PAPER

Reliability Analysis and Modeling of ZigBee Networks

Cheng-Min LIN[†a)], ***Member***

SUMMARY The architecture of ZigBee networks focuses on developing low-cost, low-speed ubiquitous communication between devices. The ZigBee technique is based on IEEE 802.15.4, which specifies the physical layer and medium access control (MAC) for a low rate wireless personal area network (LR-WPAN). Currently, numerous wireless sensor networks have adapted the ZigBee open standard to develop various services to promote improved communication quality in our daily lives. The problem of system and network reliability in providing stable services has become more important because these services will be stopped if the system and network reliability is unstable. The ZigBee standard has three kinds of networks; star, tree and mesh. The paper models the ZigBee protocol stack from the physical layer to the application layer and analyzes these layer reliability and mean time to failure (MTTF). Channel resource usage, device role, network topology and application objects are used to evaluate reliability in the physical, medium access control, network, and application layers, respectively. In the star or tree networks, a series system and the reliability block diagram (RBD) technique can be used to solve their reliability problem. However, a division technology is applied here to overcome the problem because the network complexity is higher than that of the others. A mesh network using division technology is classified into several non-reducible series systems and edge parallel systems. Hence, the reliability of mesh networks is easily solved using series-parallel systems through our proposed scheme. The numerical results demonstrate that the reliability will increase for mesh networks when the number of edges in parallel systems increases while the reliability quickly drops when the number of edges and the number of nodes increase for all three networks. More use of resources is another factor impact on reliability decreasing. However, lower network reliability will occur due to network complexity, more resource usage and complex object relationship.

key words: *ZigBee network, system reliability, mean time to failure, reliability block diagram, wireless sensor networks*

1. Introduction

According to the ON World forecast in 2005 [1], the number of deployed wireless sensing network nodes will increase to 127 million in 2010 from 1.2 million in 2005. These network systems can be applied in home automation [26], battlefield surveillance, health care applications [6], [15] and vehicular environments [4], [24]. These applications are designed using a wireless personal area network (WPAN). The WPAN standard is defined in the 15th working group of the IEEE 802.15, including 802.15.1 (Bluetooth), 802.15.3 (UWB), and 802.15.4 (ZigBee).

The ZigBee standard based on IEEE 802.15.4 was completed in May 2003, and it specifies the physical layer and medium access control (MAC) for low rate WPAN (LR-WPAN). The ZigBee-style networks created by the Firefly Working Group in 1999 (becoming ZigBee later), but the group does not exist now. Today's ZigBee was adopted in 2003 and built on the IEEE 802.15.4 LR-WPAN standard. The ZigBee Alliance ratified the first ZigBee standard in December 2004 [2]. ZigBee follows IEEE 802.15.4 standard and operates in unlicensed RF worldwide (2.4 GHz global, 915 MHz Americas or 868 MHz Europe). There are 27 channels allocated in ZigBee standards as shown in [2]. Channel 0 uses the frequency at 868.0 ∼ 868.6 MHz, while the data rate is 20 kbps. Channels 1 ∼ 10 use the frequency at 902.0 ∼ 928 MHz, where each channel can provide 40 kbps data rate. Channels 11 ∼ 26 use the frequency at 2.4 ∼ 2.4835 GHz, where each channel is 250 kbps.

In recent years there has been renewal of interest in the ZigBee technique. To support dynamic routing, the ZigBee routing protocol uses the Ad-hoc On-demand Distance Vector (AODV) concept [18]; an on-demand approach for finding routes. Taehong Kim et al. proposed shortcut tree routing to improve the shortcomings of ZigBee tree routing [14]. Lee et al. used ZiCL [16] to improve the AODV shortcoming [18] which has higher routing overhead produced in the route discovery phase. ZiCL divides the ZigBee topology into several logical clusters. Cho et al. proposed the maximum likelihood location estimation (MLLE) algorithm for home network environments [7]. Wang et al. demonstrated that ZigBee can support a limited range of voice services [26]. Tsai et al. reported results on a ZigBee-based case study conducted in a vehicle [24]. According to their results, ZigBee was shown to be a viable and promising technology for implementing an intra-car wireless sensor network.

Although much research in ZigBee has been spent on routing and applications, only a few attempts have been made at the reliability issues. Ray and Dunsmore [20] proposed explicit reliability formula to compute reliability for star and ring topologies. Najjar and gaudiot [17] had addressed network fault tolerance using probability of disconnection for regular graph network topology. Above research results focus on regular graph network not suit for mesh topology. Notice that the vulnerability and downtime of wireless sensor networks will seriously impact our daily life when more systems are designed by the networks for daily use. Some real-time systems, including emergency rescue systems, accident notification systems and catastro-

Manuscript received June 23, 2009.
Manuscript revised September 10, 2009.

[†]The author is with the Department of Computer and Communication Engineering, Graduate Institute of Electrical Engineering & Computer Science, Nan Kai University of Technology, Tsao Tun, 542, Nan Tou County, Taiwan, R.O.C.
a) E-mail: lcm@nkut.edu.tw

DOI: 10.1587/transinf.E93.D.68

phe monitoring systems are widely in service. Issues related to reliability issues in wireless sensor networks have become very important. Some misconceptions among reliability engineers working on modeling and analysis were presented by Grottke et al. in 2008 [8]. Several reliability models were proposed to evaluate distributed programs [25], embedded software [13], computer [19], and embedded system [21]. The most useful tools for evaluating reliability are RDB [21] and fault tree [19]. RDB is used in the paper to evaluate reliability of ZigBee networks because any kind of networks can be easy to be represented by series-parallel systems except mesh networks.

We will focus on reliability analysis and modeling ZigBee physical, MAC, network, application layers to provide recommendations for stable network service. Three motives were combined in this paper on ZigBee reliability; how to evaluate that reliability of a wireless sensor network to provide higher quality of services, how to model three kinds of ZigBee networks to deploy a better network, and how to know application reliability when an application profile is selected. Recently, a few of researchers use RBD to evaluate network performance. Bein et al. [3] presented Markov reliability models using different types of sensors and spares that replaced failed sensors. Their schemes used single-type spares and pooled spares to efficiently solve system reliability for star and tree networks. Jain et al. [11] presented a bottom-up scheme to evaluate the lifetime performance for square-grid and hex-grid networks. However, these schemes are useful for regular networks, such as star, tree, and grid networks but they are not appropriate for irregular networks, ex. mesh networks.

The rest of this paper is organized as follows. Section 2 presents a system model, including the foundation of technology for ZigBee networks, the definition of reliability, mean time to failure (MTTF), and reliability block diagrams used to describe the composition of system reliability. Section 3 introduces modeling physical and MAC layer. Three kinds of topology introduced in the ZigBee specification will be modeled to calculate the reliability in Sect. 4. A division algorithm is proposed to calculate reliability for mesh networks in Sect. 5. Section 6 discusses the application framework and application profiles. In Sect. 7, we use the SHARPE tool to simulate the three kinds of networks according to the equations derived in Sects. 3, 4, and 6. Concluding remarks are presented in Sect. 8.

2. System Model

The reliability issue is always presented because it is related to the safety problems in our daily life. Numerous deployed sensors are required in our environment to collect real-time information. To analyze network reliability, a system network model should be established. In this section, we will focus on modeling the ZigBee network. Network reliability is defined next using the theory of probability. The RBD technique will then be introduced.

2.1 ZigBee Network

A wireless sensor network based on ZigBee technology providing context-aware services can be expressed as a graph $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$, where $\boldsymbol{V}$ denotes the set of *nodes* and $\boldsymbol{E}$ represents the set of logical *edges*. The node is indexed using a finite set $\boldsymbol{I}$, where $\boldsymbol{I}$ is the set, $\{1, 2, 3, \ldots, |\boldsymbol{V}|\}$. Two different types of nodes are defined in an LR-WPAN, a full function device (FFD) and a reduced function device (RFD). A FFD can communicate with RFDs and other FFDs, while a RFD can only communicate with a FFD. FFD can operate in three device modes, coordinator, and PAN coordinator, while RFD can only operate in the device mode. For any two nodes v_x, $v_y \in \boldsymbol{V}$, a logical edge $e_{x,y}$, where $e_{x,y} \in \boldsymbol{E}$, implies that v_x has a wireless channel to v_y under the current transmitting range of v_x.

According to the ability of ZigBee devices, we can divide them into FFDs and RFDs. FFDs have a lot of resources than RFDs, including computing capability, memory, and power. These topologies are made up using three types of devices. The most important device type is the ZigBee coordinator. Any topology can have only one coordinator. The coordinator in a ZigBee-based network must be a FFD. The coordinator is responsible for network formation and maintenance. The second device type is the ZigBee router. The router is a FFD. However, the resources in a RFD has less than that in a FFD. The router is responsible for forwarding packets in the network. The last type of devices is the ZigBee end device. The end device is the RFD and it cannot forward packets. In other words, the end device cannot relay data from other devices and can only talk to their parent devices. The ZigBee specification [2] provides three types of topologies: star topology, mesh topology, and tree topology as shown in Fig. 1. This is different than other networks, such as Bluetooth. Only one coordinator exists in every ZigBee network for the three kinds of topologies.

2.2 Reliability Definition

A reliability model for modeling a product presents a bathtub curve and can be divided into three regions, infant mortality (smaller than one year), steady-state operation (1-20

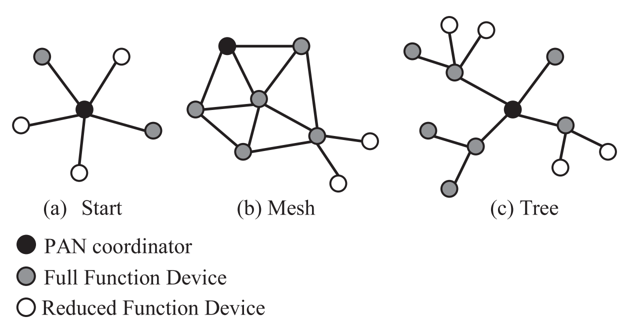


Fig. 1 Three Topologies of ZigBee.

years), and wearout (larger than 20 years) [9]. Each region can be modeled with a different reliability function. Infant mortality, steady-state operation, and wearout models use Weibull, exponential, and log-normal types of reliability distributions, respectively. In this paper, we focus on steady-state operation during customer use. Hence, we use the exponential distribution having a constant failure rate.

Let the random variable $\boldsymbol{X}$ represent the lifetime for $t \geq 0$. In general, a lifetime distribution with a constant failure rate λ is represented using an exponential distribution. According to the definition in [5], the reliability can be defined as the probability that the software will not cause a system failure for a specified amount of time under specified conditions. Hence, the probability of reliability presented in [23] can denote to the system continues to function until time t to be given by

$$R(t) = \Pr(X > t) = 1 - F(t) = e^{-\lambda t}, \quad (1)$$

where $F(t)$ is the cumulative distributed function (CDF) of system lifetime.

In addition, MTTF is closely related to the reliability. It is the expected time that a system will operate before the first failure occurs. Hence, the average of the system's lifetime distribution $E[X]$ presented in [23] is

$$E[X] = \int_0^\infty R(t)dt = \int_0^\infty e^{-\lambda t}dt = \frac{1}{\lambda}. \quad (2)$$

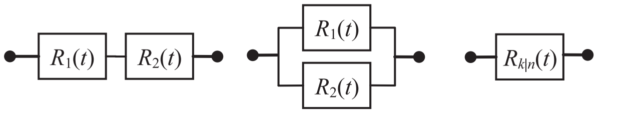
Next, we consider a network consisting of n nodes. The RDB technique is used for introducing the relationship between nodes or edges in the next subsection.

2.3 Reliability Block Diagram

RBD is the most widely used formalism in system reliability modeling. A RBD graphically represents a series-parallel system in which its components are combined into blocks in series, in parallel, in bridge or in k-out-of-n configuration as shown in Fig. 2. For a network, a component is a node or an edge defined in this paper. A series-parallel system having both series and parallel parts constitute n serial stages where stage i consists of n_i identical components in parallel. We assume that all components in the series-parallel system are independent. The system reliability $R(t)$ can be computed by

$$R(t) = \prod_{i=1}^{n} \left[1 - (1 - R_i(t))^{n_i}\right]. \quad (3)$$

A k-out-of-n system consists of components having independent exponentially distributed lifetime to be the sum



(a) Series system (b) Parallel system (c) k-out-of-n system

Fig. 2 Reliability block diagram.

of $(n - k + 1)$ exponentially distributed random. Thus, the reliability of a k-out-of-n system is given by

$$R_{k|n}(t) = \sum_{i=k}^{n} \binom{n}{i} R^i(t)(1 - R(t))^{n-i}. \quad (4)$$

The reliability of a k-out-of-n system can be denoted by a symbol $R_{k|n}(t)$. The symbol is also used for representing a series system or a parallel system. For a series system consisting of n components, $R_{n|n}(t)$ can be used to represent the system reliability while $R_{1|n}(t)$ denotes the system reliability of a parallel system with n components. In other words, a series system will fail if any one of its components fails. For a series system, Eq. (3) can be rewritten to $R(t) = \prod_{i=1}^{n} R_i(t)$. We call the equation the product law of reliabilities that a system's reliability quickly degrades with an increase in complexity. In contrast, the reliability of a parallel system with n components has the product law of unreliability's to represent $R(t) = 1 - \prod_{i=1}^{m}(1 - R_i(t))$ formed by Eq. (3) when $n = 1$ and $n_i = m$. However, a parallel system is the simplest method to increase the reliability of a system. The method is called parallel redundancy.

3. IEEE 802.15.4 Modeling

In this section, we will establish two mathematical models for evaluating reliability in the IEEE 802.15.4. Through both models, we can better understand reliability behavior for ZigBee devices in the physical layer and medium access control (MAC) layer. In a ZigBee device, using node descriptor describes itself capabilities. The descriptor is mandatory for each node. We will introduce two fields, frequency band and MAC capability flags in Sects. 3.1 and 3.2, respectively.

3.1 ZigBee Physical Layer

Recently, a few of researchers presented multi-band or multi-channel schemes [12], [27], [28] to reduce interference and to improve transmission performance. The ZigBee specification follows IEEE 802.15.4 standard and operates in unlicensed RF worldwide. Three frequencies of 868 MHz, 915 MHz and 2.4 GHz, are used to be denoted by α, β, and γ, respectively. Above bands whether is used or not to be stored in the frequency band field of the node descriptor denoted by $b_0b_1b_2b_3b_4$. Bits 0, 2, and 3 are represented by 868 MHz, 915 MHz and 2.4 GHz used, respectively. Bits 1 and 4 are reserved. However, a system equipped more frequency bands can efficiently promote its reliability. Hence, the three bands are regarded as a parallel system for reliability evaluation. For a ZigBee device with using m channels of 915 MHz and n channels of 2.4 GHz, the reliability equation of modeling physical layer denoted by R^{Phy} is given using

$$R^{Phy}(t) = 1 - \Bigg[(1 - R^{\alpha}(t))^{b_0} \times \left(1 - \prod_{i=1}^{m} R_i^{\beta}(t)\right)^{b_2} \times \left(1 - \prod_{j=1}^{n} R_j^{\gamma}(t)\right)^{b_3}\Bigg], \quad (5)$$

where $1 \le m \le 10$ and $1 \le n \le 16$.

3.2 ZigBee MAC Layer

The MAC capability flag field defined in the node descriptor specifies the node capabilities required by the ZigBee MAC layer. In the field, there are two sub-fields related to reliability evaluation, including device type and power source. When the device type sub-field, b_1 defined in the specification is set to 1, the ZigBee device is a FFD otherwise, it is RFD. We analyze FFDs and RFDs characteristics. We have found that a FFD device can be viewed as a component in a parallel system for reliability evaluation because the FFD device has an ability to be connected with each others. In contrast, a RFD only connects with a FFD device. Hence, each RFD is a component in a serial system for reliability evaluation. As discussion above, we have concluded that the reliability for modeling MAC layer have two parts. One is device role and device power ability. Hence, the reliability equation of modeling MAC layer denoted by R^{MAC} is given using

$$R^{MAC}(t) = \left[1 - \prod_{i=1}^{n}\left(1 - R_i^{FFD}(t)\right)^{b_1}\right] \times \prod_{i=1}^{n}\left(R_i^{RFD}(t)\right)^{(1-b_1)}, \quad (6)$$

where R_i^{FFD} and R_i^{RFD} represent both role reliability of FFD and RFD. The FFD reliability is higher than RFD because FFD has routing capability but RFDs does not. The capability can efficiently enhance network reliability.

Excepting the node descriptor, the node power descriptor is also very important parameters for reliability evaluation. In the node power descriptor, there are four parts and each sub-field has four bits in length. First, the current power mode field is specifies the current sleep/power-saving mode of the node. Second, the power sources available on this node are defined in the available power sources field. Third, the current power source field describes the current power source being utilized by the node. Last, the current power source level field presents the level of charge of the power source. We more concern with available power sources and the current power source level. We can view available power sources as a parallel system. Current available power sources have mains power, rechargeable battery and disposable battery to be defined in bit $0(b_0)$, $1(b_1)$, and $2(b_2)$, respectively. Their reliability can be expressed as R^{MP}, R^{RB}, and R^{DB}, respectively. Hence, the reliability in power issues can be calculated by

$$R_i^P(t) = \left[1 - \left(1 - R_i^{MP}(t)\right)^{b_0} \times \left(1 - R_i^{RB}(t)\right)^{b_1} \times \left(1 - R_i^{DB}(t)\right)^{b_2}\right], \quad (7)$$

where i is node index, $1 \le i \le |\boldsymbol{V}|$, and b_0, b_1, and b_2 are represented whether the current available power sources is available or not. The bit value is one if its related power source is available otherwise is zero. The three sources are defined in bit 0, 1, and 2 of the available power sources field. The charge level is critical, 33 %, 66 %, and 100 % when the current power source level value is 0, 4, 8, 12, respectively. Unfortunately, all other values in this filed are reserved in the ZigBee specification; hence, only four levels of power source level are obtained to evaluate reliability.

4. Network Modeling

In this section, we will establish three mathematical models for the three kinds of ZigBee topologies. Through these models, we can better understand network reliability behavior. However, network layer's reliability depends on MAC and PHY layer's reliability.

4.1 Star Topology

In ZigBee networks, a start network is the most basic topology. It constitute only one central node and n child nodes connected to the central node as illustrated in Fig. 1 (a), where $n \ge 1$. The central node must be FFD also called PAN but the others are FFD or RFD. Hence, the number of nodes, $|\boldsymbol{V}|$ is $n+1$ and the number of links, $|\boldsymbol{E}|$ is n. The central node is a bottleneck for an entire network. It should be noticed that the network has a breakdown when the central node is out of order.

A star network is a series system for computing reliability. We assume that lifetime of the central node and the ith child node for the network are exponentially distributed with parameters λ_c and λ_i, respectively. In addition, both of node and link in reliability analysis are considered together because two nodes in the network is not functioning indicated information exchanged between them if their existed link is not well established. However, they are considered for computing network reliability. Hence, node reliability and link reliability are represented by $R^{\sigma}(t)$ and $R^{\varepsilon}(t)$, respectively. For a star network, the network has failed in spite of one of nodes or links failing. Thus, a node and its link linked to the central node can be viewed as a serious system for reliability analysis. Then, system reliability is given by

$$R^{star}(t) = R_c^{\sigma}(t)\prod_{i=1}^{n}\left(R_i^{\sigma}(t)R_i^{\varepsilon}(t)\right) = e^{-\lambda_c^{\sigma}t}\prod_{i=1}^{n}\left(e^{-\lambda_i^{\sigma}t}e^{-\lambda_i^{\varepsilon}t}\right). \quad (8)$$

For a star network, its reliability quickly degrades with an increase of n. For example, if a star network has 10 child nodes, each node having a reliability of 0.98 and each link having a reliability of 0.99, then the network reliability is $0.98^{11}0.99^{10} = 0.724$. Now if the network complexity is increased that it has 100 child nodes, its reliability would be reduced to $0.98^{101}0.99^{100} = 0.048$. It is surprise for us that the network reliability is closely to zero when the network size is very large. Hence, a start topology is not applicable for a larger scale of a wireless sensor network. Thus, the lifetime of the network is also exponentially distributed with parameter $\lambda = \sum_{i=0}^{n} \lambda_i$. Therefore the network MTTF is

$$\frac{1}{\lambda_c^\sigma + \sum_{i=1}^{n} \lambda_i^\sigma + \sum_{i=1}^{n} \lambda_i^\varepsilon}. \tag{9}$$

Although the advantages of a star network are simple, low cost, and easy to deploy, it is easy to occur system breakdown when n is rapidly increased.

4.2 Tree Topology

In the previous subsection, we discussed computing network reliability in star topologies. A star is a basic unit of networks. In general, it is applicable for a smaller network. When the size of a network grows, a tree topology is usually adapted because there are nodes to share the coordinator's communication load in exchanging information. We assume that a tree is a connected acyclic graph and a tree has no parallel edges and no loops. A tree can be divided into several subtrees. Each subtree is also divided into at least one subtrees or a node. Through above discussion, we know that the tree topology is naturally a recursion of tree. The reliability of a tree network, R^{tree}, constitutes the product form of among the root reliability R_{root} and several reliabilities in subtrees, R_i^{tree}. If a tree network has n subtrees, then its reliability can be represented as

$$R^{tree}(t) = R_{root}(t) \prod_{i=1}^{n} R_i^\varepsilon(t) R_i^{tree}(t). \tag{10}$$

Using the above equation compared with Eq. (5), we found that a tree network is also a series system. Hence, its disadvantage is same as with a star network but its central node has a lower load than a star network. In usually, a star and tree networks are used to small-size and medium-size wireless sensor networks. According to Eq. (2), we can infer that the tree network's MTTF is

$$MTTF^{tree} = \frac{1}{\lambda_{root}^\sigma + \sum_{i=1}^{n} \lambda_i^{tree}}, \tag{11}$$

where n is the number of subtrees.

4.3 Mesh Topology

In the previous two subsections, we discussed about reliability issues in star and tree topologies. We found that such topologies are not applicable for use in larger wireless sensor networks consisting of ZigBee devices. However, it is necessary that over one thousand wireless sensors are needed for deployment in forests, battlefields, cities, outer space, etc. for collecting the required sensing information from the network. Hence, how to design a novel topology for a larger size wireless sensor network has become an important issue.

According to the ZigBee network layer description in the ZigBee specification [2], three topologies are supported, including the star, tree and mesh. As above, the star and tree topologies are not applicable for larger wireless sensor networks. Only the mesh topology remains. However, it is difficult to analyze the reliability of a mesh network because a good structure is not provided within such networks. The core of the problem is how to compute network reliability using a series-parallel system. Fortunately, *division* technology is proposed in this study for solving this problem. A ZigBee mesh network consists of n nodes and at least n links. The number of nodes is less than the number of edges, $|V| < |E| + 1$ for a mesh network but $|V| = |E| + 1$ for a star or tree network. For a mesh network, all of the nodes can be viewed as a series system but some parts of the edges cannot be viewed as a parallel system. Although some edges are removed from a mesh network, the network is still functioning.

As discussed above, the division technology is used to divide a mesh network into m stages of non-reducible series systems and $m - 1$ edge parallel systems. A non-reducible series system means that any node or edge can removed from the network and the network is still connectable, in other words, no isolated node exists in the network, such as Fig. 1 (a) and 1 (c). Note that a network having only one node is also a non-reducible series system. A star or tree network is a classical non-reducible series system. In other words, no redundant element exists in the system. In addition, an edge parallel system consisting of at least one edge is used to connect both non-reducible series systems. The coordinator node is a non-reducible series system. In Fig. 1 (b), there are three non-reducible series systems existing in the mesh network. Hence, the reliability for a mesh network is given by

$$R^{mesh}(t) = R_c^\sigma(t) \prod_{i=1}^{m-1} R_i^\gamma(t) \prod_{i=1}^{m-1} \left[1 - \left(1 - R_i^\varepsilon\right)^{n_i}\right], \tag{12}$$

where $R_i^\gamma(t)$, $R_i^\varepsilon(t)$, and n_i are represented by ith non-reducible series system, ith edge parallel system, and the number of edges exist in ith edge parallel system, respectively. Notice that Eq. (12) is a general form for Eq. (8) and Eq. (10) if n_i and m are equal to 1 and $n + 1$. R_i^γ represents nodes in Eq. (8) and subtrees in Eq. (10). As an example of modeling a mesh network, let us consider using the division technology to analyze the reliability of mesh networks as shown in Fig. 3. In Fig. 3, a mesh network can be classified into a coordinator, two non-reducible series systems,

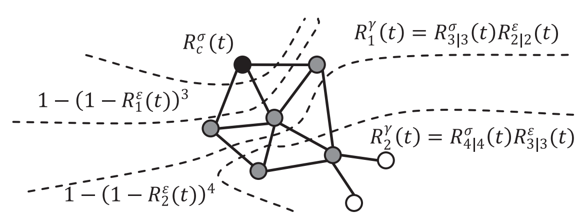


Fig. 3 Reliability analysis using division technology for the mesh network in Fig. 1 (b).

```
float division (G)
{
   if (G is not cycle) return Rn^|V|×Re^|E|;
   G is divided into G1, G2, and Ep;
   n = |Ep|;
   retrun division (G1)× division (G2)× [1-(1-Re)^n];
}
```

Fig. 4 *Division* algorithm for reliability evaluation.

and two edge parallel systems. These components are represented by $R_c^{\sigma}(t)$, $R_1^{\gamma}(t)$, $R_1^{\varepsilon}(t)$, $R_1^{\gamma}(t)$ and $R_1^{\varepsilon}(t)$, respectively. $R_c^{\sigma}(t)$ denotes the coordinator of the mesh network.

5. Division Algorithms

In Sect. 4.3, we had mentioned our division idea to calculate the mesh network reliability. The division scheme not only is suit for mesh networks but also for any connected graph, including star and tree networks. In general, star and tree architectures are easy to calculate by a series system, but components in mesh architecture are difficult to discriminate between series and parallel. Our proposed division algorithm can easy to solve this problem. Figure 3 illustrates an example for evaluating a simple mesh network and Eq. (12) provides a calculated method consisting three parts, including the network coordinator, non-reducible series systems, and edge parallel systems. In fact, the network coordinator can be viewed as a non-reducible series system. In this section, we will utilize a divide-and-conquer technical to design our division algorithm.

In Sect. 2.1, we had defined a wireless sensor network denoted by the graph $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$. The set of nodes is $\{v_1, v_2, \ldots, v_{|V|}\}$ and the set of logical edges is $\{(v_x, v_y) : (v_x, v_y) \in \boldsymbol{E}$ and $1 \leq x, y \leq |\boldsymbol{V}|\}$. Next, we discuss our division algorithm. First of all, the graph $\boldsymbol{G}$ can be detect whether it contains cycle or not. Eqs. (8) and (12) are used to calculate the graph reliability if the graph has no cycle; otherwise the graph G can be divided into two sub-graphs, $\boldsymbol{G}_1$ and $\boldsymbol{G}_2$, and a set of edges, $\boldsymbol{E}_p$, connected with both subgraphs. Hence, the graph reliability can be calculated using

$$R_{\boldsymbol{G}}(t) = R_{\boldsymbol{G}_1}(t) R_{\boldsymbol{G}_2}(t) R_{\boldsymbol{E}_p}(t) \tag{13}$$

Figure 4 illustrates the division algorithm for evaluating any graph reliability. Eq. (3) can be used to obtain $\boldsymbol{E_p}$ reliability. In other words, $\boldsymbol{E_p}$ reliability is approximately calculated by $1-(1-R_e)^n$ if $\boldsymbol{E_p}$ has n edge and each edge reliability is R_e. For $\boldsymbol{G}_1$ and $\boldsymbol{G}_2$, a recursion procedure is called using above divide-and-conquer technical for evaluating their reliability.

6. Application Modeling

In this section, we will introduce modeling application supporting and framework. In addition, some application profiles, including personal healthcare monitoring, smart energy, and wireless sensor networks are discussed.

6.1 Application Supporting and Framework

The functionality of application support sub-layer (APS) is to provide an interface between application layer and network layer. A binding table, $\boldsymbol{B_i}$ is maintained by the APS to allow ZigBee devices to create a designated destination, where i is a ZigBee device index and $1 \leq i \leq |\boldsymbol{V}|$. Each designated destination, d_j contains an address and an endpoint identifier, where $1 \leq j \leq |\boldsymbol{B_i}|$. The address can be a specific device or a group address. The endpoint identifier is optional. An application object, O_k is assigned an endpoint identifier k from 1 to 240. Hence, each ZigBee devices can provides up to 240 application objects that are components of the top portion of the application layer. A client/server model is employed in both ZigBee devices using cluster binding. As we understand, an application object and its all binding objects can be viewed as a serial system for reliability evaluation. Hence, for a Zigbee device, V_k hosting n application the reliability denoted by R^{APP} in the application layer is given by

$$R_k^{APP}(t) = \prod_{i=1}^{n} \left(R_i^o(t) \times \prod_{j=1}^{|\boldsymbol{B}_i|} R_j^o(t) \right), \tag{14}$$

where R_i^o is hosted in V_k and R_j^o is a designated destination existed in R_i^o's bind table.

6.2 Application Profiles

These binding objects form a cooperative application called an application profile. Application profiles provide a common language for exchanging data among application objects and define the set of processing actions. Hence, ZigBee devices produced by different manufactures can interoperate each other. In this subsection, we will introduce three application profiles as follows.

(1) The HA profile frequently provides the complete ZigBee cluster library defined in the ZigBee Cluster Library (ZCL), especially in on/off, level control, lighting, intruder alarm system (IAS), and heating, ventilation, air conditioning (HVAC) clusters. For instance, a system is designed using a on/off switch, O_s to control a light, O_l. The system reliability in the application layer, $R^{HA}(t)$ is $\left(R_s^o(t) \times R_l^o(t)\right)^2$.

(2) The WSA profile is designed to enable WSN applications. There are many sensors having been defined in the ZCL, such as temperature, pressure, flow, relative humidity and occupancy sensors. For example, a WSN consists of a sink, O_k and n sensors. Each sensor object, O_s is hosted in a ZigBee device. We assume that each sensor has same reliability. The network reliability, $R^{WSA}(t)$ in the application layer is calculated by $(R_s^o(t))^{n+1} \times \left(R_l^o(t)\right)^{2n}$.

(3) The PHHC profile has an important task that is to monitor patient health data, including blood pressure,

SpO_2, and heart rate, using a device called data collect unit for gathering the data from ZigBee devices. We modeling the task obtain its reliability, $R^{HA}(t)$ to be $\left(R_d^o(t)\right)^4 \times \left(R_p^o(t)\right)^2 \times (R_s^o(t))^2 \times \left(R_h^o(t)\right)^2$, where d, p, s, and h represent the data collect unit and three sensors mentioned above, respectively.

7. Numerical Results

In this section, we evaluate the reliability of three kinds of ZigBee networks, including star, tree, and mesh. In the previous sections, their equations were derived for computing reliability. According to these equations, we use the SHARPE tool that is a symbolic hierarchical automated reliability performance evaluator. It was originally developed in 1986 by Sahner and Trivedi at Duke University [10]. We use the RBD function through a graphical user interface provided by the SHARPE tool to computing reliability and draw several components in the tool for representing a series-parallel system. The default value of MTTF is 1,000,000 hours according to [22].

7.1 Experiments of the Physical Layer

As mentioned in Sect. 3.1, three frequencies of 868 MHz, 915 MHz and 2.4 GHz are used in ZigBee network having 1, m up to 10, and n up to 16 channels used, respectively. The three types of frequencies form a parallel system for reliability evaluation but channels in the same frequency band belong to a series system due to requirement consideration. According to this characteristic, designing the simulated code is illustrated in Fig. 5. A function of *Channel* with two parameters is called to evaluate reliability in the physical layer. Both parameters of m and n respectively represent the number of channels used in 915 MHz and 2.4 GHz. In this block, there are components to be R_c, $block_1$, and $block_2$ to represent the three frequency banks. For a function of k of n, there are four parameters, including block's name, the value of k, the value of n, and a component of reliability. A k-out-of-n system is called a series system if the value of k is the same with that of n. A keyword of series represents to make a series system. In Fig. 5, a series system called $serie_0$ consisting three components of R_c, $block_1$, and $block_2$.

Figure 6 illustrates that used channel reliability evaluation is simulated for the physical layer when one channel, m channels, and n channels are used in 868 MHz, 915 MHz and 2.4 GHz. We know that the reliability will decrease when the execution time is increased and more channel resources are required.

7.2 Experiments of the MAC Layer

We design a function called *Role* to evaluate reliability according node role, FFD and RFD, for the MAC layer. The function has two parameters of n and m representing the number of FFDs and the number of RFDs. We assume that MTTF for a FFD and a RFD is 1,000,000 and 500,000 hours, respectively. We consider more functions build in a FFD than that in a RFD. $Block_0$ represents a parallel system for all FFDs and $block_1$ is a series system for all RFDs. The simulated source code for the MAC layer generated by the SHARPE tool is shown in Fig. 7.

For a ZigBee network, there are two device roles, FFD and RFD. An experiment consisting 1000 ZigBee devices is design to evaluate reliability in the MAC layer mentioned in Sect. 3.2. Figure 8 demonstrates the system reliability when the number of FFDs is 100, 200, 400, 600, 800, and 900, respectively. The system reliability will increase when the number of FFDs increases and the number of RFDs decreases because of FFDs having routing ability.

7.3 Experiments of Star Networks

A star network is a basic ZigBee network. Figure 1 (a) illustrates the topology of a star network consisting of a coordinator and five child nodes among two FFDs and three RFDs. In addition, we had known from Eq. (8) that there are three components in a star network for calculating the net-

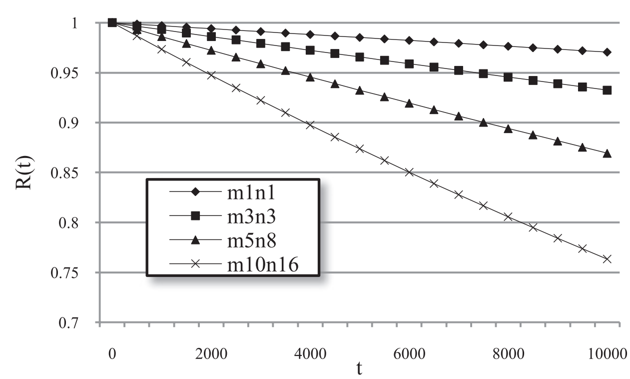


Fig. 6 Reliability evaluation is simulated for the physical layer when one channel, m channels, and n channels are used in 868 MHz, 915 MHz and 2.4 GHz.

block *Channel*(m, n)
  comp R_c exp(0.000001)
  kofn $block_1$ m, m, R_c
  kofn $block_2$ n, n, R_c
  series $serie_0$ R_c $block_1$ $block_2$
end

Fig. 5 The simulated source code for the physical layer.

block *Role*(n, m)
  comp R_{FFD} exp(0.000002)
  comp R_{RFD} exp(0.000001)
  kofn $block_0$ $1, n, R_{FFD}$
  kofn $block_1$ m, m, R_{RFD}
  series $serie_0$ $block_0$ $block_1$
end

Fig. 7 The simulated source code for the MAC layer.

work reliability, including $R_c^{\sigma}(t)$, $R_{5|5}^{\sigma}(t)$, and $R_{5|5}^{\varepsilon}(t)$. Three components in Eq. (8) form a series system for computing network reliability. There are three parameters needed to specify the experiment, including the number of child nodes N, execution time t, and mean time to failure MTTF.

Figure 9 illustrates the simulated source code for a star network generated by the SHARPE tool. In this code, a function of block named Star is called with two parameters, λ and N, represented by failure rate and the number of child nodes. For a star network, all are a series system in spite of nodes or edges. Furthermore, the number of child nodes is equal to the number of links. Lastly, the name of the series system *series*$_0$ is used to connect the three components in the series system and a keyword of series is used to create a series system.

We observe star network's reliability when is within 1,000 hours and N is 10, 20, 30, 40, and 50 as shown in Fig. 10. The network reliability descends quickly when n increases. When t is 1000 hours, the network reliability is 0.98, 0.96, 0.94, 0.92, and 0.9 when N is 10, 20, 30, 40, and 50, respectively.

In addition, we show the reliability variation for a star network consisting of 10 to 100 child nodes, as shown in Fig. 11 when t is 100, 1000, 10000, and 100000 hours, respectively. The impact in reliability is very large for a longer time when the size of a star network increases. The network reliability is close to zero for t is 100000 hours as the size of a star network is larger than 30. The network reliability will rapidly decrease in spite of N or t increasing. The numerical results demonstrate that a star network is not suitable for use in a larger size wireless sensor network.

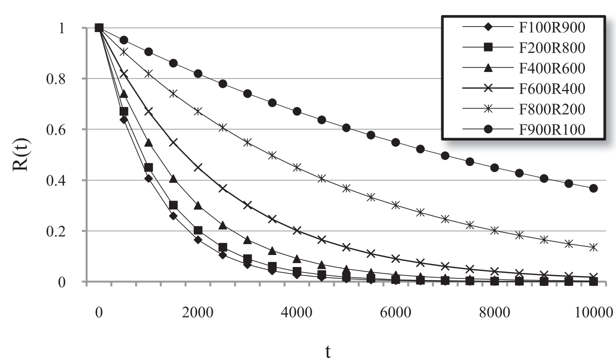


Fig. 8 The simulated source code for the MAC layer.

```
block Star (λ, N)
comp R      exp(λ)
kofn  block1  N, N, R
kofn  block2  N, N, R
series  serie0  R  block1  block2
end
```

Fig. 9 The simulated source code for a star network.

7.4 Experiments of Tree Networks

A tree network can be divided into several trees or star networks. In order to simplify in our experiments, two groups of six tree networks can be considered. (1) The first group network denoted by $T(3, N)$ has three star networks, where N is the number of child nodes in a star network to be 100, 300, and 500 child nodes, respectively. (2) The second group of tree networks denoted by $T(5, N)$ has the same number of child nodes per star network with $T(3, N)$ but there are five star networks existed in the second group of networks . In other words, the size of the tree network is over one thousand nodes in the tree network for $T(3, 500)$, $T(5, 300)$ and $T(5, 500)$.

The two simulated codes representing the two groups of tree networks are presented as shown in Fig. 12 (a) and 12 (b), respectively. These simulated codes are similar to that in Fig. 9. The last line of codes should be noticed in Fig. 12 to represent creating a series system for making up three star networks and five star networks in Fig. 12 (a) and 12 (b), respectively. Figure 13 illustrates that the reliability degradation speed accelerates when the network complexity increases. The reliability of all networks excepting $T(3, 100)$ is lower than 0.5 when t is 1000 hours. It is very terrible that $T(5, 500)$ is closely to zero when t is 1000 hours.

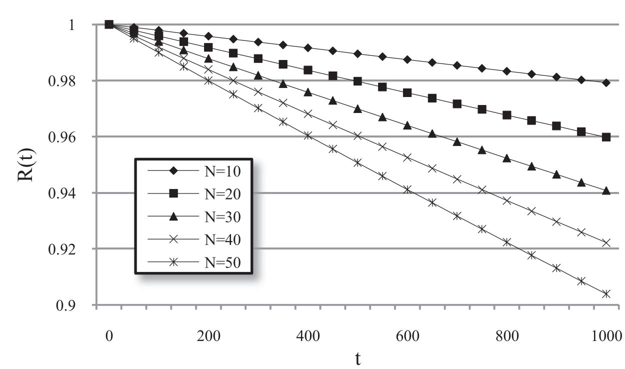


Fig. 10 Reliability analysis for a star network consisting of 10 to 50 child nodes.

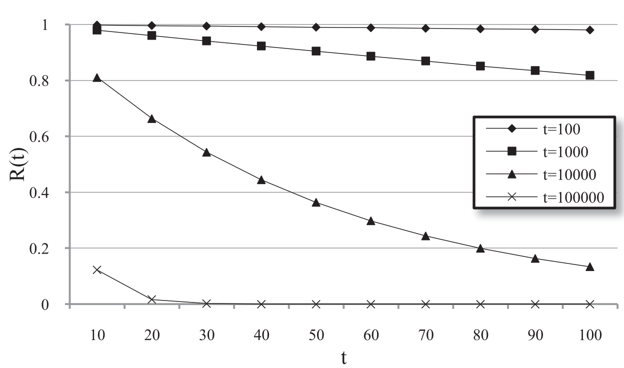


Fig. 11 Reliability analysis for a star network when t is 100, 1000, 10000, and 100000 hours.

block $Tree_3(\lambda, N)$
comp R $\exp(\lambda)$
kofn $block_2$ N, N, R
kofn $block_3$ N, N, R
kofn $block_6$ N, N, R
kofn $block_7$ N, N, R
kofn $block_8$ N, N, R
kofn $block_9$ N, N, R
series $serie_0$ R R
$block_2$ $block_3$ R $block_6$
$block_7$ R $block_8$ $block_9$
end

(a) A tree network consisting of three star networks

block $Tree_5(\lambda, N)$
comp R $\exp(\lambda)$
kofn $block_2$ N, N, R
kofn $block_3$ N, N, R
kofn $block_5$ N, N, R
kofn $block_6$ N, N, R
kofn $block_8$ N, N, R
kofn $block_9$ N, N, R
kofn $block_{11}$ N, N, R
kofn $block_{12}$ N, N, R
kofn $block_{14}$ N, N, R
kofn $block_{15}$ N, N, R
series $serie_0$ R R $block_2$ $block_3$ R
$block_5$ $block_6$ R $block_8$ $block_9$ R
$block_{11}$ $block_{12}$ R $block_{14}$ $block_{15}$
end

(b) A tree network consisting of five star networks

Fig. 12 The simulated source code for two tree networks.

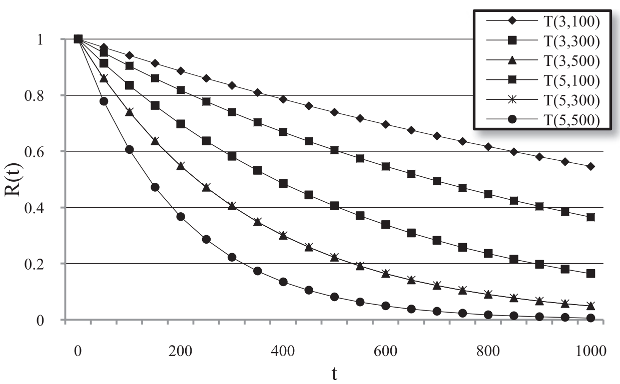


Fig. 13 Reliability analysis when MTTF is 1,000,000 hours for six networks.

7.5 Experiments of Mesh Networks

The mesh network structure can be viewed as irregular. Hence, drawing a reliability block diagram is more difficult than the others. Fortunately, a mesh network can be viewed having four main components according to Eq. (12). The first is the coordinator. The second is a parallel system with m parallel edges and its MTTF is 1000 hours to be smaller than the other components due to observe parallel edges for impacting reliability. The third and fourth are two series system consisting of N nodes and $N-1$ edges, respectively. The two series systems are combines into a star network or a tree network. The MTTF of all components is 1000000 hours except for the parallel system. Four components form a series system in the mesh network consisting of a coordinator, a parallel system of m edges, a series system of N nodes, and a series system of $N-1$ edges. The simulated code of the mesh network is shown in Fig. 14.

Figure 15 illustrates the reliability for a mesh network with a star network consisting 100 nodes and 99 edges. The reliability of the mesh network degrades as the execution

block $mesh(\lambda_n, \lambda_l, m, N)$
comp R_l $\exp(\lambda_l)$
comp R_n $\exp(\lambda_n)$
kofn $block_1$ $1, m, R_l$
kofn $block_2$ N, N, R_n
kofn $block_3$ N-1, N-1, R_n
series $serie_0$ R_n $block_1$ $block_2$ $block_3$

Fig. 14 The simulated source code for a mesh network.

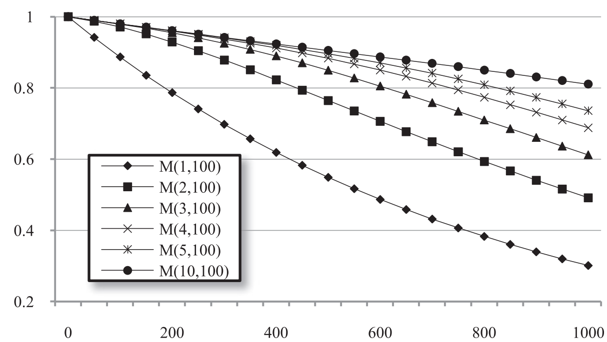


Fig. 15 Reliability analysis for mesh networks when the MTTF of nodes and links in the series system is 1000000 hours and the MTTF of links in the parallel systems is 1000 hours.

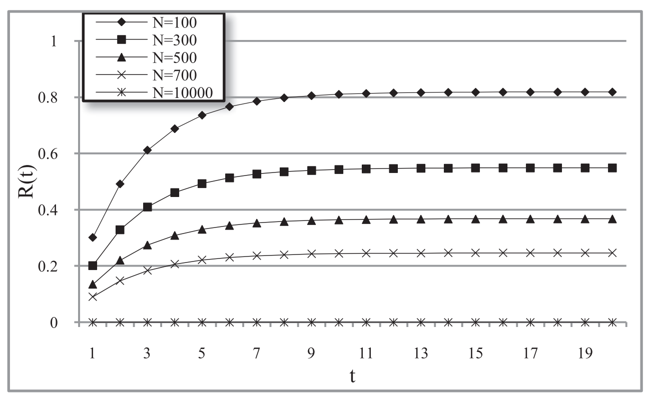


Fig. 16 The reliability of mesh networks increases when the number of edges in an edge parallel system increases as the MTTF of nodes and links in the series system is 1000000 hours and the MTTF of links in the parallel systems is 1000 hours.

increasing. We found that the reliability increases when the number of edges, m in the parallel system increases. However, the reliability quickly descends when m is 1.

To observe the m impact on reliability, we changed the value of m from 1 to 20 in the experiment as shown in Fig. 16. When m is larger than 9, the network reliability arrives at a saturation status. Furthermore, the network reliability is very low when the network complexity is very large.

7.6 Experiments of Wireless Sensor Applications

In Sect. 6, we first introduce application objects running the ZigBee application framework and then present three appli-

block *WSA*(*n*)
  comp R_s exp(0.000001)
  comp R_k exp(0.000002)
  kofn *sink* *n*+1, *n*+1, R_k
  kofn *sensors* 2*n, 2*n, R_s
  series serie$_0$ *sink* *sensors*
end

Fig. 17 The simulated source code for a wireless sensor application.

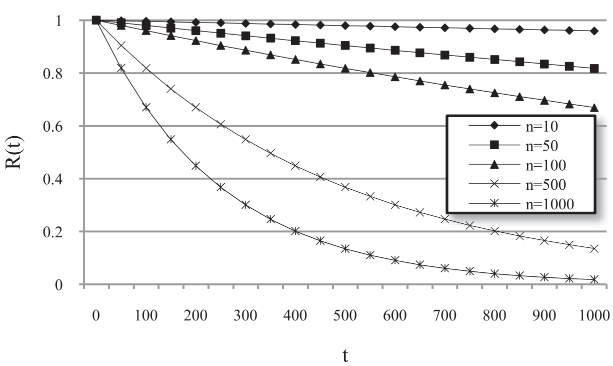


Fig. 18 Reliability analysis for a wireless sensor application when *n* is 10, 50, 100, 500 and 1000 nodes.

cation profiles. In this section, we will evaluate one of three application profiles called wireless sensor applications. In this experiment, a sink object connects *n* sensor objects for a wireless sensor application. According to Sect. 6.2, we design the simulated code as shown in Fig. 17. We assume that the failure rate in the sink is higher than any sensor because the sink requires more computation and transmition. Figure 18 illustrates reliability evaluation result for above wireless sensor application. Reliability decreases when the number of sensors, *n* increases especially in *n* is larger than 500.

8. Conclusions

This paper modeled the full ZigBee protocol stack. In physical layer, three frequencies used in ZigBee are discussed the reliability among their used channels. Both roles of RFDs and FFDs construct a series-parallel system to evaluate reliability in the MAC layer. In addition, some power issues for the ZigBee system configuration are discussed. In network layer, three kinds of networks frequently represented in ZigBee networks; star, tree and mesh. The former two always belong to a series system while the latter is a series-parallel system. For mesh networks, the division technique is used to divide a complex network into several simple networks. In application layer, we address reliability evaluation between application objects and their binding objects. In this work, the RBD diagram is used to describe the reliability relationship and its components in a network. Several contributions are made by this paper as follows. (1) The full protocol stack in reliability is evaluated. (2) Any kind of network can be represented by a series-parallel system using the RBD diagram. (3) Three useful functions of network reliability were derived. (4) Using the division technique, an irregular network can be divided into several simple series or parallel systems. Hence, computing the reliability of mesh networks has become an easy task. (5) The numerical results demonstrate that network reliability degrades with an increasing number of nodes. (6) Adding parallel edges to increase reliability is helpful. (7) The reliability for ZigBee application profiles are driven according the application's object-binding relationship.

Acknowledgments

The authors would like to thank the National Science Council of the Republic of China, Taiwan for financially supporting this research under Contract No. NSC 97-2221-E-252-016. The excellent comments of the anonymous reviewers are greatly acknowledged that have helped a lot in improving the quality and readability of the paper.

References

[1] The ON WORLD web site, http://www.onworld.com
[2] Zigbee Alliance, "ZigBee specification: ZigBee document 053474r13," 2006.
[3] D. Bein, V. Jolly, B. Kumar, and S. Latifi, "Reliability modeling in wireless sensor networks," International Journal of Information Technology, vol.11, no.2, pp.1–8, 2005.
[4] G.S. Bickel, "Inter/Intra-Vehicle Wireless Communication," http://userfs.cec.wustl.edu/~gsb1/index.html
[5] G. Bolch, S. Greiner, H. de Meer, and K.S. Trivedi, Queueing Networks and Markov Chains Modeling and Performance Evaluation with Computer Science applications, John Wiley & Sons, United States of America, 1996.
[6] T. Bolt, S. Kano, and A. Kodate, "Emerging market for mobile remote physiological monitoring services," IEICE Trans. Inf. & Syst., vol.E87-D, no.6, pp.1446–1453, June 2004.
[7] H. Cho, M. Kang, J. Kim, and H. Kim, "ZigBee based location estimation in home networking environments," IEICE Trans. Inf. & Syst., vol.E90-D, no.10, pp.1706–1708, Oct. 2007.
[8] M. Grottke, H. Sun, R.M. Fricks, and K.S. Trivedi, "Ten fallacies of availability and reliability analysis," Proc. 5th International Service Availability Symposium, pp.187–206, Tokyo, Japan, May 2008.
[9] D. Crowe and A. Feinberg, Design for Reliability, CRC Press LCC, 2001.
[10] C. Hirel, R.A. Sahner, X. Zang, and K.S. Trivedi, "Reliability and performance modeling using SHARPE 2000," Proc. 11th International Conference on Computer Performance Evaluation: Modeling Techniques and Tools, pp.345–349, Springer-Verlag, London, UK, 2000.
[11] E. Jain and Q. Liang, "Sensor placement and lifetime of wireless sensor networks: Theory and performance analysis," Proc. IEEE GLOBECOM, pp.173–177, 2005.
[12] M.S. Kang, J.W. Chong, H. Hyun, S.M. Kim, B.H. Jung, and D.K. Sung, "Adaptive interference-aware multi-channel clustering algorithm in a ZigBee network in the presence of WLAN interference," 2nd International Symposium on Wireless Pervasive Computing (ISWPC '07), pp.200–205, Feb. 2007.
[13] T. Katayama, T. Nakajima, T. Yuasa, T. Kishi, S. Nakajima, S. Oikawa, M. Yasugi, T. Aoki, M. Okazaki, and S. Umatani, "Highly, reliable embedded software development using advanced software technologies," IEICE Trans. Inf. & Syst., vol.E88-D, no.6, pp.1105–1116, June 2005.
[14] T. Kim, D. Kim, N. Park, S. Yoo, and T.S. Lopez, "Shortcut tree routing in ZigBee networks," Proc. ISWPC '07, pp.42–47, Feb. 2007.

[15] E.J. Ko, H.J. Lee, and J.W. Lee, "Ontology-based context modeling and reasoning for U-HealthCare," IEICE Trans. Inf. & Syst., vol.E90-D, no.8, pp.1262–1270, Aug. 2007.
[16] K.K. Lee, S.H. Kim, Y.S. Choi, and H.S. Park, "A mesh routing protocol using cluster label in the ZigBee network," Proc. Mobile Ad-hoc and Sensor Systems (MASS), pp.801–806, Oct. 2006.
[17] W. Najjar and J. Gaudiot, "Network resilience: A measure of network fault tolerance," IEEE Trans. Comput., vol.39, no.2, pp.174–181, Feb. 1990.
[18] C.E. Perkins and E.M. Royer, "Ad-hoc on-demand distance vector routing," Proc. WMCSA '99, pp.90–100, Feb. 1999.
[19] L.L. Pullum and J.B. Dugan, "Fault tree models for the analysis of complex computer-based systems," Proc. Reliability and Maintainability Symposium, pp.200–207, Las Vegas, NV, 1996.
[20] G.A. Ray and J.J. Dunsmore, "Reliability of network topologies," IEEE INFOCOM, pp.842–850, March 1988.
[21] M. Sahinoglu and Chittoor, "RBD tools using compression, decompression hybrid techniques to code, decode, and compute reliability in simple and complex embedded systems," IEEE Trans. Instrum. Meas., vol.54, no.5, pp.1789–1799, 2005.
[22] B. Schroeder and G.A. Gilson, "Disk failure in the real world: What does an MTTF of 1,000,000 hours mean to you?," Proc. 5th USENIX Conference on File and Storage Technologies, San Jose, CA, Feb. 2007.
[23] K.S. Trivedi, Probability and Statistics with Reliability, Queuing and Computer Science Applications, John Wiley & Sons, United States of America, 2002.
[24] H.M. Tsai, O.K. Tonguz, C. Saraydar, T. Talty, M. Ames, and A. Macdonald, "ZigBee-based intra-car wireless sensor networks: A case study," IEEE Wireless Commun., vol.14, no.6, pp.68–77, Dec. 2007.
[25] T. Tsuchiya, Y. Kakuda, and T. Kikuno, "Three mode failure model for reliability analysis of distributed programs," IEICE Trans. Inf. & Syst., vol.E80-D, no.1, pp.3–9, Jan. 1997.
[26] C. Wang, K. Sohraby, R. Jana, L. Ji, and M. Deneshmand, "Voice communications over ZigBee networks," IEEE Commun. Mag., vol.46, no.1, pp.121–127, Jan. 2008.
[27] K. Xuan and K.F. Tsang, "A novel tunable dual-band low noise amplifier for 868/915 MHz and 2.4 GHz ZigBee application by 0.35um CMOS technology," Asia-Pacific Microwave Conference, pp.1–4, Dec. 2008.
[28] A. Zainaldin, I. Lambadaris, and B. Nandy, "Vido over wireless ZigBee networks: Multi-channel multi-radio approach," International Wireless Communications and Mobile Computing Conference (IWCMC '08), pp.882–887, Aug. 2008.

Cheng-Min Lin was born in 1964. He received the B.S. and M.S. degrees in electronic engineering from National Taiwan University of Science and Technology, Taipei, Taiwan, in 1989 and 1991, respectively, and the Ph.D. degree in Department of Information Engineering and Computer Science, Feng-Chia University, Taichung, Taiwan. Currently, he is an Associate Professor in the Department of Computer and Communication Engineering, Graduate Institute of Electrical Engineering and Computer Science, Nan Kai University of Technology. His research interests include embedded systems, mobile computing, distributed systems, and telematics. Dr. Lin is a member of the IEEE Computer Society.