A QoS-aware Routing Service Framework for Biomedical Sensor Networks

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***Abstract*— Biomedical sensor networks have been widely used in medical scenarios. Examples include patient monitoring, elderly assistance and disaster response. In medical applications, where data packets usually contain vital sign information and the network used for communications should guarantee that these packets can be delivered to the medical center within a given time and a certain packet delivery ratio. In other words, a set of Quality of Services (QoS) must be satisfied.**

In this paper, a cross-layer designed QoS-aware routing service framework is proposed. The main goal of the framework is to provide prioritized routing service and user specific QoS support. Routes are determined by user specific QoS metrics, wireless channel status, packet priority level, and sensor node's willingness to be a router. Furthermore, the routing service can send feedback on network conditions to the user application, so the medical application service level can be adjusted to obtain the highest adaptability and robustness.

Simulation results have shown that the routing service framework performs well in respects of QoS metrics and energy efficiency in various medical scenarios. The routing service can provide guaranteed QoS for users of high priority level and acceptable network performances for 'best effort' required users.

I. Introduction

The integration of biomedical sensors with wireless networks has led to the emergence of biomedical sensor networks, which have great potential applications in medical scenarios. Body temperature, blood pressure, electrocardiogram (ECG), Pulse Oximeters (SpO2) and heart rate, are sensed and transmitted to a medical center, where the data is used for health status monitoring, medical analysis and treatment [1]. The biomedical sensor networks become helpful in providing the freedom of movement while ensuring that the patients are continuously monitored and cared for.

The main function of the biomedical sensor networks is to ensure that packets can be sensed and delivered to the medical center reliably and efficiently. Routing protocol becomes an essential part of the biomedical sensor networks. Due to the dynamic topology of biomedical sensor networks, severe constraints on power supply, computation power and communication bandwidth of sensor nodes, the design of QoS-aware routing protocol is a challenging task. Recently, many routing protocols, such as Cluster-Tree Algorithm [2] and NST-AODV [3], have been proposed for sensor networks [4], [5]. Most of the research are focus on how to prolong the network lifetime, few of them have considered the differential QoS requirements in medical applications. Therefore research on QoS-aware routing protocols is still needed.

In this paper, we proposed a cross-layer designed QoS-aware routing service framework, which can provide prioritized routing service and user specific QoS support. In the proposed routing service framework, routes are determined by user specific QoS requirements, wireless channel status, packet priority level and sensor node's willingness to be a router. Furthermore, the routing service can send feedback on network conditions to the user application, so the application service level can be adjusted to adapt to the network conditions. To our best knowledge, this is the first routing framework considering differential user QoS requirements and prioritized routing service in medical applications.

II. Design Goals

In medical applications, the QoS requirements for different users can be quite different. For instance, the packets generated by the sensor nodes attached to patient-in-risk must be delivered in 'real-time', or within guaranteed end-to-end delay. While other users may compromise on some real-time requirements to achieve long network lifetime, so low power consumption is their preferred QoS requirements. For some high data rate sensors (e.g. image sensors), the selected route must satisfy the required communication bandwidth. Also, for packets containing information with higher importance (e.g. vital signs), the network should make more efforts in delivering them.

The aim of the QoS-aware routing service framework is to provide prioritized routing service and differential QoS support in the sensor network. The main functions of the routing service are described as follows:

- QoS-aware routes establishment and maintenance
- Prioritized packet routing
- Application Programming Interfaces (APIs)
- Feedback on network conditions to user application
- Adaptive network traffic balance

- Power supply level aware of sensor node

III. System Architecture and Design Issues

As shown in Fig. 1, the routing service framework is modular designed. It interfaces MAC layer and application layer directly, but cross-layer design allows the routing framework to use the link quality information (e.g. received signal strength indication (RSSI), signal-to-noise-ratio (SNR)) from physical layer to achieve high adaptivity and robustness.

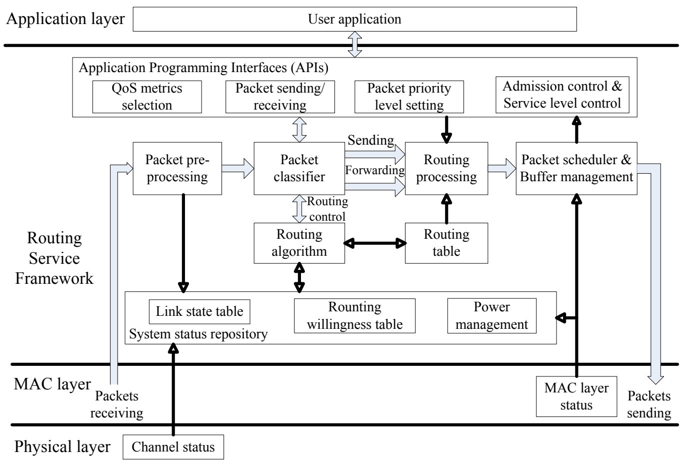

Fig. 1. Architecture of QoS-aware routing service framework

The QoS-aware routing service framework mainly consists of 4 modules: Application Programming Interfaces, routing service, packet queuing and scheduling, and system information repository. The details of these modules are discussed in the following subsections.

A. *Application Programming Interfaces Module*

The APIs module provides the main programming interfaces for user application, which can set the preferred QoS metrics, send and receive data packet, and adjust service level depending on network conditions. The main API's functions are listed as follows:

- QoSMetricsSet(E2EDelay, DeliveryRatio, PowerConsumption): User application can set their preferred QoS metrics according to the specific medical scenarios.
- SendPacket(DestinationID, SourceID, PriorityLevel, Payload): User application sends payload (sensed data) to sink node or other sensor nodes in the network for data aggregation. The application data packet includes 4 fields: destination ID, source ID, priority level and payload. The packet will be processed by the routing service framework further.
- RecPacket(): Get payload from received data packet. The payload can be aggregated with its own sensed data.
- Admission&ServiceLevel(): This function returns the feedback on network conditions to user application. User application can get the network conditions by calling this function regularly.

TABLE I

Packet Priority Level Classification

Packet Type	Priority Level
routing information	8 (reserved)
link probe	7 (reserved)
vital signs	6
real time	5
long term monitoring	4
user defined	1 - 3

B. *Routing Service Module*

The task of the routing module is routes establishment and maintenance. The routing protocol is based on proactive table-driven algorithms, which means each sensor node maintains routing information to the sink node(s). All available routes to the sink node(s) are stored in the routing table, which is indexed by its one-hop neighbor node's ID. Note in the routing table, there are could be more than 1 route to the sink node(s), and also may have routes to different sink nodes provided there are multiple sink nodes.

In the route setup phase, sink node(s) broadcast sink advertisement (ADV) packet indicating their existence. When sensor nodes within the communication range of the sink node(s) receive the ADV packet, they will store the route in their routing table. Then the sensor nodes broadcast the route information (RI) packets, indicating they could be available routers to the sink node, to their neighbor nodes. The neighbor nodes will establish their routing table and broadcast the RI packet to their own neighbor nodes as well. Thus after a certain amount of time, all the sensor nodes will establish at least 1 route to the sink node(s).

Since the network topology may change due to node mobility or node failure, and/or changing wireless channel, the routing information should be updated periodically. Currently, the sink nodes broadcast ADV packet in a fixed period. Upon receiving the ADV or RI packet, all the sensor nodes check the route information in the packet, update the routing tables and broadcast the RI packets.

C. *Packet Queuing and Scheduling Module*

To provide prioritized packet routing, all the packets, including data packets and control packets, are classified into different priority categories. Table I lists the detailed priority level classifications.

Currently there are 8 priority levels. The maximum and minimum value represent the highest and lowest importance levels respectively.

The highest priority levels (8 and 7) are reserved for control packets generated by the routing service framework. These packets will be processed and forwarded with the highest priority. Data packets can be assigned with priority level ranging from 1 to 6, depending on their importance level.

When the number of packets in the buffer reaches a pre-assigned threshold, which means the sensor node cannot access the wireless channel to send/forward packets caused by network congestion. The packet queuing and scheduling module will signal user application, asking for lower service level and willingness level to be a router, to avoid packet dropping and more serious network congestion.

D. System Information Repository Module

There are 2 tables in the information repository: link state table and routing willingness table. Link state table stores the link state to all other sensor nodes, including link quality, end-to-end delay, communication bandwidth and average packet delivery ratio. The willingness table provides the information of all the sensor nodes's willingness to be routers. The sensor node adjusts its willingness level according to the link state, buffer status and power supply level. These tables are updated periodically, depending on the network conditions and nodes's mobilities. Invalid entries, caused by node mobility, failure or wireless link broken, will be removed.

In order to get link state information, each sensor node exchange probe (PRB) packet with its one-hop neighbors periodically. The packet includes its routing information, link state with its neighbors, and willingness information. By exchanging the PRB packet, each sensor node gathers link state information of all the other sensor nodes in the network.

The following methods are used to get the link state information:

- Delay estimation: by computing the timestamp difference between PRB packet sent and the Acknowledgment (ACK) packet received, sensor node can get the average delay with its communication partner. One-hop delay can be calculated as follows:

$$Delay = \frac{timestamp_{ACK} - timestamp_{PRB}}{2}. \quad (1)$$

  It should be noted that the delay estimation does not take the different packet queuing and processing time into account. This is a tradeoff between accuracy and constraints on computation capacity of sensor node. More advanced method can be found in [6].
- Packet delivery ratio (PDR) estimation: average packet delivery ratio can be formulated as:

$$PDR = \frac{NumberofACK}{NumberofPRB}. \quad (2)$$

  $NumberofPRB$ is the number of PRB has been sent, and $NumberofACK$ is the number of ACK has been received. The PDR value represents the average packet reception rate of the two communication nodes.
- Link quality indication (LQI)
  The LQI measurement is a characterization of the strength and/or quality of a received packet. The LQI measurement can be performed for each received packet, either data packet or control packet. The result should be an integer ranging from 0x00 to 0xff. The minimum and maximum LQI values (0x00 and 0xff) shall be associated with the lowest and highest link quality.

TABLE II
QoS Requirements for Different Sensor Nodes

Sensor Node	**QoS Requirements**		
	End-to-end Delay (S)	**Packet Delivery Ratio**	**Packet Priority Level**
ECG	0.5	95 %	4
SpO2	2	90 %	2
Temperature	best effort	90 %	1

  Both LQI value and packet delivery ratio can be used by the routing service framework to get the link state information. Detailed information can be found in the IEEE 802.15.4 standard [7].

The mechanism of PRB exchanging introduces significant communication and computing burden. The frequency of PRB exchanging should be adapted to the network conditions. For instance, in a network where most of the sensor nodes are stationary, the frequency of PRB exchanging should be lower. While in a high mobility sensor network or rapidly changing wireless channel, the frequency should be higher. This part is left for future research.

Data packets, which are sent from the application layer or received from the MAC layer to be forwarded, are classified into different categories depending on their priority level. After routing processing, the packets will be sent to the packet scheduler for priority-based queuing. Packets with higher priority level will be routed with higher network effort. When the buffer is full or network congestion is detected, the routing service will send feedback to the application layer.

When network congestion happens in a specific area, or some sensor nodes are busy in sending packets contain vital sign information, or some sensor nodes are in lower power supply level. They will lower the level of their routing willingness and send this information to other sensor nodes through PRB exchanging. The network will avoid forwarding packets to the sensor nodes with low level willingness.

When a sensor node wishes to send or forward a packet with a set of QoS requirements, the routing service will estimate if there is a route that can satisfy the user requirements. If so, a route will be selected and the packet will be sent to the intermediate node according to the routing table. If not, the packet will be sent with 'best effort' or dropped, depending on user specific requirements.

IV. Performance Evaluation

To study the performance of the QoS-aware routing service, we simulated a typical patient monitoring sensor network. Twenty sensor nodes and 2 sink nodes are distributed uniformly in a 400 $\times$ 200 square meters area. Six of the sensor nodes are moving with walking speed in random directions, while other nodes are stationary. The network consists of 3 different kinds of sensor nodes, ECG, SpO2 and temperature sensors. The QoS requirements are listed in Table II.

Castalia [8] wireless sensor network simulator, which is based on the OMNeT++ [9] discrete event simulation platform,

TABLE III

SIMULATION PARAMETERS

Parameters	Value
channel model	log shadowing wireless model
path loss exponent	2.4
collision model	addictive interference model
data transmission rate	250 kbps
buffer size	1024 kbytes
simulation time	400 s
L_{PHY}	6 bytes
L_{MHR}	13 bytes
$macMinBE$	3
$aMaxBE$	5
$macMaxCSMABackoffs$	4

TABLE IV

SENSOR NODE SPECIFICATIONS

Sensor Node	Payload Size (bytes)	Transmission Rate (packets/s)	Number of Sensors
ECG	50	10	4
SpO2	25	8	10
Temperature	2	1	6

TABLE V

SIMULATION RESULT STATISTICS

Sensor Node	Non-QoS Support	QoS-aware
ECG	82 %	95 %
SpO2	95 %	92 %
Temperature	96 %	90 %

is used as the simulation environment. We modified some of the source files of Castalia simulator to make the MAC layer and physical layer compliant with the IEEE 802.15.4 standard, which has been widely used in Wireless Personal Area Networks (WPAN).

Table III and IV describe the detailed simulation parameters and sensor node specifications, respectively.

L_{PHY} and L_{MHR} are the overhead length of the physical layer packet and MAC layer packet respectively. $macMinBE$ is the initial value of backoff exponent, $aMaxBE$ is the maximum number of backoff exponent, $macMaxCSMABackoffs$ is the maximum number of backoffs the CSMA algorithm will attempt before declaring a channel access failure.

The percentage of packets delivered to the sink nodes with satisfied services (both end-to-end delay and packet delivery ratio) are listed in Table V. From the statistics of simulation results, we observed that in QoS support sensor network, packets with higher priority level (e.g. ECG data packet), can get better performance than packets with lower priority level (e.g. temperature data packet). This is because the routing service framework determines routes according to the selected QoS metrics and their priority levels. Also, by introducing network traffic engineering (packet queuing and scheduling), the QoS support network makes more efforts in delivering packets with higher priority level.

V. CONCLUSIONS AND FUTURE RESEARCH

In this paper, we proposed a QoS-aware routing service framework for biomedical sensor networks. By introducing differential user QoS and prioritized routing service, the routing framework can provide guaranteed QoS for users of high priority level and 'best effort' for ordinary users. For biomedical sensor networks with severe constraints on communication bandwidth, computation power and power supply, the proposed framework looks reasonable from an optimality point of view.

In the initial simulation results, the overhead of maintaining the routing table and link state table at each sensor node is significant, especially when the number of sensor nodes is huge. One possible solution is to adjust the frequency of route updating and link state updating according to the network conditions. In future research, an adaptive algorithm will be developed to reduce the communication and computation overhead caused by the control packets. Also we plan to implement the routing service framework on Tmote Sky sensor node platform [10], and extensively test the routing service framework in different medical scenarios (e.g. congested network, high mobility network).

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