Fuzzy-Logic Based Medium Access Control Model for Battery Lifetime Enhancement in Wireless Body Area Networks

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ABSTRACT

Wireless body sensor networks in healthcare system operate under mismatched conditions. Our aim is to improve the battery lifetime of body sensors while guaranteeing the reliable, timely message delivery and reduced packet delay, which is significantly important for the patient monitoring networks. In this paper, Distributed Queuing Body Area Networks (DQBAN) protocol is introduced as an alternative enhancement to 802.15.4 medium access control (MAC). It includes cross-layer fuzzy-rule scheduling algorithm and energy-aware radio activation policies. The main idea is to amalgamate the fuzzy-logic system in each body sensors to deal with multiple cross-layer input variables of dissimilar nature and independent manner. It guarantees low energy consumption and suitable under coexisting scenarios. DQBAN MAC model has shown to achieve higher reliability than other possible MAC implementation.

Key words: Body sensor network, energy consumption, fuzzy-logic, health care system, medical applications, medium access control, quality of service, scheduling

1. INTRODUCTION

The aging population in many developed countries and the rising costs of health care have triggered the introduction of novel technology driven enhancements to current health care practices. For example, recent advances in electronics have enabled the development of small and intelligent biomedical sensors which can be worn on or implanted in the human body. These sensors need to send their data to an external medical server where it can be analyzed and stored. Using a wired connection for this purpose turns out to be too burdensome and involves a high cost for deployment and maintenance.

The use of a wireless interface enables an easier application and is more cost efficient. These devices provide continuous health monitoring and real-time feedback to the user or medical personnel. The sensors are used to measure certain parameters of the human body, either externally or internally. Examples include measuring the heartbeat, body temperature or recording a prolonged electrocardiogram (ECG). The patient experiences a greater physical mobility and is no longer compelled to stay in a hospital. The devices are located on the human body that can be in motion. Wireless body area networks should therefore be robust against frequent changes in the network topology. The data mostly consists of medical information. Hence, high reliability and low delay is required. Regular patient monitoring using ECG is required, along with other investigations, to aid diagnosis so that prompt treatment can be initiated to prevent long-term related complications. Apart from ECG, patient monitoring is normally in the form of further vital sign measurements (blood pressure, heart rate, respiratory rate, temperature). In hospitals, where a large number of patients are treated every year, body sensor networks (BSNs) offer a special benefit.

The challenges faced by BSNs in healthcare environments are in a certain way similar to those already existing in wireless sensor networks (WSN) applications. Section II provides a brief description of these special requirements that characterize BSNs, while analyzing the standard factor for WSNs, the low-rate IEEE 802.15.4 medium access control (MAC)/physical layer (PHY) standard (802.15.4). Section III introduces a new MAC protocol model with an energy-aware radio activation policy that pursues the idea to satisfy these specific medical requirements under BSNs in realistic hospital care scenarios. For that purpose, in Section IV, a novel cross-layer fuzzy-logic scheduling algorithm is introduced and thus optimize MAC layer overall performance in terms of quality of service (QoS) and energy consumption by applying fuzzy-logic decision techniques. Section VII shows the simulation results used to evaluate the whole system performance under specific hospital settings. The last section concludes the paper.

2. PROBLEM STATEMENT

The MAC layer is liable for synchronizing channel admission, with the aim of maximizing throughput efficiency, by avoiding collisions and scheduling data transmissions, at an acceptable packet delay and minimal energy consumption. The 802.15.4 MAC is proposed to serve a set of applications with very low energy consumption, with contented demands for data rate and QoS. However, taking our prior examination into account, wearable and entrenched wireless sensors for clinical settings do have stringent QoS requirements. Besides, IEEE 802.15.4 MAC saturated throughput efficiency and energy consumption performance significantly declines as the number of sensors in the network increases. It was noted that the scalability of 802.15.4 is not a given feature. In [1] the improvement of the packet transmission delay distribution and the channel usage efficiency of wireless ad hoc networks when using the DQMAN (distributed queuing MAC protocol for mobile ad hoc networks) at the MAC layer are achieved. Computer simulations show that this proposal increases the channel usage efficiency up to one order of magnitude, and reduce the mean transmission delay standard deviation by a factor of three. In [2] the MAC model has been evaluated in a star-based BSN under two different realistic hospital scenarios with diverse medical body sensor characterizations. A stand-alone BSN, as well as co-existence scenarios where the body sensors operate in the presence of voice, video and Information Technology traffic is simulated [3]. The results indicate that although 802.15.4 and 802.11e can provide an acceptable compromise between power consumption and QoS in some scenarios, there are situations (e.g., co-existence with video and heavy data traffic) in which both performance criteria cannot be met simultaneously. It was pointed out that [4] the 802.15.4 MAC is energy efficient in controlled environments, (i.e., without interference), but it fails in supporting QoS in co-existing scenarios, which is a severe issue for medical applications. The performance of 802.15.4 devices under interference conditions caused by other 802.15.4 devices and by wireless local area networks using IEEE 802.11b is evaluated [5]. In [6] a model of distributed queuing random access protocol (DQRAP)-based voice packet system is presented along with results of simulation studies.

IEEE 802.15.4 MAC does not fully satisfy BSN requirements highlight the need for the design of new scalable MAC solutions. These guarantee low energy consumption to all different kinds of body sensors while ensuring rigorous QoS under co-existent scenarios in healthcare systems.

3. SYSTEM CHARACTERIZATION

The use of the DQRAP for local wireless communications was already proposed in 1993 [7]. The authors demonstrated the performance of the DQRAP in a multiple access voice packets environment. DQRAP divides the time division multiple access slot into an access sub-slot that is further divided into access mini-slots, and a data sub-slot. The access requests are carried out in the access mini-slots, while the data-sub-slot is committed to collision-free data transmission. As explained [8], every station in the system joins one of the two common logical distributed queues; the collision resolution queue (CRQ) or the data transmission queue (DTQ). The CRQ controls station accesses requests into the access mini-slots, while the DTQ is employed in scheduling the packets into the data sub-slot following a first-come first-served discipline. Another exciting feature of DQRAP is its capacity to behave like an ALOHA (means say Hello) type protocol, (i.e., it does not check whether the channel is busy before transmitting). In order to overcome the difficulties, this article suggests the Distributed Queuing Body Area Network (DQBAN) protocol as an alternative development to 802.15.4 MAC in medical settings. DQBAN corresponds to a new MAC model. It includes novel cross-layer fuzzy-logic scheduling mechanism and energy-aware radio activation policies to satisfy energy-efficient and stringent QoS demands in healthcare scenarios. DQBAN satisfies the QoS requirements in terms of reliability, message latency and energy consumption, while being flexible to changing conditions, such as heterogeneous traffic load, interferences, and the number of sensors in a hospital BSN. It behave like slotted ALOHA type protocol, (i.e., the station can send only at the beginning of the time slot) hence collision is reduced and follows cross-layer fuzzy-logic scheduling algorithm as explained in the later section.

4. CROSS-LAYER FUZZY-LOGIC SCHEDULER

The new cross-layer fuzzy-rule based scheduling algorithm tracks the idea of playing a determining role between the different PHY states and the particular body sensors applications. Its main goal is to optimize MAC layer performance in terms of QoS and energy consumption by applying fuzzy-logic rules into the DQBAN system modelling. However, instead of keeping a first-come first-served discipline in DTQ, a cross-layer fuzzy-rule based scheduler is introduced in the DQBAN logic system model as depicted in Figure 1.

The use of the scheduler permits a body sensor, though not occupying the first position in DTQ, to transmit its data in the next collision-free "data slot" in order to achieve far more reliable system performance. This is achieved by assimilating a fuzzy-logic system (FLS) in each body sensor in the BSN. Fuzzy-logic approach allows each particular body sensor to individually deal with multiple cross-layer inputs of diverse nature [i.e., X1, X2, to *xk* in Figure 1] and react accordingly to demand or refuse the next frame data slot.

5. FUZZY-LOGIC SYSTEM

Body sensors consider relevant cross-layer system constraints, such as PHY signal quality, packet system waiting time (WT), and residual battery lifetime, to demand or refuse the next frame collision-free data slot via the scheduling mini-slots, as explained in the previous section. To achieve this, a fuzzy-logic system is integrated with each body sensor in the body area network (BAN). The significance of a fuzzy-logic system is its simplicity of implementation and scalability when dealing with nonlinear systems with multiple inputs of diverse nature [9]. That is, it is cost efficient in introducing a new input variable in a fuzzy-logic system than re-designing

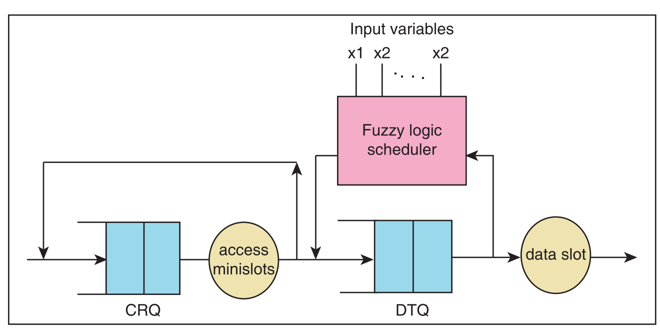

Figure 1: Distributed Queuing Body Area Networks logic system design

a predetermined cost function as [10]. In general, an FLS is a nonlinear mapping of input data vector into a scalar output.

Figure 2 illustrates an FLS that is widely used in fuzzy-logic controllers. It contains four components: Fuzzifier, fuzzy rules, the inference engine, and defuzzifier. The fuzzifier turns the input real values (also called crisp values) into linguistic variables. The fuzzy rules are the linguistic rules, which make up the fuzzy-logic controller decision behavior. The fuzzy inference process matches the linguistic input variables with the linguistic rules. The result of the fuzzy inference process is that, the linguistic values are assigned to a set of linguistic output variables. Here, the use of the defuzzifier is not required, since body sensors make use of a unique output linguistic variable (Decision), whose linguistic values remain invariable independently of the number of input real variables [11].

5.1 Fuzzifier

The QoS fuzzy-logic scheduler mechanism is a nonlinear system and can be interpreted as a fuzzy-logic controller implemented in every body sensor. The FLS is fulfilled with three sensor-dependant time-variant input variables from diverse nature:

i. Signal-to-noise ratio (SNR [i, t]): Derived at the reception of a feedback frame
ii. WT in the system — WT (i, t): Calculated from an inherent clock, and
iii. Residual battery life (BL [i, t]): Derived from an inner hardware memory.

However, in order to assist the execution design at the entrance of the fuzzy-logic scheduling system, we use normalized values with respect to each body sensor specific constraints: SNR_{min} (i) derived from the bit-error-rate (BER [i]); WT_{max} (i) and BL_{min} (i), which consider application-related latency and minimal battery lifetime requirements. Thus, at the entrance of the fuzzifier there will be the following normalized input crisp variables:

$$(SNR\ [i, t]) = SNR\ (i, t) - SNR_{min}\ (i) \quad (1)$$

$$(WT\ [i, t]) = WT\ (i, t) - WT_{max}\ (i) \quad (2)$$

$$(BL\ [i, t]) = BL\ (i, t) - BL_{min}\ (i) \quad (3)$$

These input normalized crisp variables in the fuzzifier are associated to the fuzzy sets with the following linguistic terms.

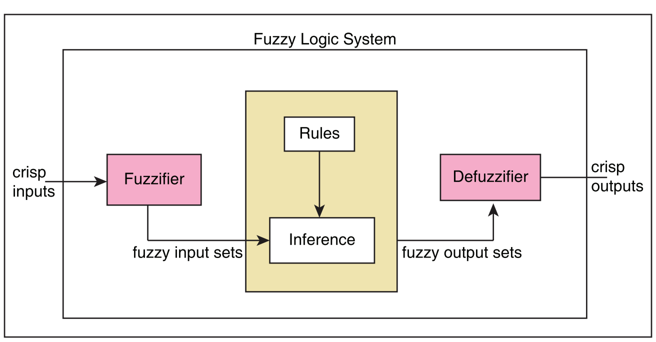

Figure 2: Fuzzy-logic system

SNR *C* (dangerous, poor, superior)

WT *C* (acceptable, boundary, excessive)

BL *C* (critical, balanced, substantial).

Figure 3 describes an illustrative example of the membership functions used in our fuzzy-logic system for all the same sort of antecedents and consequents. The representation of linguistic2 is an isosceles triangle and the corresponding (X1, X2, X3) figures were implementation dependant for each input fuzzy variable and adjusted as a function of the known values SNR_{min} i, WT_{max} i and BL_{min} i. We choose the triangular membership function for its simple expression (i.e., low implementation cost and processing power) as explained [9].

5.2 Fuzzy-logic rules and fuzzy inference process

Since the linguistic input variables SNR, WT, and BL have each three different states, the total number of possibly ordered triplets of these states is 27 (3 × 3 × 3). For each of these ordered triplets of states, we have to determine the appropriate state of the output linguistic variable Decision, that is linked to the fuzzy set (delay, onschedule, forward), which form the consequents of our fuzzy rules as shown in Table 1.

Decision C (delay, onschedule, forward)

A body sensor can delay its transmission to the future DQBAN super frame by sending Decision delay, to keep body sensor in its current position in DTQ by sending onschedule, or

Table 1: Consequents of fuzzy rules

Rule	Condition			Decision
	SNR	WT	BL	
Rule 1	Dangerous	Not excessive	Not critical	Delay
Rule 2		Acceptable	Critical	Delay
Rule 3	Not superior	Acceptable		Delay
Rule 4	Superior	Acceptable	Not critical	Onschedule
Rule 5	Not dangerous	Boundary	Not critical	Onschedule
Rule 6		Excessive		Forward
Rule 7		Not acceptable	Critical	Forward

SNR: Signal-to-noise ratio; WT: Waiting time; BL: Battery life

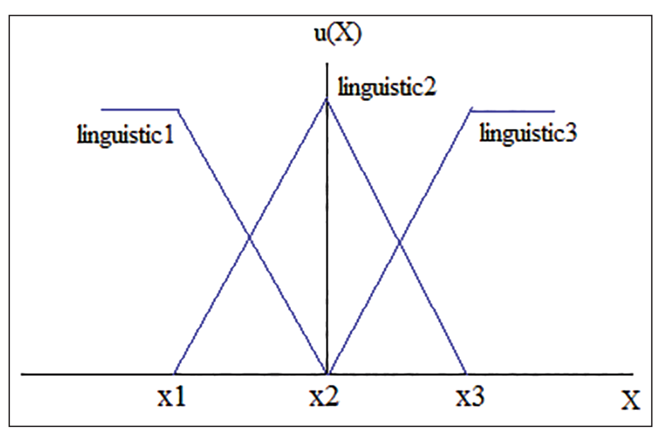

Figure 3: Membership function example for antecedents and consequents

to demand the next frame data slot by indicating forward. A suitable way of defining all required fuzzy-logic rules, to determine the output linguistic values of Decision, is with a decision table as the one shown in Table 1. Next we provide seven high level fuzzy rules for the output linguistic variable (Decision) with their antecedents and consequent, as a result, of the combination of the states in Table 2.

The first three rules indicate when data transmission requires to be delayed. Rule 1 is used to detect a bad link channel before transmitting. If there is still enough time and battery lifetime left, the aim is to defer data transmissions; otherwise it may not be possible to guarantee a particular (*BERi*) for the lowest power transmission state. Rule 2 claims to wait until batteries have been replaced, so that enough battery lifetime can be guaranteed during a packet transmission interval. In the same line, Rule 3 delays a transmission waiting for a better link channel.

The result of the fuzzy inference engine is that a set of linguistic values of the fuzzy variables SNR, WT, BL is assigned to a linguistic output value of the fuzzy variable DTQ as,

Rule: If SNR_1 is a_1^1 and WT_1 is a_2^1 and BL_1 is a_3^1 then DTQ is $c^l \times a^l$ and c^l are the fuzzy sets corresponding to the antecedent and consequent of the l^{st}-rule.

6. PERFORMANCE EVALUTION

The DQBAN protocol is working in a star-base topology where a BAN coordinator transmits feedback information about the current status of the queues at the end of each frame. This scenario matches most monitoring applications, since body sensors send periodical data to a single monitor or data storage device. Here in DQBAN, everybody sensor updates the current position and status in the CRQ and DTQ to the BAN coordinator. Thus, all the body sensors in the queue gather information about the other body sensors through the feedback. In practice, the queuing system implementation is simply run through four integers in each sensor; two common numbers shared among all body sensors representing the total amount of occupied positions in CRQ and DTQ, and two other different integers, pRQi and pTQi, which exclusively indicate the body sensor position in each queue. Additionally, a fuzzy-logic controller is used by everybody sensor as explained before.

Table 2: Output linguistic values of decision

WT	SNR			BL
	Dangerous	Poor	Superior	
Acceptable	Delay	Delay	Onschedule	Substantial
Acceptable	Delay	Delay	Onschedule	Balanced
Acceptable	Delay	Delay	Delay	Critical
Boundary	Delay	Onschedule	Onschedule	Substantial
Boundary	Delay	Onschedule	Onschedule	Balanced
Boundary	Forward	Forward	Forward	Critical
Excessive	Forward	Forward	Forward	Substantial
Excessive	Forward	Forward	Forward	Balanced
Excessive	Forward	Forward	Forward	Critical

SNR: Signal-to-noise ratio; WT: Waiting time; BL: Battery life

6.1 Case study

In this section, we describe how to systematically model the three sensor-dependent time-variant input variables; $SNR_i\,(t_i)$ $WT_i\,(t_i)$, and $BL_i(t_i)$ used by the fuzzy-logic system, integrated with each body sensor. The performance of the proposed techniques is valuated in a star-based topology BSN where different body sensors with their specific medical requirements communicate with the BAN coordinator in a hospital care scenario through a shared wireless indoor radio channel. For scalability reasons, the proposed techniques have been assessed in homogenous scenario characterized by a BSN with only wireless ECG body sensors. As explained before, SNR is derived at the reception of feedback frame. We can know about the battery life time of body sensors from the inner hardware memory. WT of body sensors can also derive from inherent clock. For simplicity, we have performed our calculations by taking the distance (d < 8 m) within the hospital. The time-variant signal model includes Additive White Gaussian Noise (AWGN) and the effect of lognormal shadowing with a standard deviation σ = 30 dB for our BSN simulation environment. The assumption of an AWGN channel is valid as long as the channel is coherent during the transmission of a packet. We use IEEE 802.15.4 MAC reference parameters with a maximum payload packet size of 118 bytes transmitted at the unique rate of 250 Kbps. Therefore, a packet transmission takes roughly 4.27 ms, which is smaller than the coherence time encountered in the 2.4 GHz band without mobility issues.

7. RESULTS AND DISCUSSION

For the overall evaluation of the DQBAN MAC system performance, we carried out the following comparisons with DQRAP (i.e., without scheduler) and DQBAN (i.e., with scheduler) in homogeneous scenario and the simulation is carried out using network simulator-2. The delivery ratio, mean packet delay and average energy consumption per utile bit metrics results are shown in Figures 4-6.

In order to evaluate the energy-saving behavior of DQBAN system with an increase in traffic load, 20% of the ECG sensors involved in each simulation are initially charged with much less amount of battery The average energy consumption per utile bit demonstrates the requirement of an energy-aware radio activation policy. In a typical DQ protocol, no energy-saving techniques are utilized. Therefore, as the traffic load increases in the BSN, body sensors remaining longer in the system may run out of battery. As a result, the average energy consumption per delivered information bit increases. Thus, Figure 4 highlights that by using energy-aware radio activation policies plus a scheduling algorithm, the MAC layer improves in terms of average energy consumption per utile bit. Here data packets are scheduled with respect to cross-layer constraints by guaranteeing the QoS requirements of high reliability, the right message latency and enough battery lifetimes to all body sensors transmissions in the BSN. In DQRQP protocol, there is no scheduling of packets, and hence delivery ratio is poor. The delivery ratio in Figure 5 proves that the use of DQBAN with the proposed cross-layer fuzzy-rule base scheduling algorithm reaches >95% of transmission

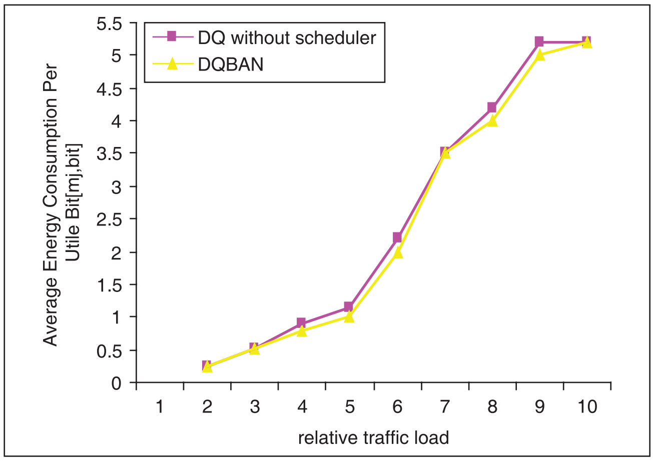

Figure 4: Average energy consumption per utile bit

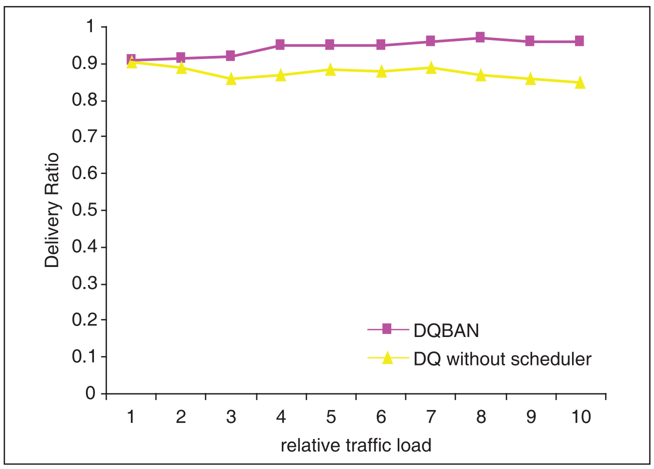

Figure 5: Delivery ratio

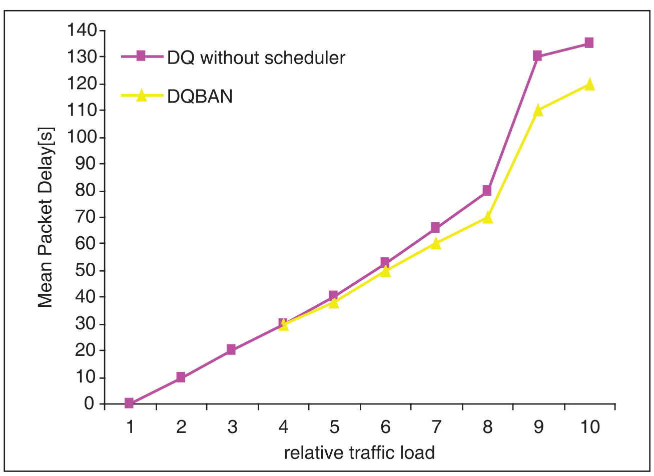

Figure 6: Mean packet delay

successes, even though 20% of the ECG sensors have critical battery constraints. It is also noted that the use of DQBAN is also appropriate in terms of mean packet delay. Using the scheduling algorithm in DQBAN mean packet delay is reduced compare to DQRAP without scheduling. Figure 6 reveals the mean packet delay with and without scheduling.

8. CONCLUSION

The new DQBAN MAC protocol commitment is to guarantee that all packet transmissions are served with their particular application-dependent QoS requirements, without endangering body sensors battery lifetime in BSNs. Body sensors able to demand or deny the next "collision-free" time slot according to their own limits. For that purpose, instead of keeping a first-come-first-served transmitting discipline, cross-layer fuzzy-rule scheduling algorithm has been introduced. This scheduling mechanism allows a body sensor, though not occupying the first position in the new MAC queuing model, to send its packet in the next frame in order to achieve a far more reliable system performance. Here body sensors will be in the idle condition after transmitting the packets to the coordinator. In idle condition, energy consumption is very less, and hence battery lifetime is increased. Our results show that the system performance with the QoS scheduler is more reliable than without the scheduler.

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