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Reliability and lifetime modeling of wireless sensor nodes

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ABSTRACT

The accuracy of system reliability analysis depends not only on system-level model construction, but also on realistic estimation of failure parameters at the component-level. In this paper, we model and evaluate the reliability and lifetime of a wireless sensor node under three typical working scenarios, contributing toward the accurate reliability analysis of wireless sensor network systems. According to the medium access control (MAC) protocols, the three working scenarios are defined based on the sensor node modes (sleep and active) and the mechanism of alternating between the modes. Reliability and lifetime of wireless sensor nodes under these three scenarios are illustrated and compared through numerical examples.

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1. Introduction

Due to recent advances in micro-electro-mechanical-systems (MEMS) technology, wireless communications, and highly integrated digital electronics, the manufacturing of small, low-cost, and low-power multifunctional sensor nodes has become technically and economically feasible [1–4]. These sensor nodes are deployed to sense and measure information from the environment surrounding them. A large number of these sensor nodes can be networked and such network is referred to as a wireless sensor network (WSN). WSN has a wide range of application areas, such as medical care, military surveillance, disaster preparation and response, manufacturing automation, home security, and so on. All these applications require a certain high level of reliability to operate safely and effectively [6–10]. Consider a typical ground surveillance application [28]. A set of sensor devices is deployed in a hostile region. These sensors detect and track occurrence of events of interest in the region, collect the required data, and report the data to a remote base station. The data may contain critical information such as enemy capabilities and positions of hostile targets, which can be used by the military command and control unit to take prompt action. These types of sensor systems have been proposed to monitor and handle emergency cases. Any network outage, unreliable component, or unreliable data transfer could have severe or harmful consequences to people or environment. Reliability modeling and analysis has become an essential and important step for design and reliable operation of such systems.

Generally, the reliability of a system is defined as "the probability that the system will perform its intended function under stated conditions for a specified period of time" [20]. Despite the rich literature on general network reliability research [21–23], the study of reliability issue in WSN is still in the early stage, especially the quantitative reliability analysis for WSN. Ref. [24] developed a reliability metric that is similar to the traditional terminal-pair reliability metric. Ref. [25] studied the reliability analysis of WSN under the application communication paradigm. Refs. [26,27] proposed reliability metrics of WSN with hierarchical clustered topology and tree topology under the infrastructure communication paradigm, respectively. All of these studies focus on system level reliability modeling and analysis, and assume the reliabilities/unreliabilities of sensor nodes and links are given. The accuracy of system reliability analysis, however, depends not only on system-level model construction, but also on realistic estimation of failure parameters at the component-level. Therefore, it is significant to model and evaluate the reliability of sensor nodes, constituent elements of WSN. In this paper, we study reliability and lifetime of sensor nodes under three different scenarios corresponding to different medium access control (MAC) protocols.

The following assumptions are made in this paper:

(1) Sensor node starts from the active mode at the beginning of mission time.
(2) The active current and sleep current are both constant.
(3) The battery discharge model adopted in this work is linear with respect to time.
(4) The initial capacity of the battery is given.

The remainder of the paper is organized as follows: Section 2 describes the sensor nodes architecture and three scenarios corresponding to three MAC protocols we study. Section 3 models reliability and lifetime of sensor nodes under these three scenarios. Section 4 presents numerical examples to demonstrate the application of the proposed reliability and lifetime models. Section 5 gives conclusions and directions for future work.

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2. Sensor nodes architecture and MAC protocols

Sensor nodes are designed to measure information from environment and then transform these measurements into signals that can be processed. Since the sensor nodes usually have limited processing and computing resources and they are typically deployed in difficult-to-access locations, a radio subsystem is implemented for wireless communication to transfer the collected data to a base station which could be a laptop, a personal handheld device, or an access point to a fixed infrastructure. Therefore, a typical wireless sensor node consists of four main components [4,5]: (1) a sensing subsystem that is composed of one or more sensors with associated analog-go-digital converters for data acquisition; (2) a processing subsystem that includes a micro-controller and memory for local data processing; (3) a communication/radio subsystem for wireless data communication; and (4) a power supply subsystem that consists of battery and direct current to direct current (DC–DC) power conversion. Depending on the specific application, sensor nodes may include additional components such as a location finding subsystem for position location, an actuator for sensor movement and configuration adjustment, and so on.

Fig. 1 shows the high-level fault tree model of a typical sensor node. The sensor node fails when any of the four subsystems fails. Among all the system elements, the battery in the power supply subsystem contributes the most to the sensor node unreliability because the battery capacity is very limited, and in most cases it is inconvenient or even impossible to recharge or replace the battery for WSN in hostile environments. Consider the military surveillance application. The surveillance mission may last several months. Due to the confidential nature of the mission and the inaccessibility of the hostile territory, it may not be possible to recharge the sensor devices during the course of the mission [28]. Therefore, the battery lifetime essentially determines the lifetime and thus the reliability of the sensor node [5,11].

To improve the lifetime of sensor nodes, techniques have been developed to minimize the energy-consumption. One of the commonly used techniques is the MAC layer design [11]. The MAC layer, described by a MAC protocol, is one of communication layers that tries to ensure that no two nodes are interfering with each other's transmissions and deals with the situation when they do [17]. In traditional MAC protocols, a node does not know when it will be the receiver of a message from one of its neighbors and thus it has to keep its radio in the receive mode all time. It has been observed that the energy consumption of a wireless transceiver listening to the idle channel is almost equivalent to its energy consumption when sending or receiving information. Therefore, most energy in traditional MAC protocols is wasted by idle listening [12]. A widely employed mechanism to reduce the energy-consumption is to schedule sensor node activity so that the nodes are able to enter the sleep mode as often as possible or remain in the sleep mode as long as possible by the MAC protocol design [13,14].

As one scheme of sleep/wakeup protocols, scheduled rendezvous schemes require that all neighboring nodes wake up at the same time. Typically, the nodes wake up periodically to check for potential communications, and then return to sleep until the next rendezvous time [5,15]. There are several different scheduled rendezvous protocols which are different in the way that the nodes sleep and wake up [15]. The simplest yet effective protocols are using fully synchronized pattern where all nodes in the network wake up at the same time [15]. S-MAC [16] and T-MAC [17] are two well-known and efficient MAC protocols that apply the fully synchronized wakeup scheme. In this paper, three different scenarios that can be respectively mapped to the traditional MAC as well as S-MAC and T-MAC are studied.

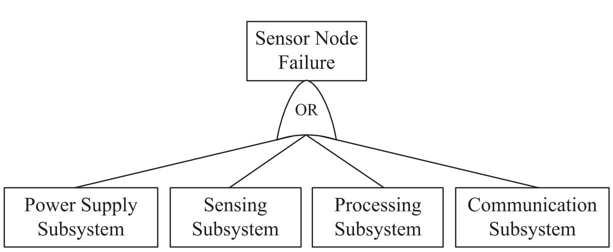

Fig. 1. Fault tree model of a typical sensor node.

2.1. Scenario 1 – traditional MAC

A sensor node keeps working in the active mode all the time. In this scenario, no sleep/wakeup scheme is applied to turn the sensor node to the sleep mode. Fig. 2 illustrates the scheme for Scenario 1.

2.2. Scenario 2 – S-MAC

A sensor node alternates between two modes: sleep mode and active mode. It consumes less power during the sleep mode than during the active mode. The duration of each mode is fixed.

The S-MAC protocol [16] is one application of Scenario 2. The base idea of S-MAC is that the time is divided into several fairly large frames. There are two parts of each frame: active part and sleeping part. During the sleeping part, a node turns off its radio to preserve energy; during the active part, the node communicates with its neighbors and sends any messages queued during the sleeping part [16]. The frame time, active time, and sleep time are fixed. Fig. 3 illustrates the scheme for Scenario 2.

2.3. Scenario 3 – T-MAC

A sensor node also alternates between the sleep and active modes. It is different from Scenario 2 in that the duration of each mode is not fixed. In particular, the duration of the active mode is bounded by [T_{min}, T_{max}] and follows a certain distribution. However, the time to activate the sensor node is fixed. Thus, the interval between two consecutive active modes or the total duration of the active and sleep modes is constant.

The T-MAC protocol [17] is one application of Scenario 3. Similar to the S-MAC protocol, the T-MAC protocol also divides the time into several frames and there are an active part and a sleeping part for each frame. Each node periodically wakes up to communicate with its neighbors and then sleeps waiting for the next frame. Messages arriving during the sleep time are queued [17]. However, different from the S-MAC protocol where the active time is fixed, the active period ends when no activation event has occurred for a timeout value in the T-MAC protocol. In other words, the active time is not fixed and the minimal active time is the timeout value. The maximum active time for each frame is the frame time [17]. Fig. 4 shows scheme for Scenario 3.

3. Reliability and lifetime modeling

Since the lifetime of a sensor node depends mainly on the lifetime of its battery, we assume other elements in the sensor nodes

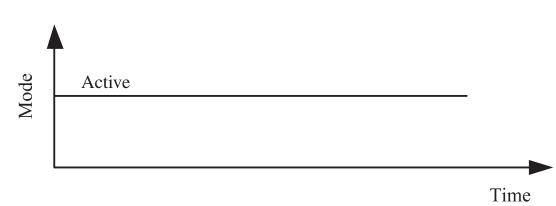

Fig. 2. Scenario 1.

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