EAR: An Environment-Adaptive Routing Algorithm for WBANs

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***Abstract*—A wireless body area network (WBAN) is constructed in the vicinity of a human body and provides various services for both medical and non-medical services. In order to provide monitoring services for medical devices, routing algorithms for wireless sensor networks (WSN) have been considered for WBANs. However, unlike WSNs, which consist of homogeneous devices, WBANs are organized with heterogeneous devices having different characteristics. Thus, directly applying routing algorithms for WSNs to WBANs is inefficient. This paper proposes a routing algorithm for WBANs. The proposed routing algorithm considers different communication costs for heterogeneous WBAN devices, and avoids faulty relay nodes for reliable transmission.**

I. INTRODUCTION

A *Wireless Body Area Network* (WBAN) consists of various electronic devices, either on, in, or around the human body, to support variety of applications, such as medical monitoring and wearable computing. It consists of a coordinator that configures and manages the network and heterogeneous devices or nodes for both medical and consumer electronics (CE) services. IEEE adopted WBAN as the next generation wireless technology for Wireless Personal Area Networks (WPANs), and a task group (referred to as IEEE 802.15.6 TG) within the 802.11.5 working group for WPAN has worked since November, 2007 [1], [2], [3], [4] to standardize the WBAN technology. WBANs support flexible transmission rates of 10 Kbps to 10 Mbps as well as a very short transmission range of at least 3 m with low power. These characteristics distinguish WBANs from existing WPANs.

WBANs have been utilized as a monitoring tool for medical applications [5], [6], [7]. The nodes in WBANs are tiny sensors, which have limited resources and employee routing algorithms used in wireless sensor networks (WSNs). However, IEEE 802.15.6 supports various services with different characteristics, such as medical and health care as well as CE services. Since different devices have different levels of energy and generate different size data, using a routing algorithm designed for WSNs in WBANs is inefficient.

IEEE 802.15.6 specifies low-complexity, low-cost, low-power, and reliable transmission as design goals. Thus, a routing algorithm for a WBAN should support not only a variety of devices but also satisfy these design requirements. In this paper, we propose the *Environment-Adaptive Routing* (EAR) algorithm based on different communication costs for heterogeneous devices and the WBAN design goals.

II. RELATED WORK

The network architecture of a WBAN is similar to a WSN, where data from member nodes are forwarded to the coordinator. Thus, routing algorithms used in WSNs are also used in WBANs. The routing algorithms for WSNs are classified as either flat or hierarchical. Since the coverage area of a WBAN is small, the flat routing algorithms, which find the shortest path from the source node to the coordinator, are mainly used. In [8], nodes construct routing tables based on the Destination Sequenced Distance Vector (DSDV) algorithm and each node selects the shortest path as a next hop. However, since WSNs consist of only tiny, resources limited devices, energy consumption is the main factor considered in data routing. In [9], routing tables are constructed based on energy cost, where each node determines a routing path by means of a probability function that depends on energy consumption of routing paths.

Although the routing algorithms used in WSNs are energy efficient, they are designed for homogeneous sensor devices. However, a WBAN consists of heterogeneous devices with different characteristics. For example, sensor devices for medical services have similar characteristics as WSN devices. In contrast, devices for CE services require relatively high resources, event-driven data, high transmission rate, etc. Some devices require resource characteristics that lie somewhere between sensor devices and CE devices. In WBANs, serious problems occur if the device characteristics are not reflected in the routing algorithm. For example, when a large data is transmitted via tiny sensor devices, the network lifetime will rapidly decrease. Thus, the proposed EAR algorithm considers not only the design goals of the IEEE 802.15.6 but also the device characteristics.

III. THE PROPOSED ROUTING ALGORITHM

The proposed EAR algorithm implements the following three modules: *Routing Table Constructor, Fault Detector*, and *Path Selector*. When the coordinator transmits a broadcast message to all the nodes to construct the routing table, each node that receives the message executes the Routing Table Constructor module to build its routing table. A node transmits

id	cost	energy	level	flag

Fig. 1. The routing table of the proposed algorithm.

TABLE I
NOTATIONS FOR THE PROPOSED ALGORITHM.

Notation	Definition
u	Previous node
v	Current node
M_u	Broadcast message received from node u
M_v	Broadcast message sent by node v
$U(v)$	Utility function to compute cost at node v
$RT_v[u][0]$	Cost field of node u in routing table of node v
$RT_v[u][1]$	Energy field of node u in routing table of node v
$RT_v[u][2]$	Level field of node u in routing table of node v
$RT_v[u][3]$	Flag field of node u in routing table of node v
f_u	Communication cost of node u
f_v	Computed cost in node v
α	Device level of node u
d	Distance between node u and node v
e	Residual energy of node u
$\{\ \}$	Group
M^c	Control message

data to the coordinator using the Path Selector module. The Fault Detector module detects whether or not this node is faulty. A node is considered faulty if it experiences congestion, a partial link problem, or a breakdown. If the node is found to be faulty, a message is sent to its neighbor nodes so that they can avoid this node during data transmission.

The routing table for a node has five fields as shown in Fig. 1. The *id* field represents ID of the next hop. The *cost* field indicates the communication cost, i.e., the routing metric, for the path from this node to the coordinator. The *level* field indicates the level of the device and is different based on the characteristic of the node. The *energy* field represents residual energy of the node and the *flag* field is a boolean value representing whether or not a path contains faulty nodes. Each node records information of neighbor nodes in its routing table based on the broadcast message from the coordinator.

The basic notations and their definitions for the proposed routing algorithm are listed in Table I.

A. Routing Table Constructor

Fig. 2 shows the algorithm for the Routing Table Constructor module at node v. A broadcast message M_u from the coordinator to node v via node u includes information of node u consisting of its communication cost f_u, residual energy e, and device level α. When node v receives M_u, the communication cost for link uv is calculated using the utility function $U(v)$ (*line 2*), which is defined as

$$U(v) = \frac{\alpha \cdot d^2}{e} + f_u, \tag{1}$$

where d represents the distance between nodes u and v and e is the residual energy of node u ($0 \leq e \leq 1$). Eq. (1) reflects the fact that using nodes with less residual energy reduces net-

$Routing\_Table\_Constructor(u, v, M_u)$

1) $C \leftarrow 0$
2) $f_v \leftarrow U(v)$
3) if $v.level \geq M_u.level$ then
4)   do if $u \notin RT_v$ then
5)   do $RT_v[u][0] \leftarrow f_v$
6) $RT_v[u][1] \leftarrow M_u.energy$
7) $RT_v[u][2] \leftarrow M_u.level$
8)   else
9)   do if $f_v < RT_v[u][0]$ then
10)   do $RT_v[u][0] \leftarrow f_v$
11) $RT_v[u][1] \leftarrow M_u.energy$
12) $RT_v[u][2] \leftarrow M_u.level$
13) else
14)   do if $u \notin RT_v$ then
15)   do $RT_v[u][3] \leftarrow flag$

16) *wait for messages from neighbor nodes*
17) $M_v.level \leftarrow v.level$
18) $M_v.energy \leftarrow v.energy$
19) loop: for each neighbor node u, $u \in RT_v$
20)   do if $C > RT_v[u][0]$ or $C = 0$ then
21)   do $C \leftarrow RT_v[u][0]$
22)   end loop
23) $M_v.cost \leftarrow C$
24) flood M_v

Fig. 2. Algorithm for the Routing Table Constructor module.

work lifetime. Moreover, nodes with different levels[1] generate different size data, and thus it is more costly to deliver a large size data to nodes with limited resources. Therefore, $U(v)$ considers these factors and determines the costs of different paths from the current node to the coordinator by accumulating the communication cost from the previous node. Then, each node selects the path with the lowest communication cost.

In the proposed EAR algorithm, a high-level node, such as a medical sensor that have limited resource, rapidly consumes energy when it receives a large size data. Thus, nodes with higher levels include other nodes with lower levels (i.e., devices with more resources) to their routing tables (*lines 3-12*). On the other hand, if node v's level is less than node u's level, node v adds node u to its routing table and sets the *flag* field (*lines 13-15*). These added neighbor nodes can be used for data routing when the Fault Detector module detects faults.

After node v receives all the broadcast messages from neighbor nodes, it constructs a message M_v based on the lowest communication cost (*lines 16-24*). Then, M_v is broadcasted, which allows other nodes to construct their routing tables.

Fig. 3 shows an example where the broadcast message is reorganized to construct routing tables of neighbor nodes. A coordinator organizes and broadcasts $M_v[f_v, e, \alpha]$ consisting of 0 of f_v, 1 of e, and 1 of α. In node v, from information of the broadcast message, f_v is computed using $U(v)$ as

[1]CE devices and the coordinator are designated as level 1, while medical devices have levels greater than or equal to 2 according to their reliability and resource availability.

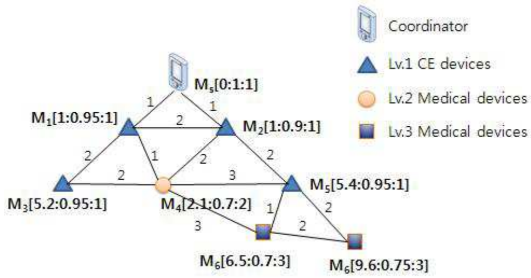

Fig. 3. An example of the reorganized control message at each node.

$Fault\_Detector(fault)$
1) $target \leftarrow 0$, $E \leftarrow 0$
2) if $fault = congestion$ then
3) do loop: for each node u with incoming data, $u \in RT_v$
4) do if $E > RT_v[u][1]$ or $E = 0$ then
5) do $E \leftarrow RT_v[u][1]$
6) $target \leftarrow u$
7) end loop
8) else if $fault = partial\ link\ problem$ then
9) do $target \leftarrow u_{fault}$, $u_{fault} \in RT_v$
10) else if $fault = breakdown$ then
11) do $target \leftarrow \{u\}$, $u \in RT_v$
12) send a message M_v^c to $target$

Fig. 4. Algorithm for the Fault Detector module.

$Path\_Selector(\{M_u^c\})$
1) $cost \leftarrow 0$, $next \leftarrow 0$
2) loop: for each node u, $u \in \{M_u^c\}$ and $u \in RT_v$
3) do $RT_v[u][3] \leftarrow flag$
4) end loop
5) loop: for each node u, $u \in RT_v$
6) do if $RT_v[u][3] \neq flag$ then
7) do if $cost > RT_v[u][0]$ or $cost = 0$ then
8) do $cost \leftarrow RT_v[u][0]$
9) $next \leftarrow u$
10) end loop

Fig. 5. Algorithm for the Path Selector module.

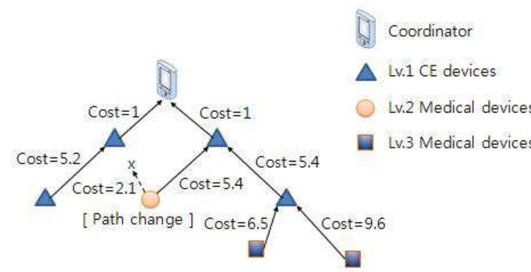

Fig. 6. An example of the path change in the routing tree.

shown in Eq. (1) and the broadcast message is reorganized to $M_v[f_v, e, \alpha]$ using information of node v as shown in Fig. 2. After the reorganization of the broadcast message, node v broadcast the message. From this process, each node can reorganize the broadcast message from the coordinator as M_1, M_2, ..., M_6 in Fig. 3.

B. Fault detector

The Fault Detector module determines when the node becomes faulty and notifies neighbor nodes. Fig. 4 shows the algorithm for the Fault Detector module. When congestion occurs, the module selects the node with the highest residual energy among the neighbor nodes with incoming traffic. Then, a message is sent to that node to notify the need for a change in its path (*lines 2-7*). If congestion persists, the paths of incoming traffic are changed one by one. When a partial link failure occurs, the link is excluded for data transmission (*lines 8-9*). In addition, when a breakdown is detected, a message is sent to all the neighbor nodes to change their paths (*lines 10-11*). Each node that receives the message then modifies its route using the Path Selector module (see Sec. III-C).

C. Path Selector

The Path Selector module searches the routing table for the node with the lowest communication cost. By excluding paths with faults, this search leads to reliable data transmission. Fig. 5 shows the algorithm for the Path Selector module. The Path Selector module sets the *flag*s for the neighbor nodes based on the M_u^c messages (*lines 2-3*). The next hop for data routing is chosen among the nodes with its *flag* field cleared (*lines 5-9*). This way, the next hop has the lowest cost and will be a reliable path. Fig. 6 shows an example of a path change. The routing tree is constructed based on the lowest communication cost for each node. The level 2 (Lv.2) node has a faulty link, which was detected by the Fault Detector module of its parent node. Therefore, the faulty link is excluded and the data is forwarded to another link.

Since each node chooses a next hop with the lowest communication cost, the routing loop problem does not occur. Even when the Fault Detector module performs path changes, a node selects lower cost than its previous link for child node to avoid the routing loop problem. In addition, the coordinator periodically broadcasts messages to have each node reorganize its routing table.

IV. Performance Evaluation

This section describes the simulation environment and evaluates the performance of the proposed routing algorithm. 10 CE devices, 5 Lv.2 medical devices, and 15 Lv.3 medical devices are randomly deployed in an area with $3m$ radius. The transmission range of the devices is $1m$. The coordinator is located in the center of the area. The CE devices with $10J$ generates 10 Kbytes of data. The Lv.2 devices with $5J$ generates 1 Kbytes of data. The Lv.3 devices with 1 J generates 50 bytes of data. For the evaluation, a simple energy consumption model based on Heinzelman *et al.* [10] is employed. The energy consumption model assumes free space and error free wireless channel. In the model, the sender expends $(50nJ/bit \times k + 10pJ/bit/m^2 \times k \times d^2)$ J and the

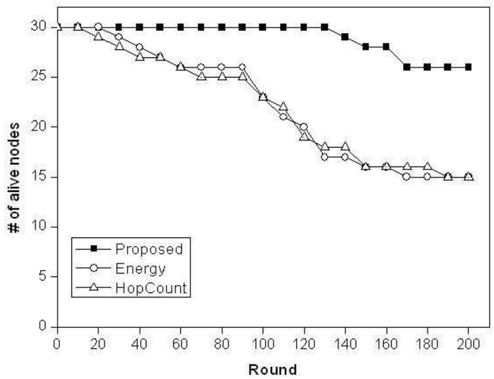

Fig. 7. The number of alive nodes.

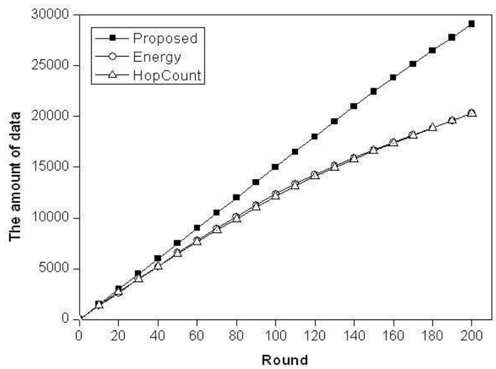

Fig. 8. The amount of data collected in the coordinator.

receiver expends $(50nJ/bit \times k)$ J to transmit k-bit data for distance d. The simulator was implemented using C++.

The proposed algorithm is compared with the Hop-count based method presented in [8] and the Energy-base method for WSNs presented in [9] in terms of the number of alive nodes and the amount of collected data in the coordinator.

Fig. 7 shows the number of alive nodes as function of *round*, where *round* is the time interval consisting of a network construction period and several data transmission periods [10]. In this paper, we assume that a round consists of one network construction period and five data transmission periods. As shown in Fig. 7, the proposed EAR algorithm increases the survivable rate of nodes by considering the characteristics of devices. Since the other two methods do not consider device characteristics, the energy consumption increases resulting in lower network lifetime.

Fig. 8 represents the amount of data collected in the coordinator when a fault occurs randomly in each device with 5% probability. The Energy-based method shows 7.7% packet loss rate and the Hop-count based method shows 8.1% packet loss rate. However, the proposed EAR algorithm does not incur any packet loss because both the Fault Detector and the Path Selector modules provide reliable transmissions by avoiding faulty nodes. Thus, as shown in Fig. 8, the coordinator can reliably collect lots of data.

V. Conclusion

In the past, the routing algorithms for WSNs have also been used in WBANs because the two network architectures are similar. However, routing algorithms for WSNs consisting of homogeneous sensor devices cannot be directly applied to WBANs with heterogeneous devices. The proposed EAR algorithm considers devices with different characteristics and detects faulty nodes, which leads to longer network lifetime and more reliable data transmission.

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