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Analytical Modeling of Multi-type Failures in Wireless Body Area Networks

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Abstract

Wireless body area network is one of the most suitable technologies for building patient monitoring systems in hospitals, residential and work environment. The reliability of wireless body area networks is an important research issue since it may jeopardize the vital human life, unless managed properly. In this paper, a new modeling and analysis of in multi-type failures in a wireless body area networks is presented. First, the nodes are classified into types in accordance with their functions. Then, the node behavior has been modeled using a novel Semi-Markov process. Simulation has finally been performed to evaluate the performance of the proposed model.

Keywords: WBAN, Performance modeling, Analysis of multi-type failures, Network security.

1 Introduction

The U-healthcare (ubiquitous-healthcare) service is one proposed solution for the health care industry. One of the major requirements for reliable u-healthcare service is that all components should be connected to the networks [1]. Te detect and transmit bio-signal, a wireless body area network (WBAN) has been being developed. A WBAN consists of multiple sensors and possibly actuators equipped with a radio interface. A WBAN usually has a sink node using PDA, smart phone, or netbook, which receives information from sensors and works as a gateway forwarding information into other networks [2].

Network reliability is the ability of a network keeping connected even while suffering failures and attacks. Increasing reliability is a current challenge for the wireless body networks. Many researchers [3, 4] have just mentioned the reliability as an issue but no further studies have been made by them, while some of researchers involved in improving reliability. In [5] authors insist on reliable clock synchronization for clustered wireless sensor network. A reliable delivering of messages is defined in [6]. Development of a distributed Bayesian algorithm for detecting and correcting sensor measurement faults has been reported in [7]. PSFQ [8], RMST [9], ESRT [10] are some approaches which have been proposed for reliable data delivery in the network.

In this paper, we present a new modeling and analysis of node misbehaviors in WBANs. First, the nodes are labeled into three types according to routing capability. Then, the nodes behaviors have been modeled using a Semi-Markov process. The proposed model is helpful in analyzing the reliability of WBANs in the presence of failures such as energy exhaustion and/or malicious attacks. Finally simulation and numerical results are given to validate the proposed models

The remainder of this letter is organized as follows. In Section 2, nodes are classified by their functions, and a model of nodes with multi-type failure is presented. In Section 3, a semi-Markov model is given to model the multi-type failures of the nodes. In Section 4, simulation is proposed. Finally the conclusion is given in Section

2 Modeling of Node Behaviors in WBANs with Multi-type Failures

2.1 Definition of Nodes in Wireless Body Area Networks

In a typical protocol for multi-hop wireless body area networks, such as WASP [11], EEMAP [12] and LDP [2], sensor nodes are divided into three types:

- Sensor nodes without routing function, denoted by NO: which can get the vital information of the human body, but cannot work as a router.
- Sensor nodes with the routing function, denoted by NR, can simultaneously get the personal information and work as router.

- The sink node, denoted by NG, works like gateway for transmitting the data to the extra-networks

2.2 Modeling of Nodes with Multi-Type Failures

The nodes are classified based upon their functions in multi-hop wireless body area networks, which are described below:

- G: A node is said to have function G when it can get the vital information from the human body, and send it to the next node.
- R: A node is said to have function R when it can forward data for other nodes. This is a key factor for the multi-hop tree in WBANs.
- E: A node is said to have function E when it attacks other nodes. It sends error data to other nodes or attacks the normal channel.

In order to provide a formal classification, an indicator function (1) is used to identify whether a node has a function A or not. For example, a given node s, $I_G(s)$ =1 means that the node s is able to get the vital information from the human body.

$$I_{\mathbf{A}}(s) = \begin{cases} 1 \text{ , } if \ \ s \ has \ a \ function \ A \\ 0 \text{ , } otherwise \end{cases} \quad (1)$$

States of the nodes in wireless body area networks can be classified as follows by using the indicator function. For sensor nodes without routing function:

- Cooperative nodes, denoted by NO_C , are the nodes that can get the vital information of the human body and send it to the next node. In other words, $NO_C \equiv \{s \in \mathbf{N} | I_G(s) = 1, I_E(s) = 0\}$.
- Failed nodes, denoted by NO_F , are the nodes which cannot get the information or cannot transfer it the next node. In other words, $NO_F \equiv \{s \in \mathbf{N} | I_G(s) = 0\}$.
- Malicious nodes, denoted by NO_M , are the nodes that attack other nodes. In other words, $NO_M \equiv \{s \in \mathbf{N}, | I_E(s) = 1\}$.

For sensor nodes with the routing function:

- Cooperative nodes, denoted by NR_C , are the nodes which can both get the vital information and transmit it to the next node and route for other nodes. In other words, $NR_C \equiv \{s \in \mathbf{N} | \ I_G(s) = 1, I_R(s) = 1\}$.
- Failed nodes, denoted by NR_F , are the nodes which can neither get the information nor route for other nodes for energy exhaustion or attacks. In other words, $NR_F \equiv \{s \in \mathbf{N} | \ I_G(s) = 0, I_R(s) = 0\}$.
- Selfish nodes, denoted by NR_S , are the nodes which can obtain their information and transmit it to the next node, but cannot forward other nodes' information because it may have to save energy for itself or it lacks of power. In other words, $NR_S \equiv \{s \in \mathbf{N} | \ I_G(s) = 1, I_R(s) = 0\}$.
- Router nodes, denoted by NR_R , are the nodes which can route for other nodes but cannot get the vital information for sensor error. In other words, $NR_R \equiv \{s \in \mathbf{N} | \ I_G(s) = 0, I_R(s) = 1\}$.

For sink node which usually performed by PDA, smartphone or netbook

- Cooperative nodes, denoted by NG_C , are the nodes which can gather received bio-signals for WBAN nodes ,and transmit them to the Internet. i.e., $NG_C \equiv \{s \in N | \ I_R(s) = 1\}$.
- Failed nodes, denoted by NG_F , are the nodes which can not route for other nodes in the WBAN . i.e., $NG_F \equiv \{s \in M | \ I_R(s) = 0\}$.

3 Modeling of Node Behaviors with Semi-Markov Model

When a misbehavior node is present, a node model is much more complicated. By taking into account misbehavior nodes based on their operations in the wireless body area network, a state space **S** of the node status, as for nodes NO is defined, $\mathbf{S} \equiv \{C \ (cooperative), F\ (failed), M\ (malicious)\}$, and for nodes NR, $\mathbf{S} \equiv \{C(cooperative), F(\ failed), R(\ route), S(\ selfish)\}$ for sink nodes NG, $\mathbf{S} \equiv \{C \ (cooperative), F(\ failed)\}$. Then, the state transitions of a node can be described as a stochastic process, denoted by $\{\ F(t)\ \}$. with state space **S.** The transition occurs at instants of $t_0 = 0, t_1, t_2 ..., \ (t_n < t_{n+1})$.

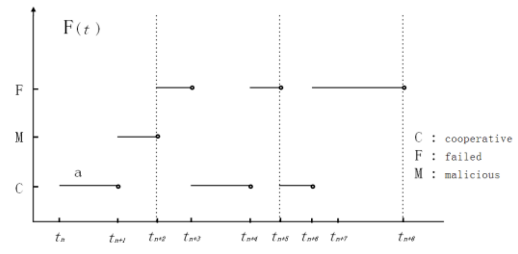

Figure 1. Sample of node without route function state transitions

Figures 1-3 show the example of behavior transitions and time intervals. In Fig. 1, a state on the Y axis corresponds to each state, and a half-closed time period on the X axis. For example, the line 'a' in Fig. 1 means that node s is in cooperative state during time interval $[t_n, t_{n+1})$. For example, the node changes its state from C to M at time t_{n+1} , depending on its behavior which is described as before.

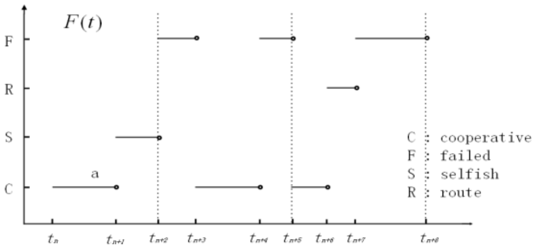

Figure 2. Sample state transitions of node with route function

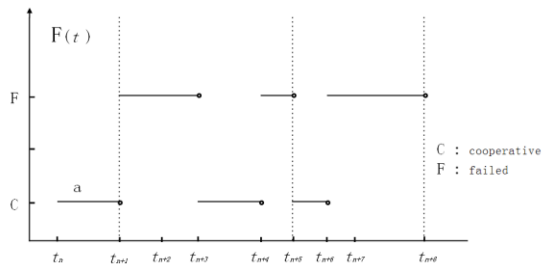

Figure 3. Sample state transitions of sink node

The future behavior of a node depends on the current behavior, but not the previous X states, if the X_n denote the transition occurring at time t_n , then we have

$$\begin{aligned}&\Pr(X_{n+1} = x_{n+1} \mid X_0 = s_0, \cdots, X_n = x_n) \\ &= \Pr(X_{n+1} = x_{n+1} \mid X_n = x_n), \qquad (2)\end{aligned}$$

Where $x_i \in S$ implies that the possible values of X_i form a countable set of **S**.

In this model, the future action of a node depends on how long it has been in the current state. The Semi-Markov Chains can be used in which the future depends on a present state and time spent in the state, and the memory is lost on state change, to characterize the evolution of node behaviors. The stochastic process $\{F(t)\}$ of node states can be defined by

$$F(t) = X_n, \quad \forall t_n \le t < \forall t_{n+1} \qquad (3)$$

$\{F(t)\}$ is a Semi-Markov process[13], and $\{X_n\}$ is called the embedded Markov chain of the process $\{F(t)\}$. X_n refers to the state of the process at transition occurring at time t_n , $F(t)$ refers to the state of the process during the period from the last transition. The transition probability from state i to state j is defined as:

$$\begin{aligned}p_{ij} &= \lim_{t\to\infty} \Pr(X_{n+1} = j, t_{n+1} - t_n \le t \mid X_n = i) \\ &= \Pr(X_{n+1} = j \mid X_n = i), \qquad (4)\end{aligned}$$

Then a matrix $\overrightarrow{\mathbf{P}} = (p_{ij})$ is the transition probability matrix of $\{X_n\}$. The construction of $\overrightarrow{\mathbf{P}}$ can be determined by the observation of empirical results. Characters of node behavior of WBAN are provided below:

- A cooperative node may become failed nodes or malicious nodes due to various reasons, such as energy exhaustion, out of the body area, and so on. For nodes with route function, the nodes are also exposed to be route nodes or selfish nodes for sensor error or power saving.
- A failed node cannot work in the wireless body area network. Nevertheless, a failed node may become a cooperative node if this node is recovered or rebooted.
- A selfish node is possible to convert a selfish node to be cooperative again by means of proper configurations. And a selfish node also can become a failed node due to power exhaustion, but it can not become a route node directly.
- A malicious node can become a failed node only.
- A route node can send messages for other nodes, but can not get its own bio-signal. However it can convert to a cooperative node for reconfiguration. It also can become a failed node.

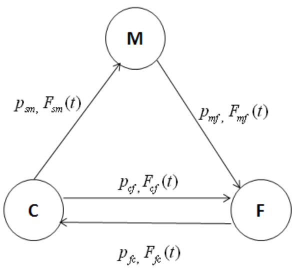

Figure 4. The Semi-Markov model for nodes without route function

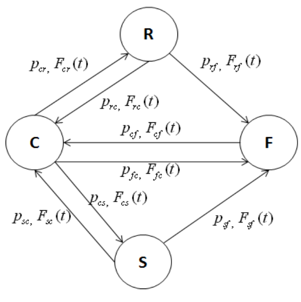

Figure 5. The Semi-Markov model for nodes with route function

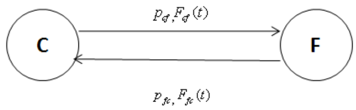

Figure 6. The Semi-Markov model for sink node

By considering the node behavior above, the transition probability matrix of $\{X_n\}$ of WBAN is given below:
For nodes NO:

$$\overline{\mathbf{P}} = \begin{pmatrix} 0 & p_{cm} & p_{cf} \\ 0 & 0 & p_{mf} \\ p_{fc} & 0 & 0 \end{pmatrix} \quad (5)$$

For node N:

$$\overline{\mathbf{P}} = \begin{pmatrix} 0 & p_{cs} & p_{cr} & p_{cf} \\ p_{sc} & 0 & 0 & p_{sf} \\ p_{rc} & 0 & 0 & p_{rf} \\ p_{fc} & 0 & 0 & 0 \end{pmatrix} \quad (6)$$

For sink node NG:

$$\overline{\mathbf{P}} = \begin{pmatrix} 0 & p_{cf} \\ p_{fc} & 0 \end{pmatrix} \quad (7)$$

The “0” in the matrix means it is not possible to make transition between the two states. For example in (6), as p_{rs} =0 means a route node cannot become a selfish node. Let T_{ij} denote the time in state i given the next state j. Then $F_{ij}(t)$ is a commonly used notation for cumulative distribution function (CDF) of T_{ij} , defined by :

$$\begin{aligned} F_{ij}(t) &= \Pr(T_{ij} \le t) \\ &= \Pr(t_{n+1} - t_n \le t \mid X_n = i, X_{n+1} = j) \end{aligned} \quad (8)$$

where $i, j \in \mathbf{S}$. The state transition diagram of the Semi-Markov node model is shown in Figure 4.-6. The states in Figure 4.-6 are labeled as C (cooperative), S (selfish), M (malicious), F (failed), R (route).

4 Simulation

In this part, we provide simulation results of the impact of the misbehavior nodes in wireless body area network on network survivability. NS2-v2.33 is used to perform the simulations. Constant Bit Rate (CBR) is chosen for traffic and the traffic is ranged from 10kbps to 10Mbps. To evaluate the previous description, NS2 is modified to support the definition. The default network parameters are listed in Table1. In these simulation scenarios, the simulation time is set to 1000s so the system can reach steady state. The results are averaged over multiple simulation rounds conducted with various random seeds.

Table 1. Network setup in simulation

Parameter	Setting
Simulation area	Human Body
System size	20-30nodes
Transmission range	2m
Link capacity	10kbps-10Mbps
Simulation time	1000s
Application	CRB

To calculate the survivability, the received packages, which are from the sensor node to the sink node, are accounted. In Figure 7, the effect of selfish nodes on network survivability is shown. In this Figure, the curves indicate that the survivability decrease when more and more selfish nodes are present. Nevertheless, the survivability does not change significantly when there is only a small amount of selfish nodes. Because when the number of selfish nodes is small, it is easy to find a new router node. While the probability of the selfish nodes is less than 15%, the survivability of the network is more 90%

Figure 8 shows the effect of cooperative nodes on network survivability. In order to observe the effects of cooperative nodes clearly, we set the recovery duration as zero. The sink failure is also set as zero such that the cooperative probability varies according to selfish nodes or router nodes. The network survivability is very low when the probability of cooperative nodes is very low, because it merely can work with limited cooperative nodes. But when the cooperative nodes reach some limit, the survivability of the network increased sharply.

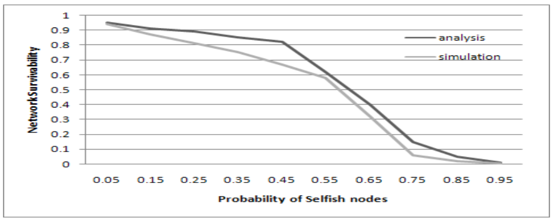

Figure 7. The effect of selfish nodes on network survivability

In order to explain the effect of the sink node NG failure, we arrange the sink nodes, while the other nodes are set to random for analysis the effect of the sink node. The sink node is the key element in WBAN. It will affect the whole networks survivability. In Figure 9, the survivability of the network in the simulation is lower than the analysis because in the simulation the environment is considered such as packets loss and time delay. And when the probability of the sink failure is more than 0.85, the network survivability is almost 0. The sink node is expected to have high quality for it will affect the survivability of the network sharply.

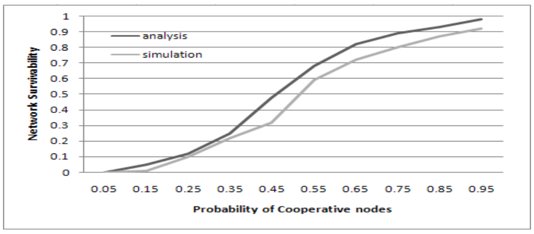

Figure 8. The effect of cooperative nodes on network survivability

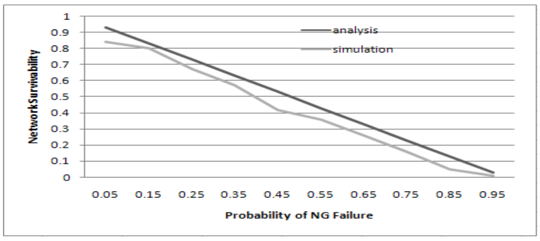

Figure 9. The effect of sink node failure on network survivability

5 Conclusion

In this paper, we have developed an analytic framework to study the misbehavior nodes in WBANs. Focus was also on the modeling and analysis of the misbehavior nodes in the network, which has been rarely studied before. First the nodes were classified into two types based on the nodes functions in the network, and then the misbehavior nodes were classified based on the node types and their operations. A Semi-Markov process is proposed for nodes behavior. In this proposed model, nodes in WBANs convert their states, i.e. cooperative, failed, selfish, and route, with transition probabilities.

This is believed to be the first attempt to model the misbehavior nodes in WBANs which is very useful to analyze the reliability of the WBANs. Further research work may give models for WBAN with both nodes failures and performance.

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