New QoS and Geographical Routing in Wireless Biomedical Sensor Networks

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Abstract

In this paper we deal with biomedical applications of wireless sensor networks, and propose a new quality of service (QoS) routing protocol. The protocol design relies on traffic diversity of these applications and ensures a differentiation routing using QoS metrics. It is based on modular and scalable approach, where the protocol operates in a distributed, localized, computation and memory efficient way. The data traffic is classified into several categories according to the required QoS metrics, where different routing metrics and techniques are accordingly suggested for each category. The protocol attempts for each packet to fulfill the required QoS metrics in a power-aware way, by locally selecting the best candidate. It employs memory and computation efficient estimators, and uses a multi-sink single-path approach to increase reliability. The main contribution of this paper is data traffic based QoS with regard to all the considered QoS metrics. To our best knowledge, this protocol is the first that makes use of the diversity in the data traffic while considering latency, reliability, residual energy in the sensor nodes, and transmission power between sensor nodes as QoS metrics of the multi-objective problem. The proposed algorithm can operate with any MAC protocol, provided that it employs an ACK mechanism. Performance evaluation through a simulation study, comparing the new protocol with state-of-the QoS and localized protocols, show that it outperforms all the compared protocols.

1 Introduction

Many research efforts have been devoted to multi-objective QoS routing in wireless sensor networks (WSN) using localization information, resulting in several routing protocols, such as DARA proposed by Razzaque et al. [1], MMSPEED by Felemban et al. [2], GREES by Zeng et al. [3], and AEM-GMR by Wu et al. [4]. Although these protocols use different QoS metrics and target multi-objective optimization, none of them provides a clear differentiation in route selection between traffic with respect to QoS requirements. They define either the same combined metric (of all the considered QoS metrics) [4, 3], several services but with respect to only one metric [2], or two classes of traffic: critical and non-critical [1]. This may be not enough for some applications, especially in biomedical WSN, where different traffic may have different QoS requirements. Our main contribution is the design of a localized routing protocol enabling to provide different QoS services according to the traffic type, while considering latency, reliability, residual energy, and transmission power all together. To our best knowledge, the proposed protocol, we call LOCALMOR, is the first that makes such differentiation and considers all the above mentioned QoS metrics. Without loss of generality we focus on biomedical applications, but the proposed protocol can easily be modified to fit for applications in other domains such as process industry, automobile, military, etc. As shown in Fig 1, several biomedical sensors (BMS) may be embedded in different parts of the patient's body to measure and transmit data either through wired or wireless links to a body sensor mote (BSM) that acts as a cluster-head of the body sensor network. It collects raw data, makes the required processing if necessary (coding, aggregation, etc.), and sends results to the sink node(s) responsible for covering the patient's area and uploading the information into the health care server. Each sink may typically have coverage of several patients. The patient can be mobile, but sinks are always fixed. Most of routers in the patient's environment relaying data to the sinks are supposed to be fixed. However, it is possible to use mobile routers, e.g. nurses' PDAs, to enhance connectivity whenever needed. We define

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two kinds of responsible sinks for each patient; primary sink and secondary sink. A separate copy of each messages requiring high reliability is sent to both sinks. This increases reliability as only one correct reception is necessary for the system. It is preferable to have as high angle of deviation as possible between the sinks, i.e. angle formed by the two sinks and the BSM in the middle. This multi-divergent-sink strategy is to ensure the two routes towards the sinks are nodes disjoint, and thus increases the probability of one correct reception compared to single sink multi-path [1]. We consider in this paper three different requirements, i) energy efficiency, ii) reliability, and iii) latency, which are all involved in the biomedical application scenario. Giving these requirements and the diversity of data traffic in biomedical applications, we classify data traffic into:

- Regular traffic: It does not have any specific requirement. It is typically the case for periodic data reflecting regular values e.g. regular measurements of patient physiological parameters, like temperature, heartbeat etc. that indicates normal values.
- Reliability-sensitive traffic: This kind of traffic should be delivered without loss, but not immediately or within a hard deadline, such like vital signals monitoring, respiration monitor, and PH monitor [5].
- Delay-sensitive traffic: this kind of traffic should be delivered within a deadline, but reasonable packet loss is tolerable. e.g video streaming.
- Critical traffic: This traffic is of high importance, requiring both the highest reliability and the shortest delay. e.g. electroencephalogram (EEG) and electrocardiogram (ECG) monitoring during a critical situation such as a surgery [5].

Following this classification the proposed protocol is designed using a modular approach, aiming to ensure exactly the required QoS for each packet, as illustrated later.

The remaining of the paper is organized as follows: Section 2 describes our network and energy models. The proposed protocol is illustrated in Section 3, while the different estimators used by the protocol are given in Section 4 and Section 5. Section 6 presents the comparative simulation study, and finally, Section 7 draws a summary and briefly describes the future work.

2 Network and Energy Models

The chosen network model is similar to those used in sensor and ad hoc networks such as [6, 7]. A network

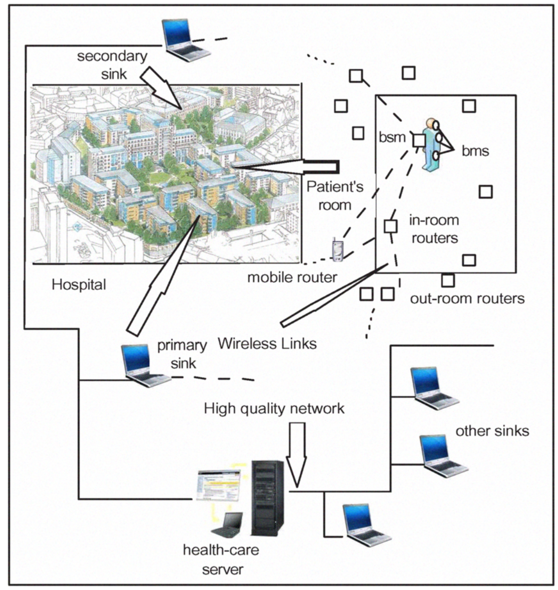

Figure 1. System Architecture

is given by a set V of nodes that are located in a three-dimensional geographic area. Each node $v_i \in V$ has coordinates, $coord(v_i) = (x_i, y_i, z_i)$. We note $dist_{v_i,v_j}$ as the linear distance between two nodes $v_i, v_j \in V$. We assume each node to be aware of its own coordinates, using a GPS device or any distributed localization service, which acts as its ID and network (global) address. In addition, the node should be aware of its current battery state B_{v_i} (also termed *residual energy*). We assume that nodes have the same and spherical transmission power range P_{range}, and that each node can control its transmission power [8]. The set of nodes in v_i's vicinity denoted by N_{v_i} consists of v_i's neighboring nodes, defined by: $N_{v_i} = \{v_j : dist_{v_i,v_j} \leq P_{range}\}$. In addition to N_{v_i} we define the set of neighboring nodes providing positive advance for node v_i towards final destination v_d, denoted by $N^{advc}_{v_i,v_d}$, as the set of neighboring nodes that are closer to the destination than v_i, given by: $N^{advc}_{v_i,v_d} = \{v_j \in N_{v_i} : dist_{v_j,v_d} \leq dist_{v_i,v_d}\}$. Like all geographic routing protocols, each node needs to know about the positions of its neighboring nodes as well as he destination. A fixed association between each body sensor mote and its responsible sinks is assumed, while a HELLO protocol is executed between neighboring nodes allowing mutual update of IDs, positions, and several parameters, as in [2, 3, 4, 9]. The HELLO protocol will be illustrated later.

A typical energy-efficient model is used in this paper [6]. This model relies on the usage of adaptive power

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according to the distance separating the transmitter and the receiver. Other models assume fixed transmission range for all transmissions, i.e., the transmission power can be either maximum or a reduced one but is fixed and pre-calculated [1, 6]. This dynamic adaptive power is power-efficient and appropriate since localization information is available. To transmit one bit from a source to a destination over a distance d, the consumed energy is given as [6]:

$$E = 2E_{elec} + \beta d^{\alpha}, \tag{1}$$

where E_{elec} is energy utilized by transceiver electronic independent of distance. βd^{α} accounts for the radiated power necessary to transmit over the distance d separating transmitter and receiver, where α is the path loss ($2 \leq \alpha \leq 5$) and β is a constant given in $Joule/(bits \times m^{\alpha})$.

3 Protocol Overview

The proposed protocol is designed using a modular approach and consists of four modules, as described hereafter.

3.1 Power-efficiency Module

This module deals with regular packets, and is also used by other modules when several nodes optimize the required data-related metrics. Power-efficiency cannot be achieved by considering only one criterion, i.e., the energy required per packet or the residual energy of routers. Both criteria should be considered when choosing the next forwarder. This tradeoff issue has been studied using weighted aggregation functions [7]. Despite the simplicity of this method, it is difficult to find appropriate wights for optimization [10]. We propose to use a non-aggregated approach, namely the min-max approach [10].

The problem is to select at node v_i that is either the source or any intermediate node, the most power-efficient node to route a packet towards destination v_d, from the set of neighboring nodes offering positive advance $N^{advc}_{v_i,v_d}$ provided by the neighbor manager (see Section 2). In Eqs. 1, the only cost related to the routing protocol is radiated (transmission) power necessary to transmit to the neighbor node. That is, for a candidate node, v_j, the required energy related to routing is given by $\beta(dist_{v_i,v_j})^{\alpha}$ - called hereafter the transmission energy link cost. The other criterion is the battery sate (B_{v_j}) of the candidate node. Obviously, the best choice with respect to the first criterion is the node that has the minimum transmission energy link cost, while the best with respect to the second criterion is the one having the highest amount of energy in its battery. Let us denote the first criterion optimum v_T, and the second v_R. For every candidate v_j, its relative deviation for each metric's optimum is calculated:

$$Z_T(vj) = \max\left(\frac{|\beta(dist_{v_i,v_j})^{\alpha}| - |\beta(dist_{v_i,v_T})^{\alpha}|}{|\beta(dist_{v_i,v_T})^{\alpha}|}, \frac{|\beta(dist_{v_i,v_j})^{\alpha}| - |\beta(dist_{v_i,v_T})^{\alpha}|}{|\beta(dist_{v_i,v_j})^{\alpha}|}\right)$$

$$Z_B(vj) = \max\left(\frac{|B_{v_j}| - |B_{v_R}|}{|B_{v_R}|}, \frac{|B_{v_j}| - |B_{v_R}|}{|B_{v_j}|}\right)$$

The min-max optimum is obtained as follows: the set, S_0, of nodes minimizing the maximum deviation with respect to both criteria, is calculated as follows:

$$S_0 = \{x : \max_{m \in \{T,B\}} \{Z_m(x)\} = \min_{j \in N^{advc}_{v_i,v_d}} \max_{k \in \{T,B\}} \{Z_k(vj)\}\} \tag{2}$$

If $|S_0| = 1$, then S_0's element is the selected optimum. Also, if the metric for which the value of $\{Z_k(vj)\}$ reaches the maximum is not unique for all S_0's elements, i.e., some nodes in S_0 (having min max value) have maximum deviation in Z_T and others in Z_B, then the node offering the best advance from S_0 will be selected. However, if $|S_0| > 1$ and the metric, say l, for which the value of $\{Z_k(vj)\}$ reaches the maximum is unique for all S_0's elements then the final solution, S, is calculated from S_0 as the set of nodes from S_0 that minimizes the deviation for the metric other than l, i.e.

$$S = \{x : Z_k(v_x) = \min_{j \in S_0} \{Z_k(v_j)\}, k = \{T, B\} - l\}. \tag{3}$$

3.2 Reliability-sensitive Module

This module routes packets requiring high reliability, which is addressed by sending a copy to both the primary and secondary sinks, increasing thus the chances of delivery to health care servers. This multi-sink single-path approach is selected instead of the single-sink multi-path approach used in [2], which results in data packets convergence near or at the sink, and consequently increases traffic contention and collisions [1]. For each copy, the most appropriate router offering the highest reliability is selected. The reliability module selects from $N^{advc}_{v_i,v_d}$ the node providing the highest packet reception ratio (prr), i.e.,

$$\max_{j \in N^{advc}_{v_i,v_d}} prr_j. \tag{4}$$

prr_j is estimated for each neighbor node. It indicates the probability of successful delivery to a neighbor node. Each node, v_i, estimates prr_j for every neighboring node using historical samples and transmits it

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in HELLO packets. Estimation method will be given later. If more than one node provide the maximum value, then the most energy efficient is selected by using the power-efficiency module.

3.3 Delay-sensitive Module

Packets requiring to be delivered within a deadline are routed by this module. We use the packet velocity approach given in [8] that has the advantage of not requiring any synchronization between nodes. However, the main difference between our approach and [8] is that the former uses a simple but memory and time-efficient estimation method instead of Jacobson's algorithm, and considers waiting time at the next hop's queue. In our approach we assume delay-sensitive packet has a delivery deadline, *dd*, specified by the upper layers and indicating the time the packet should be delivered to the sink node. We define two velocities to be used in routing process; required velocity (speed), s_{req}, and offered (actual) velocity, s_{vj}, for node v_j. The required velocity is proportional to the distance and the time remaining to the deadline, rt. Upon receiving a packet the recipient node will stamp the corresponding reception event locally. To account for all the possible delays in the node, i.e., queuing, contention, retransmission, etc., it updates the deadline prior to each transmission in the MAC layer to account for the delay from receiving the packet until it reaches its final transmission. If the reception time, either from some previous node or the upper layer in case of source node, is denoted by t_{rec}, the transmitting time by t_{tr}, the bandwidth, bw, and the packet size $size$, then rt is updated at node, v_i, as
$rt = rt_{req} - (t_{tr} - t_{rec} + size/bw)$,

where rt_{req} is time, rt, at time of reception, and $t_{tr} - t_{rec} + size/bw$ gives whole delay from the reception of the packet at v_i until the transmission of the last bit. It includes both queueing delay $(t_{rec} - t_{tr})$ and data transfer delay $(size/bw)$. Propagation delay can smoothly be added but it is omitted since it can be negligible. Upon reception of the packet at v_i, the required speed is calculated using both the remaining time to the deadline (stamped in the packet either by the previous node or the upper layer) and the remaining distance to the destination as given
$s_{req} = \frac{dist_{v_i,v_d}}{rt}$.

This way we propose a solution to handling the end-to-end deadline as local problem of satisfying the required velocity at each hop. Furthermore, no global time stamping is used but only relative time, which does not require clock synchronization.

To achieve the required velocity, the delay-sensitive module at node, v_i estimates velocity offered by neighboring nodes providing positive advance. We consider waiting time at the queue of node, v_i, transmission time to the next node, and waiting time at the queue of the latter node. None of the previous solutions in the literature considers the waiting time at next hop queue. This delay is taken into account to provide more accurate selection. Detailed description on how these parameters are estimated are given in Section 5. We denote the above mentioned waiting time as w_{v_i}, dtr_{v_j}, and w_{v_j}, respectively. Note that delay due to transmission, dtr_{v_j}, includes estimation of the time interval from the packet becomes head of v_i's transmission queue until its reception at v_j. This includes all delays due to contention (channel sensing, RTS/CTS if any, slots, etc. depending on used MAC protocol) and data transfer delay. The estimated velocity for node, v_j, is given by $s_{v_j} = \frac{dits_{v_i,v_d} - dist_{v_j,vd}}{w_{v_i} + dtr_{v_j} + w_{v_j}}$.

After computing velocities of all candidate nodes, the delay-sensitive module calculates the set of nodes supposed to meet the required deadline, $N_{v_i,v_d}^{s_{req}}$, as,

$$N_{v_i,v_d}^{s_{req}} = \{v_j \in N_{v_i,v_d}^{adv} : s_{v_j} \geq s_{req}\}. \quad (5)$$

This set is then transferred to the power-efficiency module to extract the most power-efficient node.

Critical packets are first routed by this module. In contrary to delay-sensitive packets, $N_{v_i,v_d}^{s_{req}}$ is passed to reliability-sensitive module that selects the most reliable candidate instead of most energy efficient.

3.4 Neighbor Manager

This module is responsible for executing the HELLO protocol, managing neighbor table, implementing estimation methods (presented in following sections), and providing the other modules with the required information according to the packet type. Neighbor table assigns an entry for each neighbor node, which includes all the information related to the node such as position, residual energy, estimated waiting time, estimated transmission delay, required transmission energy towards it, and estimated packet delivery (reception) ratio. The three latter parameters are estimated by the neighbor manager, while the others are estimated by the neighboring nodes themselves using their own neighbor managers. They are updated upon each reception of a HELLO packet. Periodically, or upon observing significant change in some parameters, each node broadcasts a HELLO packet including its current position, residual energy, and its estimation of the other local parameters. It is obvious that high frequency (short period) of HELLO packets provides

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relevant and up-to-date information but it would become resource consuming. This means it is required that this period should be carefully selected to maintain proper balance between information freshness and cost. Neighboring nodes use HELLO packets to update existing entries, add new entries when new nodes move within the node's vicinity, and delete entries when neighboring nodes move away or break down, which can be detected in case of not receiving HELLO packets after a defined period of time (timeout). Neighbor manager is the first module that receives the packet from the higher layers. It executes appropriate module depending of the packet type and provides the module with all information it needs such as the set of nodes ensuring positive advance N^{advc} and current values of the required parameters of each of them. Note that in case of reliability sensitive packet, the neighbor manager duplicates it and provides a copy to be submitted for each sink (primary and secondary). Subsequently it provides a separate N^{advc} for each copy since the destinations are different.

4 PRR Estimation

A good estimator reacts quickly to large changes while being stable, i.e., it should not be affected by sporadic, large deviated measurements. Furthermore, it should particularly have small memory footprint and simple computational process, given the constraints of nodes forming a wireless sensor network [11]. Window Mean Exponential Weighted Moving Average (WMEWMA) or Exponetial Weighted Moving Average (EWMA) estimation in general is suitable for WSN compared to the other estimation methods such as flip-flop estimator, Kalman filter, and linear regression [3, 11]. EWMA can react quickly to significant changes, while being stable, and has the advantage of being simple and less resource demanding. Most of the state-of-the-art estimation techniques use *statistically meaningful median* upon previous estimates' variation, which is variance-calculation based and requires important storage resources. In contrary EWMA does not need large storage capacity. WMEWMA is very similar to EWMA but has the advantage of updating the estimated parameter in regular time intervals instead of doing it for every packet, which is more computation efficient. In the following the WMEWMA-based link reliability estimation is described. Let us denote the link reliability of a given link relying node v_i to v_j by $prr_{i,j}$, which represents the packet reception ratio illustrating the probability of successful delivery over the link. This parameter is updated by v_j at each time window, w, and inserted into the HELLO packet for usage in the next window. The time window is expressed in terms of number of packets transmitted by node, v_i. At the end of time window, t, $prr_{i,j}[t]$ is updated using the previous estimate, $prr_{i,j}[t-1]$, as,

$$prr_{i,j}[t] = \alpha prr_{i,j}[t-1] + (1-\alpha)\frac{r}{r+f}, \qquad (6)$$

where r is the number of packets received at node, v_j, during the current window, f is the number of known missed packets at v_j, and α is a tunable parameter. r and f are reset to 0 each time their sum exceeds the time window, i.e., $r + t \geq w$. Appropriate values for α and w for a stable WMEWMA are $w = 30$ and $\alpha = 0.6$ [11]. f can be calculated easily by using packet sequence number. Each time v_j receives a packet it adds to f the number of missed packets between the current and past reception. If we note, sc, the sequence number of the current received packet, and, sp, the one of the previous received packet, then the number of missed packets is simply $sc - (sp + 1)$. This requires MAC protocol at every node to receive all the packets transmitted by its neighboring nodes otherwise some sequence numbers will be missed. However, it is possible to eliminate such a requirement and thus enable a completely free sleep mode at the MAC layer, i.e., one node can go to sleep mode even if its neighboring nodes are transmitting [1]. In this case each transmitter node manages a separate sequence number for each neighboring node instead of using a single sequence number for all the outgoing packets. This sequence number is to be increased each time a packet is transmitted to the appropriate neighboring node. A broadcast packet can be considered as a packet transmitted to all neighboring nodes and thus results in increasing all the sequence numbers.

5 Delay Estimation

Let us explain the estimation of parameters used by the delay-sensitive module, notably w_{v_i} (w of node v_i), dtr_{v_j}, and w_{v_j} of each neighboring node v_j. We do not use the variance-calculation based estimation methods, which require important historical storage to calculate the variance. As in [2], the EWMA approach is adapted, but it is used for both transmission delay and queueing delay. Note that the latter has not been considered in the literature. Each node, v_i, estimates dtr_{v_j} of outgoing link and its w_{v_i}, and broadcasts the latter in the HELLO packets. Therefore, for a given

[1]note that the feasibility and utility of this possible scheduling depends on the MAC layer protocol and is out of the scop of this work

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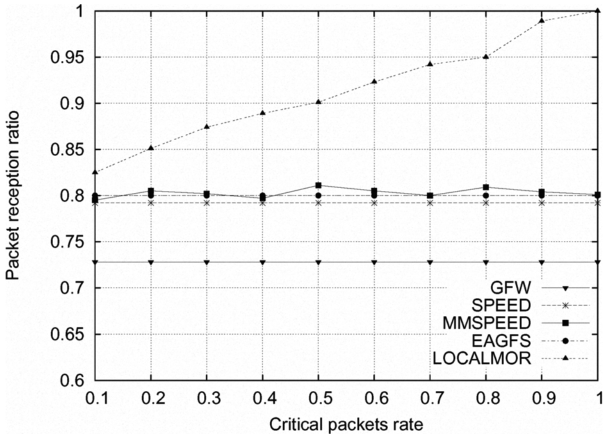

Figure 2. Packet Reception Ratio

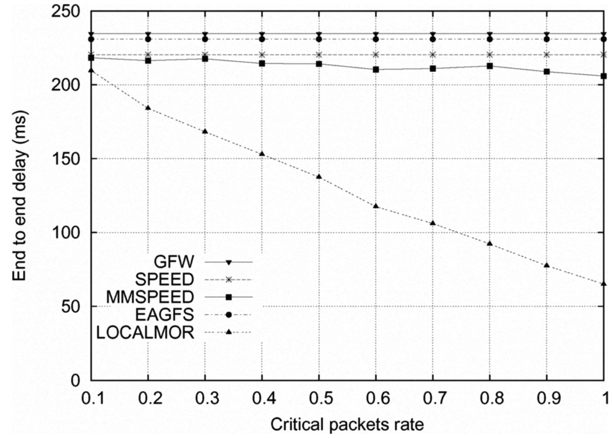

Figure 3. End-to-End Delay

node, v_i, every w_{v_j} is obtained from v_j. Now it remains to estimate w_{v_i}. This delay represents the time between packet reception (insertion into the queue) and when it becomes at the position of transmission. The exact waiting time of each packet that can be calculated through a local time stamping, say ω, is used to asses the moving average as given by

$$w_i[t] = \alpha w_i[t-1] + (1-\alpha)\omega. \tag{7}$$

The same approach is adapted for estimating dtr_{v_j}, by replacing w_i with dtr_{v_j} in Eq.7. However, delay of packet transmission cannot be obtained directly by subtracting from time stamps. It can be easily calculated as follow: if t_0 denotes the first transmission time of the packet, t_{ACK} the time of ACK reception, bw the bandwidth and $size(ACK)$ the size of the ACK packet, then: $\omega = t_{ACK} - size(ACK)/bw - t_0$.

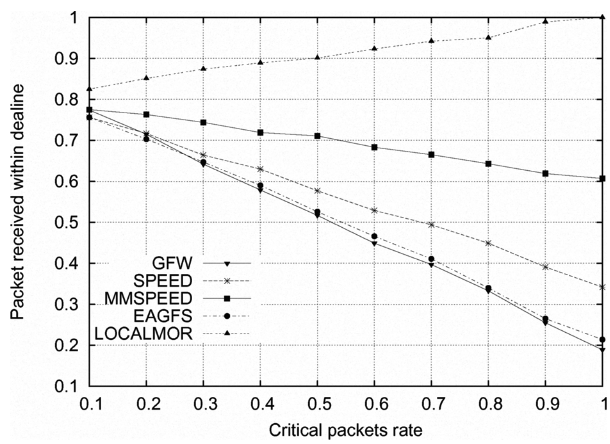

Figure 4. Packets Arriving Within Deadline

6 Simulation Study

To investigate the proposed protocol and assess its performance a simulation study has bee performed. An extended version of GloMoSim was used [12], on which we implemented the proposed protocol, called here after LOCALMOR, as well as several state-of-the-art localized and QoS routing protocols, namely SPEED [13], MMSPEED [2], the basic greedy forwarding protocol (GFW), and EAGFS [14]. We performed a comparative simulation study among these protocols including different scenarios of traffic diversity. The simulation setup consists of 400 nodes located in a $(1200m, 1200m)$ area, and $1000s$ of simulation time. Critical packets and regular packets were used in the traffic. These two classes allow to test all the modules since both delay-sensitive and reliability-sensitive modules are employed to route critical packets. Critical packets rate was varied from 0.1 to 1 to measure the performance metrics. The performance metrics we used are; the end-to-end delay, the end-to-end packet reception ratio (prr), and the rate of packets arriving within the deadline. The deadline was fixed in this simulation to $0.2s$ for all critical packets. The simulation results, which are depicted in Figures 2, 3, and 4, show that LOCALMOR outperforms all state-of-the-art schemes with respect to all metrics. LOCALMOR has the highest packet reception ratio and the lowest delay. Furthermore, while the other protocols performance with respect to latency and prr are rel-

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atively stable, LOCALMOR linearly increases its performance as a function of critical packet rate. This can be explained when the number of critical packets increases, they are routed through faster and more reliable routers, unlike the other protocols that do not make such a differentiation, except MMSPEED. MMSPEED makes a certain differentiation with respect to delay requirement, but LOCALMOR considers the estimation of queueing delay at the next hop, in addition to traffic differentiation. This consideration is the reason that LOCALMOR performs better than MMSPEED regarding the end-to-end delay. To achieve reliability, MMSPEED uses a multi-path single-sink strategy (for all packets without making any distinction), which results in packet congestion either at the final sink or intermediate nodes. Whereas, our protocol differentiates packets' with reliability-sensitive from reliability-unsensitive packets, and for the former it uses the efficient duplication technique towards geographically divergent sinks. Unlike in the previous metrics, the percentage of packets reaching the deadline of the protocols that do not make any differentiation among packets is dramatically affected by the rise of rate of the critical packets. MMSPEED is relatively less affected but its performance is less than LOCALMOR, whose performance even increases linearly with the critical packets' rate, and thus exhibit a tremendous improvement.

7 Conclusion

To consider the traffic diversity typical for biomedical applications, and provide a differentiation routing for different quality of service (QoS) metrics, a new localized multi-objective routing protocol has been proposed in this paper. The data traffic is classified into several categories according to the required QoS metrics, where different routing metrics and techniques are accordingly suggested for each category. The protocol attempts for each packet to fulfill the required QoS metrics in a power-aware way, by locally selecting the best candidate. It employs memory and computation efficient estimators, and uses a multi-sink single-path approach to increase the reliability. Energy can be considered as data traffic unrelated QoS metric. It is, however, considered for all packets and achieved by always selecting the most power-efficient candidate offering the required data-related QoS (delay and/or reliability). Power efficiency is defined with respect to both transmission power and residual energy, which represents one of the essential features of our protocol. Furthermore, considering and differentiating both delay and reliability requirements distinguish the proposed protocol from the other state-of-the-art protocols published in the literature. Our design does not depend on a specific MAC protocol and requires only minor modifications at the MAC layer for calculating estimates. Therefore, it can operate with any protocol, provided that it employs an ACK mechanism. Simulation results show that the proposed protocol provides a significant improvement, and outperforms all compared state-of-the-art routing protocols. As a future work, we plan to investigate the scalability of the proposed protocol using configurations including a high number of nodes and to consider implementation in a real sensor network using motes.

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