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NerveNet: A Regional Platform Network for Context-Aware Services with Sensors and Actuators

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SUMMARY Wireless access networks of the future could provide a variety of context-aware services with the use of sensor information in order to solve regional social problems and improve the quality of residents' lives as a part of the regional infrastructure. NerveNet is a conceptual regional wireless access platform in which multiple service providers provide their own services with shared use of the network and sensors, enabling a range of context-aware services. The platform acts like a human nervous system. Densely located, interconnected access points with databases and data processing units will provide mobility to terminals without a location server and enable secure sensor data transport on a highly reliable, managed mesh network. This paper introduces the motivations, concept, architecture, system configuration, and preliminary performance results of NerveNet.

key words: *network platform, regional network, sensor and actuator network, context-aware*

1. Introduction

The New Generation Network (NWGN) [1], [2] has been researched with an aim toward realization as part of society's infrastructure in the 2020s. Diverse wireless access technologies will be introduced, applying various transmission technologies such as optical packets and path integrated transport, and an enormous number of myriad devices, including sensors, actuators, ID tags, consumer electronics, automobiles, and robots, will be interconnected via the network. These new networked devices, particularly those that are wirelessly connected, are likely to become the mainstream, and network architecture and functions for accommodating them will be the primary factors in determining the full NWGN. The network is expected to greatly enrich the lives of mobile users with novel, context-aware, situation-adapted services via the use of sensor data and providing a variety of high-quality multimedia content.

From this perspective, we have proposed a conceptual regional platform network called NerveNet, which accommodates servers and various new devices, as well as mobile phones and PCs. Sensors perceive weather, traffic, disasters, crime, regional events, family, and individual movement. In response to this information, NerveNet provides information and services needed for localities or individuals, sometimes by activating actuators such as beepers, vibrators, pop-ups, and future networked robots. In this sense, NerveNet works like a human nervous system, which is the origin of its name.

The rest of the paper is organized as follows. In Sect. 2, motivations and needs for future access networks are explained. The concept of NerveNet is introduced in Sect. 3. In Sect. 4, the system and functional architecture are provided. Example applications are introduced in Sect. 5. In Sect. 6, current implementation of the evaluation system and preliminary performances are presented.

2. Motivations and Needs

The motivations and needs for future access networks can be broken into four areas of focus. First is the need for localized, personalized services and applications. A variety of services and applications that use sensor data are expected [3]. One example is a security application that warns families when elderly family members or children during their commute get close to a dangerous area or face an emergency. Burglarproofing crops before harvesting is another potential use. Providing health advice and suggesting the best menu based on eating and exercise history, or advertising products and services of small, local stores or startups to the right customers based on their interests and potential needs are other examples expected to enrich local regions and the lives of their citizens. These services and applications generally need customization of many aspects because individuals and local regions by nature have different interests, problems, and needs. For security applications, locations of security cameras and motion detectors, and their network configuration differ from region to region. This encourages cost-effective, flexible networking technology for providing localized and personalized services and applications.

The second focus is the nature of locality and privacy of sensor data. Existing access networks, such as cellular and wireless mesh networks, are a part of communication networks that mainly provide end terminals with an "access pipe" for accessing the core, central network. This core-oriented model has been efficient in accumulating a massive amount of relatively "static" data and information used by many users. Yet this model becomes inefficient and ineffective because future services and information produced by processing sensor data in a local region are mainly for that region and its citizens, which are local-oriented and time-sensitive, and have a sense of privacy. Therefore local net-

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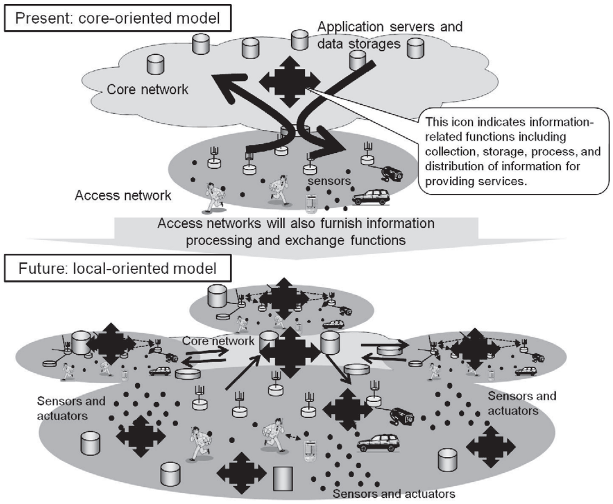

Fig. 1 Transition from the core-oriented to the local-oriented model.

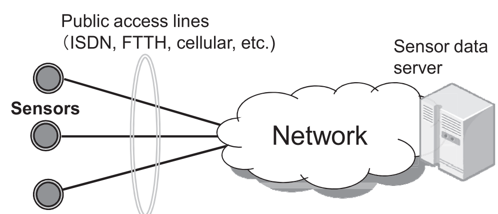

Fig. 2 Current typical deployment model of installing sensors.

works, rather than the core network, are good at circulating, accumulating, and processing sensor data and producing services and information for users within the networks. This local-oriented model could reduce the volume of traffic between local and core/backbone networks, better protect data and users' privacy from potential breaches in global networks, and provide context-aware services with an immediate response to processed sensor data. An image of the transition from the core-oriented to the local-oriented model is shown in Fig. 1. An architecture that bears a certain, conceptual similarity in localizing data traffic within access networks without routing to the core network is being considered for future cellular-type mobile networks [4].

Third is the need for technology for connecting sensors to the network in an efficient, practical way. Figure 2 shows a typical network configuration of currently available sensor network systems such as weather forecasting and car traffic monitoring. Each sensor installed outdoors is connected to the network through public access line services such as an Integrated Services Digital Network (ISDN), fiber to the home (FTTH), and cellular systems. Since data communications charges including a monthly fee are typically required for each sensor, it is difficult to profitably deploy a large-scale sensor network with a huge number of sensors. A sensor gateway with a sensor cell and connecting with the network through public access lines could economically aggregate data from the sensors and forward it to the sensor data server (see top of Fig. 3). This is typical of sensor network

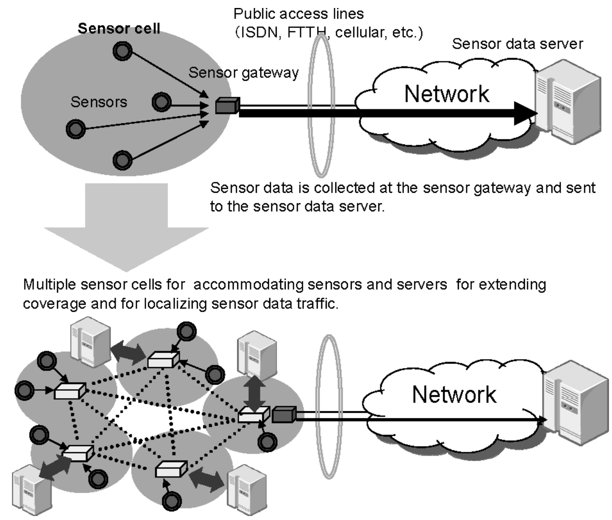

Fig. 3 Cost-effective deployment model using sensor gateways (top) and proposed model (bottom).

models that have been considered by research communities [5]. It is, however, still not easy to extend the area where sensors are deployed, even with this model. As shown at the bottom of Fig. 3, interconnecting multiple sensor cells is beneficial for extending the area and increasing the number of sensors to be accommodated. If these can accommodate sensor data servers as well, it will decrease traffic to/from the external networks and the associated cost [6].

Fourth is the need for densely located base stations. A wireless link speed of one gigabit per second or more is a prerequisite for future mobile networks with reasonable power consumption from mobile devices, as well as base stations beyond fourth-generation cellular networks [7]. Increasing the spatial density of base stations is one approach, though the networking of a large number of base stations would be a tradeoff. The wireless multi-hop concept of interconnecting base stations wirelessly has gained increased attention since it is thought to be an effective means for economically and flexibly deploying numerous base stations [8], [9]. This concept effectively accommodates not only mobile devices but also sensors and actuators that would need much greater power saving than mobile devices.

3. Concept of NerveNet

3.1 Overview

NerveNet is a form of regional network infrastructure that provides a variety of services by the use of sensor information and regional information-sharing and exchanges in order to solve regional social problems and improve the quality of residents' lives. Figure 4 provides an illustration. End terminals, such as mobile terminals, sensors, and actuators, are accommodated by densely deployed base stations (BSs) interconnected through wired or wireless connections in a mesh topology. Community Service Gateways (CSGs) are placed in various regional centers, educational

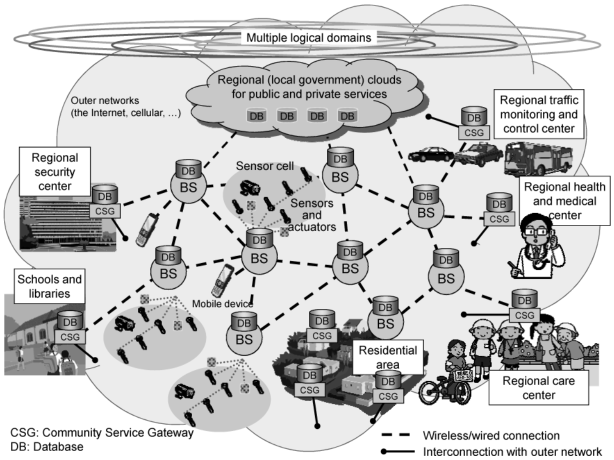

Fig. 4 Configuration and service image of NerveNet.

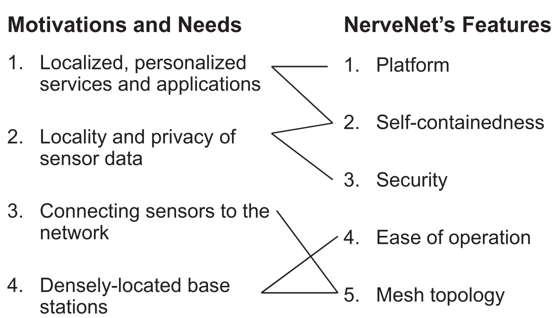

Fig. 5 Relationship between motivations/needs and features.

facilities, companies providing services, and private homes. Services for disaster prevention, health and medical care, social services, transportation, education, and other government, civil, or private services and functions are provided by each CSG, which has a sensor database and computing capability. For example, a CSG in Mr. A's house can record the location information of mobile terminals owned by his family. This information is not provided to third parties, and can be used for monitoring his children or for measuring walking distance for health improvement.

The features of NerveNet can be split into five areas of focus: mesh topology, platform, self-containedness, security, and ease of operation. The relationship between the features of NerveNet and the motivations and needs for future access networks are shown in Fig. 5.

3.2 Platform

Since living environment differs greatly from region to region, services using sensor data will also differ by region. These services, however, will not be equipped with a set of single-purpose sensor networks because of the high amounts of time and expense. Certain service may also not be profitable because their market size is significantly smaller than that of a basic and common service such as telephones. NerveNet therefore must be a platform that enables simultaneous provision of a variety of services and applications. Different service providers must also be able to provide their own services while sharing the physical resources, decreasing the cost of service provision.

3.3 Self-Containedness

Conventional access networks such as cellular and mesh networks [10] are basically for accommodating end terminals or clients and providing them with connections to servers on the outside network. In contrast, NerveNet should be capable of housing application servers and provide communication between servers and clients and among the clients within it. In Internet-based sensor networks with the conventional access networks, as shown in Fig. 2 and the top of Fig. 3, servers gathering sensor data might be located far from sensors across global networks. This could decrease network resource usage efficiency, increase delays in providing reactive services based on sensor information, and increase the likelihood of security incidents.

3.4 Security

Since the existing IP network uses a connectionless protocol, it is difficult to know who gained access to the network, where they accessed it from, and through which path they connected. User-level authentication with user ID and password also usually takes the place of device authentication. As a result, firewalls and encryption-based security protocols, such as the Internet Protocol-Virtual Private Network (IP-VPN) or Secure Socket Layer-Virtual Private Network (SSL-VPN), are being used. This increases system management, operation, and equipment costs. NerveNet should be able to manage device access to the network, transport of information inside the network, and communication with outer networks.

3.5 Ease of Operation

Equipment must be compact and have low power consumption so that it can easily be utilized. It must also be able to be easily installed or removed in order to reduce installation costs. Conventional networks require advanced system-level knowledge and understanding of protocols, configurations, and operation and management. With such networks, administrators in local regions would have to exert a great deal of effort to manually configure and manage the network based on changes in the local conditions, which would be extremely expensive. NerveNet should be capable of being managed and operated as automatically as possible. The network configuration must be changed to adapt to frequent changes of regional characteristics (increase or decrease in numbers of houses or people).

4. Architecture and System Descriptions

4.1 System Overview

A managed mesh network is designed as the base network,

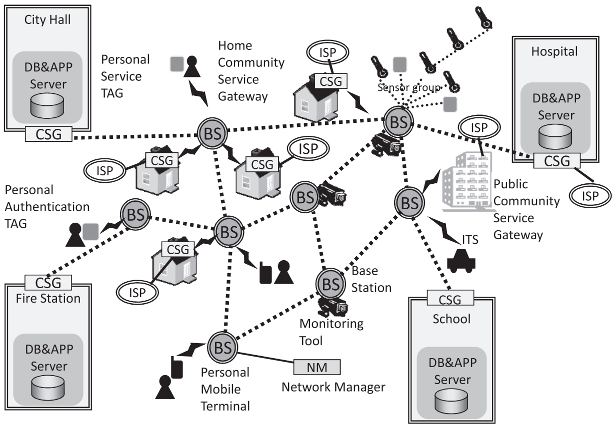

Fig. 6 Overview of a managed wireless mesh.

performing all communications for NerveNet [11]–[15]. The logical components are the base stations (BSs), community service gateways (CSGs), network manager (NM), and devices such as mobile terminals, sensors, and cameras, as shown in Fig. 6.

BS establishes wireless links between neighboring BSs. To detect the neighboring BSs and establish wireless links, an original layer 2-based neighborhood discovery protocol like NHDP [16] is running on every BS, continually monitoring the quality of the links. Under the NM's control and management, a BS establishes logical paths over the links. Each BS has a database and data processing capability. The database stores two types of data: data about registered mobile terminals and their locations that are used for the control and management of mobile terminals, and application content. Data in the databases of all the BSs can be synchronized if necessary. This allows a BS to authenticate a mobile terminal upon request for initial connection to the network, whereas conventional networks need data exchange between a terminal and a remote server like a home location register (HLR) for authentication, causing a delay due to the round-trip messaging, increasing traffic between local and remote networks, and the increasing possibility of data interception. Synchronization could contribute to fast mobility management and distribution of application contents. A CSG is for service management. It establishes and maintains a single or multiple logical domains in which the CSG and devices that belong to the domain can communicate securely with each other. Multiple application software can run on a CSG to provide application services with use of the sensor data stored in it. It also serves as a gateway to the external network.

An NM is a control and management unit. It monitors the status of the network by collecting information about the quality of links between BSs from each BS. Based on the information, the NM first calculates all the logical routes to be established when it is setting up the entire network. It then sends a control command to each BS to configure the logical routes. When a link suffers serious damage, the NM determines to switch logical routes being used for application communication from the logical routes on the damaged wireless link to another route and sends a command to the BSs to perform the switching. These procedures are for ease of operation. The functions enable an optimal network to continually be constructed automatically even if the configuration frequently changes due to removing or installing additional network component equipment.

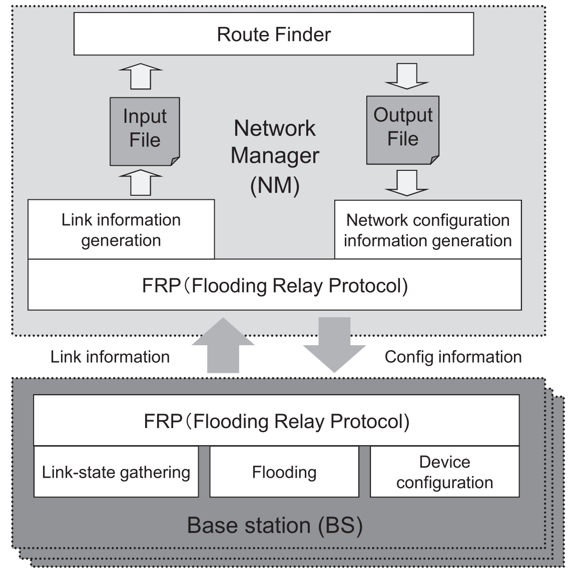

Fig. 7 Functional configuration of network manager and base station.

4.2 Base Networking Layer

After wireless links have been established between BSs, a flooding relay protocol (FRP) that we have developed is performed in the MAC layer between them in order to broadcast link information. (The FRP is not described in this paper due to space limitations.) To save the amount of control information, each BS calculates a multipoint relaying (MPR) set to cover all the two-hop neighbor nodes, and notifies the network manager (NM) of connectivity only to the MPR set's nodes. The way the MPR sets calculations follows the specifications of the existing optimized link state routing (OLSR) protocol. The link information obtained by each BS is distributed in the network with the FRP. The NM recognizes the existence of all the established links and BSs within the network by collecting all the pieces of flooded information. In the NM, a link information file is created by compiling all the pieces of flooded information and is provided to the Route Finder function, as shown in Fig. 7.

The Route Finder in the NM calculates multiple tree routes with a certain BS as the reference point; which it performs for all BSs. An output file is resultantly provided to the function of generating network configuration information. This information is composed of the input and output file where the virtual LAN (VLAN) IDs are assigned to the trees and is distributed to all BSs by the FRP. All the routes calculated by NM are automatically built after each BS configures its layer-2 settings based on the configuration infor-

INPUT FILE

```
[LINK/1]
NODEID=10
PORT=1
COST=1
NODEID=17
PORT=5
COST=2
[LINK/2]
NODEID=17
PORT=7
COST=2
NODEID=85
PORT=7
COST=2
….
```

OUTPUT FILE

```
TREEID=1
[LINK]
[LINK/8517]
NODEID=85
NODEID=17
[LINK/1710]
NODEID=17
NODEID=10
…
[CONNECTION]
[CONNECTION/17085]
NODEID=170
NODEID=153
NODEID=85
[CONNECTION/170102]
NODEID=170
NODEID=102
[CONNECTION/17068]
NODEID=170
NODEID=153
NODEID=136
NODEID=68
[CONNECTION/17051]
NODEID=170
NODEID=102
NODEID=51
[CONNECTION/17017]
NODEID=170
NODEID=153
NODEID=85
NODEID=17
…
```

Fig. 8 Example of input file and output file.

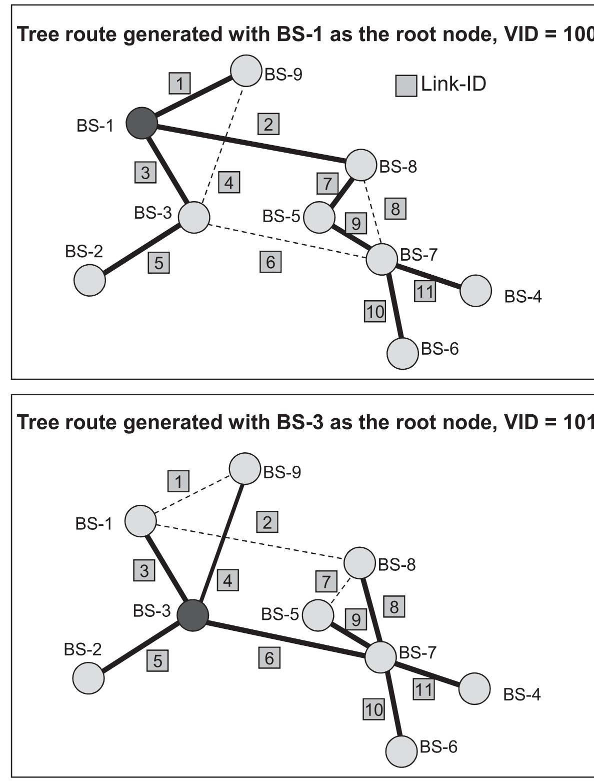

Fig. 9 Example of tree route.

mation containing pairs of a VLAN ID and port number.

Figure 8 shows examples of the input and output file. The input file defines links between BSs. A link is defined as a set of two pairs of a NODE ID, PORT number, and COST. The output file defines trees discovered by the Route Finder. A set of information about one tree is listed below TREEID. Below [CONNECTION], information about routes that compose the tree is written. In this example, information about routes from a root node of NODEID=170 is listed.

Figure 9 shows two examples of tree routes with BS-1 and BS-3 as the respective route nodes. In the first example, 100 is assigned as the VLAN-ID (VID), with 200 in the second example. These examples show multiple logical tree routes identified by VLAN-IDs, which are overlaid on one physical mesh network. By changing the VID specified in a packet (Ethernet frame) header, the tree route on which that packet flows can be changed packet by packet.

This mechanism avoids load concentration on the root part of the tree, which is a problem of a conventional method, the spanning tree protocol (STP) [17]. A disconnected link, which is not used during normal operation with STP, can also be used even when the mesh network is operating normally, increasing the total capacity of the network. In Fig. 9, the physical links with Link-ID is 4, 6, and 8, which are not used by the tree route with VID=100, are used by the tree route with VID=200, which has BS-3 as the route node. As a result, all links are used.

The use of multiple routes is effective when a link failure occurs. A BS recognizes the failure by receiving link state information produced by the link monitoring protocol described in Sect. 4.1, and then distributes the information to all the BSs by sending it to all the routes available to it. Other BSs that have received the link state information search for destination BSs with which they cannot communicate. If CSGs or terminals that are currently being accommodated by each of the BSs are communicating through the destination BSs with which it cannot communicate, it also changes the route table of the internal layer-2 switching function. The route table contains pairs of a MAC address of an accommodated CSG or a terminal and a VLAN-ID of a route. By changing the route to another with a different VLAN-ID having the next lowest priority, the communication route is switched and communication is recovered.

In the example shown in Fig. 10, two pairs of M1 and M2, and M3 and M4 are communicating on the logical route with BS-1 as the root node (same as the route with VID=100 in Fig. 9). When a failure occurs on Link2 between BS-1 and BS-8, the communication between M1 and M2 can remain on the route. On the other hand, the route for the communication between M3 and M4 is switched to another with BS-3 as the root node. In contrast, with distributed dynamic routing used by a conventional IP router, since routing is performed at each router when a link failure occurs, even if communication between terminals was performed on a route that has no failed link, the route of the communication may change, degrading the quality of communication.

Figure 11 shows the procedure when two terminals start communicating and when a failure occurs. When communication begins (Fig. 11(a)), both terminals construct a tunnel between the terminals to communicate by exchang-

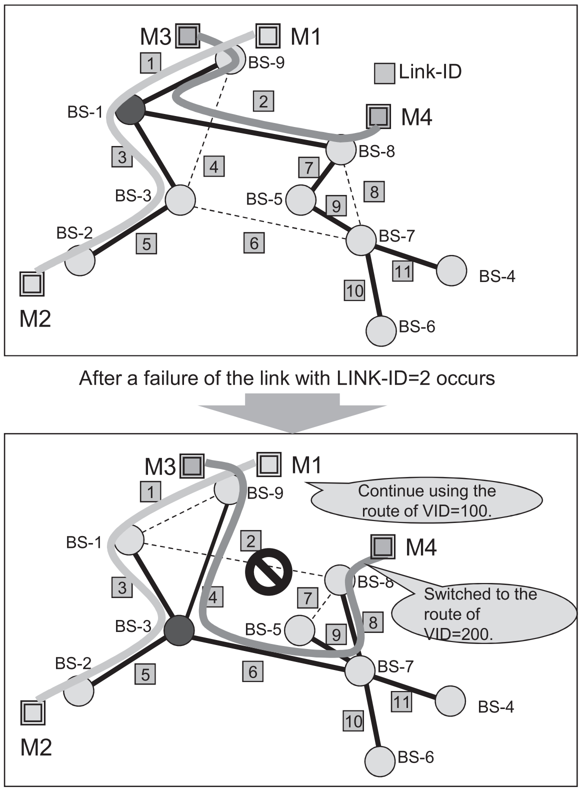

Fig. 10 Example of route switching when a failure occurs.

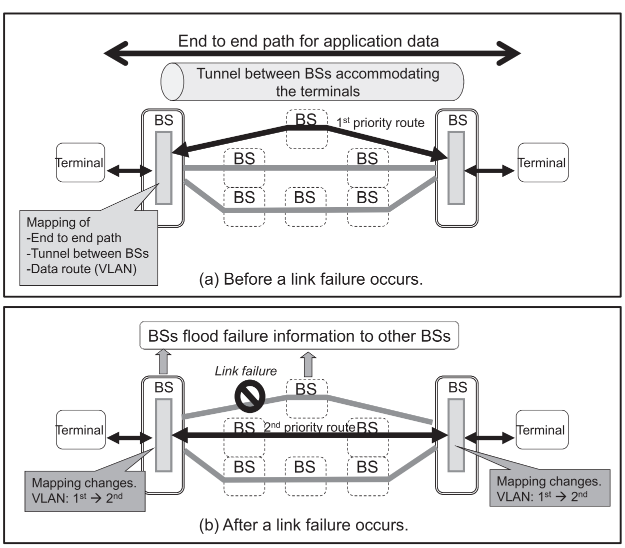

Fig. 11 Route switching method.

ing signals with the respective BSs accommodating them through other BSs. The BSs, which have multiple VLAN-IDs, communicate by using the route with the highest priority among the communication routes that were set in advance. When a link failure occurs somewhere in the network (Fig. 11(b)), BSs that detect the link failure will flood link state information to all VLAN-configured tree routes. Each BS using a route relevant to this failure link stops using that

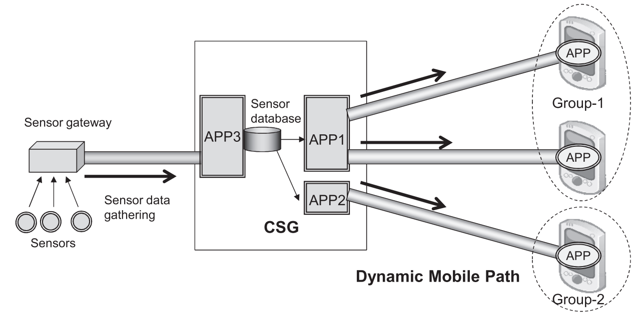

Fig. 12 CSG can initiate grouped DMPs to terminals for multi-service provisioning.

route and uses the route with the next highest priority.

4.3 Communication Layer

Virtual paths between CSGs and terminals should be dynamically constructed and able to be flexibly grouped together at the CSG side for application services. Such whole-path management is named a Dynamic Mobile Path (DMP). A path that is established between a terminal and a CSG is also called a DMP here. A group, which is a single domain on the network, is managed by a CSG. Multi-service and multi-access functions are implemented when individual terminals are connected by DMPs to multiple different domains.

Figure 12 explains the multi-service function. The CSG provides application 1 and application 2 to terminals. For providing application 1, it establishes DMPs with terminals belonging to Group 1 (a service domain) on the network in advance. Also, for providing application 2, the CSG configures another service domain named Group 2 and sets up DMPs with terminals in that group. The multi-service function is provided by configuring multiple DMPs between terminals and CSGs in this way. Unlike a conventional VPN with which a client initiates establishment of a VPN path to a server, CSGs can also initiate DMPs to terminals if necessary for providing push-type services or information securely in response to the sensor data gathered at the sensor database in the CSG, as shown in Fig. 12. It should also be noted here that a DMP is a path mapped onto a logical route of which components (links and BSs) are explicitly known, while the conventional VPN, peer-to-peer on ad-hoc networks, or application-layer overlay techniques do not know about it. A path with high throughput or small delay, for instance, can be intentionally assigned to a DMP.

Figure 13 explains the multi-access function. In the example, the terminal can have three separated DMPs to three different CSGs for three applications. The establishment and closing of a DMP and its destination CSG depend on applications. This allows users to subscribe to services provided by different providers and, in turn, gives providers competitive but open business chances.

Since sensor data may include an individual's interests and preferences, health information, or emotions, it should be kept completely hidden from others. Therefore, a mechanism is required that avoids having the data stored and managed on a server operated by an organization not directly known by the individual in question, as is done in the conventional model shown in Fig. 2. In other words, it must be possible for user to send sensor data to a sensor server that they specify.

The proposed architecture with the DMP shown in Fig. 14 enables sensor data and related personal information to be securely collected at a sensor database server on a CSG operated and administered by the individual or others (e.g., service provider) without that individual having to be aware of its collection. The server will process data by combining it with other previously collected data or other data about that individual, generate service information as the result, and provide it to that individual at appropriate times. Figure 14 shows a situation in which information from the same sensor camera is transported on separate DMPs that were constructed for users A and B for their respective servers.

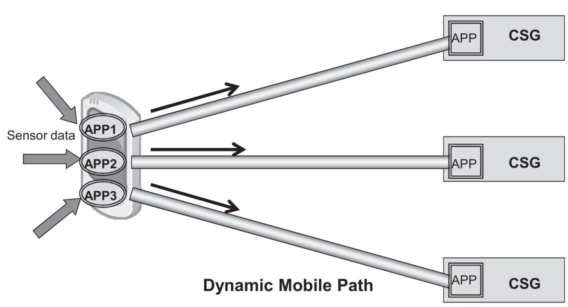

Fig. 13 Multi-access from a terminal to CSGs, which is implemented by configuring DMPs with the CSGs that provide each application.

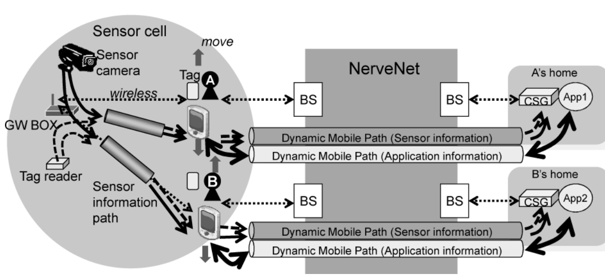

Fig. 14 Sensor-terminal-network cooperative architecture.

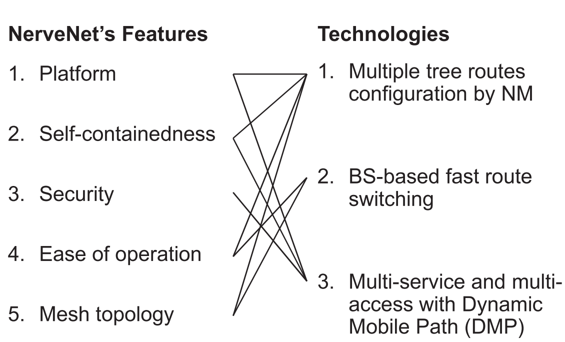

Fig. 15 Relationship between features and technologies.

The relationship between the features of NerveNet and the technologies for realizing them is determined as shown in Fig. 15.

5. Example Applications

5.1 Health Advisory Service

Assume that a man is regularly using a sensor network to check his health. Figure 16 illustrates the operation of a linked personal terminal and CSG applications involved in the health check. First, consider a scenario in which the man eats at a restaurant. The personal terminal senses the menu of the restaurant and sends it to the household CSG. Then, it senses the man's order information and sends that to the household CSG. The man's health application running on the household CSG automatically creates advice on menu selections based on the sensed information and sends it to the terminal. The terminal also senses information about each meal the restaurant served with him and meal status video information (including information from sensors in the environment that was received by the terminal) and sends it to the store CSG. The store CSG determines the meal time or amount of leftovers for each meal and calculates the total number of calories and provides this information as a customer information service. The store CSG also runs a menu consulting application, which helps improve the restaurant's management and make it more efficient by using customer sensing information to collect and analyze the order rates of its menu items, the amounts of leftovers, and the status of customers' meals (such as meal durations or facial expressions) in real-time. Service information that the store CSG sent to the terminal is also transferred from the terminal to the household CSG, and a household CSG application associates it with detailed meal guidance or insufficient nutrition and then analyzes the man's health status and reports it to the terminal.

5.2 Interactive Advertising

In April 2009, a proposal on "R&D on a real-time advertising system for regional businesses based on user context" was accepted for project funding under the Strategic Information and Communications R&D Promotion Programme (SCOPE) under the Ministry of Internal Affairs and Communications (MIC) [18]. By placing advertisements in newspapers, distribution can to some extent be controlled, but it is not possible to know precisely who has received

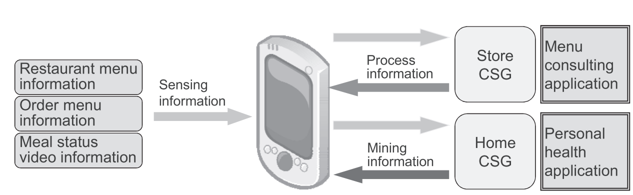

Fig. 16 Example healthcare service by linking restaurant's CSG and household CSG.

the ad or to quantitatively determine how effective the advertising is. This research uses attributes configured on a mobile terminal, such as interests and current location, but does not make use of personal information such as users' names or addresses. New ads are delivered to locations the store believes will have many people desiring their services, thus the system allows the store to quantitatively determine the effectiveness. The system automatically detects whether users actually enter the store after viewing advertising, and this information can be provided as a quantitative indication. Adjusting the target users area, and timing can optimize delivery. This is one application that can be made possible by NerveNet.

6. Current Implementation and Preliminary Performance Evaluation

6.1 Base Station Implementation

We implemented the NerveNet base station by using currently available hardware to evaluate the proposed network architecture concept. The base station consists of a layer-2 VLAN switch (8 PoE port, firmware is customized), four wireless LAN access points, and a control unit (CPU is Geode LX800 500 MHz, memory is 256 MB, OS is Debian Linux kernel 2.6). One of four access points is used for communicating with user terminals (operated in IEEE802.11g infrastructure mode), and the rest are used for BS-to-BS communications (operated in IEEE802.11a 5.6 GHz band [W56] where 11 20 MHz interval channels are available outdoors in Japan; Wireless Distribution System: WDS mode). Wireless APs and the control unit are connected with a layer-2 switch via Ethernet cables.

The control unit provides various functions essential for NerveNet operation, such as layer-2 VLAN switch configuration management, routing, wireless link discovery and sensing, user terminal management, IP-in-IP tunneling, VLAN tag attachment, and SIP proxy. We have implemented all these protocols.

6.2 Settings

The evaluative environment is shown in Fig. 17. A managed mesh network of 10 BSs was configured, connecting them via Ethernet. The Network Manager (NM) was connected to BS_1. The photo in Fig. 17 shows the appearance of a BS. Tree routes were calculated at the NM and the configuration information was broadcast to all the BSs, as described in Sect. 4. Figure 18 shows two tree routes with BS 85 and BS 102 as the root nodes that were displayed on the NM.

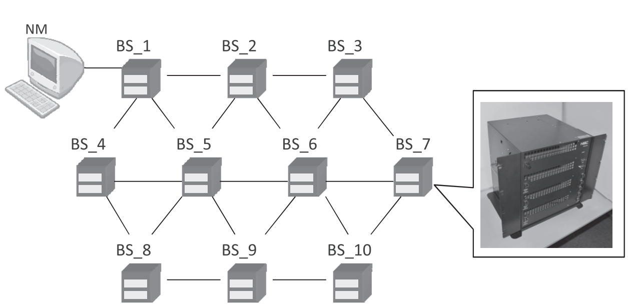

Fig. 17 Managed mesh of 10 base stations with wired Ethernet connections used for evaluation.

6.3 Evaluation under Scenario A: Route Reconfiguration from Double Link Disconnections

The evaluation procedure under this scenario is as follows:

1. The server initiated simultaneous disconnection of the two connections between BS_2 and BS_5, and BS_6 and BS_9. Hereafter only the procedure for BS_2 and BS_5 is described but it is the same for BS_6 and BS_9.
2. After each of BS_2 and BS_5 detected the disconnection, it flooded the information on the disconnection to neighbor BSs. The time of flooding was recorded.
3. All the BSs in the network received the flooded information. The time when a route table control module of each BS recognized the disconnection was recorded.
4. Each updated the route table according to the received information. The time when the update was completed was recorded for each BS.

It takes time for a BS to detect a link disconnection by the link monitoring protocol described in Sect. 4.1 after the disconnection occurs, depending on the setting of the protocol. Detection time is currently outside the scope of our research though fast detection is a general issue needing resolution. Therefore, to eliminate the elapsed time for detection, the time when BS_2 detected the disconnection is set to 0 as the reference since it detected it faster than BS_5.

Table 1 shows the results associated with the link disconnection between BS_2 and BS_5. The second column shows the elapsed time from the detection of the disconnec-

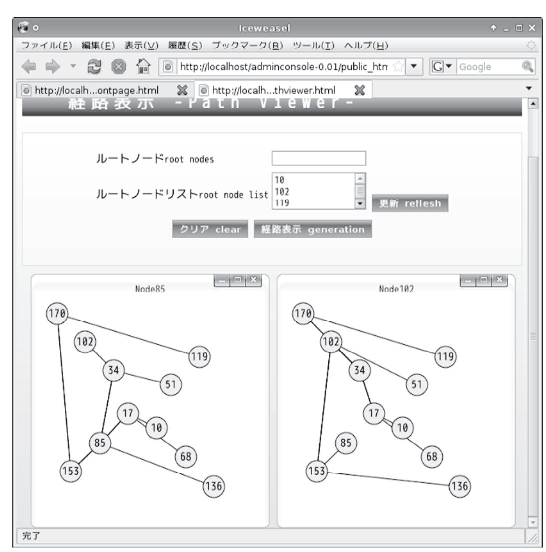

Fig. 18 Two tree routes with BS 85 and BS 102 as the root nodes calculated by Route Finder at the NM.

Table 1 Delay in recognizing the disconnection between BS_2 and BS_5 and delay in completing route table update at each BS.

BS number	Time of recognizing the change of link status [msec]	Time of completing route table update [msec]
1	9	54
2	2	45
3	9	53
4	7	51
5	9	50
6	8	49
7	8	57
8	9	55
9	10	50
10	9	56

Table 2 Delay in recognizing the disconnection between BS_6 and BS_9 and delay in completing route table update at each BS.

BS number	Time of recognizing the change of link status [msec]	Time of completing route table update [msec]
1	8	51
2	9	54
3	10	58
4	8	57
5	9	56
6	9	44
7	8	58
8	10	65
9	2	49
10	9	56

tion by BS_2 (reference time) to the recognition by the route table control module of each BS. Note that even for BS_2 it took 2 ms to recognize the disconnection at the control module level after detecting it at the link level. The maximum and average times in the second column were 10 ms and 8 ms, respectively. Notification of the link disconnection to all BSs appears fast and without deviation because of flooding over the mesh network. The third column presents the time from the reference to the completion of the route table update at each BS. The maximum and average were 57 ms and 52 ms, respectively. There was no large deviation. This means that it took only 57 ms to complete the route change in the entire network. On the other hand, it takes a few to tens of seconds with the existing ad-hoc routing-based mesh networks.

Table 2 shows the results associated with the link disconnection between BS_6 and BS_9. The time when BS_9 detected the link disconnection is set to 0 as the reference. The maximum and average in the second column were 10 ms and 8.2 ms, respectively. The maximum and average in the third column were 65 ms and 54.8 ms, respectively. The results are similar to those in Table 1.

Here it should be noted that two disconnections were initiated simultaneously. All processes, such as flooding, for the notification of the disconnection and route table update at each BS for single disconnection were doubly and simultaneously performed. Accordingly, it can be said that even if two disconnections occur at the same instance, only 110 ms, the double of 55 ms, is required for sequential updates of the route table of each BS because the time for completing the route table update at each BS was less than 55 ms on average for both disconnections.

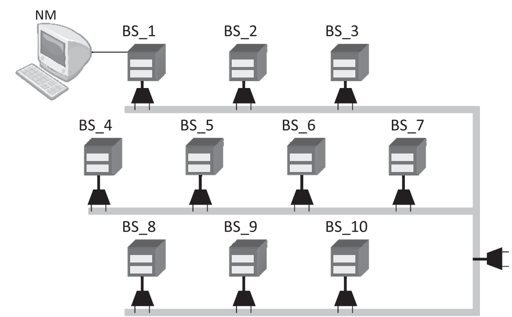

Fig. 19 Configuration for evaluation under scenario B. Power cables of all the base stations are interconnected.

6.4 Evaluation under Scenario B: Startup from Power On

It is preferable to reduce the time of recovery from breakdown due to natural phenomena such as earthquakes and thunderbolts to the extent possible. Scenario B assumed that the power supply was cut off due to such disasters and we measured time from turning on the power supply to all the base stations to completing the resetting of their route tables. It is typical for a network composed of many pieces of conventional communications equipment to require several hours to recover, even if the power is re-supplied after a blackout, since the blackout causes the set up information that was temporarily stored in volatile memory such as RAM within equipment to disappear. NerveNet can automatically make a detour even if a base station breaks down because of decentralized network management and mesh topology. The evaluation under this scenario, however, will be presented on another occasion.

1. All the BSs are powered on. The configuration of them is shown in Fig. 19. The NM starts PING commands to them.
2. Link monitoring protocol starts after a control unit of each BS has completed booting up.
3. Each BS broadcasts link information by the FRP after all the links it monitors by it have been set up.
4. The NM collects all the information, calculates configuration of routes, and distributes the result to all the BSs by FRP.
5. Each BS that has received the information sets up its route table.

The control unit of a BS runs with an operating system of a Linux kernel 2.6 and has a 256 MB memory and a Geode LX800 (500 MHz) CPU.

We performed 10 trials of the procedure and measured the time from power on to the receipt of a PING response at the NM from each BS. The minimum, maximum, and average time were 2:20, 3:03, and 2:38 (minutes:seconds), respectively. Since the boot up time of the Linux OS was 1:31 on average, only about a minute and a half was required

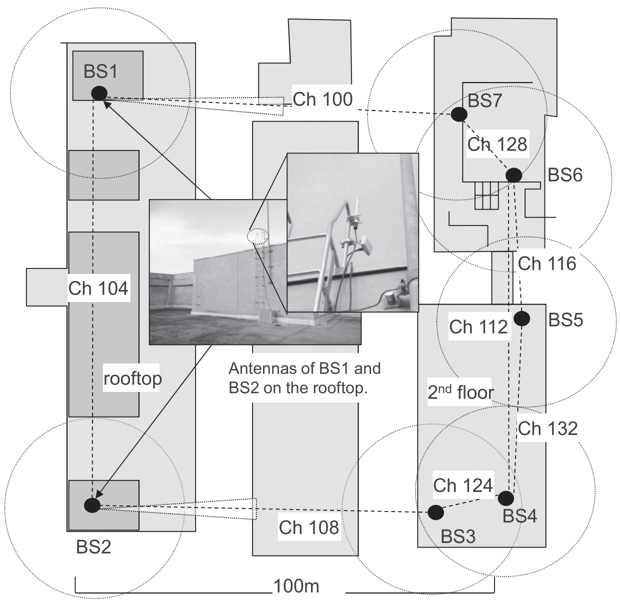

Fig. 20 BS placement, link establishment between BSs and channel assignment for scenario C.

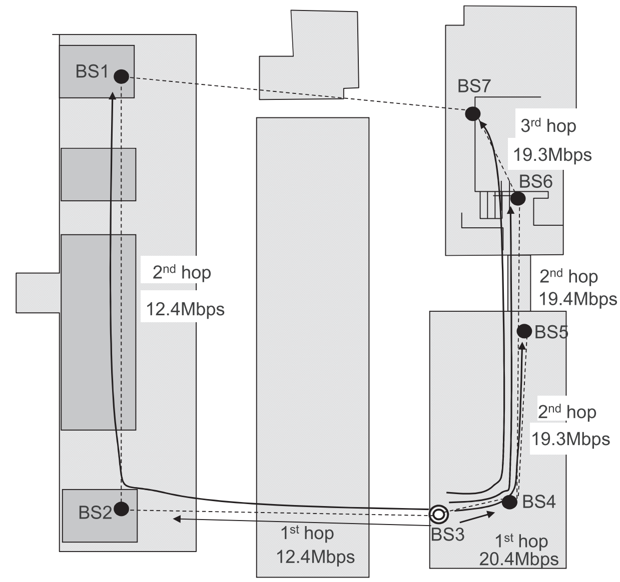

Fig. 21 UDP path throughput from BS3 and its hop count under scenario C.

for configuring the network after booting up.

6.5 Evaluation under Scenario C: Multi-Hop Throughput in a Real World Environment

To evaluate wireless multi-hop throughput in a real world environment, we installed seven base stations in our laboratory buildings. Two base stations were installed on the top of the building (BS1 and BS2) and the rest were installed on the second floor of the other building, as shown in Fig. 20. Co-liner omni-directional antennas were installed in each wireless interface of each base station. A directional antenna was also installed in BS1 and BS2 to communicate with BS7 and BS3, respectively. Different channels were assigned to different wireless links to avoid inter-link interference. The channel number is also shown in Fig. 20. In this environment, UDP throughput and round-trip time were evaluated in each node pair to view the wireless multi-hop performance. Iperf [19] was used to evaluate UDP performance, UDP payload size was set to 1440 bytes, and the transmit output rate was set to 25 Mbps.

The UDP path throughput and hop count are shown in Fig. 21. This figure only shows the results for which BS3 is the source node. Usually mesh points and mesh portals of IEEE802.11s have a single wireless interface with a single channel, so multi-hop throughput decreases while the hop number increases [20]. But the results show that UDP throughput stayed high even if the hop number increased as it used multiple interfaces with multiple channels, and it could avoid inter-path interference. The averaged round trip times were 1.1 ms, 1.96 ms, and 2.83 ms for the first, second, and third hops, respectively. NerveNet BS relays a frame based on the VLAN tag attached on a frame header in layer 2 so it can achieve a low roundtrip time compared to layer-3 routing like mobile ad hoc networks (MANETs).

6.6 Discussion

The time for completing network reconfiguration at each BS is believed to not tend to depend on the number of hops from the BSs that have one or two failed links. Therefore high-speed route switching is expected for a large-scale network composed of about 100 BSs, which is the target size of NerveNet. Even when more than two links fail at the same time or when a BS breaks down, fast route switching is expected because such failures have little impact on the performance due to the decentralized management and mesh topology. These evaluations clarify one feature of NerveNet — ease of operation. It is also found that IEEE802.11, which was originally designed as a wireless communication protocol for LAN, could give high throughput even for multiple hops. Future work should include more evaluations to fulfill these expectations.

7. Related Work

In existing cellular networks, communications between devices in a neighborhood must loopback in the upstream flow of the network, which is inefficient for community communications in which the circulation of information is likely to be closed in a relatively local area. In NerveNet, a path between any two base stations allows direct communication between two devices including terminals and servers within the network.

In existing wireless mesh networks provided by vendors such as Strix Systems [21] and Tropos Networks [22], wireless mesh networks with IEEE802.11s [23], and wireless mesh networks under research (e.g., [24]–[26]), mesh configurations are created to deal with performance drops due to unstable wireless links. Yet to the best of our knowledge, reconfiguration of the network when a fault occurs takes a few seconds to a few minutes. (This kind of factual data about commercial mesh network product performance is basically not disclosed. We questioned some sales companies and received those figures.) During this long period of failure, all communications need to be suspended. Basically, static routes are configured with a gateway as a root point since the products are positioned as an "access network" that connects devices to an outer network such as the Internet. A network with a single gateway has a problem of a single failure point and has difficulty in making full use of network capacity. Some products can have multiple gateways but a nearest gateway is assigned to a terminal to communicate with an outer network. The managed wireless mesh, on the other hand, can have multiple gateways to the outer network and any device can be connected to the outer network through any gateway by assigning an appropriate route between them. The assignment is also not static. The best route can be assigned dynamically to communication when it is initiated. Since each node of existing wireless mesh networks changes routes in an autonomous distributed manner, the network is basically unstable and it takes a relatively long time to reconfigure it, as mentioned earlier. Route switching is not studied in [25], [26] though multipath routing for load balancing where multiple routes are used for avoiding traffic congestion is dealt with in [25] and multipath routing for throughput enhancement is focused on in [26]. The OSPF Opaque LSA Option defined in RFC2370 [27] is a protocol to distribute link-state advertisements (LSA) to nodes across the network. The frequency at which new LSA instances may be originated is set to equal once every five seconds. The frequency at which new LSA instances are accepted during flooding is once every second. These settings make the propagation delay of LSA longer as the size of the network becomes larger.

8. Conclusion

The major features of NerveNet can be summarized as follows. Multiple logical paths between any two base stations are configured on a physical managed mesh network. Integrated management composed of a centralized operation by the NM in the beginning configuration phase and decentralized operation by BSs for maintaining the network is performed. Flexible assignment of multiple routes to any communication enables various logically separated services to be constructed and provided by different service providers on a single physical network. This helps the network work as a platform. A path between any two base stations allows communication between two devices including terminals and servers within the network, realizing self-containedness. Even if link failures occur, communications can be maintained by switching them onto an alternate logical path, providing ease of operation. System throughput can be increased by using multiple logical paths simultaneously. We believe that NerveNet will be a future access network operating as a regional, open platform with which we can enjoy services that enhance our lives and on which service provider companies, including local startups, can offer services.

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