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Low-Energy-Consumption Ad Hoc Mesh Network Based on Intermittent Receiver-driven Transmission

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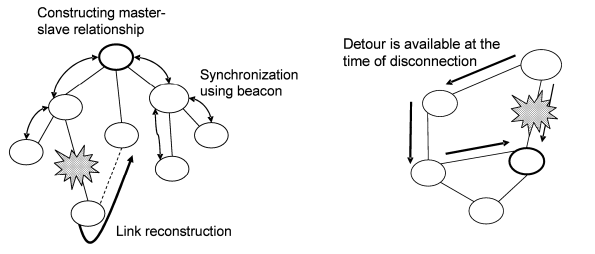
Abstract
In the ad hoc network, it is considered that mesh structure topology can achieve high communication reliability. However, since the power consumption in an ad hoc network of the mesh configuration becomes large, it is an important research topic to control it. In efforts to develop a method for controlling such power consumption, this research targets a network in which communication starts when multiple receiver nodes transmit their own IDs intermittently and a transmitting node receives them. However, the basic characteristics of an ad hoc mesh network constructed using this method is not yet clear. Therefore, in this study we clarify, by simulation, the influence that parameter values which determine operation of the system have on basic system properties, such as data collection rate, average delay, and power consumption. Furthermore, we show that the power consumption of the whole node which performed load sharing is reducible about 10% by setting up an intermittent cycle individually according to the load for every node.

Keywords: *Ad hoc network, Mesh network, Sensor network, Intermittent transmission, Energy consumption, Simulation.*

1. Introduction
Due to the advance of wireless technology and the miniaturization of the computer in recent years, it has become possible to build ad hoc networks in which small nodes equipped with communications facilities can build networks autonomously. Furthermore, sensor networks made up of nodes that have sensing functionality are widely used in rescue operations in disasters, for environmental monitoring, and for security management in large-scale institutions.

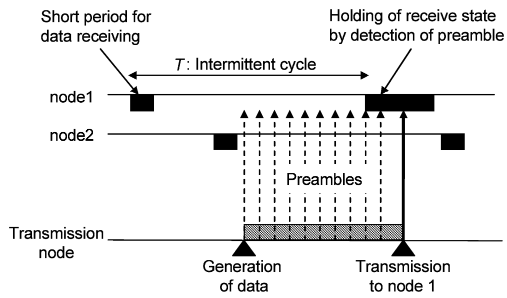
These small wireless nodes are driven with batteries, and since they are used in environments where power cannot be provided from the outside in many cases, managing energy consumption is the most important subject in realization of a sensor network [1]. Many communication techniques based on intermittent operations have been proposed to control the power consumption of sensor networks [2-5]. These methods suppress power consumption by making a node enter a state of sleep, and communicate by using an active state intermittently. Although making a node enter a state of sleep reduces power consumption, a control to establish a link is needed in order to communicate between different nodes. The communication mode for intermittent operations can be divided into synchronous systems [6] and asynchronous systems [7-9] using control techniques. In order to easily establish a communications link, a synchronous system periodically transmits a packet called a *beacon* between nodes, and maintains a synchronous state. Systems of this type are well suited to applications that collect data periodically. On the other hand, in an asynchronous system, a beacon is not transmitted and synchronization is not performed between nodes. It turns out that asynchronous systems are advantageous for applications that access timings when the frequency of packet generation is low and arbitrary [8].

On the other hand, there has been considerable research carried out on the influence that the topology has on the power consumption of an ad hoc network. There are two classifications of topologies for ad hoc networks; a cluster tree structure, and a mesh structure [10]. In the

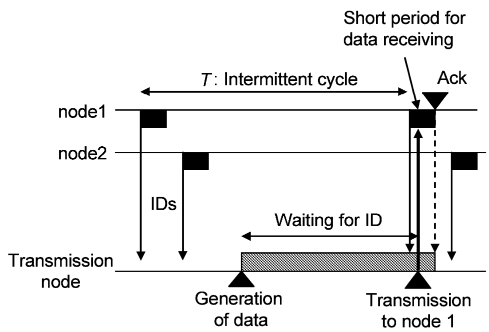


(a) Cluster tree topology (b) Mesh topology

Figure 1. Comparison of a cluster tree topology and a mesh topology



(a) Low Power Listening (LPL)



(b) Intermittent Receiver-driven Data Transmission (IRDT)

Figure 2. A communication method used in ad hoc networks that operates asynchronously and intermittently

cluster tree structure shown in Figure 1(a), it is possible to maintain a master slave relationship for every node, and it is easy to adopt a synchronous system. However, since the link connections have little redundancy, network reconstruction is needed if a node breaks down or a link is disconnected. On the other hand, although it is difficult to adopt a synchronous system when using a mesh structure as shown in Figure 1(b), the link connections have high redundancy and the communication reliability is higher than that of a cluster tree structure. However, power consumption of a mesh structure is large since each node can communicate with all the nodes which exist in its surroundings.

We target an application that operates for several years without replacing the battery in a situation where data-generating frequency is comparatively small. When building an ad hoc network that suppresses power consumption with intermittent operations and collects data at a low frequency, it is appropriate to adopt a system that operates asynchronously. Moreover, in order to perform reliable data collection, an ad hoc network with a mesh structure is preferable. The Low Power Listening (LPL) method was proposed as a method to achieve such an ad hoc network that carries out intermittent operations asynchronously [9]. In the LPL method, each node performs intermittent operations that repeat a packet receive state and sleep state (Figure 2(a)). Each receiving node checks whether the channel is being used by surrounding nodes between the short receive states. If the channel is not being used, the node will shift to sleep state again. When transmitting a packet to node 1, the transmitting node tells the surrounding nodes that there is a *Request to Send to node 1* by performing a fixed time transmission of the preamble. When node 1 receives the preamble, communication starts and the transmission node can transmit a packet to node 1. When using the LPL method, since the transmission node transmits the preamble at a fixed time continuation previous to the transmission of the packet, the channel will be occupied at the time of packet transmission. Furthermore, the LPL method has a restriction about communication destination because it needs to specify a communication destination in the preamble.

We proposed the Intermittent Receiver-driven Data Transmission (IRDT) [11] system as an asynchronous communication method in order to resolve the restrictions inherent in the LPL method. By implementing IRDT, we are developing a meter reading system which can be operated with a battery for a long period of time. In the IRDT system, multiple receiving nodes (receiving nodes 1 and 2 shown in Figure 2(b)) transmit their own IDs periodically and intermittently, and the transmission node waits for it with its transmission data. The transmission node communicates by establishing a communication link between the receiving nodes to which the ID arrived first. In the IRDT system, the channel will not be occupied by a preamble as with the LPL method. Furthermore, since it is possible to wait for multiple nodes to become a communications destination candidate, it is expected that communication reliability can be improved. However, the basic performance characteristics of IRDT systems are not yet clear, and the implemented parameter values are decided experimentally. The scope of the IRDT system will become clear by showing the influence that parameter values (e.g., the interval of intermittent operations) have on system performance (e.g., such as network delay and power consumption). In this paper, we clarify the influence that parameter values that determine the operation of the system have on basic performance characteristics by performing a computer simulation of the operations of the ad hoc mesh network done using the

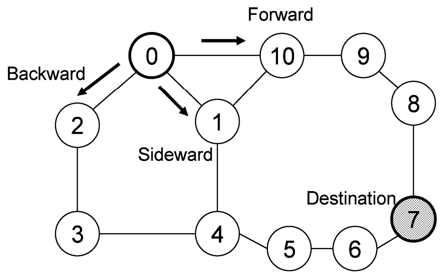


Figure 3. Example of classifying adjacent nodes

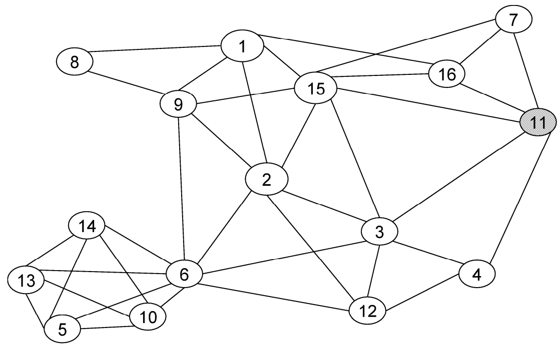


Figure 4. Simulation model with 16 nodes

IRDT method. Furthermore, we will propose parameter settings that can further improve system performance.

This paper is organized as follows. In Section 2, we explain the outline of the ad hoc mesh network based on the IRDT method. In Section 3 we will evaluate its performance using a simulation. In Section 4, we propose parameter settings to improve performance. Finally, we conclude this paper in Section 5.

2. System Description

2.1 Intermittent operation

First, we will explain intermittent operations and the routing protocol of the ad hoc mesh network based on IRDT method. Each node in the mesh network is identified by allocated ID. When each node does not have a data packet for transmission, it is in the waiting to receive packet state and performs intermittent operations as shown in Figure 2(b). In intermittent operations, each node will transmit its own ID to another node, and then will enter sleep state again after a short waiting to receive packet state. Then, the node transmits its own ID again after remaining in the sleep state for T seconds. The node that holds the packet to be transmitted waits for its ID from its adjacent nodes. If an ID is received from a node that is suitable for a transmission destination, the transmission node will transmit a packet during the period in which the node is in the short waiting to receive packet state. The receiving node sends an Ack to the transmission node that sent the packet. Communication terminates normally when the transmission node check the Ack sent from the receiving node. In Figure 2(b), receiving nodes 1 and 2 are performing intermittent operations. Since the transmission node received an ID from receiving node 1, the packet has been transmitted from the transmission node to receiving node 1. In IRDT, a transmission node does not need to transmit a preamble that occupied the channel for a fixed period, as required by the LPL method. Furthermore, since a transmission node is able to wait for multiple receiving node candidates, IRDT is suitable for mesh networks that provide multiple paths to the destination.

2.2 Routing protocol

In this system, each node performs packet relay to other nodes, and also performs multi-hop communications. In order to minimize packet transmission delay, it is most desirable to transmit packets to the adjacent node that has the minimum number of hops to the destination node. However, in some cases transmission via the shortest path may fail due to the quality degradation of a wireless channel, or for some other reason, in which case this system has a function that will transmit the packet to an adjacent node to be used as a detour path that exists in a mesh network [12]. In this system, each node classifies the adjacent nodes into the following three categories according to the number of hops to the destination node (Figure 3).

Forward: Minimum number of hops to the destination node.

Sideward: Minimum number of hops to the destination node plus one.

Backward: Minimum number of hops to the destination node plus two or more.

Let the priority in which the transmitting node chooses the receiving node for the packet be forward, sideward, and backward. When two or more adjacent nodes with the same priority exist, the transmission node transmits the packet to the adjacent node that first received an ID. When transmission to all of the forward nodes fails during packet transmission processing, the transmission node will resend the packet by extending the transmission destination to the sideward nodes. If the transmission continues to fail, the transmission node will extend its transmission destination to the backward nodes as well. Thus, this system offers high communication reliability by allowing the path to be chosen flexibly using the path redundancy that the ad hoc mesh network provides [13].

In order to choose the appropriate adjacent node mentioned above, it is necessary for each node to hold information on the route to all of the nodes in the network. Therefore, in this system, each node saves and manages the information on the route to the configuration management table. For example, when node 0 transmits to node 7 in the network shown in Figure 3, the information from the adjacent node on (Forward: 10, Sideward: 1, Backward: 2) is registered into the table of node 7. In this system, in order to adapt to a change in

Table 1. Parameter settings

Parameter	Value
Cycle of intermittent operation	3.0 s
Maximum communication range	100 m
Maximum transmission number	5
Current consumption (TX)	20 mA
Current consumption (RX)	25 mA
Current consumption (Sleep)	0 mA
Packet size	128 byte
Transmission speed	250 kbps
Capacity of battery	7.1 Ah

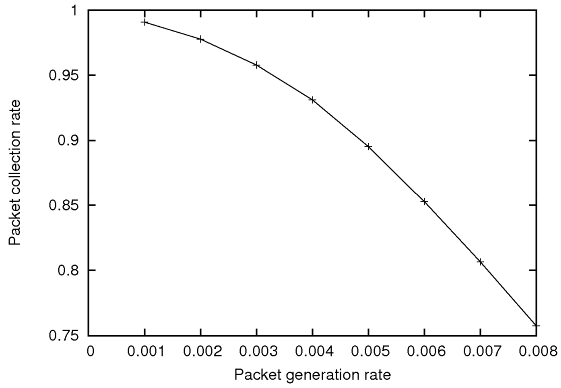
network topology, the configuration management table is updated by exchanging configuration control packets periodically between each node.

3. Performance Evaluation by Simulation

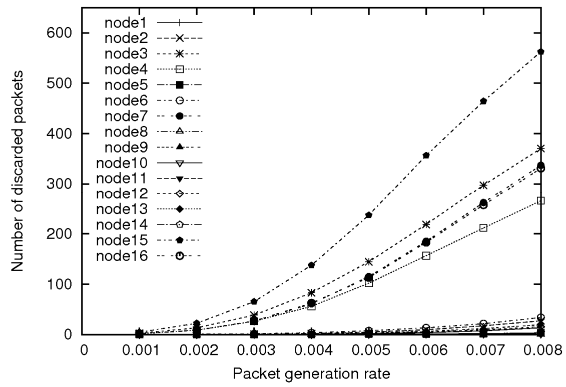
In this section, we will clarify the basic performance characteristics of ad hoc mesh networks based on IRDT using a computer simulation. We developed an original simulation program described by C++ based on the specification of IRDT protocol. Then, we used the mesh network topology with 16 nodes described in Figure 4, to evaluate the basic performance characteristic. Here we define the data packet generating number per second as the packet generation rate. Each node generates a data packet at a random time according to the packet generation rate decided beforehand and transmits it to node 11. Here we define the data packet generating number per second as the packet generation rate. Hereafter, we will refer to node 11 which is the data collection point as the *center node*, and the nodes adjacent to node 11 as *center adjacent nodes* (node 3, 4, 7, 15 and 16).

In order to create a simulation model, we introduce the following assumption:

- The network configuration is assumed not to change during the simulation period. That is, transmission and reception of configuration control packets between nodes will not be performed, but a configuration information managed table will be given to each node before the simulation starts.
- When transmitting a packet, each node performs a carrier sense in order to prevent transmitted packets from colliding. We assume that attenuation of the transmitted signal will not take place. Moreover, it is assumed that packet loss due to transmission errors other than the packet collision will not occur with nodes within the possible communication distance.
- When a node holding a data packet that will be transmitted receives a new data packet, the packet that has yet to be transmitted will be discarded and the transmission processing for the new packet will begin. That is, each node is not equipped with a buffer to hold multiple data packets.



(a) Packet collection rate



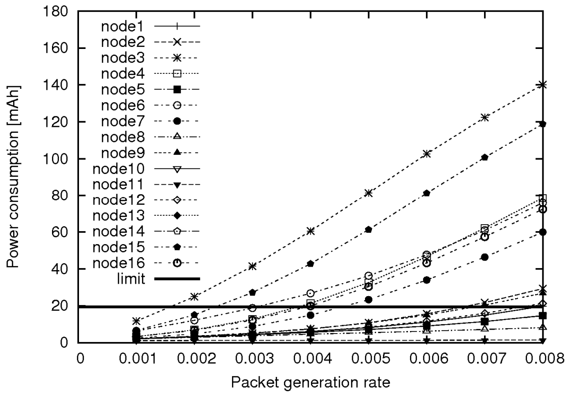
(b) Number of packets discarded by each node

Figure 5. System properties regarding the packet generation rate

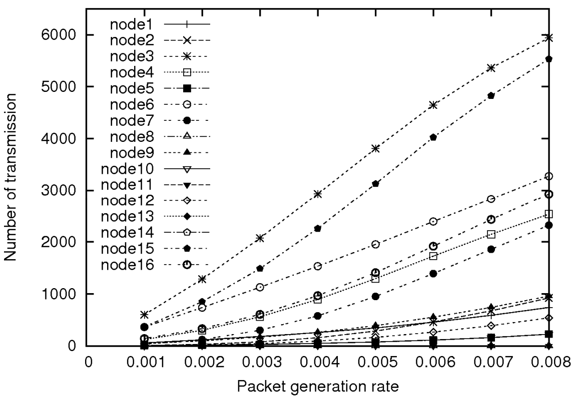
We performed the simulation using the parameter settings shown in Table 1. Here, the maximum transmission number is the maximum number of times relay transmission of the packet is performed. We introduced this in order to prevent packets which have yet to reach the center node from remaining on the network for a long time. Packets which exceed the maximum transmission number are discarded.

3.1 Packet collection rate

First, we investigated the change in the performance measure when the packet generation rate, which creates a load on the entire network, is changed. Figure 5(a) shows the change in the packet collection rate. We define the ratio of the number of packets received by the center node to the number of packets generated as the packet collection rate. The packet collection rate decreases with increased load, because the number of packets discarded from the network due to them exceeding the maximum transmission number will increase. As shown in the network in Figure 4, all of the shortest paths from each node to the center node are less than 3 hops, but if a packet is retransmitted by the collision or passes along a detour, the number of transmissions required until it reaches the center node will increase. That is, since the

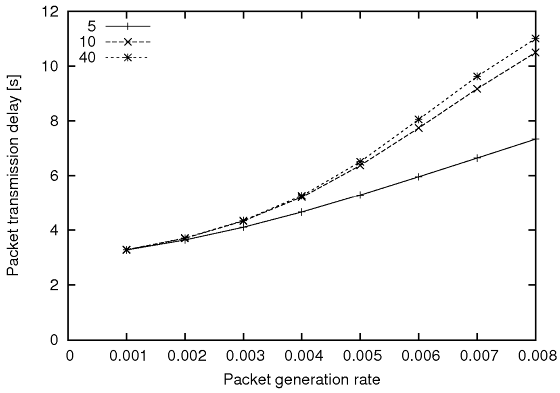


(a) Power consumption

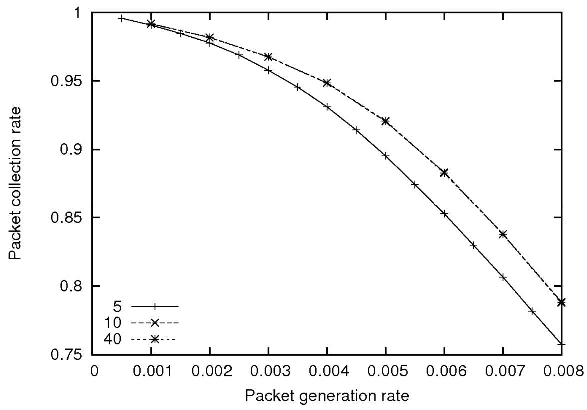


(b) Number of transmissions

Figure 6. System properties regarding power consumption



(a) Packet transmission delay



(b) Packet collection rate

Figure 7. Influence of the maximum transmission number

packet loss due to collision increases and the number of relays to sideward nodes increases with an increase in network load, the packet collection rate will decrease.

We show the number of discarded packets for each node in Figure 5(b). As shown in this figure, there are many packets discarded by nodes 3, 4, 7, 15, and 16, which are center adjacent nodes. The packets for the center node collide with each other more often in these nodes and the packets exceeding the maximum transmission number are discarded in order to repeat the transfer to another sideways node until transmission is successful.

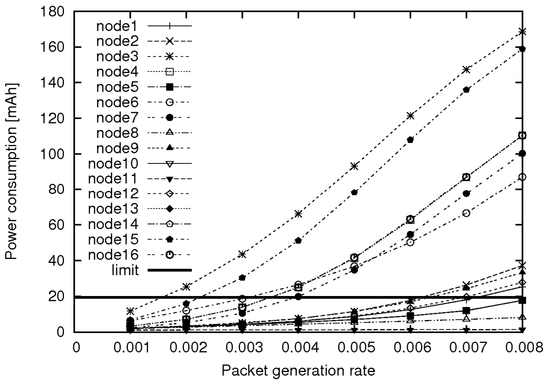
3.2 Power consumption

Next, we will show the power consumption of each node used to change the packet generation rate in Figure 6(a). The “limit” line in this figure expresses the power consumption value allowed per day to operate a node for one year with a battery with a capacity of 7.1Ah. This figure shows that the power consumption in nodes 3, 4, 7, 15, and 16, which are center adjacent nodes, and node 6, which has a concentration of packets, is large. Figure 6(b) shows the number of times that each node transmitted, and it turns out that a node with large power consumption performs many transmissions. Since data is concentrated in center node in the target network system, the load of the center adjacent node becomes very high. As a result, the power consumption of the portion becomes very large, and performances, such as a network life, are also governed by center adjacent nodes' characteristic. Therefore, the topology of the whole network is not so important about performance.

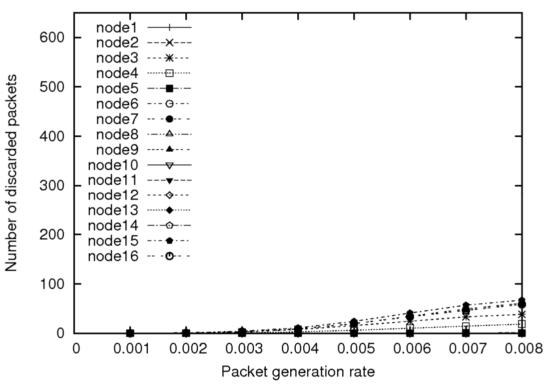
4. Improving Performance using Parameter Settings

4.1 Influence of maximum transmission number

As mentioned above, at a center adjacent node, there are many packets discarded when the number of times a packet is relayed exceeds the maximum transmission number. Then, we investigated the influence on the packet collection rate and packet propagation delay when the maximum transmission number is changed. Figure 7(a) shows a comparison of the packet transmission delay when the maximum transmission number is changed to 5, 10, and 40. Moreover, Figure 7(b) compares the packet collection rate. It turns out that both of the results do not have a large difference in the cases where the maximum transmission number was 10 and 40. If the maximum transmission number is increased, the packets discarded due to exceeding the maximum transmission number will decrease, and the packets can exist for a longer period on the network. However, in this system, when a new packet



(a) Power consumption



(b) Number of packets discarded by each node

Figure 8. The result when the maximum transmission number is 10

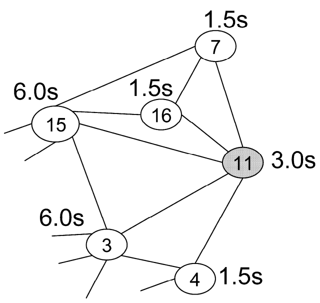
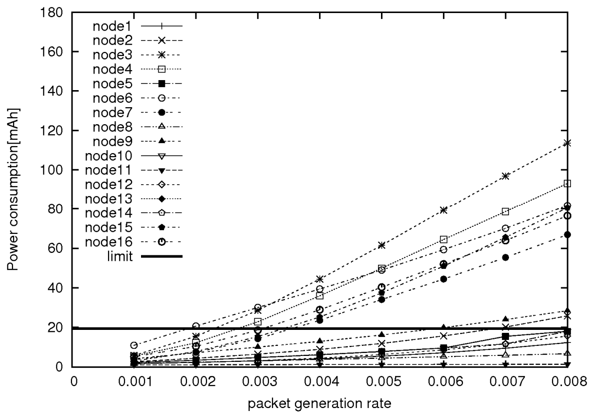


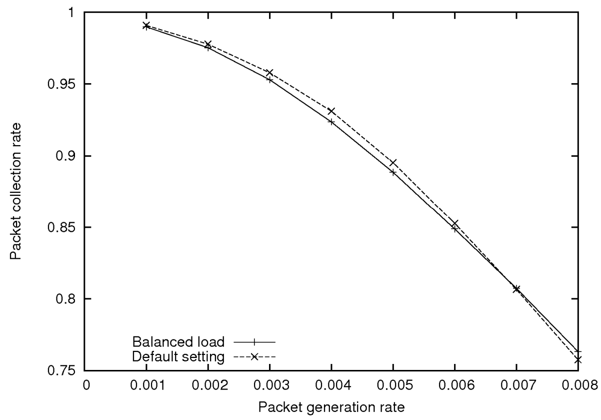
Figure 9. Assignment of an intermittent cycle according to the load for every node

is received before transmission is completed at each node, the packet which has not transmitted will be discarded and the node will shift to the send action for the new packet. Therefore, even if the maximum transmission number increases, there is a limit to how much the packet collection rate can be improved.

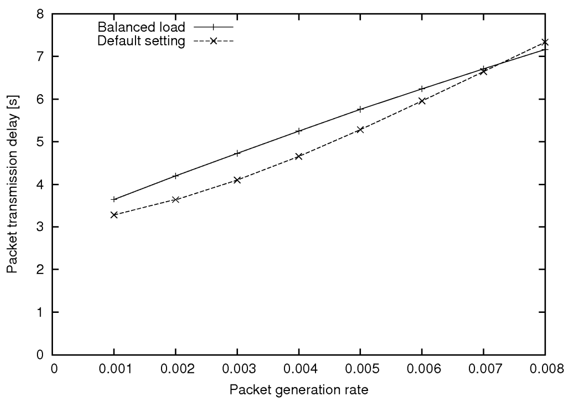
Figure 8(b) shows the number of packets discarded at each node when the maximum transmission number is set to 10. It turns out that the number of the packets discarded by the center adjacent node decreased compared with the cases when the maximum



(a) Power consumption



(b) Packet collection rate



(c) Packet transmission delay

Figure 10. Performance improvement by load balancing

transmission number is 5 (Figure 5(b)). Figure 8(a) shows the power consumption for each node when the number of maximum relays is 10, and the power consumption in a center adjacent node increases when compared with power consumption when the maximum transmission number is 5 (Figure 6(a)). That is, if the maximum transmission number is increased, the power consumption imbalance will increase and the life of the network may shorten due to battery depletion. Thus, the value of the maximum transmission number needs to be set to a suitable value according to the battery capacity and the operation period of the system, while taking into consideration the shortest hop number from each node to the center node.

4.2 Intermittent cycle according to the load of each node

From the result of the power consumption (Figure 6(a)) of each node when the intermittent cycle of all the nodes is 3.0 seconds equally, the power consumption of node 3 and node 15 is especially large. This is because the loads of node 3 and node 15 are high because there are many nodes containing those nodes in the shortest path to the center node. Such an imbalance of power consumption will cause power depletion of a specific node, and as a result will reduce the network operation period [14, 15]. Then, the intermittent cycle of nodes with high loads will be relatively lengthened, and consideration is given to decreasing the amount of packets received in order to achieve a balance of load and power consumption.

As shown in Figure 9, we set the intermittent cycle of nodes 3 and 15 to 6.0 s, the intermittent cycle of nodes 4, 7, and 16 to 1.5 s, and set it for the other nodes in the network to 3.0 s. As shown in Figure 10(a), the power consumption of nodes 3 and 15 are decreasing, but it turns out that the power consumption in nodes 4, 7, and 16 is increasing conversely. We show that the power consumption as the whole center adjacent node can be suppressed about 10%. That is, a part of packet which originally travelled via nodes 3 and 15 are considered to have gone via nodes 4, 7, and 16 due to a different intermittent cycle being assigned. Although the power consumption of nodes 4, 7, and 16 increases due to this assignment, since the power consumption of a node that has the largest power consumption can be suppressed, the network operation period will be prolonged. Thus, we showed that it is possible to balance the load by setting up an intermittent cycle according to the load for every node.

As shown in Figure 10(b), when performing load distribution by changing the intermittent cycle, a large difference in the packet collection rate was not observed. Moreover, we discovered that by performing a load distribution, packet transmission delay can be decreased (Figure 10(c)).

5. Conclusion

In this paper, we proposed the IRDT technique based on intermittent ID transmission of multiple receiver nodes, and we investigated the fundamental performance characteristics of an ad hoc mesh network and applied it using a computer simulation. As a result, we showed that the cycle of intermittent operations and the number of maximum relays influence the performance of this system. Furthermore, by assigning an intermittent cycle according to the load for each node, we show that the power consumption of the whole node which performed load sharing is reducible about 10% by setting up an intermittent cycle individually according to the load for every node.

As we showed in this paper, assigning an intermittent cycle according to the situation of each node is effective, but it is difficult for the manager to assign them to all the nodes at the time of a network design or employment, and it is not realistic. Moreover, dealing with a time change in a load or topology is also an important subject. Therefore, we believe that a control system that ensures that each node sets up an intermittent cycle autonomously according to its situation is required. We expect that a robust network can be built that is able to withstand failure or an environmental variation by introducing such an autonomous technique. Now, we are performing further improvement of IRDT and are developing the ad hoc network for data collection which implemented it. In the near future, we are operating the network which implemented IRDT in a real environment, and are going to verify the influence of variation of communication environment and transmission errors.

6. Acknowledgements

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Biography

Masashi Sugano received the M.E. and D.E. degrees in Information and Computer Science from Osaka University, Japan, in 1988 and 1993, respectively. In April 1988, he joined Mita Industrial Co., Ltd. (currently, Kyocera Mita Corporation) as a Researcher. From 1996 to 2003, he was an Associate Professor in Osaka Prefecture College of Health Sciences. From 2003 to 2005, he was an Associate Professor with the Faculty of Comprehensive Rehabilitation, Osaka Prefecture College of Nursing. From 2005 to 2009, he was with the School of Comprehensive Rehabilitation, Osaka Prefecture University, and from April 2009, he has been a Professor of Osaka Prefecture University. His current research interests include performance evaluation of computer communication network, network reliability, and ad hoc and sensor network systems. He is a member of IEEE, ACM, IEICE, and IPSJ.

Ryo Fukushima received the B.E degrees from Osaka University, Japan, in 2008. He is currently a graduate student at the Graduate School of Information Science and Technology, Osaka University, Japan. His research interest includes refactoring support environment based on source code analysis.

Masayuki Murata received M.E. and D.E. degrees in Information and Computer Science from Osaka University, Japan, in 1984 and 1988, respectively. In April 1984, he joined Tokyo Research Laboratory, IBM Japan, as a Researcher. From September 1987 to January 1989, he was an Assistant Professor with Computation Center, Osaka University. In February 1989, he moved to the Department of Information and Computer Sciences, Faculty of Engineering Science, Osaka University. From 1992 to 1999, he was an Associate Professor in the Graduate School of Engineering Science, Osaka University, and from April 1999, he has been a Professor of Osaka University. He moved to Graduate School of Information Science and Technology, Osaka University in April 2004. He has more than three hundred papers of international and domestic journals and conferences. His research interests include computer communication networks, performance modelling and evaluation. He is a member of ACM, The Internet Society and IPSJ.

Takaaki Hatauchi received the B.E. degrees in Electronic Engineering from Kinki University, Japan, in 1982. He joined Fuji Electric Co., Ltd. in the same year, and belonged to the electronic developing equipment section. Since 2003, He has been belonging to Fuji Electric Advanced Technology Co. Ltd., and engaging in the development of a wireless system. His research interests include the technology of low power consumption for the sensor network. He is a member of IEICE and IEEJ.