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# A fuzzy priority based congestion control scheme in wireless body area networks

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**Abstract:** Congestion management is one of the major challenges in wireless body area network (WBAN) applications. This study proposes a technique similar to the random early detection (RED) active queue management (AQM) to indicate congestion. A two-input-single-output fuzzy logic system is used to dynamically adjust the maximum drop probability (maxp) parameter of the RED algorithm, then two adaptive values the minimum threshold (minth) and the maximum threshold (maxth) are used to estimate the congestion level of each sensor nodes. We adjust send rate of the parent node with a fuzzy logical controller (FLC) based on the child's node traffic load, considering the different amounts of data being transmitted. The simulation results show that the proposed protocol achieves high performance as compared to PCCP and PHTCCP, in terms of packet loss, end-to-end delay and energy.

**Keywords:** wireless sensor network; healthcare application; congestion control; fuzzy logic controller; active queue management.

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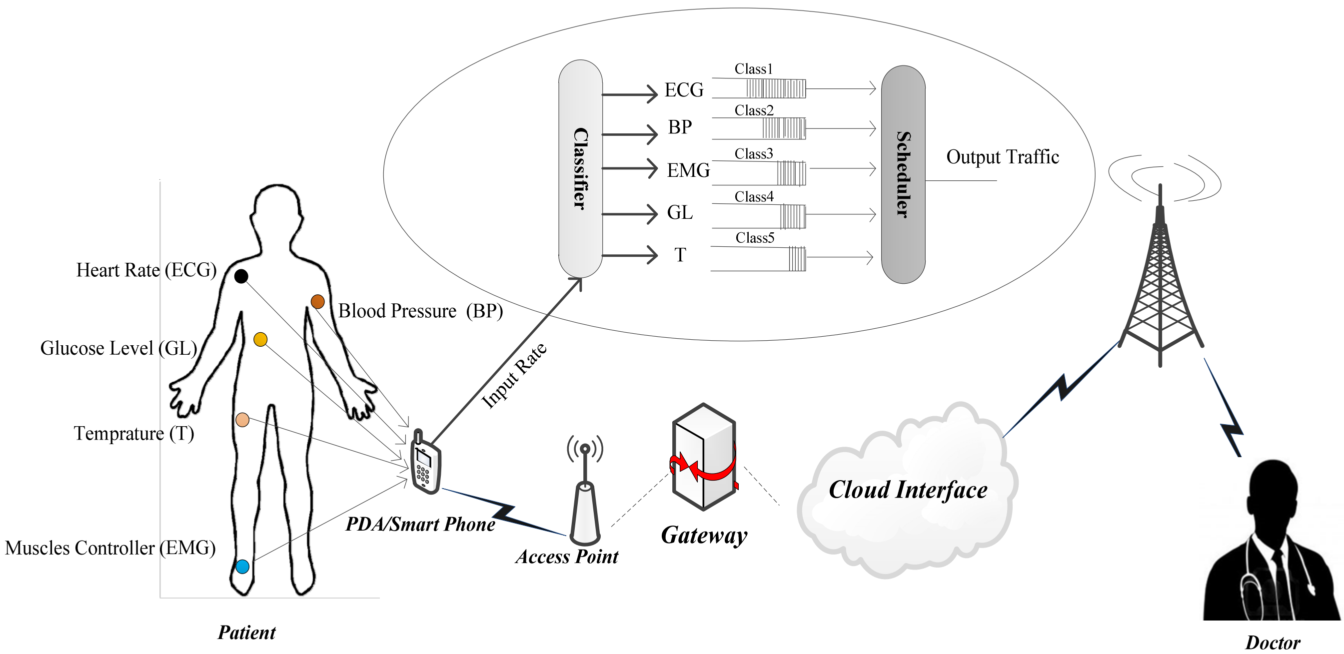
## 1 Introduction

A wireless sensor network (WSN) is a set of tiny wireless modules of sensor nodes (Shelke et al., 2016) which are spatially and autonomously distributed to monitor physical or environmental conditions such as temperature, sound, pressure, etc. Sensor nodes record and transfer this information to a central unit called *sink*. WSNs have been applied in several fields (Li et al., 2006) such as military applications, healthcare, medical applications, etc. These networks are also widely used to monitor the patients' health status (Moravejosharieh et al., 2015). It was mentioned that, one of the applications of this system is to remotely monitor patients who do not require the doctors' presence. As illustrated in Figure 1, several sensors are placed on the body, which are capable of detecting both vital signs (pulse, heart rate and breathing) and less vital data (movements like foot sensors). This data, received by intermediate nodes (such as PDAs/smart phones) is then sent to the control unit. Vital information requires shorter delays and lower packet loss ratio while less vital information has a higher tolerance for delays and packet loss. Sensors used in the network are chosen according to the data they are going to provide doctors or medical experts. There are two different types of sensors, internal and external sensors. Internal sensors such as those which are made to record body temperature can fit in a capsule and then be swallowed. External sensors on the other hand can be intentionally placed on or removed from the patient's body, e.g. the heartbeat sensor (Virone et al., 2006).

In medical and emergency applications, these sensors are able to collect a lot of information (e.g. heart rate, blood pressure, etc.) in a short time and attempt to send this information to the medical centre (sink) through middle nodes. This load of outgoing data packets would result in the information explosion and thus congestion in the middle nodes. Congestion is simultaneously related to the end-to-end delay increase, packet loss, energy consumption in the nodes and network conductivity. One of the main concerns in medicine is how to send the critical information of high-risk patients to the doctors at the right time and with high reliability using tiny wireless sensors with limited battery life (Shelke et al., 2016). In case a battery on a sensor dies or malfunctions either a data packet gets lost, an exacerbation of illness or death of a human being may occur. This is one of the reasons for congestion management in medical applications to be critical. Therefore, one of the major concerns in these networks is to reduce congestion. Vital signs of patients are used in areas related to sensor networks for medical items such as medical emergencies and monitoring. Since the transmitted data is important and sensitive, it is essential to avoid probable congestion (in case of not having another choice, managing the data is our next option), more over the data packets containing this information are directly linked to life and well-being of the patients and loss of these data packets might endanger human's life. In most existing congestion control protocols (Ghanavati et al., 2003; Ee and Bajcsy, 2004; Hull et al., 2004; Baek et al., 2009), data send rate is reduced immediately after congestion is detected. But, in healthcare environments, it is not logical to decrease the traffic streams related to vital signs. In addition, since the existing congestion control protocols for WSNs do not consider the special nature of the signals carried in a WBAN, they cannot be directly applied in WBANs. Therefore, there is a need to propose a congestion control mechanism for WBAN systems with respect to the related special features and QoS requirements. In this paper, we propose a fuzzy congestion control protocol with the priority-based rate for WBAN with multiple biosensors capable of a patient monitoring and data transfer over a network to a remote data centre.

**Figure 1** Different sensors on a patient's body



The proposed protocol consists of three steps. In the first step, a two-input-single-output fuzzy logic system adjusts dynamically the maximum drop probability ($max_p$) parameter of the RED algorithm, the inputs are average queue size and average queue size changes. Then two adaptive values the minimum threshold ($min_{th}$) and the maximum threshold ($max_{th}$) are used to calculate the congestion indicator of each sensor nodes. If congestion occurs in the second step, an Implicit Congestion Notification (ICN) is sent, then via the FLC with two input variables; transmission rate error and error change, the TLP is adjusted in order to optimise the transmission rate of each sensor node.

### *1.1 Motivation*

Since we face human lives, any decision in this area would be so important. In these systems various sensors may be installed in the patient's body or under his/her skin, which should work for months, or even years without battery interruptions, and it is difficult to replace the sources of energy in them. Therefore, optimising the sensor nodes energy consumption is a prime concern. Furthermore, in most healthcare applications, different nodes sense large numbers of events. Then, all of nodes try to transmit their sensed raw data to the sink node (control centre) with the aid of the other intermediate nodes. This may lead to congestion at the intermediate nodes especially the nodes near sink. Coupling this fact with the high levels of energy, limitations in the sensor nodes make the congestion problem in WBAN more challenging than the congestion problem in other application domains. Given these two issues, we motivated to propose a special congestion control protocol for health sensor systems. We choose the two important protocols, PCCP (Wang et al., 2007) and PHTCCP (Monowar et al., 2012) among the existing congestion control protocols to get a better protocol for WBAN applications.

The remainder of this paper is organised as follows: Section 2 consists of an investigation of RED algorithm, fuzzy logic controller and related research regarding congestion control protocol in WABN; Section 3 provides details about proposed congestion control protocol; Section 4 is about the performance evaluations, and comparisons are performed through experiments; Section 5 contains our conclusions and future research directions.

## 2 Background and related work

In this section, we describe the RED algorithm, fuzzy logic controller and congestion control protocols in WBAN.

### *2.1 Random early detection (RED) algorithm*

RED is one of the techniques applied in active management of queues, which are vastly used in large networks. The duty of this algorithm is to identify the probable congestion in the network and in case it detects one, it drops or marks the arriving packet. In fact, RED uses an average weighted length of the queue ($q_{avg}$) to make decisions dealing with the packet (Aweya et al., 2002; Ryu et al., 2004). When a packet arrives, if the weighted average is lower than a threshold limit ($\min_{th}$), the arriving packet will place in the queue. However, if $q_{avg}$ is higher than a threshold limit ($\max_{th}$), the packet will drop or mark.

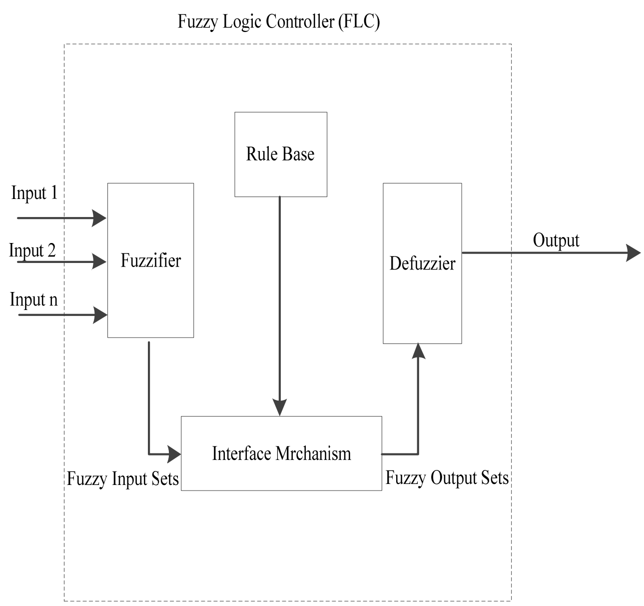
In some cases, it is possible that $q_{avg}$ is between the lower threshold ($\min_{th}$) and the upper threshold ($\max_{th}$) so these packets are marked with the sign $P_a$ ($P_a$ is the probability for marking the packets related to a certain connection). In the following function, the way to deal with the packet and to calculate the marking probability is illustrated (Masoumzadeh et al., 2011; Zhang et al., 2004). Moreover, $\max_P$ is a control parameter, maximum probability to mark packets is calculated as follows:

$$\begin{cases} 0 & q_{avg} < \min_{th} \\ \dfrac{q_{avg} - \min_{th}}{\max_{th} - \min_{th}} \times \max_p & \min_{th} < q_{avg} < \max_{th} \\ 1 & \max_{th} < q_{avg} \end{cases} \tag{1}$$

### *2.2 Fuzzy logic controller*

Two difficult items in uncertain environments are decision making and taking appropriate measures. In an environment in which decision making depends on some rules and conditions, a fuzzy logic controller (FLC) is needed to extract a good measure (Wang et al., 2009). In fact, in order to reach an appropriate decision, a controller has five parts: a fuzzification interface, a fuzzy set database, a rule base, an inference engine and a defuzzification interface (Li and Gatland, 1995). The block diagram of a fuzzy controller is shown in Figure 2.

**Figure 2** Block diagram of fuzzy logic controller (FLC)



Using a fuzzy logic controller will result in an improvement in decision making and a reduction in resource consumption. Some areas where fuzzy logic has been used include a cluster head selection (Shelke et al., 2016), security (Yang et al., 2016), data collection (Lazzerini et al., 2006), routing (Kim and Cho, 2007), MAC protocol (Xia et al., 2007) and quality of service (QoS) (Seth and Gupta, 2012).

## *2.3 Congestion control protocols in WBAN*

Recently, the congestion control protocols in wireless sensor networks with healthcare applications have been extensively investigated in some recent research. In the following paragraph, we are going to consider some of these approaches as listed in Table 1.

**Table 1** Comparison of congestion control protocol

| *Protocol* | *Congestion detection* | *Congestion notification* | *Rate adjustment* |
|---|---|---|---|
| PCCP | Arrival time and packet service time | Implicit | Hop-by-hop |
| CCF | Packet Service Time | Implicit | Hop-by-hop |
| LACAS MLACAS | Difference between entry and exit rates | Implicit | Learning automata |
| PHTCCP | Packet service ratio | Implicit | Hop-by-hop |
| QMCC | Queue occupancy | Implicit | Hop-by-hop |
| HOCA | RED-based congestion detection | Implicit | To achieve minimum data packet loss |
| PBCCP | Automata-based congestion detection | Implicit | Learning automata |
| CALRTH | Loss prediction | Implicit | Hop-by-hop |
| OCMP | Automata-based congestion detection | Implicit | To achieve maximum bandwidth efficiency |

CCF (Ee and Bajcsy, 2004) is a congestion control and fairness protocol. This protocol uses packet service time and hop-by-hop approach to detect and control congestion, respectively.

PCCP (Wang et al., 2007) is a priority-based hop-by-hop upstream congestion control protocol which proposed for wireless sensor network. In PCCP, congestion degree is calculated on the basis of the ratio of packet inter-arrival time to the packet service time. It uses cross-layer optimisation and performs a hop-by-hop manner to control congestion. It has also been proven that PCCP can obtain energy efficiency and weighted fairness for both single-path and multipath routing.

LACAS (Misra et al., 2009), is a congestion control based on learning automata which proposed for healthcare wireless sensor network. The role of LACAS is controlling the congestion resulted by the last information about congestion in each sensor. In LACAS protocol packet loss ratio is used as a factor to congestion detection. Each node is equipped with a piece of code which enables them to have an intelligent reaction. The automata in the nodes can learn from the past and choose the optimal data flow rate according to the number of packets lost and thus avoid congestion. This method prevents data packets from getting stored in the queue resulting shorter delays, by equating the input rate and packet service rate. LACAS was proposed for using by stationary patients and doctors. When a patient is in an ambulance to go to the hospital, mobile medical care is required. So the MLACAS protocol (Gunasundari et al., 2010) is designed to follow LACAS for mobile healthcare services.

QMCC (Samiullah et al., 2012) is designed based on efficient management of queues to provide reliability and reduce packet loss in body sensor networks. The aim of this protocol has been to achieve energy efficiency to a greater extent, using reducing packet loss. To identify congestion, each node checks the queue length of itself and its parents. A field called queue status is added in each packet header. Each intermediate node updates this field based on local queue status of itself and their parents. The value of the queue status field depends on the congestion level and transmission rate is defined based on node local occupancy and upper-stream nodes. The congestion level is determined as medium if half of the queue length is occupied, otherwise it is considered as high.

PHTCCP (Monowar et al., 2012) is a congestion control protocol based on prioritised heterogeneous traffic. It can be applied in medical applications. It is presumed that all the sensor nodes take advantage of CSMA/CA protocol on the MAC layer. Coming packets are classified into their own traffic classes based on their priorities. As entering packets to the node have already passed through some nodes and if they get lost more energy will be wasted, they are assigned a higher priority than those generated in the node itself. An implicit congestion notification and a hop-by-hop congestion control method are used in this protocol.

PBCCP (Yaghmaee et al., 2013) is a congestion control protocol based on learning automata and prioritising system for patient's vital signs monitoring. The PBCCP provides a better service quality by categorising different vital signals priorities. There are two separate parts. Firstly, an AQM mechanism based on learning automata is used in intermediate nodes to choose the best action among others hence minimising the drawbacks. Secondly, the required bandwidth is assigned to each node by a bandwidth assignment mechanism. The amount of bandwidth is determined based on congestion and priority index. By setting the source rate, this protocol can decrease the packet loss ratio and increase efficiency. Unlike LACAS various rewards and penalties are defined by the congestion level. In addition, service ratio is different in intermediate nodes, important packets are assigned a higher priority in comparison with other packets.

CALRTH protocol: The elderly are usually exposed to several diseases such as heart attacks or strokes, high blood pressure, blood sugar and so on. Monitoring such patients requires placing more than one kind of sensors in the body. To reduce the cost of caring for these patients, sensors must be small in size so they can work for a longer period of time. In Hu et al. (2009) a system of medical sensors with wireless capabilities is designed. In this system, a piece of hardware with capability of multiple monitoring is designed for patients. In this hardware, the signal processing is used to extract the patient's vital parameters which then are compressed to be sent. This helps to reduce the congestion. The hardware can also perform error recovery operation.

HOCA (Rezaee et al., 2014) prevents congestion which is avoided in the routing phase using multipath and QoS aware routing. If congestion cannot be avoided, an optimised congestion control algorithm will help. The entering packets of the intermediate nodes are classified into high priority, low priority and medium priority for sensitive, insensitive and control data, respectively. Because of the importance of the delay in the sensitive data traffic, RQ priority queue scheduling algorithm is employed in each intermediate node. When the data rate increases and congestion occurs, a mechanism based on RED algorithm is used to detect congestion. The implicit congestion notification mechanism and an optimal source rate adjustment are used to minimise packet loss.

OCMP protocol (Rezaee et al., 2014) utilises active queue management mechanisms to calculate the probability of packet loss, avoid full queues and as a result prevent congestion occurrence. This protocol presumes the separate priority for each child node. The congestion detection unit of this protocol is based on automata. Also, implicit congestion notification (ICN) and optimal rate adjustment are applied to maximise the network bandwidth efficiency.

In (Chen et al., 2012) a new method of active queue management is proposed to improve network congestion and it studies problems in TCP congestion control method. This method is a combination of the RED method for congestion detection and fuzzy proportional integral-derivative approach.

## 3 Proposed protocol

The aim of this protocol is to detect congestion and control it in the event of congestion occurrence. This protocol acts in the transport and network layers. Our proposed protocol improves the existing popular congestion control protocols such as PCCP and PHTCCP.

The PCCP protocol cannot provide relative priority in case of different congestion situations. If low congestion occurs, PCCP increases the scheduling and data rate of all traffic sources without paying attention to their priority index. In case of high congestion, PCCP decreases the sending rate of all traffic sources based on their priority indexes. There is another problem of PCCP; it considers only geographical priority and does not support multi-sensor with dynamic priority situations (patient's overall health status) which is necessary for HWSNs. The source rate changes with regard to node congestion status in PHTCCP protocol, but this is not acceptable for high priority related packets to critical health conditions and diseases which have strict delay constraints. Another problem of PHTCCP is that it uses a static priority for each type of traffic class that is assigned by the base station, and it does not consider the patients with different level of importance and different sensors are fitted to their bodies. As a result, various priorities are not supported by this protocol. PHTCCP also uses the data centric routing protocol directed diffusion and forwards all the packets from the same path. The proposed protocol solves the problem by a proper adjustment of the send rate of each child node using an exponential weighted priority-based rate control (EWPBRC) schemes with TLP schemes control congestion by adjusting transmission rates relative to various data types.

Figure 3 indicates the proposed congestion detection and control system architecture and detailed description about subsystems. Similar to other available protocols like PCCP, HOCA, QMCC, it consists of three units: Congestion Detection Unit (CDU), Congestion Notification (CNU) and Rate Adjustment Unit (RAU). The notations which are used in this paper are shown in Table 2.

**Figure 3** The structure of proposed protocol

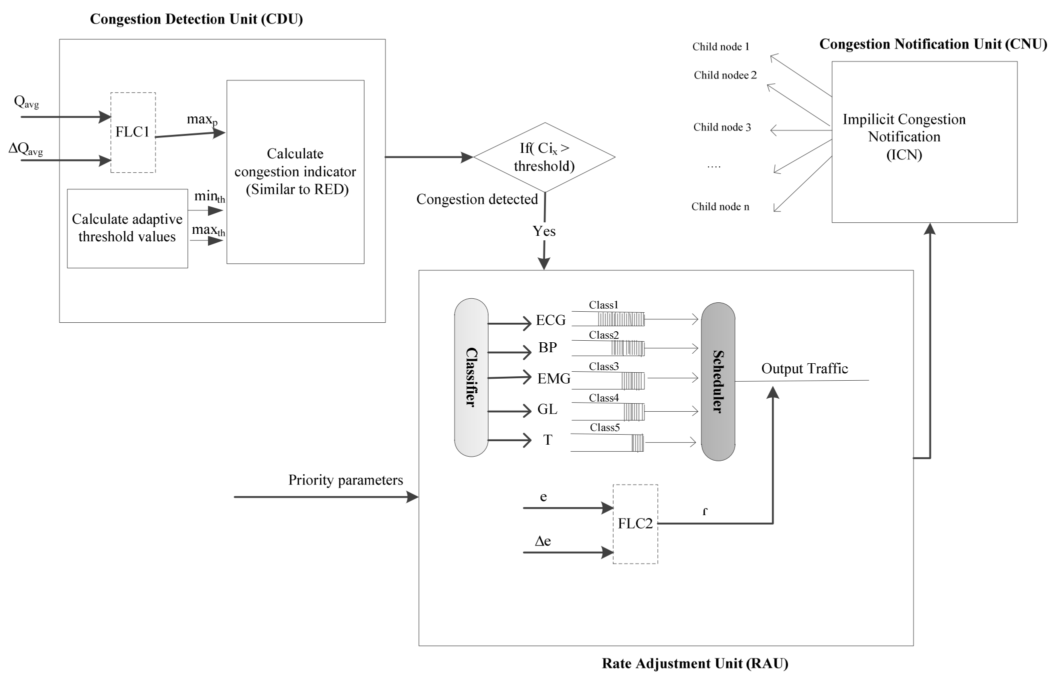


**Table 2** Term description

| *Term* | *Descriptions* |
|---|---|
| $max_{p\,i}^{\,j}(t)$ | Maximum drop probability |
| $Q_{avg}$ | Average queue size |
| $\Delta Q_{avg}$ | Difference between average queue size and instantaneous queue size which |
| $max_{th\,i}^{\,j}(t)$ | Maximum threshold of queue *j* of node *i* |
| $min_{th\,i}^{\,j}(t)$ | Minimum threshold of queue *j* of node *i* |
| $q_i^j(t)$ | Queue size for traffic class *j* in node *i* |
| $CI_{x\,i}^{\,j}(t)$ | Congestion indicator for the queue |
| $Rate_{in\,i}^{\,j}(t)$ | Input transmission rate of node *i* |
| $Rate_{out\,i}^{\,j}(t)$ | Output transmission rate of node *i* |
| $minr_{in\,i}^{\,j}(t)$ | Minimum input rate of class *j* to node *i* |
| $maxr_{in\,i}^{\,j}(t)$ | Maximum input rate of class *j* to node *i* |
| $P_{traffic}^i$ | Traffic class priority |
| $SP_j^i$ | Traffic class for the source data of each sensor node *i* |
| $Rate_{out}^{sink}(t+1)$ | Sink output send rate at time instant *t* + 1 Output send rate of node *i* ( $Rate_{out}^i$ ) |
| $Glob_{priority}^i$ | Global priority of each node *i* |
| *C*(*i*) | Set of child nodes of node *i* |
| C(Sink) | Set of all the child nodes of node sink |
| $Glob_{priority}^{sink}$ | Sum of the global priorities of the sink node |
| $Rate_s^i$ | Node *i* measuring data from itself |
| $\Delta Rate^i$ | Send rate difference of node *i* |
| $\tau$ | Traffic load parameter (TLP) |
| Td | Delay unit |
| e | Error |
| $\Delta e$ | Error change |
| $U_i$, | Fuzzy subsets |
| $W_i$ | Fuzzy singleton |

## 3.1 Congestion detection unit (CDU)

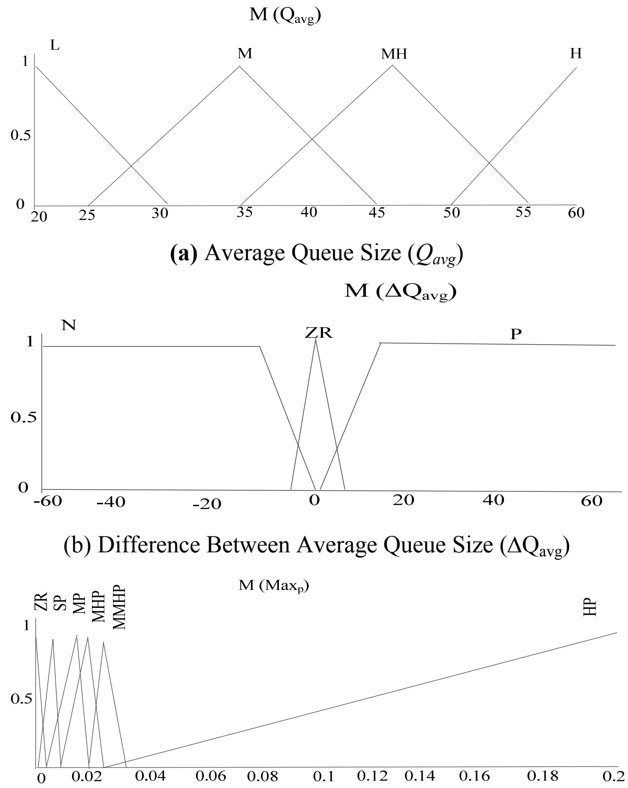
Congestion detection unit detects how much traffic is transmitted through the queues of each node in the network. We use an active queue management algorithm which is similar to RED mechanism to detect congestion.

There are two steps in CDU:

*Step 1:*

At first a fuzzy logic system is designed to dynamically adjust the maximum drop probability $(max_{p\,i}^{\,j}(t))$ parameter of the RED algorithm to reduce the number of packet loss that are transmitted. To achieve this target, a two-input-single-output fuzzy logic system is used. The inputs of the system are (1) *average queue size* ($Q_{avg}$), (2) *difference between average queue size and instantaneous queue size* which is denoted by $\Delta Q_{avg}$. The membership functions for the first input are four linguistic variables (*Low* (*L*), *Medium* (*M*), *Medium High* (*MH*), *High* (*H*)), shown in Figure 4a, while for the second input is three with linguistic variables (*Negative* (*N*), *Zero* (*ZR*), *Positive* (*P*)) shown in Figure 4b. The output membership functions is six with linguistic variables (*Zero* (*ZR*), *Small Probability* (*SP*), *Medium Probability* (*MP*), *Medium High Probability* (*MHP*), *Medium Medium High Probability* (*MMHP*), *High Probability* (*HP*)) shown in Figure 4c.

**Figure 4** Membership function for the fuzzy set values in FLC1




**(a)** Average Queue Size ($Q_{avg}$)

(b) Difference Between Average Queue Size ($\Delta Q_{avg}$)

(c) Output Parameter ($Max_p$)

The rule that is used to map the fuzzy input to the fuzzy output is shown in the Table 3.

**Table 3** The fuzzy logic system rules of FLC1

| | | *Input 1* | | | |
|---|---|---|---|---|---|
| | | $Q_{avg}$ | | | |
| *Input 2* | $\Delta Q_{avg}$ | L | M | MH | H |
| | N | ZE | SP | MP | MHP |
| | ZR | SP | MP | MHP | MMHP |
| | P | MP | MHP | MMHP | HP |

*Step 2:*

After adjusting the *maximum drop probability* $(max_{p\,i}^{\,j}(t))$, two values including the minimum threshold ( $min_{th\,i}^{\,j}(t)$ ) and maximum threshold ( $max_{th\,i}^{\,j}(t)$ ) are used to estimate the congestion level of the queue for each queue *j* of a sensor node *i*. Assuming $q_i^j(t)$ is the queue size for traffic class *j* in node *i*, the congestion indicator $CI_{x\,i}^{\,j}(t)$ for the queue and $q_i^j(t)$ are defined as follows.

$$CI_{xi}^{\ j}(t) = \begin{cases} 0 & q_i^j(t) < \min_{th\,i}^{\ j}(t) \\ \dfrac{q_i^j(t) - \min_{th\,i}^{\ j}(t)}{\max_{th\,i}^{\ j}(t) - \min_{th\,i}^{\ j}(t)} \times \max_{p\,i}^{\ j}(t) & \min_{th\,i}^{\ j}(t) < q_i^j(t) < \max_{th\,i}^{\ j}) \\ 1 & \max_{th\,i}^{\ j}(t) < q_i^j(t) \end{cases} \tag{2}$$

$$q_i^j(t+1) = q_i^j(t) + Rate_{in\,i}^{\ j}(t) - Rate_{out\,i}^{\ j}(t) \tag{3}$$

When the queue length is less than $min_{th\,i}^{\ j}(t)$, then there is no congestion and then congestion index $CI_{xi}^{\ j}(t)$ is set to zero, so there is no need for a child node to decrease its transmission. Otherwise, when the queue length is greater than $max_{th\,i}^{\ j}(t)$, then there is severe congestion and the congestion index is set to 1. In this case, a child should decrease its send rate to reduce the probability of packet loss at the parent node. When the queue length is between $min_{th\,i}^{\ j}(t)$ and $max_{th\,i}^{\ j}(t)$ then $CI_{xi}^{\ j}(t)$ will vary between 0 and 1, depending on the queue length. Unlike in RED active queue management, the values for $min_{th\,i}^{\ j}(t)$ and $max_{th\,i}^{\ j}(t)$ are not fixed. They are instead calculated automatically depending on the send rate of each traffic and the current buffer occupancy as shown in equations (4) and (5).

$$min_{th\,i}^{\ j}(t) = \frac{minr_{in\,i}^{\ j}(t)}{minr_{in\,i}^{\ j}(t) + maxr_{in\,i}^{\ j}(t)} \times q_i^j(t) \tag{4}$$

$$max_{th\,i}^{\ j}(t) = \frac{maxr_{in\,i}^{\ j}(t)}{maxr_{in\,i}^{\ j}(t) + minr_{in\,i}^{\ j}(t)} \times q_i^j(t) \tag{5}$$

where $minr_{in\,i}^{\ j}(t)$ and $maxr_{in\,i}^{\ j}(t)$ refer to the minimum and maximum input rate of class $j$ to node $i$ and $q_i^j(t)$ the queue length at queue $j$ of node $i$. To reduce the effect of abrupt changes of the send rate on the overall calculated threshold values, we average both threshold values by using the exponential weighted.

### *3.2 Congestion notification unit (CNU)*

When congestion is detected, a signal is sent to intermediate nodes. Implicit Congestion Notification (ICN) (Yi et al., 2008) and Explicit Congestion Notification (ECN) are two methods used for this task (Aghdam et al., 2014). In our proposed protocol, ICN mechanism is applied to piggyback congestion information in the header part of data packets. This avoids sending additional control messages. Consequently, energy-efficiency is improved.

### *3.3 Rate adjustment unit*

In this section, our proposed scheme combines a priority-based rate with FLC to regulate TLPs for the improvement of transmission performance. We propose a new scheme such that the FLC for traffic load parameter (FTLP) is based on EWPBRC. Hence, we can obtain the optimum TLP and send rate for all child nodes and diminish the delay time and loss probability for WBAN. In the simulation phase, we set up the sensor node traffic classes in advance according to their function. The transmission data are generated randomly and data are sent to the sink node according to their transmission path. We use the EWPBRC scheme to estimate new transmission rates for the next time; then, the new send rate allocates each sensor node according to its priority. In the end, the FLC is combined with the TLP scheme for adjusting send rate.

#### *3.3.1 Traffic classes model*

Figure 5 shows the simulation model, symbols and scheme (Yaghmaee and Adjeroh, 2009) of the proposed and simulated WBAN environmental hypothesis. There are 21 nodes, one sink node and the base station (BS). We defined five different types of data with regard to amount and priority class among the 21 nodes, which are: heart rate (ECG), blood pressure (BP), muscles controller (EMG), glucose level (GL) and temperature (T). It is possible to extend the traffic classes to support a large number of tasks without loss in generality. However, in this study we selected the top five important vital signals in healthcare applications. We allocate the highest priority level to the heart rate signal and less priority level to temperature. In fact, higher traffic classes need to have higher throughput and less delay. As shown in Figure 5, there are five traffic classes assigned to the ECG, BP, EMG, GL and T data stream, respectively. This classification is application-based and can be varied based on situation of each patient. As the Figure 6 shows, each traffic class has its separate queue. Each arriving data packet is navigated to its corresponding sub-queue using a traffic class identifier which is provisioned in the PDA.

It is assumed that there is a single-path network in which each node has only one next hob to route the data. The data type of the packet is located in the header part of the packet. Then, data are routed to MAC layer based on their weighted priority using a weighted fair queuing (WFQ; Ohba, 2009) scheduler.

**Figure 5** The simulation model

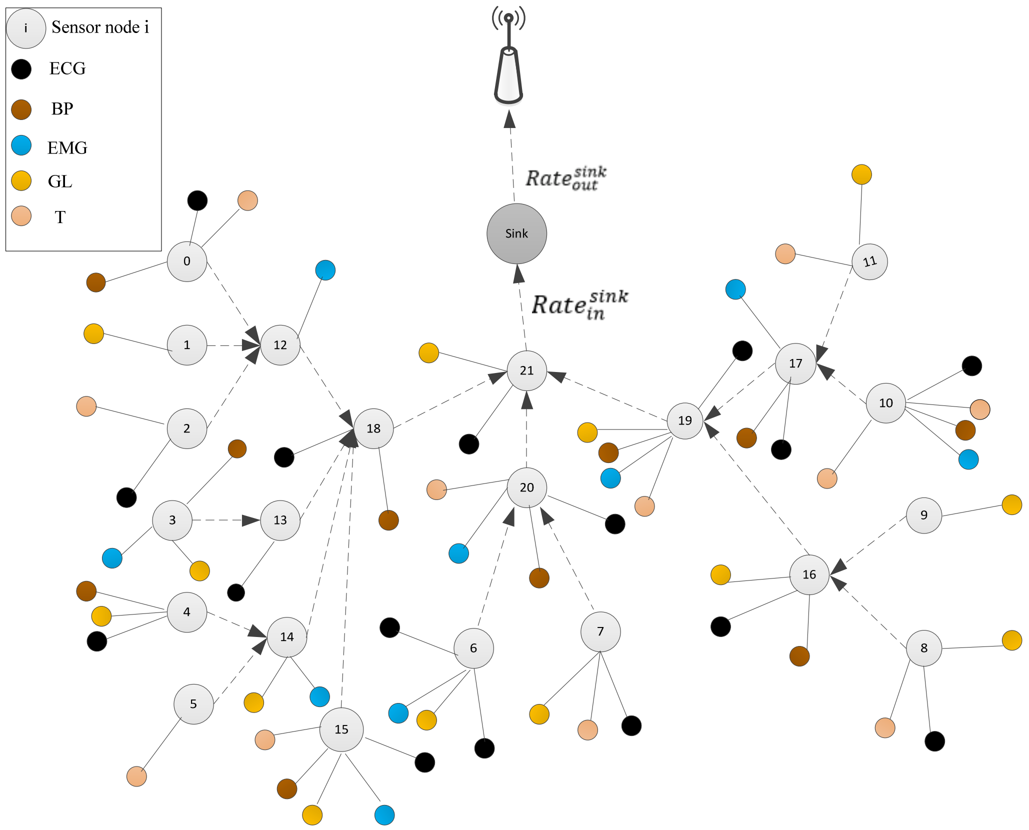
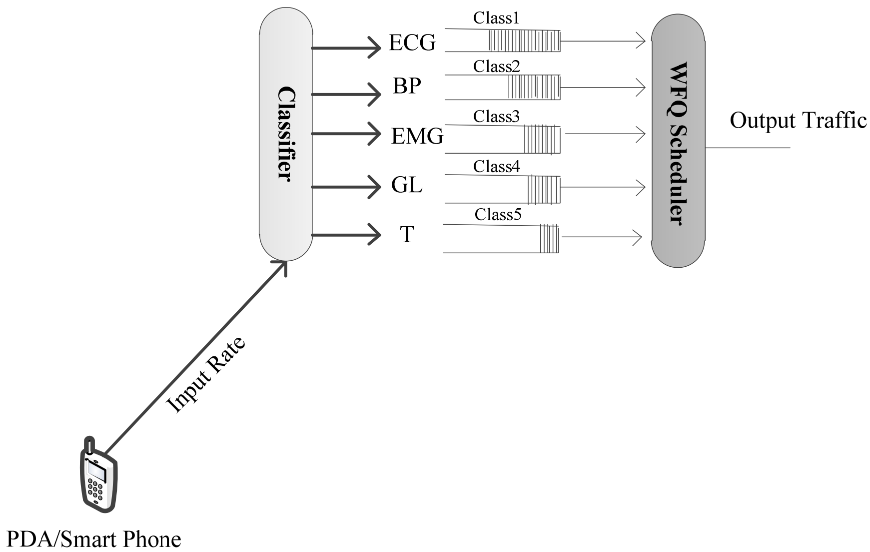



**Figure 6** Rate adjustment model




### *3.3.2 Rate adjustment*

In the rate adjustment unit, we define traffic class priority ($P_{traffic}^{i}$), which is the sum of the $SP_j^i$ of the traffic class for the source data of each sensor node *i*. It is represented as follow:

$$P_{traffic}^{i} = \sum SP_j^i \tag{6}$$

where $SP_j^i$ is the traffic source priority *j* in sensor node *i*; the priority order $SP_j^i$ of the source priority can be manually set up with service differentiation, and the higher the $SP_j^i$ value, the higher the traffic class, and *j* demonstrates the traffic class; *j* belongs to {ECG,BP,EMG,GL,T}.

Our proposed transmission rate calculation scheme is divided into three phases as follows:

### *3.3.2.1 Sink output send rate adjustment phase*

The output send rate ($Rate_{out}^{sink}(t+1)$) is obtained at time instant $t$ + 1, using average send rate $\overline{Rate_{out}^{sink}}(t)$ and $Rate_{out}^{sink}(t)$ at time instant *t*:

$$Rate_{out}^{sink}(t+1) = \overline{Rate_{out}^{sink}}(t).(1-\alpha)+\alpha.Rate_{out}^{sink}(t) \quad (7)$$

where $\alpha$ is constant, $0 \le \alpha \le 1$.

### *3.3.2.2 Child output send rate adjustment phase*

The global priority ($Glob_{priority}^{i}$) of each node *i* is calculated as follows:

$$Glob_{priority}^{i} = \sum\nolimits_{k\in C(i)} Glob_{priority}^{k} + P_{traffic}^{i} \quad (8)$$

where $C(i)$ is the set of child nodes of node *i*.

$Glob_{priority}^{sink}$ is the sum of the global priorities of the sink node (all nodes), $C(Sink)$ is the set of all the child nodes of node *sink*:

$$Glob_{priority}^{sink} = \sum\nolimits_{k\in C(\sin k)} Glob_{priority}^{k} \quad (9)$$

The output send rate of node *i* ($Rate_{out}^{i}$) is calculated based on the distribution of the output send rate from the sink node ($Rate_{out}^{sink}$) to node *i* according to the proportion of the global priority of child node $Glob_{priority}^{i}$ the global priority of *sink* node $Glob_{priority}^{sink}$:

$$Rate_{out}^{i} = Rate_{out}^{sink} \cdot \frac{Glob_{priority}^{i}}{Glob_{priority}^{sink}} \quad (10)$$

### *3.3.2.3 Parent output send rate adjustment phase*

For the aim of obtaining the optimal send rate of each sensor node, an FTLP is proposed in this phase. Then, the sending rate of the parent node will follow the TLP scheme (Yaghmaee and Adjeroh, 2009) to achieve a sending rate distribution on each of the sensor nodes.

The input send rate of node *i* ($Rate_{in}^{i}$) calculated as follows:

$$Rate_{in}^{i} = \sum\nolimits_{k\in C(i)} Rate_{out}^{k} \quad (11)$$

where $C(i)$ is the set of node *i*, and $Rate_{out}^{k}$ indicated as the output rate of the *k*th child of parent node *i*. $Rate_{out}^{i}$ is node *i*'s output send rate and is calculated as:

$$Rate_{out}^{i} = Rate_{s}^{i} + Rate_{in}^{i} \quad (12)$$

where $Rate_{s}^{i}$ node *i* measures data from itself. $\Delta Rate^{i}$ is the send rate difference of node *i* and is given by:

$$\Delta Rate^{i} = \tau.Rate_{out}^{i} - Rate_{in}^{i} \quad (13)$$

where the TLP $\tau$ is the defuzzification output value. In Section 3.3.2.4, an FLC is used to obtain the optimum TLP $\tau$. Each parent node *i* generates a new send rate to be distributed among all the child node *k* output send rates; this is calculated as:

$$Rate_{out}^{k} = Rate_{out}^{k} - \Delta Rate^{i} \cdot \frac{Glob_{priority}^{k}}{Glob_{priority}^{i}} \quad (14)$$

### *3.3.2.4 Proposed FLC2 model*

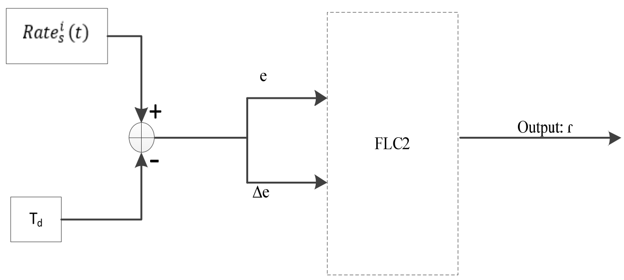
As shown in Figure 7, we have used FLC to determine TLP $\tau$, where $Rate_{s}^{i}$ is node *i* measuring data from itself and *Td* is the unit delay. Two input variables error (*e*) and error change $(\Delta e)$ are used in the FLC.

$$e(t) = Rate_{s}^{i}(t) - Rate_{s}^{i}(t-1) \quad (15)$$

$$\Delta e(t) = e(t) - e(t-1) \quad (16)$$

where $e(t)$ is the error between $Rate_{s}^{i}(t)$ and ($t$ − 1) and $\Delta e(t)$ is the error change of two continuous times of *e* in time instant *t*.

**Figure 7** Block diagram of FTLP rate control



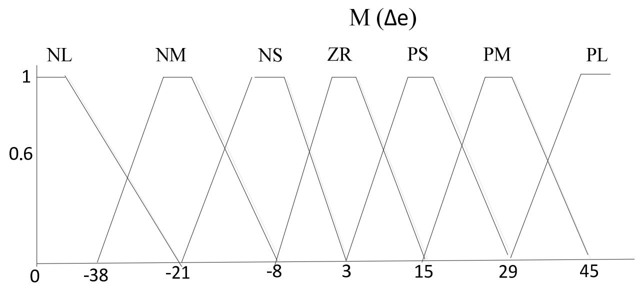

Fuzzy sets and memberships function values provide a possible model for inexact concepts and subjective judgments for all types of estimation. Fuzzy set B in a universe of discourse Y is defined as the following set of pairs:

$$B = \{(\tau_B(y), y) : y \in Y\} \quad (17)$$

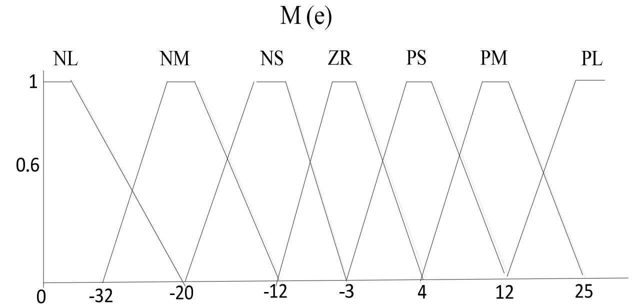
where $\tau_B : Y \rightarrow [0,1]$ is mapping such that the membership function of the fuzzy set B and $\tau_B(y)$ is called the degree of membership value of $y \in$ Y in the fuzzy set B. Figure 8 illustrates the seven trapezoidal membership function switches which have been used. The associated membership functions are the commonly used trapezoidal functions. The fuzzy linguistic variables are listed in Table 4.

The fuzzy rules are based on the relationship between oscillations in dimension of the solution vector during the iterations and the speed of convergence. The rule for convergence is that controlling increment has the same sign as $e$ and $\Delta e$. Nevertheless, we use the FLC in this system when the overshoot is drastically reduced and oscillation is effectively excluded. The rate of convergence of the FLC is nearly the same as the rate of convergence of the proportional controller. Furthermore, the performance of the regulatory control parameter can be characterised by a performance index called tracking error. Therefore, our proposed scheme can reduce transmission queuing delay and packet loss probability without causing the system to be unstable.

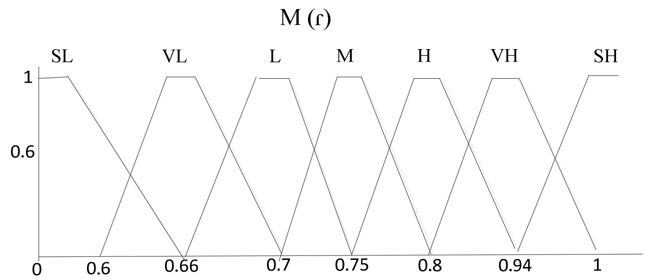
**Figure 8** Membership function for the fuzzy set values




(a) Transmission Rate error change ($\Delta e$)




(b) Transmission Rate error (e)




(c) Output Parameter (r)

**Table 4** Fuzzy linguistic variables

| *Seven fuzzy two-input values linguistic variables* | *Seven fuzzy output linguistic variables* |
|---|---|
| (NL) Negative Large | (SL) Sorely Low |
| (NM) Negative Medium | (VL) Very Low |
| (NS) Negative Small | (L) Low |
| (ZR) Zero | (M) Medium |
| (PS) Positive Small | (H) High |
| (PM) Positive Medium | (VH) Very High |
| (PL) Positive Large | (SH) Sorely High |

The fuzzy rule base includes a set of linguistic terms in the following form (Elmas et al., 2009):

$$R_i : if\ eU_i\ and\ \Delta e\ is\ V_i, then\ \tau\ is\ W_i \quad i = 1, 2, \ldots m \tag{18}$$

where $U_i$ and $V_i$ are fuzzy subsets in their universe of discourse and $W_i$ is a fuzzy singleton. Since every input can take seven different values so 7*7 fuzzy rules are used, as listed in Table 5.

**Table 5** Fuzzy rules of FLC2

| | | | *Input 1 c* | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | *NL* | *MN* | *NS* | *ZR* | *PS* | *PM* | *PL* |
| Input 2 | Δe | NL | SL | VH | H | M | M | L | M |
| | | MN | SL | VH | H | M | M | M | SL |
| | | NS | SL | VH | H | M | M | VL | SL |
| | | ZR | SL | VH | H | M | L | VL | SL |
| | | PS | SL | VH | M | M | L | VL | SL |
| | | PM | SL | M | M | M | L | VL | SL |
| | | PL | M | H | M | M | L | VL | SL |

From Figure 7, the defuzzification output value $\tau$ is calculated by:

$$\tau = \frac{\sum_{i=1}^{n} u_i U_i}{\sum_{i=1}^{n} u_i} \tag{19}$$

## 4 Simulation results and analysis

### *4.1 Experimental setup*

In this section, we use OPNET and MATLAB to evaluate the results of the proposed protocol. We compare proposed protocol with PHTCCP and PCCP, since both share some similarities and PHTCCP is one of the common wireless sensor network congestion control protocols in healthcare applications. Fuzzy systems have been implemented using MATLAB and the simulation process has run with the OPNET network simulator. OPNET can be integrated with MATLAB. We decided to make a connection between MATLAB and OPNET using C++ compiler, because C++ is the main programming language of the both software. The simulation model consists of two parts, the first part is simulating the packet generation and packets flow using OPNET simulator, in the second part, when fuzzy systems are required, parameters are placed in an array and the function in MATLAB is called for calculation. MATLAB function returns the results as an array to OPNET. Therefore, while the simulation is in progress, the two programs work simultaneously.

In Figure 5, there exist 21 sensor nodes in the simulation model, one sink node and the BS. The transmission data collected by sensor nodes are generated randomly and there are five types of traffic class ( ECG, BP, EMG, GL and T) which have been set manually in advance by the sensor nodes. The scenario for the proposed protocol can be used for patients who are not able to move and bedridden in a special ward of a hospital or private clinic, and suffer from heart attack or brain death. A summary of the simulation parameters is shown in Table 6.

**Table 6** Simulation parameters

| | |
|---|---|
| Network field | 500 m × 500 m |
| Number of sensor nodes | 21 |
| Number of sinks | 1 |
| Deployment type | Uniform, grid |
| Initial node energy | 100 J |
| Initial service rate | 600 packets/sec |
| Network architecture | Homogeneous, flat |
| Application type | Event-driven |
| Packet size | 512 Byte |
| Buffer size of sensor | 50 packets |
| Buffer size of sink nodes | 100 packets |
| Nodes simulation time | 1000 s |
| Type traffic | Non-sensitive and sensitive (ECG, BP, EMG, GL, T) |

**Algorithm 1** Proposed protocol's algorithm

*Algorithm Description*

*//Setup initial sensor nodes in the network.*

*//Assign the capability to all nodes to sense the data.*

*//Set the send rate for each node.*

*//Assign the attributes of queues*

//CUD:

*PacketReceive ();*

$Max_p$ *=FLC1(*$Q_{avg}$, $\Delta Q_{avg}$*);*

*// Calculate* $q_i^j(t)$ *using input and output rate (Using equation 3).*

*Calculate_Adaptive _thresholds();(Using equations 4 and 5 )*

*If(* $q_i^j(t) < min_{th\,i}^{\;j}(t)$ *)*

*//No Congestion in the network and there is no need for a child node to decrease its transmission.*

$CI_{x\,i}^{\;j}(t) = 0$;

*If (* $max_{th\,i}^{\;j}(t) < q_i^j(t)$*)*

$CI_{x\,i}^{\;j}(t) = 1$;

*// There is severe congestion and a child should decrease its send rate to reduce the probability of packet loss at the parent node.*

*If (* $min_{th\,i}^{\;j}(t) < q_i^j(t) < max_{th\,i}^{\;j}$*) )*

*//Calculate* $CI_{x\,i}^{\;j}(t)$ *which will vary between 0 and 1 (using equation 2).*

*If(* $CI_{x\,i}^{\;j}(t)$ *> threshold)*

*//congestion detected.*

**//RAU:**

*// Allocate priority levels to top five important vital signals in healthcare applications (ECG, BP, EMG, GL and T).*

*//Using a weighted fair queuing (WFQ) scheduler to route data to MAC layer based on their weighted priority.*

*Calculate_sink _output _transmission_ rate();(Using equation 7 )*

*Calculate_child_output_transmission_rate ();(Using equations 8–10 )*

*Calculate_parent_output_transmission_rate ();(Using equations 11–14 )*

$\tau$ *=FLC2(* $e(t)$, $\Delta e(t)$ *);*

//**CNU (Implicit congestion notification):**

*//When a node receives a new rate assignment message from its upstream node, the node is*

*expected to adjust its traffic rate accordingly*

*}*

The proposed structure of the packet header is shown in Table 7.

**Table 7** Structure of packet header

| SDA | PKT | CAT | NTH |
|---|---|---|---|

SDA (Sender Address) illustrates the transmitter sensor address. PKT (Packet Type) can determine control packets and data packets. And CAT (Created Time) is used to delay calculation. NTH (Next Hob) determines the next receiver node.

Table 8 is a simulation: it is assumed that all the sensor nodes will collect the data from the five different traffic classes of which the weight values are five, four, three, two and one, respectively. Each node will be allocated a send rate according to the priority weight of the data transmission rate class. The send rate of each child node will be allocated by the sink node according to the weight of the data. In Figure 7, we have calculated $P_{traffic}^1$ of Node 1, which contains ECG, BP and GL traffic classes and is equal to 11. This is presented in Table 8.

## 4.2 Performance results and discussion

In the following sections, we present performance results of the proposed protocol.

### 4.2.1 Packet loss ratio

In wireless sensor networks, on the basis of the application, some packets might get lost. The packet loss rate is calculated as follows:

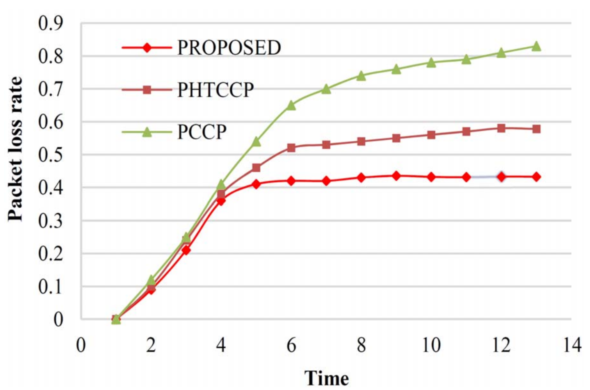
$$Loss\ Rate = Packet\_loss \ / \ Time \tag{20}$$

*Packet_loss* is the number of packets loss per unit of time. Figure 9 represents the packet loss ratio over time with the initial source rate of 100 packets per second. As illustrated in Figure 9, in our proposed protocol at the beginning of the simulation when congestion is not yet detected and also rate adjustment does not take place in the proposed protocol, the loss rate is high. On the other hand, since the rate adjustment process is carried out from congested nodes toward source node of the traffic in a hop-by-hop manner and is in the first 5 seconds, packet loss ratio is high. After this initial phase, the rate is adjusted and thus loss ratio decreases. Our congestion control protocol has the highest performance compared to PCCP and PHTCCP. For instance, after 6 seconds, packet loss rates of the PCCP and PHTCCP are 0.65 and 0.52, respectively while it is around 0.42 for our proposed protocol. The reason is that each sensor node is able to analyse their current conditions such as average queue size, the changes of average queue size and then calculate adaptive thresholds to ensure about the congestion occurrence. As a result, data traffic is reduced and congestion detection accuracy is improved.

**Table 8** The state of traffic classes in each sensor node

| *Number of node* | *ECG (W=5)* | *BP (W=4)* | *EMG (W=3)* | *GL (W=2)* | *T (W=1)* | $P^{i}_{traffic}$ |
|---|---|---|---|---|---|---|
| Node 0 | ON | ON | OFF | ON | OFF | 11 |
| Node 1 | OFF | OFF | OFF | ON | OFF | 2 |
| Node 2 | ON | OFF | OFF | OFF | ON | 6 |
| Node 3 | OFF | ON | ON | ON | OFF | 9 |
| Node 4 | ON | ON | OFF | ON | OFF | 11 |
| Node 5 | OFF | OFF | OFF | OFF | ON | 1 |
| Node 6 | ON | ON | ON | ON | OFF | 14 |
| Node 7 | ON | OFF | OFF | ON | ON | 8 |
| Node 8 | ON | OFF | OFF | ON | ON | 8 |
| Node 9 | OFF | OFF | OFF | ON | OFF | 2 |
| Node 10 | ON | ON | ON | ON | ON | 15 |
| Node 11 | OFF | OFF | OFF | ON | ON | 3 |
| Node 12 | OFF | OFF | ON | OFF | OFF | 3 |
| Node 13 | ON | OFF | OFF | OFF | OFF | 5 |
| Node 14 | OFF | OFF | ON | ON | OFF | 5 |
| Node 15 | ON | ON | ON | ON | ON | 15 |
| Node 16 | ON | ON | OFF | ON | OFF | 11 |
| Node 17 | ON | ON | OFF | ON | OFF | 11 |
| Node 18 | ON | ON | OFF | OFF | OFF | 9 |
| Node 19 | ON | ON | ON | ON | ON | 15 |
| Node 20 | ON | ON | ON | OFF | ON | 13 |
| Node 21 | ON | OFF | OFF | OFF | OFF | 5 |

**Figure 9** Packet loss ratio



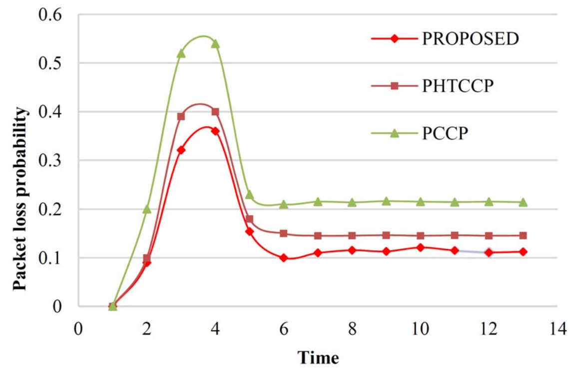

### 4.2.2 *Packet loss probability*

The packet loss probability is calculated as follows:

$$Ploss = Packet\_loss\_num / Packet\_loss\_num + Packet\_Recive \quad (21)$$

where *Packet_loss_num* and *Packet_Recive* are the numbers of packet loss and delivered packets, respectively. As there is no optimised rate adjustment in PCCP and PHTCCP, Figure 10 shows high packet loss at the beginning stages of these protocols. Our proposed protocol can keep packet loss ratio low in the beginning stages because of using fuzzy rate adjustment and smart calculation of packet loss probability.

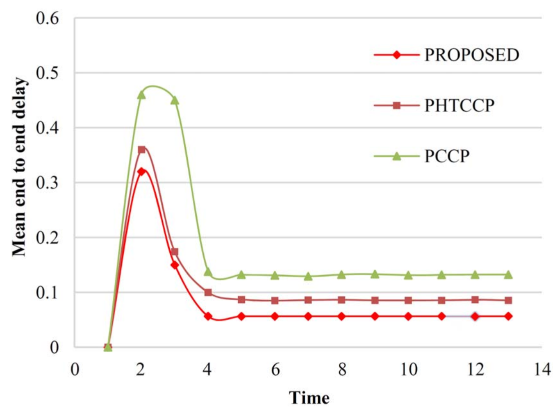
**Figure 10** Packet loss probability




### 4.2.3 *Means end-to-end delay*

An important factor in medical use for wireless sensor networks is end-to-end delay which is defined as the time between generation of data packets and reaching the destination. As illustrated in Figure 11, our protocol provides a better and more stable end-to-end delay than PCCP and PHTCCP protocols. At first stage of simulation, the delay of our protocol increases which the reasons include control packets and lack of rate adjustment. Passing a short time network node, handling fuzzy rate adjustment, the delay decreases. The proposed protocol is able to detect congestion more quickly than the other two protocols and then calculate the best sharing rates for intermediate nodes so the final end two end delay is more efficient. Low delay is essential for packets that carry patient's vital information.

**Figure 11** Mean end-to-end delay



### *4.2.4 Queue length*

Queue length is the number of packets in the queue and an essential measurement in calculating the delay. When inter-arrival time of a packet goes higher than the packet service time, the queue length increases, so a longer delay in the network occurs. Queue length is one of the parameters we use to assess delay status and waiting time of the intermediate nodes. The better the congestion control algorithm works, the shorter the length of queues in the nodes gets. Congestion algorithm also reduces packet delay in nodes, so packet loss ratio declines. Failure of congestion control algorithm causes queue length at intermediate nodes to increase and thereby packet delays become longer. In this case, the algorithm would not be good enough for delay-sensitive applications.

Proposed protocol allocates the amount of send rate for each node in a way so that output rate will be always higher than input rate using fuzzy rate adjustment unit. This leads to avoid delay and long queue length. Figure 12 shows the mean queue length in one of the nodes close to the sink. As can be seen from Figure 12, the proposed protocol has shorter queue length and as a result, end-to-end delay is reduced. These results illustrate that our proposed protocol is more appropriate for medical applications and it can meet the requirements of service quality of such systems. Figure 13 demonstrates the instantaneous queue length in a close node to the sink. All the nodes close to the sink contribute in passing the packets. In proposed protocol after about 37 seconds, the mean queue length is less than approximately 48 packets per second, because our protocol can better manage the length of the queue using a fuzzy AQM mechanism and rate adjustment unit. Meanwhile, the average changes over time in PHTCCP and packet may be lost. There is only one queue in LACAS and similarly PCCP which all packets enter this queue. But since the service ratio has not modified and the arrival rate is one of the selected five available ratios, the queue length is subjected to the early ratio sets and the source ratio. If service rate is higher than these rates, there is no congestion in the network and the length of the queue will remain short, otherwise queue length will increase.

**Figure 12** Mean queue length at node 21 close to the sink

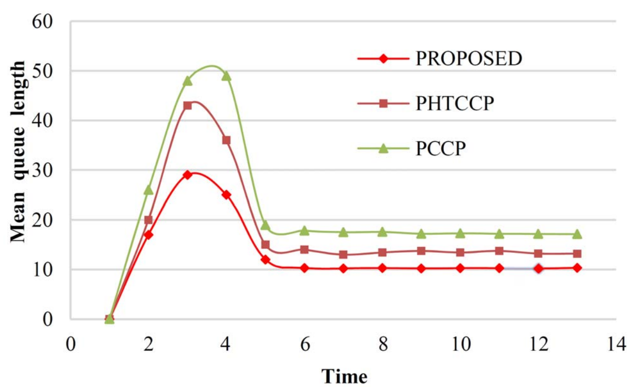
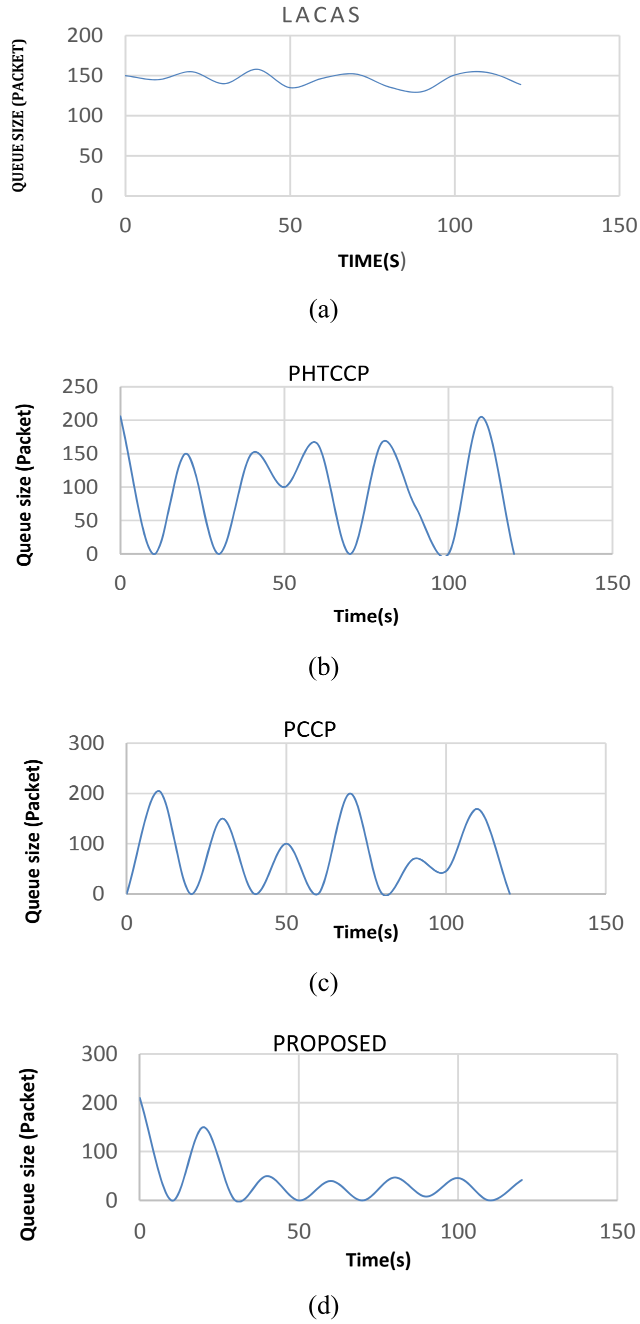


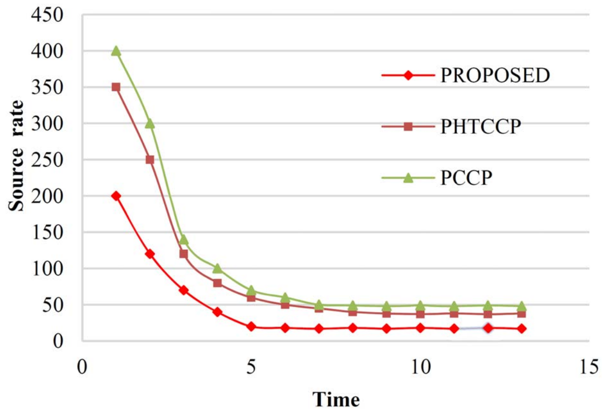

**Figure 13** Momentary queue length in node 21, close to the sink in different protocols: (a) LACAS, (b) PHTCCP, (c) PCCP, (d) proposed protocol




### *4.2.5 Sender's rate adjustment*

The generation rate of a transmitter in time is shown in Figure 14. Rate adjustment process in the proposed protocol is carried out from the node with congestion toward source nodes in a hop-by-hop manner and continued until network congestion is controlled and there is no notification sent to the sender to adjust the rate. Figure 14 shows that initially, the sender rate is high, but over time the transmitter has remained at a fixed rate without any congestion.

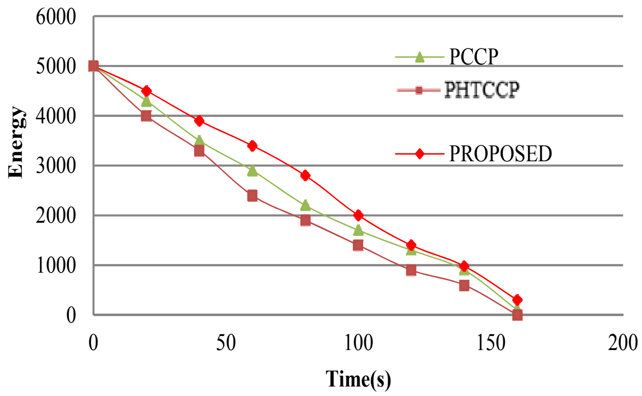
**Figure 14** Source rate vs. time




### 4.2.6 Mean energy

Figure 15 compares the energy consumption of the closest node to the sink in the proposed methods with PCCP and PHTCCP. As it is evidenced, the average energy consumption of the proposed approach for transferring different traffic loads is less than PCCP and PHTCCP and this can lead to increase of network longevity using a fuzzy rate adjustment.

**Figure 15** Average energy consumption in closest node to sink




## 5 Conclusions and future work

In this paper, a new priority-based congestion control protocol is proposed for wireless body area networks. The best scenario for this proposed protocol is that the way which sensor nodes show the patients who are in stationary manner or bedridden in a special ward of a hospital or private clinic, and suffer from heart attack or brain death. The packet loss probability is calculated by an AQM method. Moreover, the output send rate of each node is estimated by a FLC and then a suitable send rate is assigned to each node. Simulation results suggest that, for considering parameters such as packet loss ratio and end-to-end delays, the proposed protocol could perform better than PCCP and PHTCCP protocols. For future research, this protocol can be studied to monitor mobile patients.

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# International Journal of Wireless and Mobile Computing

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**Scope** The explosive growth of wide-area cellular systems and local area wireless networks which promise to make integrated networks a reality, and the development of "wearable" computers and the emergence of "pervasive" computing paradigm, are just the beginning of "The Wireless and Mobile Revolution". The realisation of wireless connectivity is bringing fundamental changes to telecommunications and computing and profoundly affects the way we compute, communicate, and interact. It provides fully distributed and ubiquitous mobile computing and communications, thus bringing an end to the tyranny of geography. (source)

## Quartiles

The set of journals have been ranked according to their SJR and divided into four equal groups, four quartiles. Q1 (green) comprises the quarter of the journals with the highest values, Q2 (yellow) the second highest values, Q3 (orange) the third highest values and Q4 (red) the lowest values.

| Category | Year | Quartile |
|---|---|---|
| Computer Science (miscellaneous) | 2006 | Q4 |
| Computer Science (miscellaneous) | 2007 | Q4 |
| Computer Science (miscellaneous) | 2008 | Q3 |

SJR

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