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Fault-tolerant ZigBee-based Automatic Meter Reading Infrastructure

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Abstract: Due to low cost, low-power, and scalability, ZigBee is considered an efficient wireless AMR infrastructure. However, these characteristics of ZigBee can make the devices more vulnerable to unexpected error environments. In this paper, a fault-tolerant wireless AMR network (FWAMR) is proposed, which is designed to improve the robustness of the conventional ZigBee-based AMR systems by coping well with dynamic error environments. The experimental results demonstrate that the FWAMR is considerably fault-tolerant compared with the conventional ZigBee-based AMR network.

Keywords: *AMR, AMI, Fault Tolerance, ZigBee*

1. Introduction

Automatic meter reading (AMR) enables utility companies to communicate remotely with residential utility meters using communications. Traditionally, field technicians accessed utility meters on the customer premises to record usage information manually. With today's smart meters, utility companies (electricity, gas, water, etc.) can now avoid this costly manual work, and set up two-way data communications between the utility's data center and the meters. More detailed customer information can serve to offer enhanced services such as time-of-use pricing, management of demand, and load profiles.

Remote meter reading systems have been developed in parallel with various network technologies for many years. The communication technology used for AMR systems can be largely categorized into wired and wireless. For a wired AMR network, a Telephone network [3, 11] or PLC [6-7, 9] has been used. In particular, PLC is an efficient way for power metering since an inherent means of communication already exists within the infrastructure. So metering data can be transmitted over the power line itself via power line communications. However, for the installation cost, and safety, gas meters or water meters cannot be electrically connected together by a power line. So, recently, the use of wireless technology is more common.

Wireless AMR networks include Cellular networks [4, 10] WLAN [4, 8], Zigbee (or IEEE802.15.4) [1-2], and other short range wireless systems [12-13]. Oska et al. [9] proposes a hybrid system: WLAN communication consisting of PLC-ethernet bridges. Recently, AMR systems associated with wireless sensor networks are introduced in [5, 14]. In particular, due to several advantages of easy inexpensive installation and development cost, flexibility, scalability, and so on, the popularity of ZigBee-based AMR systems is explosively arising.

However, the ZigBee devices are extremely limited in resources including processing, memory, and power. In addition, ZigBee is an autonomous network. Therefore, the network is not always in user-intervention, but operates self-regulated. Sometimes these characteristics of ZigBee can make the devices more vulnerable to unexpected error environments.

In this paper, a fault-tolerant wireless AMR network (FWAMR) is proposed, which is designed to improve the robustness of the conventional ZigBee-based AMR systems by coping well with dynamic error environments.

The remainder of this paper is organized as follows: Section 2 examines some weaknesses of ZigBee-based AMR networks. The proposed FWAMR scheme is introduced in Section 3. Performance is evaluated in Section 4 through experiments based on real system implementation. Finally, this paper concludes with Section 5.

2. Vulnerabilities in ZigBee AMR networks

ZigBee [15], based on IEEE802.15.4 [16] which characterizes a low-cost, low power, and short range wireless communications, aims to construct a scalable and autonomous network. In particular, the ZigBee devices are extremely limited in resources including processing, memory, and power. In addition, ZigBee is an autonomous network. Therefore, the network is not always in user-intervention,

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but operates self-regulated.

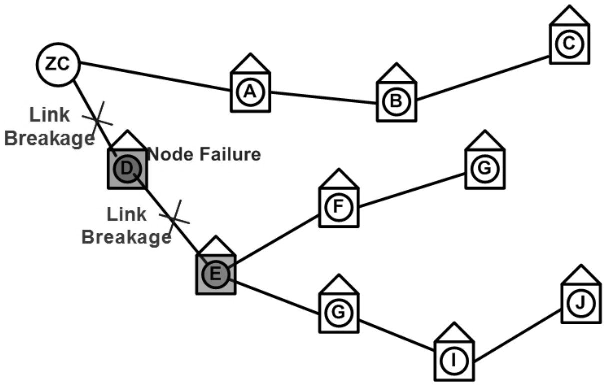
Sometimes these characteristics of ZigBee can make the devices more vulnerable to unexpected error environments such as abrupt system failure link errors, and resets. These errors are caused by various hardware faults, battery depletion, or Memory errors (such as stack overflow). In addition, the 2.4GHz band, which is one of the most popular frequency bands supported by the standard, is directly exposed to numerous other interference sources, such as IEEE802.11, Bluetooth, and other ZigBee (IEEE802.15.4) networks. These error environments of the ZigBee network may create node failure or frequent link breakages. Specifically, in the case of the ZigBee-based AMR network (which covers a large area with innumerable ZigBee devices), these fault environments might obstruct its normal operation, and paralyze even the whole network.

ZigBee standard provides a simple self-configuration and self-healing mechanism based on the orphan procedure of the IEEE 802.15.4. For a mesh network using AODV Jr., a routing maintenance method based on [17] is supported. However, the scheme is only possible when all the devices always stay awake.

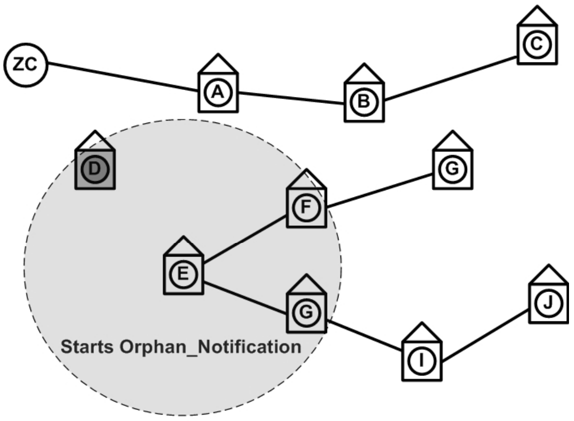
According to the ZigBee standard, after finishing the association procedure of all the devices in the network, every beacon issued periodically by a coordinator is relayed to the entire network, and each device synchronizes with every beacon. Thereby, each device sets an active period for communication, and the sleep period for its parent and children, respectively. If a device does not consecutively receive periodic beacons (default value of *aMaxLostBeacons* is 4), it is regarded as a link breakage to its uplink and declares a loss of synchronization. Then, the device attempts an orphan scan procedure.

Even though this orphan procedure based on IEEE802.15.4 can cope with some problems within the local (one-hop) area, in the case of a multi-hop network, it creates several problems.

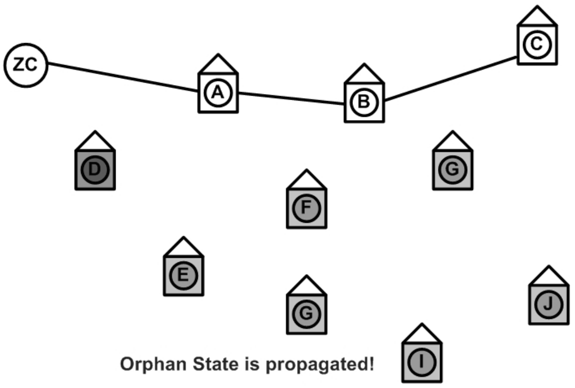
Consider a ZigBee network as shown in Fig. 1. It is assumed that all the devices within the tree are router-enabled device. If device D fails by any error, ZC (ZigBee Coordinator: That is also used for an AMR concentrator) and device E may lose their downlink and uplink, respectively. That means device D and E are disconnected. On the identification of its uplink loss, device E starts an orphan procedure by broadcasting an orphan notification message to the local area. Here, device E can recognize its uplink loss by consecutive beacon loss, or no data acknowledgement of device D. Then, the router waits for a response with the orphan notification. If there is no response during the time defined as *aResponseWaitTime* (32**aBaseSuperframeDuration* symbols), the device is regarded as an orphan device disconnected with the active PAN. It is important to note that the device E cannot send beacons to its children, during and after orphan procedure. Therefore, it



(a) Node Failure



(b) Orphan Process



(c) Orphan Propagation

Fig. 1. An example of Fault Propagation Problem

s children, F and G, also become orphans because they could not receive periodic beacons from their parent E. They also attempt an orphan procedure. This orphan state may be propagated to all the descendants of an initial orphan device as shown in Fig. 1 (a), in worst case scenario Eventually, this orphan propagation problem can bring big confusion to the network. According to the ZigBee standard, for this kind of problem, whether each device attempts an association procedure again or not, absolutely depends on a decision of its application layer. In the case that all the orphan devices perform the reassociation procedure, a large amount of delay overhead and additional energy wastage of each device are required. Even though some researches [18-20] are interested in the beacon problem, none of the existing solutions provide a method to cope well with several fault environments as well as the orphan propagation problem.

3. FWAMR: Fault-tolerant Wireless AMR networks

In this Section, we develop fault-tolerant wireless AMR networks (FWAMR). At first, in order to cope well with several unexpected error environments, our design considerations include the followings:

Quick fault detection: To maintain the network connectivity, the link error or breakage should be quickly and correctly detected.

Local orphan repair: To prevent the orphan propagation, an orphan should be repaired in the local area.

Dynamic Reconfiguration: To make a network adaptable for dynamic environments, the tree should be dynamically reconfigured.

The FWAMR is capable of accommodating three ZigBee topologies: Tree, Star, and Mesh. However, tree based topology is intensively focused on We basically consider the beacon-enabled mode of IEEE802.15.4. Also, all the links within the tree are bi-directional. Initial tree construction is conducted by association procedure based on IEEE802.15.4 and network formation function in the ZigBee network layer.

The FWAMR is implemented by supplementing cross layer functionality between IEEE802.15.4 MAC layer and ZigBee network layer without requiring a large amount of modification of the original stack. Therefore, the FWAMR provides interoperability with conventional ZigBee.

3.1 Development of Fault-Tolerant ZigBee Networks

In this Subsection, the major components and the development process of the FWAMR are presented.

First, in order to efficiently cope with network error environments, we define three types of states for FWAMR devices as follows: Active State, Orphan State, and Local Agent. *Active state* is the normal state of a device in the network, which maintains a good connection with the active tree without any problems, after completion of network formation. That means if there is no problem in the network, all the devices are in the active state. However, if some links of a node are broken due to any error, and thus the current path is not valid any more, the node gets lost in the network. This state is called *Orphan state*. Unlike the ZigBee standard, in the FWAMR an orphan node is capable of freezing its children to prevent orphan propagation to its descendants. Freezing is to make the children operate independently without regard to its parent's state (orphan state). Here, the frozen child goes to *Local agent state*. So, it temporally operates as a root of the partitioned tree until rejoining active tree is completed. Fig. 2 shows the FWAMR state transition diagram. Each state transition is triggered by the related events.

In addition to device states, FWAMR includes three important messages: Freeze message, Orphan join request, and Orphan join confirm. *Freeze message* is used when an orphan device make its children operate independently without regard to its parent for a while. If a device receives a freeze message from its parent, the device's state is changed into local agent. If, During passive rejoin scan of an orphan device, the device hears a beacon of an active device on the currently active tree, the orphan tries to join the route by sending an *Orphan join request* message to the

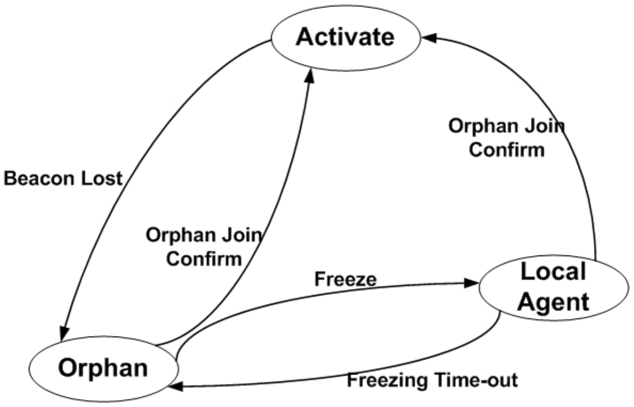


Fig. 2. State Transition of FWAMR

prospective parent device. On the reception of the Orphan join request, the prospective parent device allows the join of the orphan device by replying with an *Orphan join confirm* message.

The FWAMR is also composed of three major procedures: Backward freezing, Passive rejoin scan, and Rejoin Route Search. *Backward freezing* procedure includes the freeze message transmission of an orphan node to its children and freeze timer management. To join active route, the orphan node performs a *passive rejoin scan* for aBaseSuperframeDuration * (2n +1) symbols, where n is the value of the ScanDuration parameter (n = 1, 2, … , 15). If the orphan device hears a beacon of an active device on the active route during the scan duration, the orphan performs *rejoin route search* procedure including orphan join request transmission and link reconfiguration.

3.2 Adaptive Local Link Reconfiguration

Fig. 3 shows an example of FWAMR operation. The network environment, in which device D loses its uplink and downlink due to device fault, is the same as in the Fig. 1. In this case, in the conventional ZigBee initial orphan state of device E is propagated to the entire partitioned tree. This is because descendents of device E will not receive the periodic beacon from their parent so they cannot maintain the network connectivity any more and thus become orphan.

On the other hand, the FWAMR can initially prevent orphan propagation by the freezing method. As shown in Fig. 1 (b), on the detection of uplink loss, the device E changes its state into orphan and sends freeze message to its children. Device F and H, which received a freeze message from device E, become local agents, so they can send periodic beacons to their children by their own schedule even though they cannot receive the beacon from device E. Therefore, the descendants can maintain the network connectivity as if there is no problem. After freezing its children, device E tries to hear a beacon from an adjacent active device by performing a passive rejoin scan during the

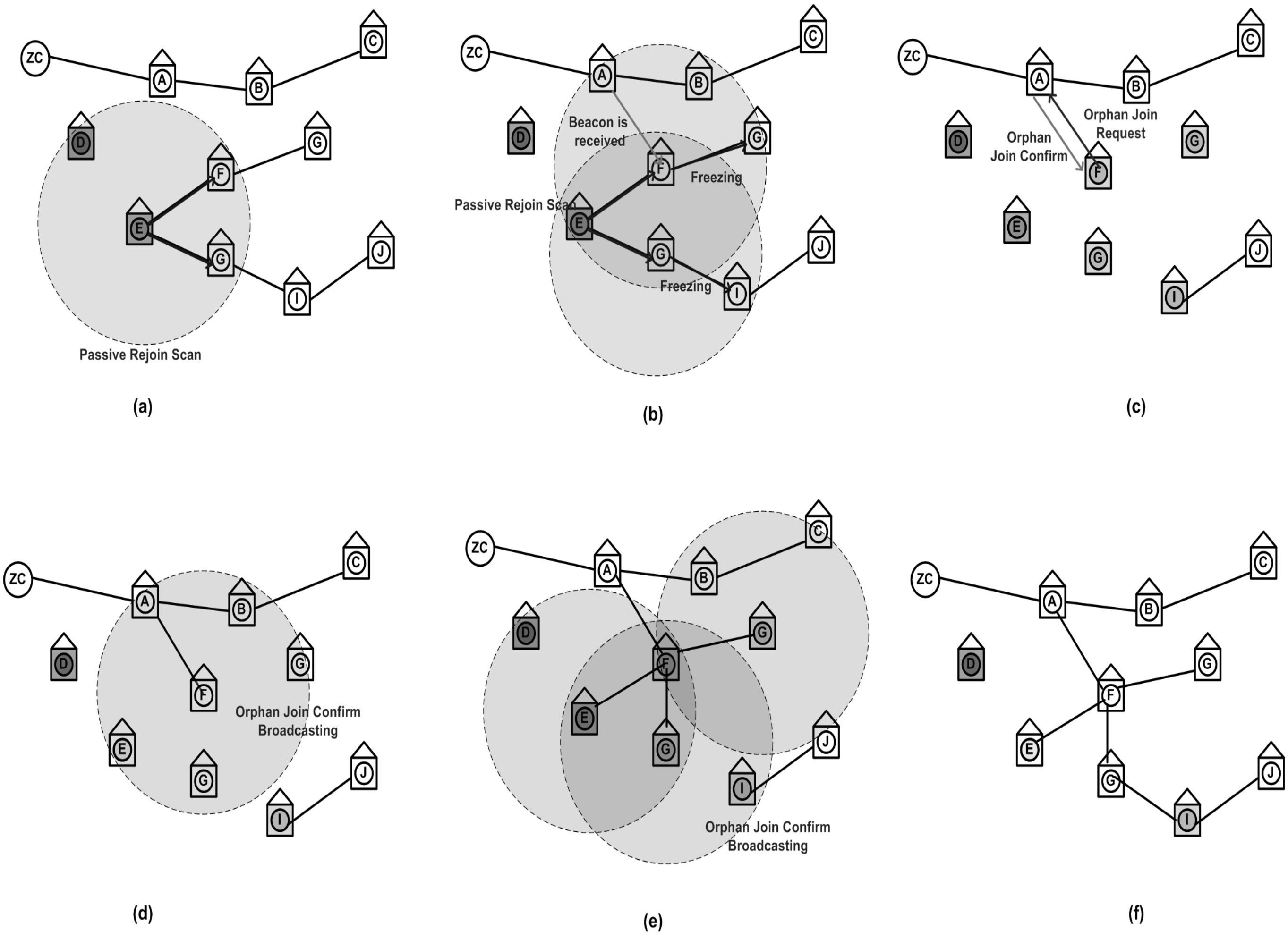


Fig. 3. An example of the FWAMR Operation

scan duration. However, as shown in that figure, device E will not hear any beacon of an adjacent active device so that the orphan state is maintained even after scan procedure. Local agents set a freeze timer by the same time as the scan duration of the former parent as soon as they receive a freeze message. If a local agent does not receive an orphan join confirm until the timer expires, which means the former parent device (orphan) is not activated, their state is changed into orphan, and their local agent role is handed to their children by sending freeze message. then they wait to hear an active beacon by performing a passive rejoin scan.

During the scan duration, device F can hear a beacon of device A which is on the active route, as shown in Fig. 3 (c). On the reception of the beacon, device F tries to rejoin the active route by sending an orphan join request. Device A replies with an orphan join confirm message, as shown in Fig. 3 (d). Then, device F makes a new connection to device A, and broadcasts an orphan join confirm, as shown in Fig. 3 (d). That is to allow the rejoining of orphans and local agent devices, which exist around device F. As shown in Fig. 3 (f), orphans and local agent devices, which hear the orphan join confirm broadcast messages, make new connections to device F and broadcast an orphan join confirm message, again. Therefore, the final tree is reconfigured as shown in Fig. 3 (g). After completion of reconfiguration, they maintain the network connectivity with the new beacon schedule. It is important to note that the shape of the tree is transformed by adaptive local link reconfiguration of FWAMR, compared to the original.

The FWAMR is capable of initially preventing the orphan propagation by the freezing method, and be quickly recovered from error environments. In addition, since the FWAMR provides a dynamically stable route making a detour of the problematic device, it is possible to guarantee more secure communications.

4. Experimental Results

In this Section, an experimental environment for the FWAMR implementation is presented. We also discuss the experimental results with respect to various metrics.

4.1 Experimental Environment

We have developed an FWAMR ZigBee-based AMR system. The developed system is composed of IEEE 802.15.4 compatible RF modem and 8051 main processor including 64Kbytes flash memory for program and 4 Kbytes internal RAM. For communication interface with a PC or Notebook, the serial (RS-232C) and USB are used. In addition, we have also constructed the FWAMR ZigBee test-bed consisting of the developed systems as shown in Fig. 4. The test-bed is composed of a PC for monitoring and aggregation, 1 FWAMR Concentrator (ZigBee coordinator) connected to the PC, and 10 ZigBee devices. For the topology, the multi-hop tree is applied as shown in Fig. 4.

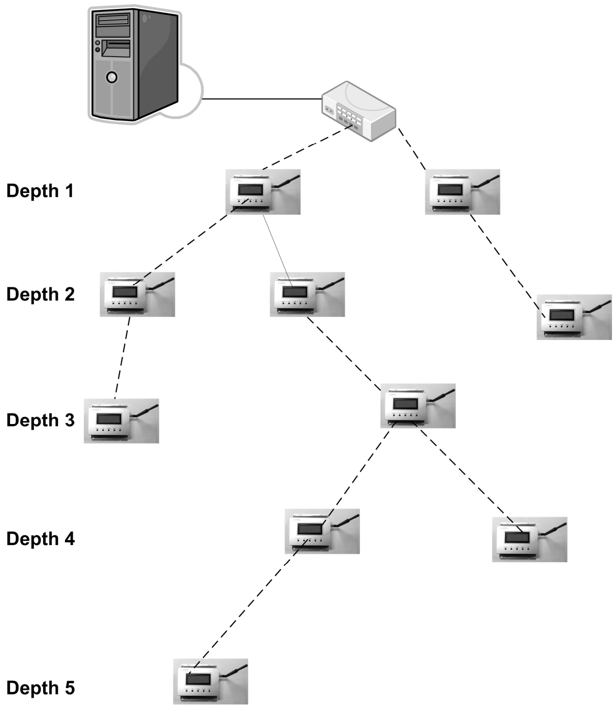


Fig. 4. FWAMR Experimental Environment

4.2 Experimental Results

Our experiment basically aims to test feasibility of the proposed FWAMR ZigBee network on real system implementation, rather than simulations. Fundamental performances are evaluated through comparative observations of the proposed FWAMR and pure ZigBee [15] certified by ZigBee Alliance, and implemented on the same test-bed. First, complete realignment time in the random node failure environment is observed, and the successfully reassociated rate is measured.

4.2.1 Complete Realignment time

After network formation, we observed the network status caused when intentionally turning off an arbitrary device on each depth (1 – 5) as shown in Fig. 4. We have first measured the complete realignment time defined as the time required for complete reassociation from the occurrence of a link breakage. Pure ZigBee is allowed for

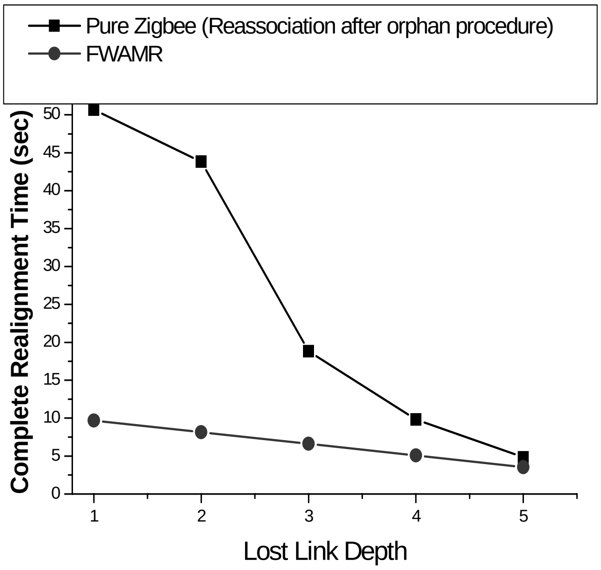


Fig. 5. Complete Realignment Time

every orphan device to try reassociation after failure of an orphan procedure. Fig. 5 shows comparative results with respect to complete realignment time. The result demonstrates that the proposed FWAMR is superior to the pure ZigBee in terms of complete realignment time. In particular, pure ZigBee shows that the more descendants the orphan has, the more delayed the network reconstruction is. That is the result from orphan propagation effect. In contrast to pure ZigBee, the FWAMR shows small realignment time even in the case of orphan nodes having a large number of descendants (Stage 1 or 2). That is why the FWAMR is able to prevent the orphan propagation by freezing the orphan's children on the identification of consecutive beacon loss (4 times), and rejoin the adjacent active tree quickly by performing adaptive local link reconfiguration. In addition, when considering the successful reassociated rate to be presented in the following Subsection, the overall performance of pure ZigBee is worse than the FWAMR.

4.2.2 Successfully Reassociated Rate (Figure. Result)

We also measured the number of successfully reassociated orphan devices within 60 seconds, after link breakage at the different stage. The Successfully reassociated rate is obtained as follows:

Successfully Reassociated Rate =
(# of reassociated devices / # of total devices in the network) x 100

Fig. 6 shows comparative results with respect to the

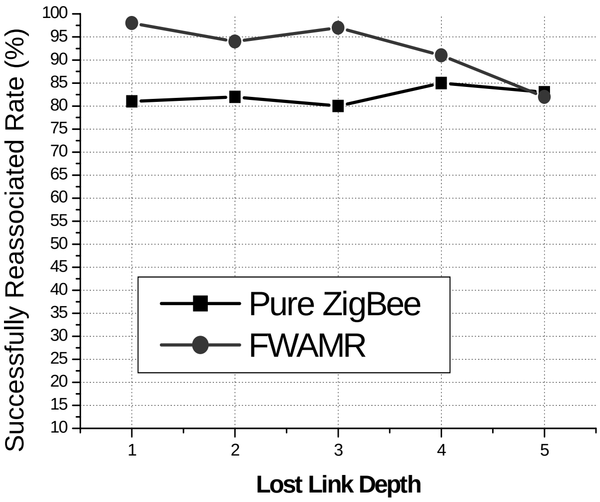


Fig. 6. Successful Reassociation Ratio

successfully reassociated rate. The experimental result demonstrates that it is hardly possible for the pure ZigBee to guarantee the successful reassociation of all the orphans.

That is why the orphan state is propagated to its descendants, and then the orphans make concurrent-intensive reassociation trials. On the other hand, it is shownthat the FWAMR maintains better performance. Since The FWAMR performs reassociation-after-frozen, orphan devices can be reassocated in phases. Also, the freezing method reduces the burst reassocation traffic, and adaptive local link reconfiguration allows the orphans to rejoin the adjacent active tree quickly. Here, the performance degradation at stage 4 and 5 is because there is no active route to join in the proximity, as shown in Fig. 4. However, if the devices are more densely deployed, the performance might get better.

5. Conclusion

Due to several advantages of easy and inexpensive installation and development cost, flexibility, scalability, and so on, the popularity of ZigBee-based AMR systems is explosively arising. However, these characteristics of ZigBee can make the devices more vulnerable to unexpected error environments.

In this paper, in order to improve the robustness of the conventional ZigBee-based AMR systems by coping well with dynamic error environments, a fault-tolerant wireless AMR network (FWAMR) has been proposed.

Based on real system implementation, the experimental results demonstrate that the FWAMR is considerably fault-tolerant compared with conventional ZigBee-based AMR network.

This work will become a major basis of our complete AMR system design. Currently, we are developing an integrated AMR/AMI system which can accommodate various meter devices and services.

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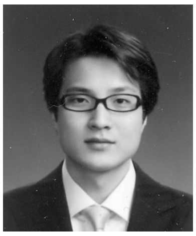

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