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A Cross-Layered Communication Architecture for WSNs based on Virtual Coordinates

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Abstract— **This paper describes our current work which aims at designing an energy-efficient, self-organizing and robust communication architecture for Wireless Sensor Networks (WSNs). We have recently proposed the 1-hopMAC protocol, which builds a list of neighbors on-demand. This removes the need to periodically exchange Hello messages. We present experimental results on energy-efficiency and collision probability which match previously published analytical and simulation-based results.**

We are currently working on using virtual coordinates as a basis for geographic routing. These coordinates are chosen randomly when a node boots and are constantly updated throughout the lifetime of the network. Nodes do not need costly GPS-like solutions, and the structure easily adapts to network dynamics, which makes it an encouraging and innovative approach for WSNs. We discuss our current work on designing a suitable updating algorithm for these virtual coordinates.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have witnessed a tremendous upsurge in recent years, both in academia and industry; this is mainly attributed to their unprecedented operating conditions and a variety of commercially viable applications [1]. From a research point of view, designing a communication architecture which allows for an entirely autonomous operation of the network is a major challenge.

WSNs are composed of a large number of battery-powered nodes rolled out in possibly hard-to-reach locations. As changing batteries every now and then is not feasible, the nodes should operate in ultra-low power mode so as to extend the network's lifetime. On current hardware, the communication part accounts for most of the energy consumption, so the Medium Access Control (MAC) protocol – controlling, among others, the state of the radio chip – should be carefully crafted.

This paper presents work in progress with respect to designing a complete energy-efficient self-organizing communication architecture. We have recently proposed the 1-hop MAC protocol [2] which is based on preamble sampling technique and allows for ultra-low power operation. It builds the neighborhood table on-demand and thus removes the need for periodically sending Hello packets. In Section II, we discuss the design of 1-hopMAC and present experimental results which match analytical and simulation results on the energy consumption and collision probability. In Section III, we then discuss the work we are currently carrying out, and which aims at designing a routing protocol which can be efficiently coupled with 1-hopMAC. This cross-layered communication architecture exhibits characteristics such as energy-efficiency, robustness and self-organization, which we believe are key features of WSN protocols.

II. 1-HOPMAC: FROM DESIGN TO EXPERIMENT

II.1. Description of the 1-hopMAC protocol

While ensuring connectivity between neighbor nodes, the MAC protocol should turn the node's radio off as often as possible to avoid unnecessary draining of the node's energy. Moreover, in WSNs, the MAC protocol has the difficult task of providing the upper routing layer with the list of the node's neighbors. Traditionally, each node stores this information in a neighbor list, which it maintains by periodically sending out Hello messages. Sending periodic messages constantly depletes energy, even when no useful traffic is being sent over the WSN.

In [2], we proposed the 1-hopMAC protocol. The idea of this protocol is for a current node to elect its neighbor node which is virtually closest to the sink, in an on-demand fashion. Each node is attached virtual coordinates which it uses to compute its virtual distance to the sink. The concept of virtual coordinates will be introduced in III. The advantage of this reactive scheme is that it does not requires nodes to build or maintain neighbor tables, which would require a regular exchange of signaling messages.

Fig. 1 illustrates how this protocol functions. Each node knows its virtual distance to the sink. After receiving a preamble from node S, nodes A, B and C wait for a time proportional to their virtual distance to the sink before sending out an acknowledgment message. Node S then selects the node which has answered first (here A) as next hop. By using the node's virtual distances to the sink, the node which S is most interested in (i.e. the one virtually closest to the sink) answers first. After the first answer, node S could thus turn off its radio it if chooses to save energy.

Using this on-demand solution, the list of neighbors (here nodes A, B and C) is implicitly learnt by the sending node (here node S) whenever a message is sent. This avoids having to pro-actively maintain a neighbor table. By having each node relay the message by using the same principle, it eventually reaches the destination. A more detailed discussion on routing protocols will follow in Section III.

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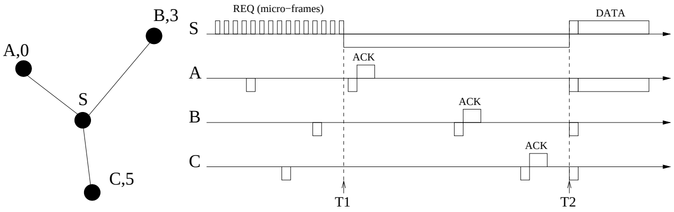

Fig. 1. (left) The topology used to explain the 1-hopMAC protocol. The number attached to each node is its virtual distance to the sink. (right) The horizontal axis represents time. A rectangle above (resp. under) the time axis means that the node's radio is transmitting (resp. receiving). When there is no rectangle, the radio is off.

1-hopMAC uses the principle of preamble sampling to keep the duty cycle as low as 1% or even less. The duty cycle accounts for the percentage of time a node has its radio on. Preamble sampling consists of each node periodically sampling the medium for a very short time. A node wishing to send a message to its neighbors first sends a preamble for a duration at least as long as the sampling period. This insures that all neighbor nodes hear the preamble. We have used a variant on this principle called Micro-Frame Preambling [3]. Although [2] describes the protocol, no experimental results were presented.

II.2. Energy Consumption of the 1hopMAC Protocol

The energy consumption of a node is reduced by turning its radio off. We use Ember EM2420 nodes to experimentally measure this consumption. This platform is equipped with a CC2420 radio chip and an AtMega128L micro-controller. After implementation, we can follow the execution of 1-hopMAC by plotting the power consumed by a node as a function of time, using an oscilloscope (see Fig. 2). In particular, we see that:

- the radio module has a major impact on the total energy budget of a node;
- sending, receiving and idle listening consume approximately the same amount of energy;
- we verify our implementation by noting that the ACK messages are sent at different instants depending on the value of the node's virtual distance to the sink.

Using Fig. 2, we extract the energy consumption of the different radio states, and the energy consumed by the different phases in the 1-hopMAC protocol (Table I). E_{Tx} refers to the energy needed by a node to send a message. The receiver of this message will spend E_{Rx} while any other competing neighbor (not the intended destination) spends E_{comp}. The neighbor which is not the intended receiver does not need to receive the data. We see that sending a message costs about 2-3 times more energy than receiving one. This has a major impact on upper-layer protocol design as having a dense network does not jeopardize energy-efficiency.

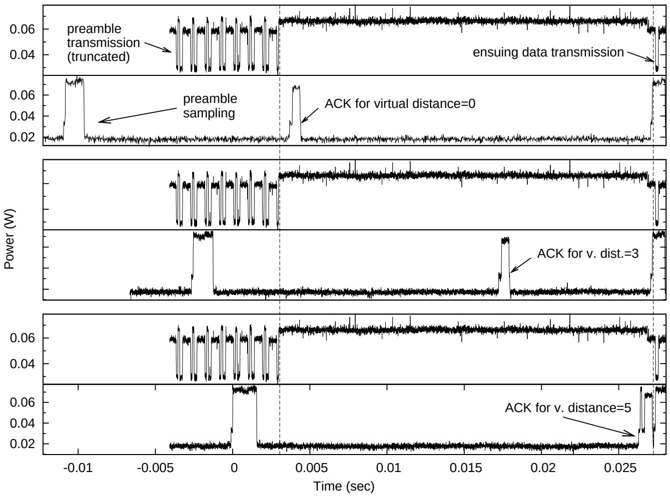

Fig. 2. Power consumption versus time when using 1-hopMAC. Measurements for a communication initiator and recipient are presented in the upper and lower parts, respectively. The experiment is repeated for a virtual distance to the sink (abbreviated to "v. dist." in the figure) equal to 0, 3 and 5, hence the three groups of figures. Note that the first part of the preamble is truncated to ease readability.

P_{sleep}	8.02 mW
$P_{idle\ listen}$	65.83 mW
P_{Tx}	66.16 mW
P_{Rx}	70.69 mW
E_{Tx}	3.50 mJ
E_{comp}	1.55 mJ
E_{Rx}	1.80 mJ

TABLE I

CONSUMPTION OF THE INDIVIDUAL RADIO STATES AND 1-HOPMAC PHASES (TRANSMISSION POWER SET TO $0dBm$)

II.3. Collision Probability at MAC level

In Fig. 1, consider that nodes A and B have (almost) the same virtual distance to the sink. In this case, both will send out their acknowledgment message approximately at the same time. These messages can then collide, and never be received by node S. This problem was addressed analytically and by simulation in [4]. In particular, it was shown that whenever virtual distance values are uniformly distributed over a range, the collision probability P is a function of the contention window size CW, the length of the acknowledgment message D_{ACK} and the number of neighbor nodes N as per (1). Fig. 4 confronts averaged-out simulation results with analytical results.

$$P = 1 - \left(\frac{CW - D_{ACK}}{CW} \right)^N . \tag{1}$$

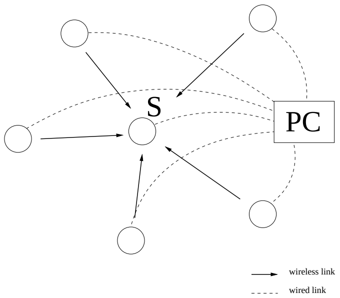

Fig. 3. The setup used to measure the experimental collision probability.

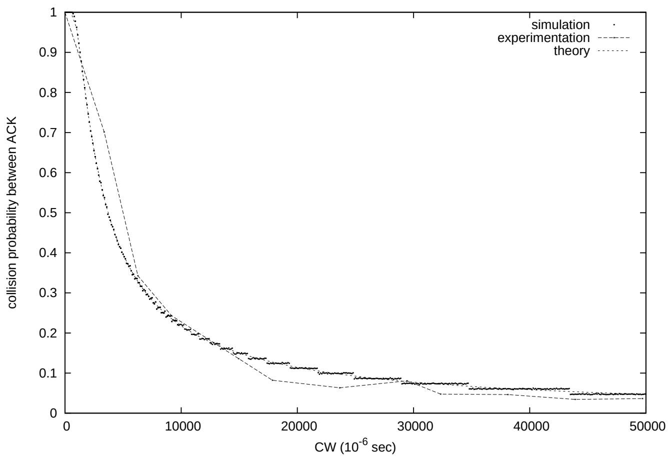

Fig. 4. Comparing the experimental collision probability with theoretical and simulation results. Presented simulation results are averaged out over 10^6; experimental results over 8000 runs.

We verify the previously published theoretical and simulation-based values by experimentation. We adopt the setting depicted in Fig. 3. A host computer is linked to 6 nodes through wired links. Through these wired links, it sends randomly and uniformly chosen virtual distance values to each of the five neighbor nodes of S, and asks S to send out a request wirelessly. It then monitors which neighbor node S picks as next hop. Remember that the communicated virtual distances are used by the neighbor nodes to determine the backoff time before sending the acknowledgment. If S does not choose the node with smallest virtual distance, it means the acknowledgment message coming from this node has collided with another acknowledgment message. We see in Fig. 4 that experimental results match theoretical and simulation-based values.

The 1-hopMAC protocol is energy-efficient in that it retrieves the virtual distances to the sink of the neighbor nodes on-demand. No periodic Hello packets are needed. We have presented new experimental results which match previously published simulation and analytical results on energy-efficiency and collision probability.

II.4. Critique on the 1hopMAC Protocol

Currently, 1-hopMAC is designed so that a node retrieves the neighbor list each time a message is sent, and then forgets this information. The rationale behind it is that this avoids using the node's already limited memory to store neighbor tables. Moreover, in an ever-changing wireless environment, those neighbor table could turn out to be outdated most of the time. Although the nodes are not necessarily moving, the wireless environment changes by cars and people moving, doors being opened, etc. Under these circumstances, it makes little sense to keep neighboring information.

Clearly, the underlying assumption is that the number of messages traversing the network is low. This protocol has been designed for applications such as automated meter reading where each node reports the (i.e. water) consumption every 24 hours or so. For applications with higher loads, an immediate optimization is to retrieve the neighbor list only for a subset of sent messages.

Our current work aims at analyzing current MAC layer approaches (including preamble sampling and synchronized-based MAC protocols), and deciding which approach should be used under which circumstances. Parameters which need to be taken into account are the size of the network and its load in number of messages, together with the energy budget and the expected communication delays. Although still under investigation, our intuition is that preamble sampling approaches (such as 1-hopMAC) make more sense under low loads; synchronized and schedule-based techniques being more efficient under high loads.

III. CURRENT WORK ON A ROBUST AND ENERGY-EFFICIENT ROUTING LAYER

We are currently working on designing a routing protocol which introduces the novel self-organization concept of virtual coordinates, while interfacing efficiently with 1-hopMAC.

A number of routing protocols have been proposed which use the geographical location of the nodes to discover multi-hop paths. Yet, this approach suffers from (1) routing voids in the topology which lower the delivery ratio and (2) the requirement to have location-aware nodes (e.g. by GPS). To address these issues, we are currently working on using entirely virtual coordinates for routing. Each node has virtual coordinates ([x,y] values) which it uses as a basis for geographic routing protocols. The aim of this work is to find a distributed protocol to initialize and update these virtual coordinates so that the geographic routing protocol running on top of them finds short routes.

Our current proposal functions as follows. When a node is switched on, it picks its virtual coordinates randomly in some range. Fig. 5 illustrates this idea. The left hand side shows the connectivity graph of the WSNs, i.e. nodes are positioned at their real location; nodes able to communicate are linked together. The right hand side shows the virtual graph, where nodes are placed at their virtual location. As can be expected, a geographic routing protocol running on this graph performs close to random walk. The key to making this approach efficient is how the virtual coordinates are updated throughout the lifetime of the network.

We propose to iteratively update the nodes' virtual coordinates so as to structure the network. The updating process should require only local information, i.e. the virtual coordinates of a node's neighbors. The resulting structure in the network has two characteristics: (1) the virtual coordinates could end up at positions close to real coordinates or (2) they could enable a greedy geographic routing protocol to discover a near-optimal path in terms of number of hops.

Our current work focuses on finding this updating algorithm. A first idea is to use a simple centroid transformation, where a node sets its virtual coordinate to the average value of its neighbors, virtually placing it at the center of gravity of its neighbors' virtual coordinates. Early simulation results show that this can result in near optimal routing paths, in number of hops.

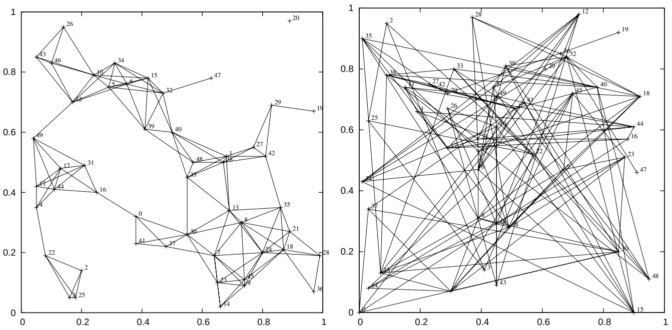

Fig. 5. The real graph (on the left) transforms into the virtual graph (on the right). Note that these graphs are identical, except that the nodes are positioned either at their real or at their virtual locations.

Such an updating process can efficiently be coupled with 1-hopMAC by having each node put its virtual coordinates into all ACK messages it sends. A node updates its virtual coordinates each time it has a message to send. At instant $T2$ in Fig. 1, node S knows the virtual coordinates of its neighbors. It can then update its virtual coordinates using the updating algorithm. This way, no specific signaling messages are needed, yielding an overhead-free routing protocol.

Another potential advantage of this communication architecture is its robustness. The updating process is continuous as long as there are data messages flowing through the network. As there is no explicit initialization phase, (1) the network can be used as soon as the nodes boot and (2) no periodic potentially heavy re-initialization is needed.

To summarize, so far we have designed and validated an energy-efficient MAC protocol for WSNs called 1-hopMAC. This protocol is the basis for a communication architecture which should include a routing protocol. We are currently designing this routing protocol by using entirely virtual coordinates. By continuously and locally updating the nodes' virtual coordinates, we can obtain an energy-efficient, self-organizing and robust communication architecture. The cornerstone, and the problem we are currently addressing, is the design of this updating algorithm.

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