A Localized Real-Time MAC-Routing Protocol for Wireless Sensor Networks

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***Abstract*—Last years, research on Wireless Sensor Networks (WSNs) mainly focused on self-organization and energy issues. This is due to the intrinsic characteristics of sensors: they run on batteries and they are often inaccessible once deployed. Nevertheless some applications require more than those features. Reliability and the respect of time constraints are characteristics that are required by critical applications on which depend costly equipments or even human life. In this paper we present the problem of real-time communications in WSNs. We show that existing solutions either are not capable to respect time bounds or are not suited to WSNs particularities. We propose a localized MAC and routing real-time protocol that addresses both issues.**

I. Introduction

WSNs applications aim at monitoring parameters of the environment. When a parameter reaches a threshold, an alarm message is sent to a dedicated node called the sink node, where the information is treated. Applications, such as volcano monitoring [3], require that the alarms are reliably sent to the sink (in multi-hop fashion) within a time bound. Protocols which can deliver messages with bounded end-to-end delay are real-time protocols. In order to guarantee bounded delays, probabilistic behaviors must be avoided in protocols.

Most of deterministic solutions of the literature have taken the centralized approach. A central authority decides upon a global schedule which integrates multi-hop routes. On the contrary, our approach is, to the best of our knowledge, the first real-time localized WSN MAC and routing protocol. By bounding the duration of one hop and the number of hops, the end-to-end delay is bounded. Decisions on medium access scheduling and forwarder election are taken locally, this allow to be more scalable and robust. The decisions rely on a virtual coordinate [2], which differentiates nodes in a 2-hop neighborhood, which gives information on the hop-count of nodes (number of hops between a node and the sink), and which depends on the connectivity with higher and lower hop-count nodes. Our solution is a MAC and routing cross-layer design in order to control delays due to the interactions between layers.

In WSNs radio links are unreliable. Under harsh channel conditions, no real-time guarantee can be given whatever the protocol used, because a message may need an infinite number of retransmissions to be correctly transmitted (even if the probability of this event is low). In this work we show that our solution outperforms non-deterministic solutions even with a probabilistic radio link. With deterministic protocols, probabilistic behaviors only appear in the physical layer. Thus, the probability that the bound is respected only depends on the channel conditions.

In section II we present existing solutions. In section III we describe our proposition. In section IV we discuss the performances of our proposition and in section V we conclude and give perspectives.

II. Related Work

[4] is a survey of existing MAC and routing real-time solutions for WSNs. For references concerning protocols described in this section please refer to this document.

At MAC layer, the propositions either do not guarantee bounded delays or do not take into account the characteristics of WSNs (unreliable radio link, limited energy, scalability issues). I-EDF and PR-MAC are in this case with an approach based on scheduling algorithms. F-MAC proposes a localized and asynchronous approach. Nevertheless, it guarantees real-time constraints only on perfect radio links, it has very a poor channel utilization, a quite high energy consumption and the maximum delay increases exponentially with the number of nodes in the same collision domain.

At routing layer, the SPEED protocol takes into account the delay in the routing metric. The metric is given by the distance to the next hop divided by the delay to reach it. SPEED does not provide guaranties on the end-to-end delay. Nevertheless, it provides a congestion detection mechanisms. MMSPEED enhances reliability of SPEED by using a multi-path scheme.

Cross-layer solutions allows to meet real-time requirements. PEDAMACS and TSMP are centralized protocols. A central authority computes a schedule that is followed by the node and ensure that packets are received before the deadline. Nevertheless, if the authority fails, the network is no more able to route information.

III. Proposition

Fig.1 depicts RTXP (Real-Time X-layer Protocol), the MAC and routing protocol we propose. It uses a duty-cycle with an activity period and a sleep period to reduce energy consumption. All the nodes wake up at the same time. During each activity period, a node: contends for the medium if it has a message to send (B phase), then it sends its message if it has won the contention (R phase). It waits for a packet from nodes with higher hop-count (other R phase) and contends to be the forwarder (BF phase), if it has received a packet. Nodes

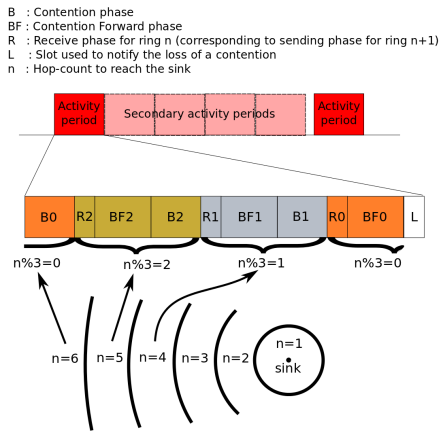


Fig. 1. Description of the proposition

execute those phases at different times according to their hop-count as depicted in Fig.1.

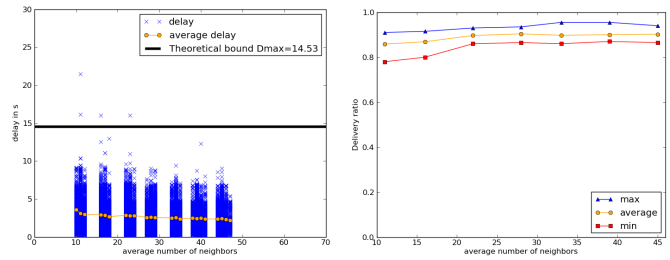
During the contention phases the nodes have a backoff that depends on their virtual coordinate [2]. We assume that the coordinate is unique in a 2-hop neighborhood so they are no collision during contention phases. The access to the channel and selections of forwarders are thus deterministic. When a node, that has a message to send, loses the contention it can tell it in the L slot, that triggers a secondary activity period for the nodes which listen the packet in the L slot. It is ensured that each packet does one hop during one activity and sleep periods (by triggering several secondary activity periods). The bound on end-to-end delay can thus be deduced by multiplying the maximum number of hops by the duration of one activity period plus one sleep period. Nevertheless if there are more packets to transmit in a 2-hop neighborhood than the number of secondary activity periods which can be executed during one duty-cycle, the bound is not guaranteed anymore (messages are not schedulable in this case). It thus defines a real-time capacity limit of the protocol.

IV. Performances

We simulated our proposition using the WSNet simulator with both perfect and unreliable radio links models. We compared RTXP performances to a centralized real-time solution: PEDAMACS [1], and to a non-deterministic solution composed of XMAC [5] and gradient routing [6] (widely used in WSNs). We simulated networks with between 100 and 800 nodes and with between 3 and 5 hops between the furthest node and the sink.

Due to lack of space, we do not present all the simulation results here. We compared RTXP and PEDAMACS under perfect links, both protocols meet their deadlines and have a 100% delivery ratio. Nevertheless, RTXP consumes less energy in the case of alarm traffic.

Fig.2(a) depicts the end-to-end delays of each packet (a point for each of the 27000 packets), the average delay, and the theoretical bound, in function of the network density for simulations with unreliable links radio model. Fig.2(a)



(a) Delay in function of network density compared to theoretical bound

(b) Delivery ratio

Fig. 2. RTXP simulation results with log-normal shadowing propagation model

shows that few packets miss the deadline. Fig.2(b) depicts the maximum, minimum and average delivery ratio. It is above 80% and increases with the network density because RTXP is broadcast-based (thus more reliable when many neighbors receive the packet). RTXP performs better than PEDAMACS, which maximum delivery ratio is under 35%.

Simulation results of XMAC with a gradient routing show that RTXP performs better than non real-time solutions under harsh channel conditions. This demonstrates the usefulness of real-time (deterministic) approaches even with unreliable links.

V. Conclusion and Future Work

In this work, we propose a localized real-time protocol for WSNs that is both scalable and takes into account energy issues. To the best of our knowledge RTXP is the first localized MAC and Routing protocol for WSN able to give guarantees on end-to-end delays. By simulation we compare RTXP and PEDAMACS, a centralized scheduling solution. We show that RTXP is more suited to alarm traffic than PEDAMACS. Under harsh radio channel conditions, it is not possible to give strict guarantees on the delay. Nevertheless by favorably comparing RTXP to a non real-time solution, we demonstrate the usefulness of real-time approaches even with unreliable links.

In the future we plan apply model checking techniques to RTXP in order to formally verify that the given guarantees are respected with sufficient probability.

References

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