allowed to switch off router function when battery power is less than a certain value. It is also possible that battery power awareness is given to a routing, which seeks to use only nodes with enough battery power as routers [16].

Another related question is how to manage nodes that originate too many packets and make the network

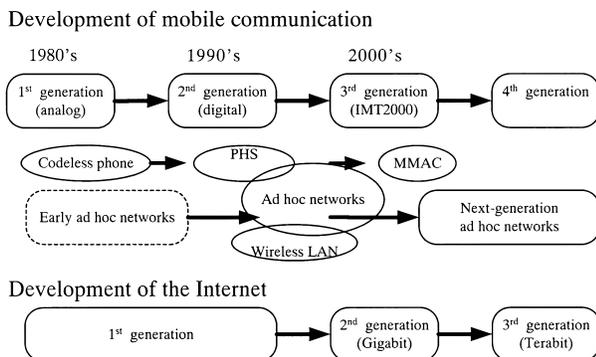


Fig. 1 Positioning of next-generation ad hoc networks.

overloaded. As an extreme case, “denial-of-service attack” may happen. One method is to set the maximum packet-originating rate per node. A mechanism to detect a node violating this rate is required. If violation is detected, nodes in the neighborhood should be allowed to switch off their router function so as to guard the network.

The two questions mentioned above refer to how the benefits received from the network are balanced by the required burden and responsibility, and further examination of both philosophy and technology is necessary.

2.5 Network Configuration

The following four scenarios are considered: (a) An ad hoc network is composed of only stationary nodes. (b) An ad hoc network is composed of only mobile nodes. (c) An ad hoc network may interwork with a conventional mobile communication network. (d) An ad hoc network is composed of nodes with special functionality, which may or may not move, in addition to mobile nodes. Scenario (d) is promising to build a general-purpose ad hoc network, where full connectivity among nodes is easily realized with the support of special nodes, which may be free from power concern.

2.6 Neighborhood Communication

Telecommunication networks are useful to realize communication beyond time and distance and may be used instead of railways and roads. Virtual communities are possible regardless of participants’ geographical locations with the support of telecommunication networks. These advantages of telecommunication networks have often been pointed out. On the other hand, communication in a local area is also important in our daily life. Local area networks and Cable TV networks are examples of networks supporting local communication, but these networks provide specific services for specific user groups in specific areas.

We may need a new paradigm of neighborhood communication, which is available for anybody, anytime, anywhere. This paradigm supports real communities instead of virtual communities, providing significant benefits in our daily life. General-purpose ad hoc networking seems adequate to create such flexible communication environments.

3. An Open Community Network

The concept of an open community network is one of the visions for general-purpose ad hoc networks [55]. Specific-purpose ad hoc networks can be built on top of the open community network. Figure 2 shows an image of an open community network, which is characterized as follows:

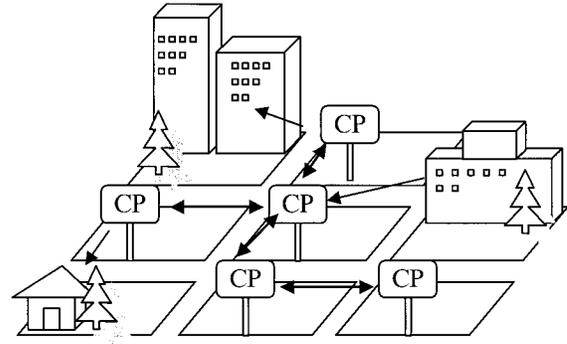


Fig. 2 Image of an open community network.

(a) It is not a temporal and closed network for a specific purpose, but an open network for general purposes, which is freely available for anybody in a local community.

(b) Communication ports (CPs) are placed at adequate intervals along avenues and streets, where commercial power or solar batteries are available.

(c) Personal computers, PDAs (Personal Digital Assistants), mobile telephone devices and sensors are examples of hosts in this network.

(d) The network is an all-wireless network, that is, wireless communication is used between a host and a CP as well as between CPs.

(e) A source host submits information (a message) to the nearest CP.

(f) A message accepted by a CP is delivered to all CPs in a specified area through wireless multihopping. All CPs that receive the message maintain it for a specified time.

(g) Any host accesses the nearest CP to download messages.

(h) A CP may support multiple mobile communication interfaces.

A node with a specific communication interface cannot communicate with a node with a different interface. To overcome this problem, a node may support multiple interfaces, resulting in an increase in node complexity and cost. Software radio technology contributes to reduce node complexity. Another approach is to implement multiple interfaces within some CPs instead of every mobile node. As a result, a node with a single interface can communicate with other nodes with different interfaces via CPs.

As described above, a CP is a key element in an open community network. It provides an interface with mobile hosts that send and receive messages. It also works as a message repository point as well as a message forwarding node.

Note that a conventional community network is targeted to realize a closed network for a specific area [58]. It is difficult for such a network to flexibly change its coverage beyond the area, or for visitors to partic-

ipate due to physical constraints. Wireless multihopping technology can realize an open community network without such barriers. In the Internet, messages are usually transmitted on demand from a source to a destination. This is possible in an open community network. In addition, another mechanism is supported in an open community network, where each CP collects and maintains messages in advance and later supplies them on demand to hosts in the neighborhood. This feature is similar to a news server in the Internet.

In an open community network, loudspeakers may become useless as guides in public places. For example, sales information is delivered to pedestrians in a shopping center, or to a residential area using the open community network, without making noise. Alarm information is spread from sensors embedded in traffic signals at intersections, or in light poles along streets to pedestrians and drivers in a neighborhood so that the number of traffic accidents significantly decreases. This system is also useful to navigate old people and the disabled walking along the street. Other benefits include crime prevention, electric power saving, and living environment improvement. In addition, an open community network is useful to maintain communication between victims and rescue workers as well as among rescue workers in emergencies and disasters. These examples require communication between nonspecific persons, which an open community network can adequately support. These are only some examples and an open community network may have various applications in the future.

4. Case Study for an Open Community Network

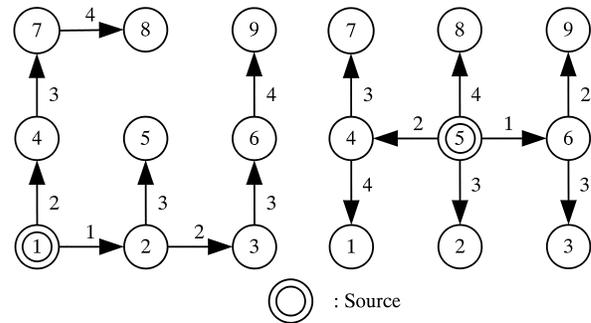
4.1 Wireless Communication Technology

We focus on circuit connection technology, in which circuit connection setup, message transfer, and circuit disconnection are performed between adjacent CPs, to transfer a message over one hop. This process is repeated until a message is received by a destination. This is a store and forward type message delivery system, and is suitable for non-real-time applications and multicasting. Another method is to set up a virtual channel between a source CP and a destination CP through intermediate CPs (end-to-end connection), which is adequate for real-time applications and unicasting. For our purpose of information diffusion among CPs, the store and forward scheme is adequate, because it easily supports one to many message deliveries.

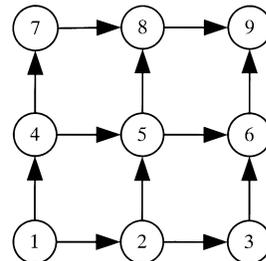
4.2 Circuit Connection Control

(1) Message-by-message forwarding scheme

In the case of packet radio scheme, each CP can broadcast a packet to neighbor CPs, while, in the case of



(a) Message-by-message forwarding



(b) Bulk message forwarding

Fig. 3 Message forwarding schemes.

wireless circuit connection, each CP can send a message only to a single CP by each connection. After the first message delivery, two CPs have the same message, and it is possible to send a message in parallel to other two CPs simultaneously. This process is repeated to diffuse a message to all CPs in the network. Assuming that a source CP knows network topology, it can compute an optimal connection tree to complete the delivery of a message to all other CPs with minimum connection steps, which is termed the minimum step tree. Examples of minimum step trees are shown in Fig. 3(a), where the number beside each arrow indicates the order of a connection (step) in a connection tree, in which the $(i+1)$ -th step may be attempted after completion of the i -th step. This tree information can be piggybacked by the message and sent from CP to CP at each connection so that the subsequent CPs can recognize the corresponding connection tree.

Message-by-message forwarding scheme is not efficient if a message is short. This is because each connection transfers only one short message, resulting in a short holding time, while each connection has an overhead of setting up and disconnecting a connection. Thus, the short holding time means that the percentage of overhead is high. Message-by-message forwarding scheme may still work well if there is only a single-source CP in the network. On the other hand, if there are multiple-source CPs in the network, blocking may occur in the network, even if each source CP independently selects its optimal connection tree, because all connection devices of a called CP are busy.

(2) Bulk message forwarding scheme

In the bulk message forwarding scheme, each CP sets up a circuit to a designated CP periodically, when calling and called CPs exchange new messages, which each CP does not have. An example of connections in this scheme is shown in Fig. 3(b). This scheme involves delay in forwarding received messages at each CP, but multiple messages can be exchanged in both directions by a single connection. It significantly reduces circuit connection and disconnection overheads as well as blocking probability, resulting in efficient message delivery, compared with the message-by-message forwarding scheme. Note that only a uni-directional channel is used in each connection in the message-by-message forwarding scheme.

(3) Call control

When a CP has multiple circuit connection devices, each may have a different number. We assume that a calling CP does not know which devices at the called CP are free or busy. In this case, a CP attempts a call to one of the devices of the called CP. If it is busy, retry is made to another device. This process continues until discovery of a free device (sequential search) [54], which is time-consuming. Alternatively, each device on the same CP may have a common number. In this case, a free device, if any, can be detected by a single attempt (key number search).

If all devices of a called CP are busy, which is termed CP busy, a call is incomplete (blocked), and a calling CP may attempt retry. However, instant retry may not be effective since all devices of the called CP may still be busy. Moreover, a deadlock may happen in the case of conflict by simultaneous attempts by different CPs. Random delay should be given before retry to avoid deadlock [54].

4.3 Performance Evaluation Based on Experiments [55]

4.3.1 Network Model

An experimental system for an open community network has been developed, where PHS is used as a wireless circuit connection device. A personal computer system with one or two PHS devices simulates the behavior of a CP, where sequential search is used. PHS supports the transceiver mode with PIAFS protocol, where circuit bandwidth is 32kb/s and effective throughput is 29.2kb/s. With the transceiver mode, two PHSs directly communicate with each other without support from the base station. In the experimental system, eight CPs are used to make a network (Fig. 4). We assign one to six CPs to be sources of messages. Source CPs send a message (51kbytes) to the rest of the CPs simultaneously by using the message-by-message forwarding scheme.

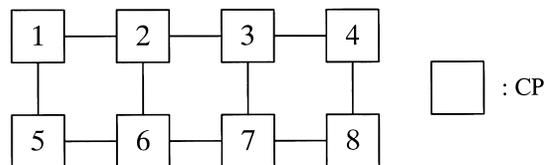


Fig. 4 Network model.

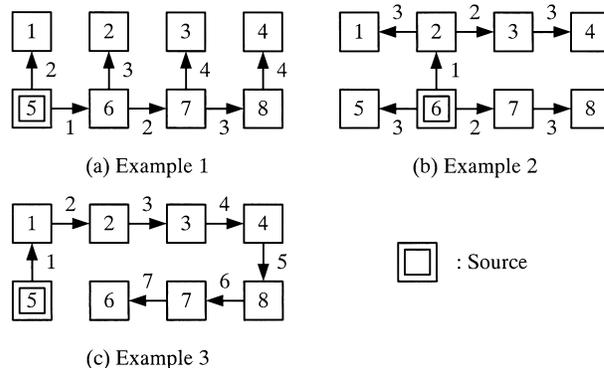


Fig. 5 Example of connection trees.

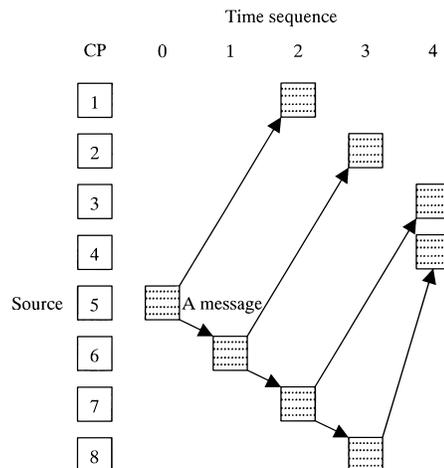


Fig. 6 Time sequence for diffusing a message.

4.3.2 Connection Tree Selection

We consider two policies in designing connection trees. In the first policy, minimum step trees are used. Figure 5(a) shows an example of a minimum step tree that originated at CP 5, which requires four steps at maximum to diffuse a message from CP 5. In this case, a message that originated at CP 5 is shared by other CPs according to the time sequence shown in Fig. 6. Figure 5(b) shows an example of a minimum step tree that originated at CP 6, which requires three steps at maximum to diffuse a message from CP 6.

In the second policy, a connection is set up along a

uni-directional loop. An example of a connection tree originating at CP 5 is shown in Fig. 5(c), which requires seven steps at maximum to diffuse a message from CP 5. There is no connection tree that requires more than seven steps; thus, this connection tree is termed the maximum step tree.

4.3.3 Retry Parameters [54]

Assuming that a call is blocked at time 0, random delay for the first retry is chosen from an interval $[t_1, t_2]$, where $t_1 = 20$ sec and $t_2 = 50$ sec for the minimum step tree, and $t_1 = 10$ sec and $t_2 = 20$ sec for the maximum step tree. The value of t_2 is updated at every retry such that the length $(t_2 - t_1)$ is doubled so as to resolve possible conflicts, when the minimum step tree is used. On the other hand, the same interval is used for successive retries, when the maximum step tree is used.

4.3.4 Performance Metric

We repeat experiments five times. We measure the time required for each connection in each experiment. This time includes time to set up a connection, time to send a message, and time to disconnect a connection. We obtain the following metrics as an average of five experiments to evaluate network performance.

Time to deliver: Average time required to complete delivery of a message

Connection failure rate: $(N_i + N_d) / N_t$

N_i = Number of incompleting connections

N_d = Number of disconnected connections in progress

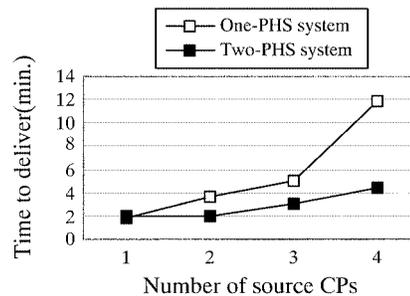
N_t = Total number of connections,

where the number of retries in sequential search is not counted to obtain N_i .

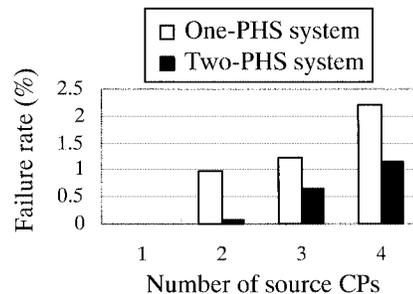
4.3.5 Results of Experiments

Figure 7(a) compares time to deliver between one-PHS system and two-PHS system, where the minimum step tree is used. When more than one source CP simultaneously dispatches messages, some CPs often become busy in the one-PHS system, resulting in a high percentage of blocking. This situation is relaxed in the two-PHS system, as shown in Fig. 7(b). As a result, time to deliver is significantly reduced in the two-PHS system compared with the one-PHS system, as shown in Fig. 7(a).

Figure 8 compares time to deliver between the minimum step tree and the maximum step tree in the two-PHS system. It is shown that the former is superior when the number of source CPs is less than 4, but inferior when that is more than 4. This is because blocking probabilities significantly increase in the minimum step tree as the number of source CPs increases. On the other hand, increase in blocking is controlled in the maximum step tree, because conflict is minimized. This



(a) Average time to complete delivery of a message



(b) Connection failure rate

Fig. 7 Comparison of one-PHS and two-PHS systems.

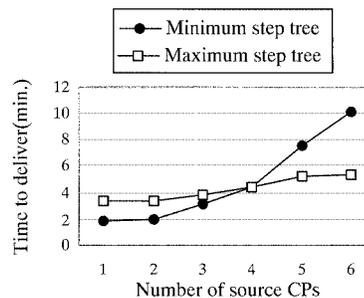


Fig. 8 Comparison of connection trees (Two-PHS system).

is why the maximum step tree is superior as the number of source CPs increases, regardless of the disadvantage in number of maximum steps in the connection tree.

5. Conclusion

Innovations and issues in ad hoc network technologies were summarized. The concept of a general-purpose ad hoc network was identified as a step toward next-generation ad hoc network development. The concept of an open community network was then presented as a vision for general-purpose ad hoc networks. An open community network is a novel information infrastructure for local communities based on wireless multihopping technologies. It is not a temporal and closed network for a specific purpose, but an open network for general purposes, which is freely available for anybody in a local community. The communication port (CP)

is a key element in an open community network. It provides an interface with mobile hosts sending and receiving messages. It also works as message repository point as well as message forwarding node.

As a case study, an experimental system using PHS (Personal Handy Phone System) was described and research issues for developing an open community network were identified. Specifically, it was shown that network performance is significantly affected by the number of PHSs per CP and the assignment of connection trees for diffusing messages in the network. Experiments are going on to evaluate network performance and to identify parameters to design an open community network. This case study investigates only a part of network design and control issues for building an open community network.

The area of next-generation ad hoc networks involves many interesting and challenging research issues including not only technical but social aspects, and further studies are required to meet new communication demands and requirements for an advanced information-oriented society in the twenty-first century.

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