Design and Implementation of Low Power Network Maintenance Protocols in Wireless Health Advanced Mobile Bio-diagnostic System for Long-Term Periodical Health Telecare Applications

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Abstract: Attempts to develop a Wireless Health Advanced Mobile Bio-diagnostic System (abbreviated as WHAM-BioS) have arisen from the need to monitor the health status of patients under long-term care programs. The proposed WHAM-BioS as presented here is developed by integrating various technologies: nano/MEMS technology, biotechnology, network/communication technology, and information technology. This study focuses on network/communication technology in the WHAM-BioS and proposes a novel clustered sensor network (CSN) architecture for long-term periodical telecare applications. In the proposed CSN architecture, most network functions are concentrated in a special purpose device called the human body gateway (HBG). The sensor nodes focus on detecting and reporting their detection results to their HBG. To reduce the design complexity and the implementation cost for the sensor nodes, the proposed architecture proposed several protocols to help each HBG to provide a contention free environment for their sensor nodes. The contention free environment avoids the power consumption in data retransmission. Besides, to further reduce the power consumption of the sensor nodes, this study also proposes a power saving mechanism which reduces the power consumption in idle listening. Based on the proposed network architecture and protocols, a prototype system is implemented.

Keywords: Clustered Sensor Network, Human Body Gateway, Network Maintenance, WHAM-BioS

1 Introduction

This paper focuses on the network design and implementation for the *WHAM-BioS*. The network design and implementation for the *WHAM-BioS* brings numerous challenges. The main challenge arises from power saving. Since all the biosensors, RF and other elements of each sensor node contest the scarce power resources, the elements of any sensor node are required to minimize their power consumption. Therefore, power consumption minimization is the goal of network design for the sensor node implementation.

Since the power consumption of data transmission increases significantly with the communication ranges [1], short range transmission becomes crucial for power consumption minimization. This implies that reporting the detection results from the sensor nodes to the Internet access points such as Wireless LAN access points or GPRS basestations is impractical. Therefore, providing a special portable device with more power resources for forwarding the detections results from sensor nodes to the Internet access points to the elders and patients is a practical approach. In this paper, the special portable device for forwarding the detection results from sensor nodes to the Internet access points is called the Human Body Gateway (HBG).

Although the approach above is practical, it still conceals some problem issues. First, the packets which are reported from the sensor nodes to the HBG may collide. Second, the transmission from the sensor nodes in one person to their HBG may interfere the transmission in another person nearby. These two events either require the sensor nodes to retransmit their detection results or eliminate the detection results. Both the two events waste the scarce power resources of the corresponding sensor nodes.

Most wireless sensor networks such as the WINS[2], the PicoRadio[3] and the AMPS[4] base their design on an ad hoc (multi-hop) network technology [5] that focus on organizing and maintaining a network formed by a group of moving objects with a communication device in an area with no fixed base stations or access points. Although ad hoc network technologies are capable of solving the MAC [6] issues above, the design and implementation of sensor networks for long-term health telecare applications can be furthered simplified to reduce power consumption and overhead.

In [7], we proposed the HSN architecture for sensor networks with immobile sensor nodes. Although the sensor node – Local Control Center (LCC) relationships in the HSN is similar to the sensor nodes – HBG relationships in human body sensor networks, the HSN architecture can not be applied in the long-term health telecare applications directly because the HSN architecture focus on the applications in which all the senor nodes are immobile. Besides, the self-organization protocol [5] for constructing the sensor node – LCC relationships can be removed from the HSN architecture since the relationship can be manually set whenever the sensor node are installed in the human body. Therefore, in this study, we appropriately modify the HSN architecture and then proposed a novel sensor network architecture called the clustered senor network (CSN) for long-term health telecare applications.

Although the proposed centralized communication protocol efficiently solves the multiple access problems [6] inside each cluster, however, this simple approach can not avoid the interference between clusters. To avoid the interferences between adjacent clusters, the HBG of a cluster should lock the radio resources inside the range covering the interference range [1] of all its sensor nodes. That is, two adjacent clusters should not be active simultaneously.

This paper is organized as follows. Section 2 presents the CSN architecture, the power saving mechanism, the inner cluster communication protocols and the inter cluster communication protocols. Based on the proposed architecture, a sensor network system prototype is implemented and evaluated in Section 3. The conclusions and future works are drawn in Section 6.

2 Network Architecture and Protocols

2.1 The Network Architecture

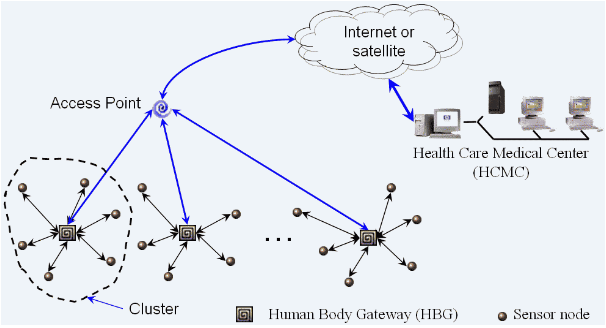


Fig. 1 The cluster sensor network architecture

Fig. 1 shows the proposed network architecture. In this architecture, the network is partitioned into several clusters each one of which maintains the status of a human body. Each cluster contains several sensor nodes and a Human Body Gateway (HBG). A sensor node has capability to detect and then reports the detection results to its HBG. The detection results are then forwarded to the nearby access points directly. The access points then forward the detection results to the Health Care Medical Center (HCMC) Internet or satellite.

In this architecture, all the sensor nodes maintain no network information. Whenever a sensor node is installed in a human body, the installer set the ID of the HBG to the sensor node and then set the ID of the sensor node to the HBG to construct the relationship between the sensor node and the HBG. Whenever the sensor node turns on and joins the network, it does nothing unless it receives an instruction from its HBG. The HBG applies the polling protocol to avoid the collision between the packets from different sensor nodes in the same cluster. This centralized communication protocol shifts most network maintenance tasks from the sensor node to the HBG and hence significantly minimizes the design and implementation complexity of the communication module of the sensor nodes.

Although the sensor nodes possess poor mobility functions, however, the proposed protocols provide group mobility functions. As long as the sensor nodes keep connection to their HBG, they can move with their HBG without any injury. Therefore, this architecture is well appropriate for sensor networks with group moving sensors.

2.2 The Power Saving Mechanism

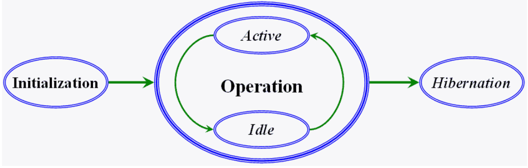


Fig. 2. The life cycle of a cluster node

Fig. 2 shows the life cycle of a cluster node. Whenever a HBG is turned on, the cluster node is in the *initiation* stage. It changes its stage to the *operation* stage once it completes the initialization tasks. In the operation stage, the cluster node may be in active mode or idle mode. A HBG is allowed to communicate with its sensor nodes if and only if the corresponding cluster node is in the active mode. This implies that the sensor nodes can largely reduce their power consumptions by turning off their antennas when their cluster nodes are in idle mode. Whenever the user turns off the HBG or the power resource of the HBG is less then a predetermined threshold, the corresponding cluster node changes its stage to the *hibernation* stage. The cluster node may revive again after someone turns on the HBG.

Although this mechanism significantly reduces the power consumption of all the sensor nodes in the operation stage, it also brings two new problems below.

1. Once a sensor node turns off its antenna, its HBG has no way to communicate with it. In this situation, the sensor node has to set up an alarm clock before its turns off its antenna. Therefore, a protocol is necessary for correctly setting the alarm clock of the sensor nodes.
2. If two adjacent cluster nodes are in active mode simultaneously, the communications in one cluster may interferes with the communications in another. This implies that adjacent cluster nodes should not be active simultaneously. Therefore, a protocol for solving the simultaneous activity problem is crucial for network maintenance.

For convenient, the protocols for solving the first problem are called the inner cluster communication protocols and the protocols for solving the second problem are called the inter cluster communication protocols. Requiring the HBG to specify the sleep time to its sensor nodes in each inner cluster communication seems to be a simple solution for solving the first problem. However, the second problem significantly raises the difficulty of the first problem. Because the inter cluster communication protocol may force some cluster nodes which are in active mode to keep silent, the awake sensor nodes may receive no instruction from their HBG and hence have no idea in setting their alarm clock. Furthermore, since the cluster nodes are mobile, two distant active cluster nodes may become adjacent. Those unavoidable exceptions heckles the robustness of the propose protocols for overcoming the two challenges above.

2.3 The Inner Cluster Communication Protocols

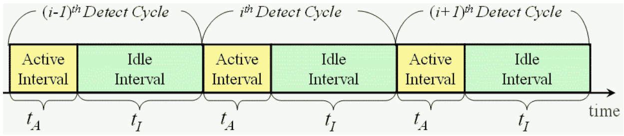


Fig. 3. The detection cycle of a cluster node

The power saving mechanism introduces the concept of detection cycle which can be partitioned into active interval and idle interval. Fig. 3 shows an example of detection cycle of a cluster node. In Fig. 3, a cluster node becomes active for t_A milliseconds and become idle for t_I milliseconds in every detection cycle.

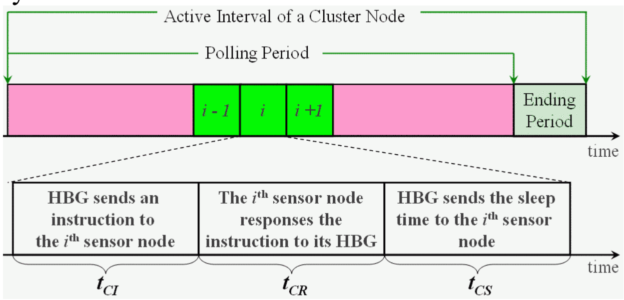


Fig. 4. The compositions of an active interval

The first inner cluster communication protocol specifies that each active interval should be partitioned into two periods as Fig. 4. In the polling period, the HBG communicates with all it sensor nodes one by one. Each communication consists of three steps. In the first step the HBG sends an instruction to the sensor node. Once the sensor node received the instruction, it performs the corresponding procedure to response the instruction to its HBG in the second step. Finally, the HBG sends the sleep time to the sensor node. Once the sensor node receives the sleep time from its HBG, it applies the sleep time to set a counter for waking up its antenna and then turns off its antenna. In this paper, the times for the three steps are denoted as t_{CI}, t_{CR} and t_{CS}, respectively. Although the value of t_{CR} varies with sensor nodes, this protocol requires that the values of t_{CR} maintained by a sensor node should be identical to what maintained by the HBG of the sensor node. And the value of t_{CR} should be invariant. Besides, this protocol also requires that the values of t_{CI} and t_{CS} are constants and are well known by all the members in the same cluster. Based to this protocol, each HBG can easily calculate the value of t_A of its cluster node. Furthermore, once the HBG determines the value of t_I, the HBG can immediately calculate the sleep time of any sensor node in the same cluster. The sleep time of the i^{th} sensor node in Fig. 4 is $t_S = t_A + t_I - (t_{CI} + t_{CR} + t_{CS})$ milliseconds.

In the ending period the HBG broadcasts the time for the incoming idle interval. Specifically, the

HBG broadcasts the value of t_I to all its sensor nodes. It seems that the time for the ending period should be t_{CS}. The ending period is very useful to the sensor nodes which have no idea about their sleep time. The second inner communication protocol provides a resynchronization mechanism for the sensor nodes which have no idea about their sleep time.

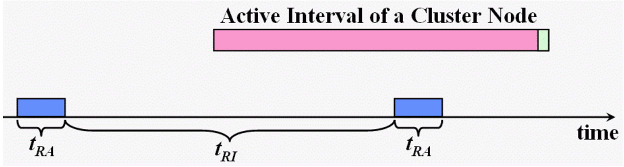


Fig. 5. The resynchronization mechanism

Fig. 5 shows the resynchronization mechanism for the sensor nodes which have no idea about their sleep time. In Fig. 5, a sensor node listens for any packet from its HBG for t_{RA} milliseconds. If its fails, it turns off its antenna to sleep for t_{RI} milliseconds. This sensor node repeats the two activities until it receives a packet whose sender is its HBG. In this situation, it keeps on listen until it receives a packet from its HBG to itself or receives the value of t_I broadcasted by its HBG in the ending period. In the first case it can learn its correct sleep time according to the first inner cluster communication protocol. In the second case the sensor node learns the value of t_I and then sleeps for t_I milliseconds. After it wakes up it should receive the packet from its HBG. In this situation the sensor node keeps listen until it receives a packet from its HBG to itself. This resynchronization mechanism significantly reduces the power consumption for learning the correct active time and sleep time of the sensor nodes, especially for the applications in which the value of t_I is much greater than the value of t_A.

It should be noted that the values of t_{RA} and t_{RI} decide the performance of the resynchronization mechanism. If $t_{RA} < max\{t_{CI} + t_{CR}, t_{CR} + t_{CS}\}$, then the sensor node may capture no complete packet from any member in the same cluster. Since the value of t_{CR} varies with sensor node, therefore, the second inner cluster communication protocol requires the value of t_{CR} should be less than or equal to a constant which is well known by all the members in the CSN. In this paper, we denote the constant as T_{CR}. Because the power consumption of idle listening increases with the value of t_{RA}, the smaller value of t_{RA} would reduce more power consumption in idle listening. Therefore, the second inner cluster communication protocol set $t_{RA} = max\{t_{CI} + T_{CR}, T_{CR} + t_{CS}\}$.

On the other hand, if $t_{RI} > max\{t_A - 2 \times t_{RA}, 0\}$, then the sensor node may miss the active interval of its cluster node. According to Fig. 5, it is clear that smaller value of t_{RI} makes the sensor node to try more times before it wakes up in the active interval of its cluster node. This implies that the protocol should try to enlarge the value of t_{RI} to reduce the power consumption in idle listening. However, this increases the possibility that sensor node miss the next active interval of is cluster node and hence enlarges the resynchronization time of the sensor node.

To reduce the resynchronization time of the sensor nodes, the HBG can enlarge the ending period to satisfy the inequality $t_{RI} \leq max\{t_A - 2 \times t_{RA}, 0\}$ and then apply the ending period to repeat the sleep time. Specifically, if the time for the ending period is $k \times t_{CS}$, then the HBG divides the ending period into k time slots. In the i^{th} time slot, the HBG broadcast the sleep time whose value is $t_I + (k - i) \times t_{CS}$.

2.4 The Inter Cluster Communication Protocols

Adjacent Relationship

To avoid the interference between adjacent clusters, the HBG should disable the inner communications of the nearby clusters to eliminate the noise from those clusters. Therefore, each HBG should notify all its adjacent HBGs to keep silent in its active interval. Although this idea is reasonable, it brings several problems.

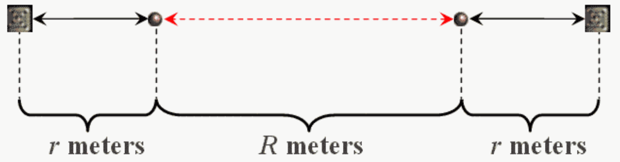


Fig. 6. Interferences between two clusters

The first problem would be the definition of the adjacent relationship. Fig. 6 is helpful in defining a conservative adjacent relationship. In Fig. 6, r and R denote the radius of the maximal communication range and interference range of the sensor nodes. Therefore, if the distance between two HBGs is less than $R + 2r$ meters, the communications in one cluster may interfere with the communications in another cluster. Based on this, the first inter cluster communication protocol requires two clusters should not active simultaneously if the distance between their HBGs are less than $R + 2r$ meters.

According to [8], the value of R is greater than $2r$. Since the received power strength decreases with the square of the distances in single-path free space, therefore, the first inter cluster communication protocol suggests that the transmitted power for inter cluster communications should be much stronger than 16 times to the transmitted power for inner communications. Besides, since the inter cluster communication beacons may interfere with the inner cluster communications in the adjacent clusters, this protocol also requires that the bandwidth for inner cluster communications should be distinct from the bandwidth for inter cluster communications. Therefore, each HBG apply at least two different bandwidths. One for inner cluster communications and the other one for inter cluster communications.

Starvation Avoidance

Applying only the inter cluster communication beacons to disable the adjacent clusters will bring the notorious *starvation* problem. Consider the scenario in which two patients lie down in adjacent sickbeds. If the values of t_A and t_I of the two cluster nodes are identical and the two clusters are expected to be active at almost the same time, then the cluster whose active interval is a little latter then the others' may be always disabled by the other.

Starvation is a notable problem in the operating systems. Most operating systems solve this problem by the aging technology. Based on this technology, the second inter cluster communication protocol requires the HBGs to apply the procedure in Fig. 7 to determine their active interval.

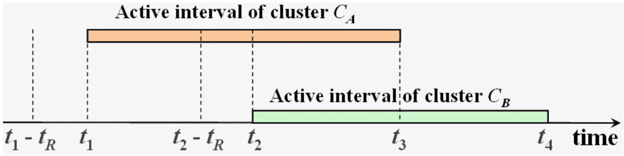


Fig. 7. Competitions of adjacent clusters

Fig. 7 shows the expected active intervals of two adjacent clusters C_A and C_B. At time $t_1 - t_R$, the HBG of cluster CA broadcasts a packet to all its adjacent HBGs. The packet contains an ordered pair (t_R, $t_3 – t_1 + t_R$) and the priority of C_A. If the priority of C_B is less than or equal to the priority of C_A, then the HBG of C_B responses nothing. Otherwise, the HBG of C_B sends a packet to the HBG of C_A which contains the ordered pair ($t_2 – t_1 + t_R$, $t_3 – t_1 + t_R$) in the time interval ($t_1 – t_R$, t_1) to disable C_A in the interval (t_2, t_3). Similarly, the HBG of C_B broadcasts a packet which contains the ordered pair (t_R, $t_4 – t_2 + t_R$) and its priority to all the HBGs nearby. The HBG of C_A response a packet containing the ordered pair (t_R, $t_3 – t_2 + t_R$) in the time interval ($t_2 – t_R$, t_2) to the HBG of C_B if its priority is greater than the priority of C_B.

To solve the starvation problem, the second inter cluster communication protocol apply the following rules to define the priority of each cluster node.

R1. The priority is an integer. 0 is the lowest priority and *M* is the highest priority.
R2. The initial priority of normal clusters is 0.
R3. For cluster *C* whose priority is less than $M – 1$, if there is any inner cluster communication of *C* is disabled by other clusters, the HBG of *C* increases its priority by 1.
R4. If all the inner cluster communications of cluster *C* are not disabled by other clusters, the HBG of cluster *C* sets its priority as 0.
R5. If the initial priority of a cluster is *M*, then the HBG does not change its priority.

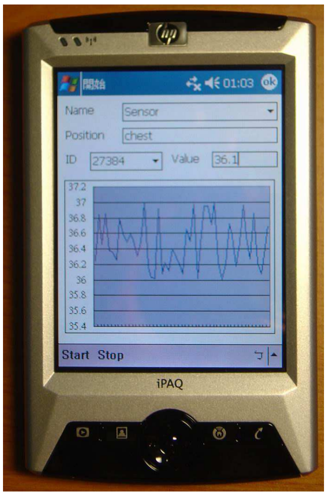
Since some patients need to be monitored periodically without any disturbance, this protocol reserves the highest priorities to those patients.

3. The Health Telecare System Prototype

We have designed and implemented a sensor network prototype for health telecare system. Fig. 8 – Fig. 10 show the sensor node prototypes and the HBG prototype for the health telecare system. The sensor node prototype in Fig. 8 is a wireless clinical thermometer. The RF of this prototype applies the 433 MHz ASK modules. We apply the same RF technology to modify a portable medical appliance in Fig. 9 by adding the RF module. The portable medical appliance contains a sphygmomanometer and a pulsimeter. The HBG can use to attribute "Parameter" to choose the sensor of this sensor node prototype.

Fig. 8. The wireless clinical thermometer prototype

Fig. 9. The wireless sphygmomanometer and pulsimeter prototype



Name Sensor
Position chest
ID 27384 Value 36.1

Fig. 10. The HBG prototype

In current stage, we implement the HBG in a HP iPAQ RX3417 PDA. Fig. 10 shows that the HBG presents the past 33 detection results of a clinical thermometer which is detecting the body temperature in the user's chest. The HBG apply its 802.11 WLAN module (in ad hoc mode) to communicate with other HBGs.

4 Conclusions and Future Works

In this paper, we proposed a clustered sensor network architecture for the ***W***ireless ***H***ealth ***A***dvanced ***M***obile ***Bio***-diagnostic ***S***ystem in long-term periodical health telecare applications**.** To minimize the power consumptions while reducing the design complexity of the sensor nodes, this study proposes a power saving mechanism and a set of inner cluster communication protocols. Besides, this study also proposes a set of inter cluster communication protocol to avoid most inter cluster interferences. The sensor node database and the inner cluster communication procedure provide a platform for numerous health telecare application processes in each HBG.

Although this team has overcame several challenges in implementing a *WHAM-BioS* prototype, there still many challenges obstruct the *WHAM-BioS* in serving the elders and patients. Scalability is the main challenge for the network functions of the *WHAM-BioS*. To overcome this challenge, specifying appropriate values for the network parameters would be the first issue. We are now designing simulations and experiments to study the relationships between the parameters and network performance. Besides, to provide a robust platform for health telecare application processes in each HBG, this team is also studying and designing an appropriate database transaction model for the *WHAM-BioS*.

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