Rate Control Scheme for Congestion Control in Wireless Body Area Networks

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Abstract—**Congestion control is one of the most important factors when a Wireless Body Area Network (WBAN) is designed, due to its direct impact in the Quality of Service (QoS) and the energy efficiency of the network. The congestion in a WBAN can produce packet loss and high energy consumption. The IEEE 802.15.6 Standard supports QoS, but it does not suggest any explicit congestion control scheme. This paper proposes a new rate control scheme for mitigating congestion in WBANs based on an energy-efficient and emergency-aware MAC (Medium Access Control) protocol and the IEEE 802.15.6 Standard. The scheme is context-aware and responses to emergency events in any node controlling the normal traffic rate. The proposed solution improves the performance of both the MAC protocol and the IEEE 802.15.6 Standard.**

Keywords—Wireless Body Area Network (WBAN); Congestion control; Energy efficiency; 802.15.6; Context-awareness.

I. INTRODUCTION

Wireless Body Area Networks (WBANs) are networks of small devices interconnected and placed in/on the human body to collect physical data, to perform preliminary processing and to send it to a hub. The hub (or sink or body aggregator) gathers the data from the nodes and can transmit it to a base station. WBANs originated from Wireless Sensor Networks (WSNs), so there are many similarities between them. However, the specific characteristics are different due to their different application purposes [1].

The applications of WBANs have been categorized into medical and non-medical. The medical applications of WBANs can also be classified into three subcategories: wearable WBANs, implants WBANs and remote control of medical devices. Some wearable WBANs applications are: the evaluation of soldier fatigue and battle readiness, sleep staging, asthma and wearable health monitoring. The implant WBANs can be used in diabetes control, cardiovascular diseases and cancer detection. Remote control of medical devices is used for patient monitoring and telemedicine systems. The non-medical applications of WBANs can also be classified into five subcategories: real time streaming, entertainment applications, emergency (non-medical with off-body sensors) applications, emotion detection and secure authentication [2].

The sensor nodes in a WBAN can have different sampling frequency. There are several high-sampling frequency devices in the market like accelerometers, electrocardiograms, electroencephalographs and electromyographs. Other devices provide low sampling frequency like blood pressure sensors, temperature sensors and carbon dioxide sensors [1]. The fairness in a WBAN should ensure all nodes get equal access to the network bandwidth, regardless their sampling frequency.

Congestion and packet loss in a WBAN have a direct impact in the Quality of Service (QoS) and the energy efficiency of the network. When a WBAN presents congestion, both the packet loss and latency increase, and it needs more energy in order to make packet retransmissions. Congestion control schemes are needed to react when congestion is detected or to avoid congestion before the WBAN is overcrowded.

The traditional transport layer solutions such as Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) are too complex for WBAN applications resulting in latency and excessive energy wastage. The transport layer in a WBAN needs to provide end-to-end reliability, QoS in an energy-efficient way and be evaluated using metrics such as Packet Loss Ratio (PLR), latency, and fairness. Therefore, the transport layer should have components for congestion control and loss recovery [3].

The IEEE 802.15.6 Standard is addressed to short-range, wireless communications in the vicinity of, or inside, a human body [4]. It supports QoS, for example, to provide for emergency messaging, but it does not suggest any explicit congestion control scheme for WBANs. Although WBANs are a subset of WSNs and they share some characteristics, some authors have suggested that the congestion control solutions for WSNs cannot be directly used in WBANs [5, 6].

This paper proposes a new context-aware rate control scheme for WBANs based on an energy-efficient and emergency-aware MAC protocol [7] and the IEEE 802.15.6 Standard [4]. The proposed rate control scheme uses a RIB (Rate-control Indicator Bit) into each beacon in the MAC protocol for indicating the sending of future rate control requests from the hub to each node with normal traffic. These requests are sent during a Slot Reallocation Phase (SRP).

The rest of this paper is organized as follows: Section II provides some related work in congestion control for WSNs and WBANs. Section III summarizes the proposed rate control scheme with the calculation of its Rate Control Factor. Section IV presents the simulation results comparing the performance of the MAC protocol proposed by authors in [7] and the IEEE

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802.15.6 standard with and without the use of the proposed rate control scheme. Section V finalizes providing conclusions.

II. CONGESTION CONTROL FOR WSNS AND WBANS

Some authors have categorized the congestion in WSNs as contention-based and buffer-based. The contention-based congestion occurs when many nodes within range of one another attempt to transmit at the same time and provoke packet collisions. The buffer-based congestion happens when the buffer in the hub (or sink) or any node in the network overflows and causes congestion and lost of packets [8, 9].

Traditionally, the congestion control schemes follow three steps starting by (i) its detection, then (ii) the corresponding notification and finally (iii) the appropriate mitigation. There are several congestion detection strategies: packet loss, buffer length, channel load, packet service time, channel busyness ratio and delay. The congestion notification can be implicit (into the data packet header) or explicit (into specific control messages). The congestion mitigation can be applied to the traffic originated in each node (decreasing the node rate) or to the network resources (exploiting idle resources). Congestion control schemes can also be categorized in three classes: congestion mitigation, congestion avoidance and reliable data transport [8, 9].

Priority-based Congestion Control Protocol (PCCP) is a congestion control approach for WSNs that uses a flexible and distributed rate adjustment in each sensor node. The strength of the protocol is that it takes into account that sensor nodes may have different priorities and would need different throughput. A sensor node with a higher priority index and those sensor nodes that inject more traffic get more bandwidth than other sensors in the network [8, 9].

Improved Rate-Controlled Reliable Transport (IRCRT) is a WSN protocol based on RCRT (Rate-Controlled Reliable Transport). The strength of the RCRT protocol is that it focuses on reliability for the delivery of packets from the sources to the hub, avoiding congestion. In IRCRT, the sensor nodes can go in OFF state, and when a node is OFF, the hub does not allocate any rate to it, so other nodes can use more bandwidth. When any part of the network becomes congested, IRCRT only decreases the rate of the sensor nodes that are in the congested part [10].

Enhanced Congestion Detection and Avoidance (ECODA) is a WSN protocol where the packets are dynamically prioritized, using three parameters: (i) their initial static packet priority, (ii) the delay and (iii) the hop-count. When receiving a back-pressure message, the source node can decrease its rate or adjust it [8].

Adaptive Rate Control (ARC) is a WSN protocol that introduces a random delay (back off) at the application layer before transmitting packets for congestion avoidance. The strength of ARC is that it uses the packet loss at each hop in order to detect collisions or congestion. Then, it adjusts the transmission rate of periodic applications. ARC guarantees the network fairness keeping two independent sets of source traffic and transit traffic [8, 9].

Energy Efficient Congestion Control (EECC) is a source rate congestion control protocol for WSNs. Each node adds its current weight (defined as the product of the channel busyness ratio and the buffer occupancy) to the packet received from its children, and passes the packet to its parent node. The sum of such weights is then used. The strength of EECC is that when the buffer size and the channel busyness ratio reach a predefined threshold, the node sets the congestion notification bit for each data packet. By receiving this notification, the parent node calculates the new rate and informs its children nodes [8].

Congestion Control and Fairness (CCF) is a many-to-one routing protocol for WSNs that modifies its rate using the packet service time (period between sending the packet from the transport layer to the network layer and the reception of the successful transmission notification). The strength of CCF is that it controls congestion in a hop-by-hop strategy. Each node uses exact rate adjustment based on its available service rate and the number of child nodes [8, 9].

XLM is a cross-layer protocol for WSNs that merges the communication layers into one protocol in order to: (i) minimize energy consumption, (ii) adapt communication decisions, and (iii) avoid congestion. A node initiates a transmission broadcasting a RTS (Request to Send). By the reception of the RTS, each neighbor node that is closer to the hub decides whether to participate or not, according to (i) the Signal to Noise Ratio (SNR), (ii) the remaining energy and (iii) its available buffer. The strength of XLM is that if no RTS are received because of network congestion, the node multiplicatively decreases its rate. Otherwise, the rate is increased for each acknowledgement received by the node [8].

Priority-based Coverage-aware Congestion (PCC) control protocol is a hop-by-hop mechanism at the network and MAC layers of a WSN. Nodes generate periodic packets at a constant rate until an event happens, where nodes generate event packets with higher rates and priorities. The strength of PCC is that the intermediate nodes forward the packets with a different priority using this indication [8].

Several congestion control algorithms for WSNs have been designed across the transport and MAC layers and even the network layer for congestion detection and control. The cross-layer design, with the interaction between different layers, helps to enhance sensor networks protocols [8]. Upstream Hop-by-Hop Congestion (UHCC) is a control protocol based on a cross-layer design for WSNs that tries to reduce the packet loss while guaranteeing priority-based fairness with lower control overhead. The strength of UHCC is that based on the congestion index, each upstream traffic rate is adjusted with its node priority in order to mitigate congestion hop-by-hop [9].

Although WBANs are a subset of WSNs, there are important differences between them. Reliability and energy efficiency are essential in both networks. The primary concern of conventional WSNs is energy saving, while QoS is essential in WBANs. Some authors have suggested that MAC and transport protocols for WSNs should not be directly used in WBANs [5, 6].

The Group-Based Reliable Data Transport (GRDT) protocol for WBANs adopts TDMA (Time Division Multiple Access) and FDMA (Frequency Division Multiple Access) schemes to control channel access. The strength of GRDT Is that it can avoid congestion and eliminate the congestion control overhead at the same time. GRDT uses a block feedback message scheme instead of synchronous acknowledgement for hop-by-hop loss recovery [11].

A transport protocol for WBANs based on queue occupancy and packet loss for controlling congestion has been proposed by authors in [12]. The proposed scheme consists of two main phases: (i) a quick Start for beginning with more number of packets, and (ii) a congestion control module composed of three sub-phases: congestion detection, congestion notification and congestion avoidance.

Another congestion control scheme based on fuzzy logic for WBANs has been proposed by authors in [13]. The proposed system is able to detect congestion considering local information such as the buffer capacity and the node rate. The advantage of this protocol is that in case of congestion, it differentiates vital signals and assigns priorities to them based on their importance.

III. Proposed Rate Control Scheme

The MAC protocol proposed by authors in [7] is an energy-efficient, emergency-aware and cross-layer design which changes transmission schedules in order to provide QoS during emergency events. This MAC protocol uses the same Management Access Phase (MAP) as IEEE 802.15.6 Standard and proposes two new phases for each beacon period: Slot Reallocation Phase (SRP) and Special Contention Access Phase (SCAP). Figure 1 depicts the three phases into each beacon period proposed by this MAC protocol.

Fig. 1. Layout of access phases in a beacon period

B	SRP	MAP	SCAP
	TDMA	TDMA	CSMA/CA

SRP allows the hub to send slot reallocations for each node and SCAP allows nodes to send connection requests when they are unconnected and to transmit packets with emergency alerts when they were not able to do it while their own assigned slots in MAP. There is no contention during SRP and MAP because of the use of the TDMA protocol. Only SCAP offers contention for emergency and management traffic with the use of the CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) protocol.

For transmission during SRP, the hub must send the RIB (Reallocation Indicator Bit) with the value of 1 into the beacon for the next beacon period, indicating a slot reallocation for all nodes. Nodes transmit normal traffic during MAP and give the highest priority to emergency traffic each time they arrive, sending each emergency packet before the remaining normal traffic.

The proposed rate control scheme is context-aware and it uses a RIB (Rate-control Indicator Bit) in each beacon for providing congestion avoidance during emergency events. When an emergency event occurs in the WBAN, the hub has to calculate the Rate Control Factor (RCF) and communicate it to all nodes in the network in order to keep the same average rate of traffic during all the emergency event. The hub uses the SRP phase with the TDMA protocol to send the RCF to all nodes. In this way, it avoids contention. The Algorithm 1 depicts the congestion control scheme used by the hub.

When an emergency event happens into any node, the node sends an alert into the application packet to indicate in advance the increase in the packet rate for the emergency node. The packet rate is increased with an Emergency Multiplication Factor (10 for the simulations).

ALGORITHM 1. Congestion control in the hub

```
If packet.alert = BUFFER_ALERT then
  EmergencyNodes.push(currentNode);
  Calculate RCF for all nodes using
  expression (3)
  For each node n do
    If n is not in EmergencyNodes then
      Create a Rate Control Request for
      the node n using RCF
    End If
  End For each
  Set RIB ← 1
End If
Send Rate Control Requests in next SRP
```

When a packet arrives with an alert of future buffer overflow (BUFFER_ALERT) due to an emergency event that happens in any node, the hub calculate the Rate Control Factor (RCF). This factor is a float number between 0 and 1 in order to decrease the rate of nodes with normal traffic. It is used for keeping almost the same average rate in the network, decreasing the rate of normal traffic in all nodes and allowing the nodes with emergency events to use more bandwidth in the WBAN.

This rate control scheme decreases the probability of contention of emergency traffic because the emergency traffic increase in any node is counteracted with the reduction of normal traffic in the remaining nodes. It also decreases the probability of packet loss due to buffer overflow of normal traffic.

After the emergency event, the hub send another RIB into the beacon, in order to reassign the original rate to each node in the WBAN. The expressions (1) and (2) depict the average packet rate for the whole WBAN with no emergency traffic ($\bar{r}$) and with emergency traffic ($\overline{r_e}$), respectively.

$$\bar{r} = \frac{\sum_{i=1}^{n} r_i}{n} \tag{1}$$

$$\overline{r_e} = \frac{\sum_{j\in n_e}(r_j \times m_j) + \sum_{i=1}^{n} r_i - \sum_{j\in n_e} r_j}{n} \tag{2}$$

where r is the packet rate for each node, n is the total number of nodes in the WBAN, n_e is the set of the current emergency nodes (the nodes sending emergency traffic and they could be more than one), and m is the Emergency Multiplication Factor (EMF) for each emergency node.

Using the expressions (1) and (2), the Rate Control Factor (RCF) for emergency events can be calculated as shown in the expression (3). This RCF must always be $0 < RCF < 1$ in order to actually decrease the rate in the nodes with normal traffic.

$$RCF = \frac{\sum_{i=1}^{n} r_i - \sum_{j \in n_e} (r_j \times m_j)}{\sum_{i=1}^{n} r_i - \sum_{j \in n_e} r_j} \tag{3}$$

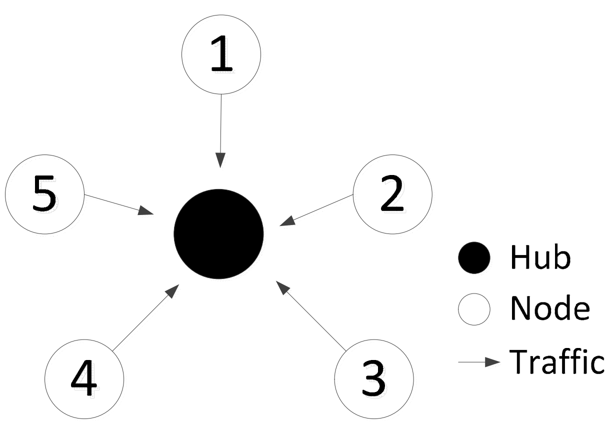
IV. Experimental Results

OMNeT++, an extensible, modular, component-based C++ simulation framework, primarily to build network simulators, was used for the simulations [14]. The Castalia simulator based on the OMNeT++ platform for WSNs and WBANs offers a model implementation of the IEEE 802.15.6 Standard, called BaselineBAN [15]. This model implementation and the implementation of the MAC protocol proposed by authors in [7] were used for the comparisons with the proposed Rate Control Scheme.

A. Simulations Parameters

Six nodes compose the simulated network: five sensor nodes and one hub. The sensor in the center is the hub and it is assumed to never go into sleeping mode. It rather goes into idle mode. The Fig. 2 shows the star topology for the simulated network with the traffic direction from the nodes to the hub.

Fig. 2. Star topology of the simulated network



The simulation time was always 300s and the normal packet rate was 20pkt/sec. When an emergency event happened in any node, the Emergency Multiplication Factor (EMF) increased the rate in ten times, producing an emergency packet rate of 200pkt/sec in each emergency node. The simulation parameters for the application layer, the MAC layer and the physical layer are shown in the Table I.

TABLE I. SIMULATION PARAMETERS

Layer	Parameter	Value
Application	Packet rate (pkt/sec)	20
	Default Priority for nodes	2
	Constant Data Payload (in bytes)	80
	Emergency Multiplication Factor	10
MAC	Maximum Transmission Tries	2
	Normal Buffer size (packets)	32
	Emergency Buffer size (packets)	32
	Allocation Slot Length (ms)	10
	Beacon Period Length (slots)	32

Layer	Parameter	Value
Application	Packet rate (pkt/sec)	20
	Default Priority for nodes	2
	Constant Data Payload (in bytes)	80
	Emergency Multiplication Factor	10
	SRP Length (slots)	3
	MAP Length (slots)	26
	SCP Length (slots)	3
	Scheduled Access Length (slots)	2
	Scheduled Access Period	1
	Contention Slot Length (ms)	0.36
Physical	Topology	Star
	Sensors	5
	Hubs	1
	TX Output Power (dBm)	-10
	Baseline Node Power (mW)	10

B. Simulation Results

The first variable used for the comparison of the proposed solution within the IEEE 802.15.6 Standard and the MAC protocol was the percentage of emergency packet loss. The second variable used for the comparison was the Energy Waste Index. This variable was calculated as the ratio between the percentage of packet loss and the average consumed energy in the whole WBAN. The lower its value the better the effectiveness of the solution.

The comparison of simulations were made between the IEEE 802.15.6 standard with no Rate Control Scheme (RCS), the same IEEE 802.15.6 standard using a part of the proposed RCS, the MAC protocol proposed by authors in [7] with no RCS, and finally, the same MAC protocol using the proposed RCS.

The emergency packet loss and the energy waste index, when the number of emergency events were changed from one to five during simulations, are depicted in Fig. 3 and Fig. 4. The RCS improves the performance of both IEEE 802.15.6 standard and the MAC protocol. Although the difference between the MAC protocol with and without RCS is small in Fig. 3, the Energy Waste Index in the Fig. 4 shows the improvement. The proposed Rate Control Scheme allows the node with emergency events to use more bandwidth, decreasing the rate of the remaining nodes with normal traffic and improving the energy efficiency of the WBAN.

Fig. 3. Percentage of Emergency packet loss vs Number of Emergency events

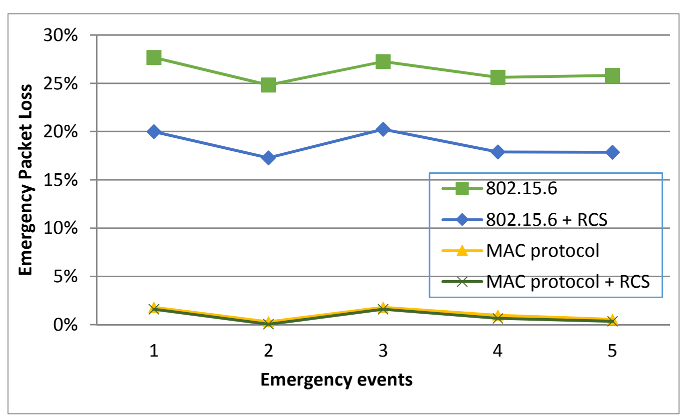
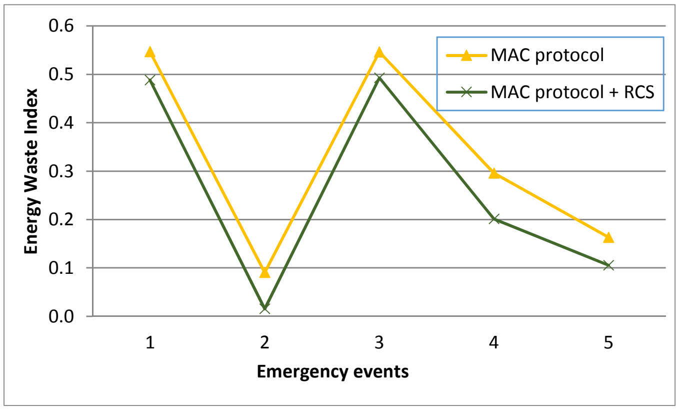
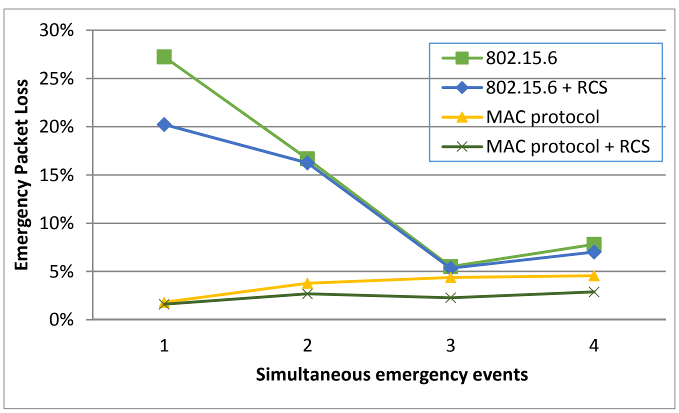


Fig. 4. Energy Waste Index vs Number of Emergency events



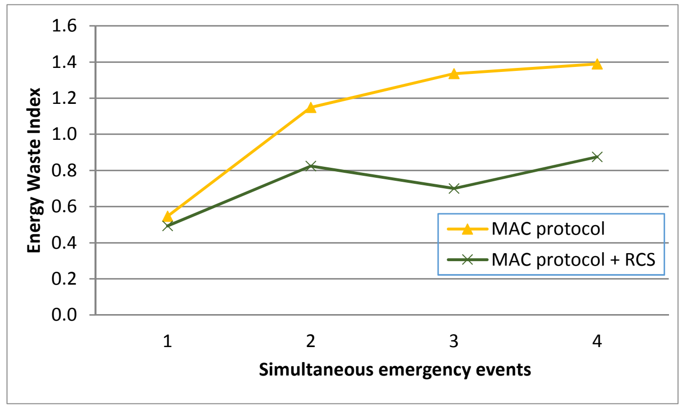
The emergency packet loss and the energy waste index, when a given number of simultaneous emergency events (from one to four) happens during simulations, are depicted in Fig. 5 and Fig. 6. The emergency nodes had simultaneous emergency events three times during the simulations. It can be seen that the RCS improves again the performance of both IEEE 802.15.6 standard and the MAC protocol. The proposed RCS decreases the rate of the remaining nodes with normal traffic in order to provide emergency-awareness to the whole WBAN.

Fig. 5. Percentage of Emergency packet loss vs Number of Simultaneous emergency events



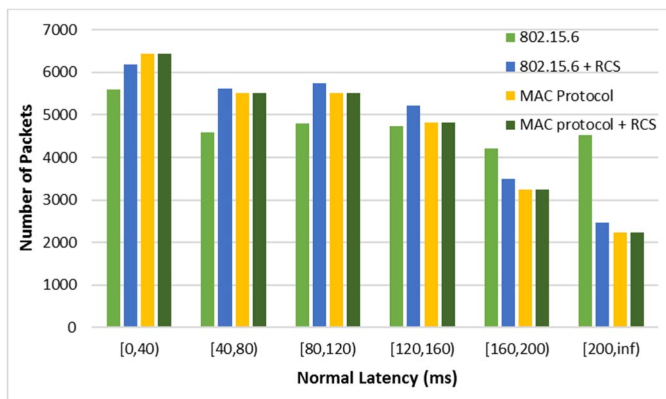
The proposed rate control scheme improved the energy effectiveness of the MAC protocol. This could be accomplished with both the reduction in the emergency packet loss due to the packet collision and the reduction in the normal packet loss due to buffer overflow. The energy effectiveness was better as the number of simultaneous emergency events increased. With the increase of emergency nodes sending emergency traffic at the same time, the Rate Control Scheme allowed to keep the same average packet rate than the WBAN with no emergency traffic. The energy effectiveness of the proposed solution (MAC protocol + RCS) is due to the best percentage of emergency packet loss and the use of free-contention transmission of the request lost packets, in order to keep a good energy consumption.

Fig. 6. Energy Waste Index vs Number of Simultaneous emergency events



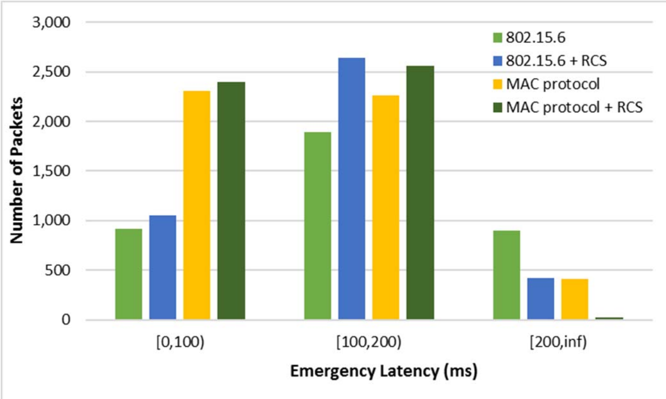
The Fig. 7 depicts the distribution of the latency for normal traffic. The total number of normal packets with low latency ([0, 160) ms) shown by the MAC protocol along with the proposed rate control scheme (RCS) was very good compared with the other solutions. We need to consider a trade-off between the good normal traffic latency depicted in the Fig. 7, and the excellent emergency traffic latency depicted in the Fig. 8. Besides, the total number of normal transmitted packets is fewer in the proposed solution (MAC protocol + RCS) than the other three solutions because the hub has previously requested the decrease in the normal packet rate.

Fig. 7. Normal Latency



The Fig. 8 depicts the distribution of the latency for emergency traffic. The total number of emergency packets with low latency ([0, 200) ms) shown by the MAC protocol along with the proposed rate control scheme (RCS) was higher than the other solutions. This is due to the priority of emergency packets in the MAC protocol and the decrease of normal traffic with the proposed rate control scheme. The MAC protocol gives more priority to emergency traffic during the MAP phase offering a free-contention transmission. Besides, the RCS improves the MAC protocol behavior because it decreases the normal traffic, allowing more emergency traffic to be sent during MAP.

Fig. 8. Emergency Latency



V. Conclusions

A new context-aware rate control scheme for congestion control in Wireless Body Area Networks (WBANs) was proposed in this paper, based on an emergency-aware and energy-efficient MAC protocol proposed by authors in [7] and the IEEE 802.15.6 standard. The hub calculates the Rate Control Factor (RCF) each time an emergency event happens in any node of the network. Then, it sends the calculated RCF to all normal nodes in order to decrease the rate of the normal traffic and to keep almost the same average rate in the whole WBAN. The RCF is sent during the SRP phase to all normal nodes. In this way, the hub avoids contention and packet collision.

For evaluating the performance of the proposed rate control scheme, three variables were used: the percentage of emergency packet loss, the Energy Waste Index (calculated as the ratio between the percentage of the emergency packet loss and the average consumed energy in the whole WBAN), and the latency for emergency and normal traffic. The proposed rate control scheme improved the performance of both the MAC protocol proposed by authors in [7] and the IEEE 802.15.6 standard, proving the energy efficiency and the context awareness of the solution.

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