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A Low-Latency Routing Protocol for Wireless Sensor Networks

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Abstract

Recent advances in Wireless Sensors Network (WSN) technology have made possible the manufacturing of tiny low-cost, low-power sensors with wireless multi-hop communication and sensing capabilities. Energy conservation for WSNs is a primary objective that needs to be addressed at all layers of the networking protocol stack. In many applications latency is another crucial factor to be addressed. However this must be done in the context of the energy constraints imposed by the network. In this paper we present an experimental evaluation of two node scheduling regimes within MERLIN (Mac Energy efficient, Routing and Localization INtegrated), an energy-efficient low-latency integrated protocol for WSNs. In particular we contrast the X and V scheduling family schemes with respect to the following properties: network setup time, network lifetime and message latency. We conduct our experiments within the OmNet++ simulator.

1. Introduction

The primary constituent components for a WSN are one or more base-stations and many sensor nodes. Such small devices are normally of low-cost and battery-operated or they scavenge energy from the environment (e.g. solar cells). They are tightly constrained in terms of energy, storage capacities and data processing. The sensor nodes typically relay their sensed data through each other or directly to the base station depending on the scale of the network and their position with respect to the gateway. In turn, the base station sends control commands down to the leaf nodes, for example, a request to increase their sampling frequency. Due to the low cost deployable infrastructure, WSNs are useful in a great variety of application domains such as surveillance, intrusion detection [5], structural monitoring, ecosystem monitoring [9](e.g. for earthquake and

fire prevention), localization of objects or animals, intelligence detection of ambient conditions such as weather or sea, medical monitoring [14] and emergency operation like disaster relief [10].

Sensors are usually deployed in an ad-hoc manner and function during long periods of unattended operation, hence they need to be self-organizing and power-aware. Consequently, careful resource management by network protocols is required. Usually, the major form of energy wastage within WSNs are [17]: *idle listening* to packets that have never been sent, *collision of packets* transmitted at the same time, *transmissions overheard* (e.g. due to control packets) and *overhearing* caused by listening to packets destined to other nodes. The MERLIN protocol for energy management within WSNs [13] was motivated by, and offers one approach to, such problems of wasteful energy consumption.

MERLIN divides the network into time-zones, thereafter it uses a combination of TDMA and CSMA techniques to decrease the node activity and the number of collisions as well as to increase the scalability. In this paper we contrast two scheduling schemes, namely the *X scheme* and the *V scheme*, with respect to the following properties: network setup time, network lifetime and message latency.

2. Related Work

Traditionally, MAC protocols have been designed with throughput as the primary issue, for example MACAW [1] or 802.11 [4]. However the power consumed by such protocols has not received as much attention. Wireless Sensor Networks present a new challenge for protocol designers due to the stringent power constraints of these devices. This necessitates a shift in the focus of the protocol and has been increasingly addressed in recent years. One of the first attempts at a MAC protocol for WSN is PAMAS, which decreased the energy consumption using a contention algorithm.

SMAC by Ye [17] for example, uses a coordinated adaptive sleeping mechanism. The main drawbacks of this approach are the latency due to the RTS/CTS mechanism and the increase of energy consumption when some nodes join the network. The latter is caused by a decrease of sleeping period, mainly due to the CSMA approach. TRAMA [12] helps to improve a nodes lifetime but introduces a high complex slot assignment algorithm and a high overhead due to exchange of schedules among neighbouring nodes. A similar protocol is DMAC [6], which incorporates a data gathering tree to reduce the latency. The main drawback of this technique is that it is suitable only for unidirectional communication flow to a single gateway.

An improvement to the SMAC protocol, called TMAC [2], uses an overhearing mechanism. Even though energy wastage due to RTS/CTS collisions are very high, latency is still present. Tiny-DB[8] describes a similar division of the medium to collect data like MERLIN. This approach tries to reduce the contention in the MAC protocol by dividing the network area into levels. An examination of different configurations of CSMA and RTS/CTS was conducted, to find a fair bandwidth allocation to all nodes [15]. No mechanisms such as multiple paths or overhearing were employed to increase the reliability and to reduce the overhead. Furthermore, tiny-DB has been designed on top of a MAC protocol which may cause latency problems. MERLIN also competes with EMACS[3] and ESR routing[16] as the communication protocol designed and implemented on the EYES sensor node[11]. With respect to the scheduling, an optimal solution to minimize the communication latency for tree based through a graph-theoretical abstraction for scheduling is proposed in [7]

3. Scheduling in Merlin

The purpose of MERLIN scheduling is to allocate time-zone slots. Nodes in the same time-zone use the same slot to transmit. Nodes send only in one slot per frame, that slot being determined by the nodes' hop count. The timing of the slots prevents most collisions.

Two schedule tables are presented in figure 1, one V-shaped in which the up and down link traffic is sequential, the other X-shaped in which up and down link traffic is combined. The first table in figure 1 shows the V-table, which performs better in terms of number of collisions and energy consumption but worse than the X-table in terms of latency and throughput. We stress the fact that latency is still very low compared with other WSN protocols. The second table in figure 1 shows that the X-table performs better in terms of throughput and latency, though to do this nodes must spend more time on. For a fair comparison of the two scheduling, we kept the same fixed length of time-slot. Furthermore, we set a number of 4 and 8 slots per frame for the X and

Figure 1. Example of scheduling tables of MERLIN called X and V scheduling implemented on the simulator

V scheduling respectively. In fact, this results in the same maximum number of hops of messages per frame. Few collisions are reported at the intersection point where adjacent nodes try to send at the same time due to the Contention Period (CP) and Collision Reporting (CR) measures [13].

4. Experimentation and Results

In order to test the efficiency of the MERLIN protocol, we conducted a series of simulation tests. The protocol has been coded by using the OmNet++ modular simulation environment based on the object oriented C++ computer language. The figure 2 shows a snapshot of the simulator running.

In particular, network setup time, network lifetime and latency related to the X and V schedules are investigated. The implementation of MERLIN uses the radio parameters of the EYES WSNs tested which contains a small processor (MSP430) with a radio transceiver [13].

4.1. Network setup time

The network setup time is the time needed for all the nodes to obtain the synchronization information then to set up their time zone and join the network eventually. Figure 1 shows two examples of schedule tables called X and V scheduling. They can hypothetically be adopted in two different application scenarios with different latency and network lifetime constraints.

Figure 2. Snapshot of the OmNet simulator running and some parameters used: Slot-Number /frame=4; DataRate=115200 bits/sec; Contention period=30ms; DataSize=16+8 Bytes(data + 3 bytes preamble + starting code.)

Figure 3. Network Setup Time for X-Scheduling and V-Scheduling.

Such allocation tables result in two different network setup times in conjunction with the node density in the area as shown in figure 3. The setup time is calculated for 4

gateways which are located in the corners of a rectangular network area as shown in figure 2. Such a location has been chosen to provide the worst case scenario since it maximizes the node-gateway distance. These graphs have been obtained by simulating numerous random static network topology of nodes. The transmitting power has been kept to a minimum while ensuring the network is connected. The figure 3 shows a doubling of the setup time of the V scheduling with respect to the X scheduling due to the greater activity of nodes in the V scheduling. For this experiment, the transmitting power of nodes has been kept to a minimum while ensuring a connected network. In fact, this results in less nodes contending the channel simultaneously hence less collision as described in the following section.

4.2. Network lifetime

In WSNs energy is a scarce resource as sensors are normally battery-operated or they scavenge the energy from the environment (e.g. by solar cells). In this section we address the operative time of a network that uses MERLIN. The network lifetime has been calculated by taking into account the battery depletion. The network is considered to fail when 30% of nodes are depleted. Such a lifetime can be adapted by adjusting the frame length.

Figure 4. Comparison of network lifetime between V and X scheduling. The parameters used are: 1 Gateway in a corner; 100 Nodes randomly distributed; 800*500 area network; Minimal signal strength (12 m); 50 msg/min sent by 5 random nodes; Static network.

In MERLIN, an increase of the frame time results in a decrease in the node activity. Such a situation can be used as a trade-off between the network lifetime and latency according to the application constraints. The graph in figure 4 shows a linear trend of network lifetime with respect to the

frame of the two types scheduling. In particular, when less latency constraints are needed V scheduling performs better than X scheduling in terms of network lifetime. The simulation has been executed by running numerous area networks topologies with 100 nodes randomly located in a fixed size area.

4.3. Latency of messages

Together with the energy consumption, the message latency can be an important parameter related to the application. As mentioned earlier in this paper, the intrinsic relative low latency characteristic of MERLIN can be used as a trade-off to extend the network lifetime in accordance with the application constraints. The optimal setting can be obtained by adjusting the frame length. Results for the two schedule tables are shown in figures 5 and 6. Each graph has been obtained by running numerous networks with nodes randomly located then calculating the mean latency for nodes in the same hop count. After the network set up time, five random nodes send a 32Bytes message periodically. Transmission time and receiving time are stored. For this experiment, a single gateway, located in one corner of the network was used.

For the X scheduling, graphs in figure 5 highlight approximately a step trend of latency at the 2nd, 5th and 9th hop counts. These zones are called *Critical X zones*. Such a behavior is probably due to the scheduling adopted, in particular caused by the intersection points between communication to the gateway and away from it. As shown in the schedule table adopted (figure 1), critical X zones are placed in hop counts 2, 5, 9 etc. and they show an increase in the average number of collisions hence packet retransmissions. For the V scheduling, graphs in figure 6 emphasize latency steps like the previous simulation. Such zones are called *Critical V zones* and they take place in hop counts 4, 8, 12 etc. As for the previous case, the reason of such a behavior is due to the V schedule table adopted. The average latency comparison of the two schedule tables is given in figure 7. Such graph has been obtained from the graphs related to the latency of X and V schedule tables.

A relevant feature of X and V scheduling to be observed is that not necessarily farther zones have higher latency of messages than nodes closer to the gateway. Such a feature that may be source of misinterpretation is due to the Implicit multi-path mechanism of MERLIN. Messages coming from higher zones are forwarded in several controlled paths, hence they can better avoid possible bottle necks at lower zones due to the channel contention so decreasing the average latency of messages.

A substantial difference to be noticed is that while Critical X zones are due to collisions implying energy wastage, Critical V zones are due to long periods of node inactiv-

Figure 5. Latency of messages with the X-scheduling with respect to the hop count number.

ity implying energy saving. This is the one point that most characterize the difference in lifetime between the two scheduling, shown in figure 4

5. Conclusions and Future Work

In this paper we described initial results emanating from the implementation of the MERLIN protocol and a comparison of two adaptive schedule schemes with the OmNet++ simulator. The graphs presented illustrate the division of the network in to time-zones by means of appropriate schedule tables, furthermore the absence of handshake mechanisms

Figure 6. Latency of messages with the V-scheduling with respect to the hop count number.

like RTS/CTS can considerably reduce the latency of messages without affecting energy consumption. Idle listening is reduced by the TDMA approach while the CSMA technique increases the scalability and reduces the number of collisions between neighboring nodes. MERLIN is also optimized by means of a controlled multi-path and overhearing mechanisms, which increases protocol reliability and reduces the overhead in transmission. Some collision on the border of subnets are reported. In such cases the random backoff procedure recovers most of the data.

The graphs showed a better performance of the X-scheduling than the V-scheduling in terms of latency of

Figure 7. Comparison of the X and V scheduling average latency.

messages and network setup time. For this reason we conclude that the X scheduling should be used for applications in which some energy can be traded off for a decrease of latency of messages and for applications in which latency is a tighter constraint. In contrast, the V-scheduling performs better than the X-scheduling in terms of percentage of collisions and network lifetime. As a result the V-scheduling is more suitable for low data traffic applications where the need of saving energy is of paramount importance. Once the kind of scheduling have been chosen in accordance with the application constraints, then the protocol can be optimized by acting on the slot length with respect to the network load. The graphs show that the intrinsic low latency of MERLIN can be effectively used to extend the average lifetime of sensors. Furthermore, we believe that the properties obtained from the two scheduling tables can be useful for setting other application-specific data-centric network protocols.

Despite the encouraging results, we need to perform more experimentation to compare MERLIN scheduling with other WSN protocols and to better clarify the impact of our design decisions with mobile nodes. The identification of contexts appropriate for the use of X or V scheduling potentially empowers MERLIN in the opportunistic adoption of the most apt scheduling regime. It is intended that protocol adaptivity be provided via the introduction of an intelligent protocol management agent. This agent will monitor the network context and determine if or when, and how to adapt the protocol. Such adaptivity is synonymous with autonomic systems principles.

Future work will investigate an optimization of the protocol to cope with the node mobility for example using the RSSI indicator already in use for the localization procedure. Another solution can be to provide in each node a table of neighbour and their time-zone. This would help nodes to better deal with mobility as well as to better choose the best

relaying node in terms of its battery level. Furthermore, the usage of two different frequencies for up and downlink could yield benefits reducing the number of collisions.

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