AreaCast: a Communication by Area in Wireless Sensor Networks

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Verimag Research Report n^o TR-2011-4

March 2011

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Abstract

To provide for reliability in Wireless Sensor Networks (WSNs), Medium Access Control (MAC) protocols must be adapted by mechanisms taking cross-layer approaches into account. In this article, after introducing existing MAC protocols, we describe AreaCast, our protocol, which is designed for enhancing reliability in WSNs. AreaCast is a MAC layer protocol independent of the routing layer, but uses only local topological and routing information to provide a communication *by area* instead of a traditional, *node-to-node* communication (i.e., unicast). In AreaCast, a source node addresses a set of nodes: an *explicit relay* node chosen as the next hop by a given routing protocol, and three other *implicit relay* nodes. The neighboring nodes select themselves as implicit relays according to their distance from the explicit relay node. This mechanism uses overhearing to take advantage of the inherent *broadcast* nature of wireless communications. Without changing the routing protocol, AreaCast is able to dynamically avoid a byzantine node or an unstable link, allowing to benefit from the inherent topological redundancy of densely deployed sensor networks. Simulation results show that AreaCast significantly improves the packet delivery rate while having a good reliability-energy consumption trade-off.

Keywords: wireless sensor networks, mac layer, routing, reliability, energy

Reviewers:

How to cite this report:

```
@techreport {TR-2011-4,
  title = {AreaCast: a Communication by Area in Wireless Sensor Networks},
  author = {Karel Heurtefeux, Florence Maraninchi, Fabrice Valois},
  institution = {{Verimag} Research Report},
  number = {TR-2011-4},
  year = { }
}
```

1 Introduction

Wireless Sensor Networks (WSNs) are formed by hundreds or thousands of low-cost and low-energy sensor devices. Sensors are densely deployed over a geographic area to collect data. Such networks have a wide range of potential applications: ambient home, smart building, environmental monitoring, body space... Despite intensive research efforts, numerous challenges remain for large-scale deployment in real environments.

Because of open medium, dynamic topology, absence of central control, and constrained capabilities, sensor networks are more vulnerable and fragile than conventional wireless and wired networks.

Indeed, wireless medium makes sensor networks more prone to interferences and collisions and the deployment of thousands of tiny sensors exposes WSNs to hardware failures.

Sharing the wireless medium in an energy-efficient way is a key point in WSNs. The role of the medium access control (MAC) is to coordinate transmission over the wireless channel common to several nodes. As a result, MAC layer design is crucial in such a context.

Studies show that cross-layer optimization (i.e., without strict boundaries between layers of the OSI communication model) is suitable in WSN [14]. However, the main existing solutions which merge routing and MAC protocols still select only one relay as the next hop. If this node is dead or faulty, the communication is stopped and the routing protocol has to re-build the route.

Contributions. In this paper, we propose a new MAC layer protocol, AreaCast. It uses routing-layer information (distance, neighborhood and route information), to enhance robustness, but it does not change the routing protocol . AreaCast uses the selected node given by a routing protocol (called *explicit relay*) but also k *implicit relay* nodes within an area close to it (Fig. 1). If the explicit relay is unable to fulfill its role, implicit relays take its place. In this way, the network redundancy is better exploited to provide robustness. Note that AreaCast is independent of the routing process and does not influence the route construction. AreaCast increases the delivery rate in an energy-efficient manner compared to Sensor-MAC [22]. Simulations are performed for faulty nodes, volatile links and a realistic propagation model.

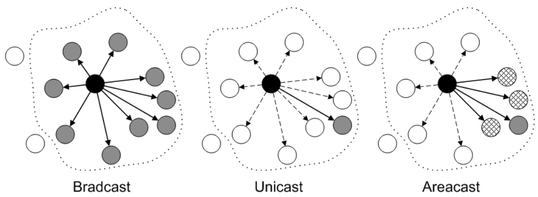


Figure 1: Communication patterns: Broadcast, Unicast and AreaCast

Structure of the paper. The rest of the paper is organized as follows. Section 2 provides an overview of MAC protocols designed for WSNs. In Section 3, we discuss weaknesses of unicast in MAC protocols and we describe AreaCast. In Section 4, the AreaCast performances are presented in terms of energy consumption and delivery rate. Finally, Section 5 contains concluding remarks and some future work directions.

2 Related work

The concurrent access to the communication channel in wireless networks has been extensively studied for both ad-hoc and sensor networks.

The MAC layer coordinates access to a medium common to several processes. It has a central role in any communication system and its behavior has an important impact on the WSNs performances. As the radio is the main cause of power consumption, the design of MAC protocols is crucial to enhance WSN lifetime.

The authors in [6] give five reasons of energy waste in communication:

- collisions, when a node receives several packets at the same time. Energy spent to transmit and to receive is wasted and re-transmissions of packets involved in the collision are generally required;

- "*overhearing*", when a node receives packets that are targeted to other nodes;
- control packets, used to avoid collisions or acknowledge data packets. RTS (Request-To-Send) and CTS (Clear-To-Send) packets are examples of control packets used in some protocols which do not carry any data information;
- idle listening, when a node listens to an idle channel to receive potential traffic;
- "*overemitting*", when a node transmits a packet when the destination node is not ready.

In multi-hop ad-hoc networks, the IEEE 802.11 DCF protocol [10] is widely used. However, it is unsuitable for sensor networks because of considerable energy consumption in idle listening: when a node does not know when it will be the receiver of a frame, it keeps its radio on while listening to the channel, waiting for potential packets.

In WSN, low-data rate is generally considered. As a result, many protocols designed for WSNs propose to periodically put nodes into sleep mode to reduce idle listening. The use of sleep periods implies to know when other nodes transmit. In this context, there are mainly two approaches: sleep/listen protocols and preamble-based approaches. In this section, we only focus on such energy-aware protocols.

In the first approach, the neighboring nodes establish virtual clusters by exchanging synchronization messages to set up common scheduler. If neighboring nodes reside in two different virtual clusters, they wake up at the listening periods of both clusters. The second approach does not establish common schedulers for sleep and wake-up periods. A long preamble frame is sent before each data packet.

2.1 Sleep/listen Protocols

In sleep/listen protocols, neighboring nodes form virtual clusters to set up a common and periodic sleep/listen periods. During the listen periods, sensors communicate in a contention-based way similar to the IEEE 802.11 DCF. The sleep phases are used to save energy. Such protocols require a certain level of synchronization in order to maintain sleep/listen phases common to network nodes.

In Sensor-MAC (SMAC) [22], the listen period sizes are fixed and the synchronization is accomplished by broadcasting periodical SYNC packets to direct neighbors. Collision avoidance is achieved by a carrier sense and an exchange of RTS/CTS packets for unicast type data packets. However, if the traffic is dense or irregular, the large size of sleeping periods leads to a strong contention in the listen period. Long listen periods reduce the contention but increase the idle listening. Short listen periods do the opposite and may result in high latency for multi-hop routing algorithms. A relay node has to wait for the next listen period to forward a data packet.

To solve the problem of fixed-size common sleep/listen periods and find an optimal period, some new protocols have been developed. For example, adaptive listening mechanisms are proposed in Timeout MAC (TMAC) [21], Separate Wake-up MAC (SWMAC) [17] or Data-gathering MAC (DMAC) [15] to improve the delay caused by sleep periods. They also use sleep/listen periods but their duration varies according to various parameters.

In TMAC, a node tries to predict channel activity during a listen period to be able to switch its radio off before the end of the listen period. A node switches to sleep state when no activation event has occurred for a time threshold *TA*. It means that no more packets have to be sent. By decreasing the listen period durations, TMAC is more energy-efficient than SMAC.

In SWMAC, the listen periods are divided into slots assigned according to the identity of nodes. Each node wakes up during its own reception slot to receive data.

In DMAC, a convergecast-communication pattern is considered. Source nodes send data to a sink through unidirectional paths. These paths could be represented as data-gathering trees. The sleep/listen schedules are determined according to the traffic load and to the depth of nodes in the tree: during the listen phase of a sensor, all of its children have to be in the transmit phase and share the channel.

The sleep/listen protocols use broadcasted control packets such as RTS or CTS, to reduce collisions or to adapt sleep period to traffic. However, this solution does not consider robustness. Indeed, if a sensor fails to transmit a data packet, the routing protocol must find an alternative route to the destination. Moreover, because of sleep periods, a node must wait for the next listen period. In our approach, we propose to exploit this existing packets to enhance robustness.

2.2 Preamble-Based Protocols

In preamble-based protocols, each node chooses independently its active schedule. Before sending data, a node sends a long preamble frame. The preamble frame must be at least as long as the period between two consecutive wake-ups (or check intervals). Sensor nodes periodically wake up to check whether there is a transmission on the channel. When a preamble is detected, the destination node keeps its radio on until the end of data transmission. After the reception, the destination node sends an ACK packet. However, if the channel is idle, a node goes back to sleep. With this approach, idle listening and synchronization overhead are reduced. For example, the preamble sampling technique has been combined with Aloha in [7].

The main difficulty is to find an optimal check interval. Reducing the check interval saves energy because the receiver can sleep for longer periods. On the other hand, it drains more energy because the transmitter must use larger preambles.

The authors in [2] use control preamble frames to inform the receiver about the remaining time until data transmission. The receiver can go back to sleep and wake up just to receive the data, instead of listening to the channel until data transmission.

In the data preamble frames protocol (DFP) [2], preamble frames are copies of the data frame. Duplicating data is used in order to increase reliability.

However, the authors consider only the "unicast paradigm", once again, to send data packets: one transmitter talking to one receiver. They do not consider faulty nodes or transmission errors. The use of a preamble frame can be very costly in case of retransmissions. A sending node has to re-send both the data packet and the preamble frame.

Our approach is able to use preamble frames to maintain awake not only the next hop but also k *implicit relay* nodes to exploit redundancy. In this way, it improves the end-to-end reliability. This mechanism allows increasing delivery ratio while keeping a low energy cost.

The authors in [13] propose a resilient packet-forwarding scheme using overhearing of the neighbors. Our aim is similar, however, they only consider the routing layer and their solution duplicates a packet to create multi-path data forwarding when they detect relaying nodes' misbehavior. Traffic redundancy leads to an important waste of energy. Our solution considers the MAC layer and is independent of routing protocols.

2.3 GeoCast based Protocols

The Geocast protocol [11] proposes a routing and addressing method to integrate geographic coordinates into Internet Protocol. Geocast enables the creation of location dependent service. Based on this method, many new protocols or improvements have been developed [19, 16, 4]. Geocast and Geocast-based protocols need GPS coordinates. However, dedicated hardware like GPS is not always suitable in embedded systems like sensor. Moreover, the proposed solutions do not tackle mac layer or robustness against faulty links or nodes. Finally, Geocast is a form of specific multicast addressing.

3 The AreaCast Protocol

3.1 Unicast in MAC protocols and its weaknesses

From our point of view, unicast addressing is particularly not suitable for dense and fragile sensor networks. When a node or a link disappears, MAC protocols unsuccessfully try to retransmit packets, instead of exploiting the natural topological redundancy. Even if a node is close to the relay node, a traditional MAC protocol considers only the latter. Before selecting another relay node, a source node tries to reach the same node until the retry limit. These retransmissions result in an important waste of energy, a source of packet loss and an increase of end-to-end delays.

3.2 Protocol Overview

To avoid useless retransmissions, AreaCast proposes a new communication pattern. In WSNs, the identity of relay nodes is useless in the multi-hop routing process. But this identity is still used to address a

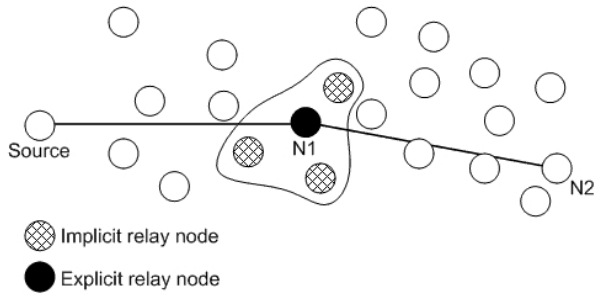


Figure 2: Self selection of the implicit relay nodes around the explicit relay node N1.

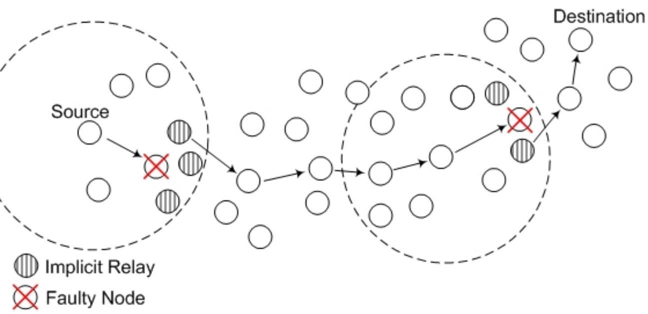


Figure 3: An example of AreaCast process. Grey nodes represent implicit relays using to bypasses faulty nodes.

particular neighboring node chosen by a given routing protocol as the next hop. In AreaCast, a source node addresses an *area* instead of addressing only one node in an unicast manner. The *area* is composed by the *explicit relay* node (the next hop) and k self-elected *implicit relay* nodes (Fig. 2). If the *explicit relay* node does not respond, an *implicit relay* node takes its place in the multi-hop routing in a transparent way. The Figure 3 shows how *explicit relay* nodes can be used to bypass the faulty nodes.

To address an area instead of one node, several difficulties have to be considered:

- the election of the implicit relay nodes
  - the criteria of selection
  - the number of implicit relay nodes
- the backoff duration among the implicit and explicit relay nodes to avoid collisions

The election of implicit relay nodes is crucial for both energy consumption and relay efficiency. If AreaCast selects numerous implicit relay nodes, the probability of reception is improved, however, the overhearing and the energy consumption are also increased. Moreover, the backoff algorithm of each implicit relay needs a special attention to avoid collisions.

Firstly, we describe the election method of implicit relay nodes, and secondly, we introduce the AreaCast protocol applied to a sleep/listen approach. Finally, we discuss the AreaCast application in the context of preamble frame protocols.

Criteria for implicit relay nodes election. Limiting the number of *implicit relay* nodes is necessary for several reasons:

- energy consumption: increasing the number of *implicit relay* nodes increases overhearing;
- end-to-end delay: each *implicit relay* node should have a time to respond;
- relay efficiency: each *implicit relay* should have characteristics close to the *explicit relay*.

Here, the maximal number of *implicit relay* nodes is limited to three to provide enough redundancy without impacting too much the delay and the energy consumption.

By exchanging periodic *hello* packets, each node has a view of its 2-hop topology. Each neighbor of the explicit relay node knows the distance between the explicit and potential implicit relays. The neighboring nodes have the same uniform view and they are able to establish the same ranking. Therefore, they elect themselves as implicit relays without exchanging extra packets.

The election algorithm of a node as implicit relay is described as follow:

- A node X is the explicit relay node if it is addressed as the next hop by a source node
- A node X elects itself as an implicit relay if and only if:
  - X is not the *explicit relay* node
  - X is a neighbor of the source node
  - X is a neighbor of the *explicit relay* node
  - X is one of the first 3 nodes in the ranking established with the following rules:
    - At the first ranks, the neighbors of the second next hop are placed according to their distance from the explicit relay.
    - At the following ranks, the nodes which are not neighbors of the second next hop are placed according to their distance from the explicit relay.

In other words, the priority is given to the nodes which are neighbors, at the same time, of the source, the explicit relay and the second next hop.

The main criterion used in implicit relay election is the distance from the explicit relay node. This metric can be determined in various manners:

- in a quantitative way, if each node has GPS information [9] or using RSSI [20] (even if the ineffectiveness of RSSI is mentioned in the literature [12, 18]) or ToA [5], etc.
- in a qualitative way, by using alternative protocols such as QLoP [8].

The quantitative distance is computed based on physical measures and is meant to be close to the real geographical distance. The quantitative distance protocols generally do not take into account the energy consumption and assume that each node is able to compute easily the time or the angle of arrival. The quantitative distance defined in QLoP is not directly connected to the real distance but computes a proximity indicator between nodes. The quantitative distance protocols use only topological information. Moreover, because QLoP provides a ranking between neighboring nodes according to their proximity, it is particularly suitable for AreaCast.

AreaCast Applications. In this section, we describe the application of AreaCast in a sleep/listen duty cycle protocol. A node wishing to send data initiates the process by sending a RTS frame. This frame is broadcasted to all neighboring nodes. The destination identity and transmission time are included in the frame. This indicates to other nodes that they should refrain from sending data at the same time. When neighboring nodes receive a RTS packet, they self-elect or not as implicit relay node according to the criteria given above. The implicit relay nodes stay awake while the other neighboring nodes go to sleep during the communication time (Algorithm 1).

If the explicit relay node does not send a CTS frame during the given time t_0, the first implicit relay node sends a CTS frame to the source node. If the first implicit relay node fails, the second implicit relay sends CTS at t_1, etc. If none of the relay nodes succeeds in the CTS sending, the source node re-transmits the RTS packet. If one relay succeeds in the CTS sending, the following relay nodes cancel their backoff. Note that each relay, implicit and explicit, has its proper backoff timer to transmit: t_0 is reserved to the explicit relay node response, and times t_1,t_2,t_3 to the response of first, second and third implicit relay nodes respectively ($t_0 < t_1 < t_2 < t_3$ are fixed). Moreover, because relay nodes are neighbors of the source, they are able to cancel their backoff timer if the communication is not disturbed.

When a source node receives a CTS packet, from the explicit or an implicit relay node, it sends the data packet to the explicit relay node (Algorithm 2).

When a node receives a data packet, the behavior is similar to the reception of a RTS: implicit relay nodes listen to the channel to know if the explicit relay node responds an ACK frame. If not, they dynamically replace it (Algorithms 3 and 4).

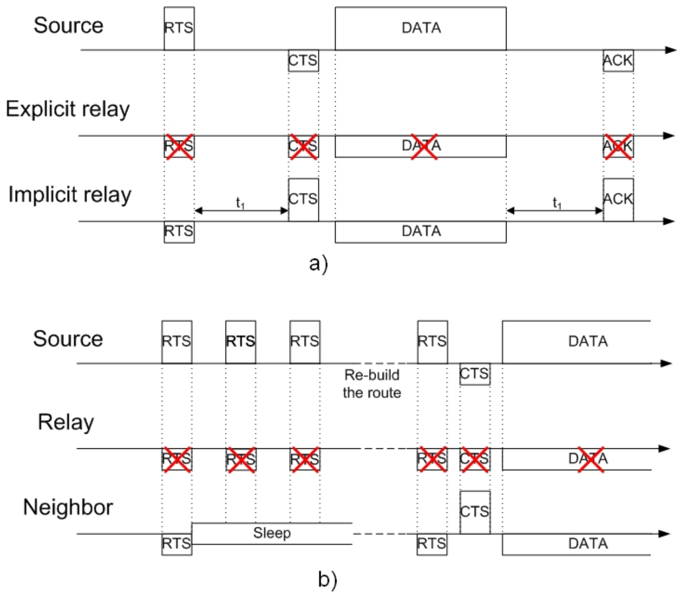


Figure 4: A comparison between a) AreaCast and b) unicast against a faulty relay node.

Algorithm 1 Node X Receives RTS

if X is explicit relay **then**
  Send CTS
else
  if X $\in$ the 3 closest neighbors of the explicit relay node **then**
    Elect itself as implicit relay and chooses its backoff timer
  else
    sleep
  end if
end if
if X is implicit relay $\wedge$ backoff timer expired **then**
  send CTS to Source
end if

Algorithm 2 Node X Receives CTS from node Y

if X is implicit relay **then**
  cancel backoff timer
else
  if X is Source **then**
    Send DATA to Y
  end if
end if

Algorithm 3 Node X Receives DATA from source node

if X is explicit relay **then**
  send ACK to source node
else
  if X is implicit relay **then**
    chooses its backoff timer
  end if
end if
if X is implicit relay $\wedge$ backoff timer expired **then**
  send ACK to Source
end if

Algorithm 4 Node X Receives ACK from node Y

if X is implicit relay **then**
  cancel backoff timer
end if

Parameter	value	
Number of nodes	100	
Field size	$100 \times 100m$	
Propagation model	ideal with no collision nor interference	realistic with log-normal shadowing propagation model
Transmission range	$20m$	
Standard deviation		$2dB$
Transmission power		$-30dBm$
Pathloss exponent		2
Simulated time	$40s$	
Simulation time	$30 - 40s$	
Number of runs	100	

Table 1: Summary of the simulation parameters.

A comparison between unicast and AreaCast against a faulty relay node is shown on Figure 4. AreaCast allows avoiding the useless retransmissions and saves energy and time.

The application of AreaCast to preamble-based protocols is quite simple. Implicit relay nodes self-elect when they receive the preamble frame (identity of the next hop is included). They stay awake during the data packet transmission and send an ACK packet according to the behavior of the explicit relay node.

4 Evaluation

In this section, after introducing simulation parameters, propagation and energy consumption models, we compare AreaCast with S-MAC in terms of delivery ratio and energy consumption.

4.1 Simulation model and assumptions

All the results provided in this section were obtained using WSNet [3], an event-driven simulator for wireless networks.

Simulation parameters. Nodes are randomly deployed on a plane square and are motionless. Each node periodically sends a `hello` packet. Such packets are essential to discover neighborhood, build and maintain a logical structure through the network. In our simulation, a unique sink is assumed at the center of the field. The sensor nodes are considered as fixed during each simulation. A central shortest path routing protocol is considered. To illustrate the dynamicity and weakness of a WSN, we consider faulty nodes and faulty links. k faulty nodes are randomly and uniformly distributed on the network. For our simulations, k varies between 0% and 50% of the node population. Faulty nodes drop RTS, CTS, ACK or DATA packets coming from their neighbors, however, they generate hello packets. We also consider the probability p of faulty links. For our simulations, p varies between 0 and $1/2$. p defines the failure probability of a communication between two nodes. The focus of our simulations is on comparing the AreaCast protocol with the S-MAC protocol. Note that S-MAC uses a classical approach (CSMA-CA with RTS/CTS exchange) to rule the contention access.

The results are averaged over 100 simulation runs for each case with a 95% confidence interval. Table 1 sums up the simulation parameters.

Propagation model. We consider two propagation models. In the first one, ideal, two processes u and v can communicate if and only if their Euclidean distance is at most rad, where rad is the transmission range. In this ideal propagation model, there are neither interferences nor collisions. Hence, each node matches a disk of radius rad in the plane. In the second model, realistic, the range of a radio system is based upon the definition of a signal-to-noise ratio (SNR) threshold. To model interferences, we replace the SNR by

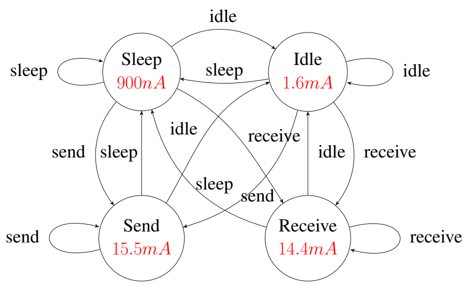


Figure 5: Radio modeled by a finite-state automaton

a signal to interference plus noise ratio, SINR, which takes into account the path-loss, the transmission power and noise level. It should be noted that this assumption leads to a neighborhood instability and coverage areas which are deformed as illustrated on the Figure 6. Moreover, links between nodes can be uni-directional.

Energy consumption model. When modeling energy consumption, there are essentially two approaches: (i) indirect modeling, in which global assumptions like "*sending a message to the sink costs k units of energy*" have to be made; in this case, evaluating energy consumption amounts to counting messages; the validity of the assumptions may be hard to assess; (ii) direct modeling of the consuming hardware elements like the radio device (usually in the form of *power-state* models), coupled with the description of the software that drives them. The latter option is the one implemented in *emulators*, where the details of the execution platform are represented.

Counting messages is too abstract because the idle listening periods (when a node listens to an idle channel to receive potential traffic) are not taken into account, although they contribute to the overall energy consumption in a significant manner.

The approach we follow here is based on an explicit modeling of the power states of the radio device. But it is more abstract than emulators, to preserve good simulation times.

The model of the radio is a 4-state automaton (Fig. 5). Each state represents a consumption *mode*: sleep, idle, receive, or send. Each state is associated with a value related to the instantaneous energy consumption while the radio is in the corresponding mode. The energy consumption labels are taken from the datasheet of the TI CC1100 [1] radio device. The Sleep mode has the lowest consumption; the radio is not able to transmit nor receive. The idle mode is the default state when the radio is not receiving nor transmitting. The receive mode is when the radio is receiving or listening on the wireless channel. The send mode is when the radio is transmitting.

To evaluate the total energy consumption of a node during a given scenario, one has to keep track of the time spent in each of the modes. For this we need to relate the current state of the MAC protocol to the current state (mode) of the radio device.

In this experiment, we consider that the MAC protocol controls the mode changes of the radio entirely. This means that we ignore the situations where the MAC protocol issues a command to the radio to reach a given state (e.g., transmit) but the radio takes some time to get there (e.g., because of a calibration process). Ignoring these intermediate states is allowed if their duration is sufficiently short. When the MAC controls the mode changes entirely, it is sufficient to track the states of the MAC protocol, to be able to track the states of the radio, and hence to compute the total energy consumption.

Our simulation approach combines the precision of a direct modeling of energy consumption, with the performances of abstract simulations. It is integrated in WSNET.

Evaluation metrics. To determine performances of the two compared MAC protocols, we measure the following metrics:

- Average delivery ratio, the ratio between the total number of sent packets and the total number of received packets. This metric allows us to measure the gain in efficiency between the two MAC protocols.
- Average percentage of packets forwarded by at least one implicit relay node,

- Average path length, the number of hops crossed for each received packet,
- Total energy consumption, expressed in mJ, is the total energy consumed by nodes. This energy consumption is computed according to time spent in different radio states.
- Average energy consumption per received packet.

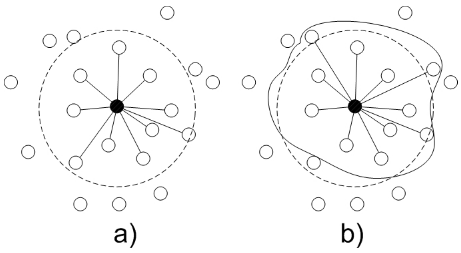


Figure 6: Neighborhood with different radio range modeling: a) Perfect unit disk, b) Links with pathloss and shadowing

4.2 Results and analysis

As expected, the average delivery ratio (Fig. 8) decreases when increasing the number of faulty nodes or links. When the AreaCast protocol is considered, the delivery ratio is significantly higher compared to S-MAC. Using implicit relay nodes allows to continue a RTS/CTS/DATA/ACK dialog at any moment. In S-MAC, the probability of a successful communication is the probability to transmit successfully RTS, CTS, DATA and ACK packets. If one of this communication fails, a retransmission is needed. While in AreaCast, at least one implicit node continues the communication in a dynamic manner. With a realistic propagation model, the delivery ratio of the S-MAC protocol is low even in the absence of faulty nodes. The shortest-path routing algorithm favors distant relay nodes and therefore, weak links. The probability to lose packets increases when the number of hops increases. Moreover, the retransmission mechanism used in the S-MAC protocol increases interferences and collisions. AreaCast is able to handle part of the traffic to the sink using implicit relay nodes to bypass faulty nodes and links. This is confirmed by Fig. 7. Finally, with AreaCast the network continues to operate even in presence of faulty nodes and links.

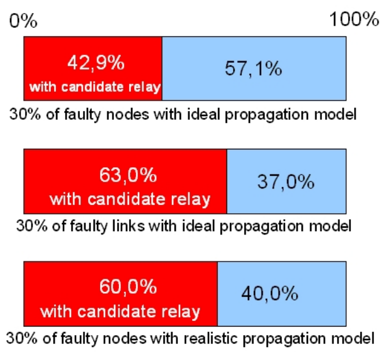
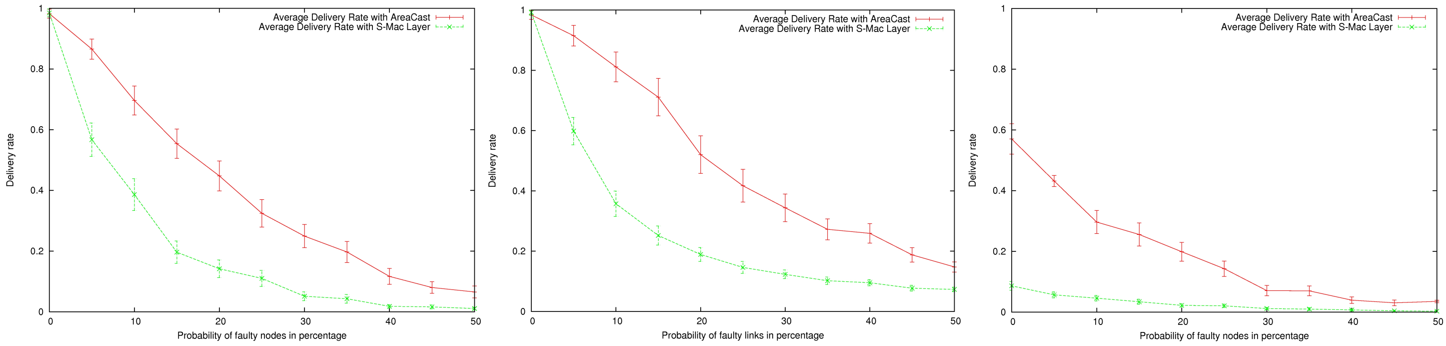


Figure 7: Percentage of received packets forwarded by at least one implicit relay node.

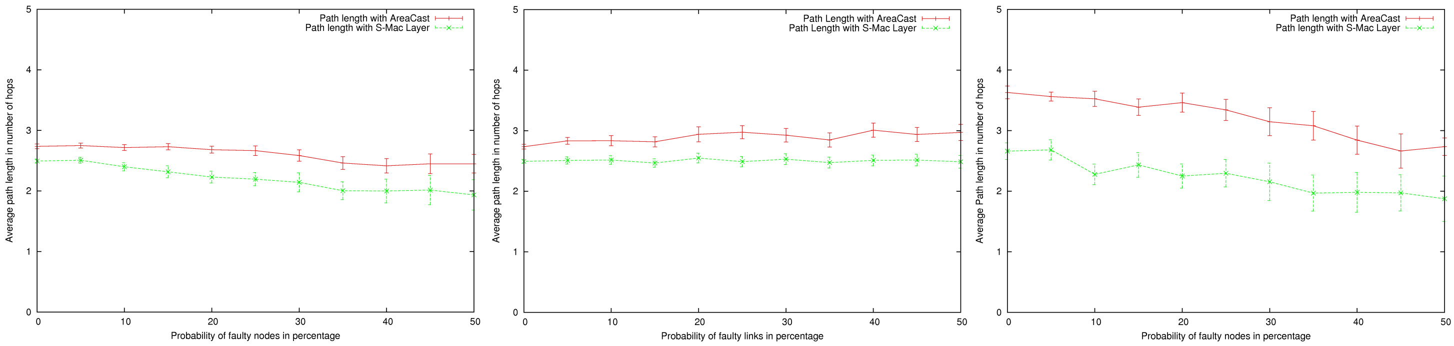
The average path length (Fig. 9) is quite constant when the number of faulty nodes or links increases. The difference of path length between the AreaCast and the S-MAC protocols can be explained by two phenomena:

- To avoid a dead node, AreaCast uses implicit relay nodes that can increase the number of hops crossed by the packet to reach destination.



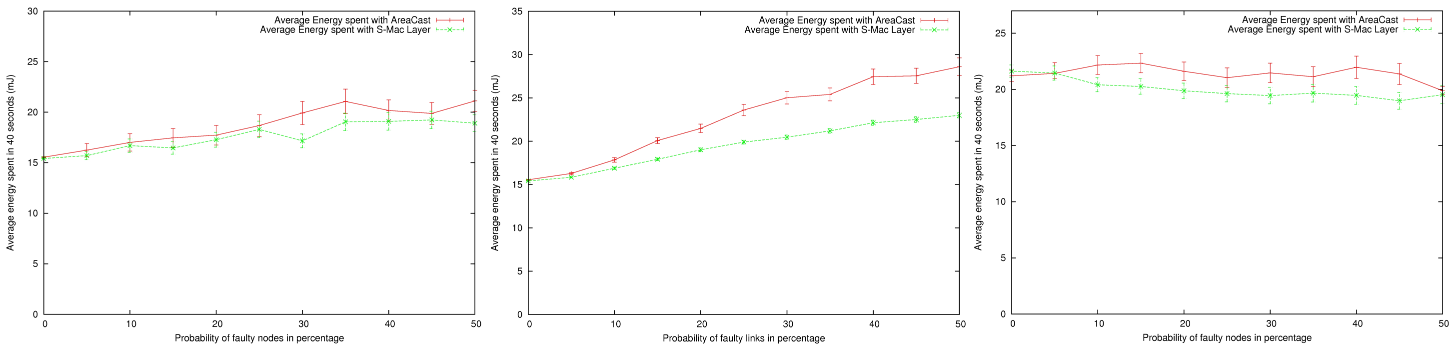
(a) (b) (c)

Figure 8: Evolution of delivery ratio: (a) against node failures; (b) against link failures; (c) against node failures in case of realistic propagation model



(a) (b) (c)

Figure 9: Evolution of average path length: (a) against node failures; (b) against link failures; (c) against node failures in case of realistic propagation model



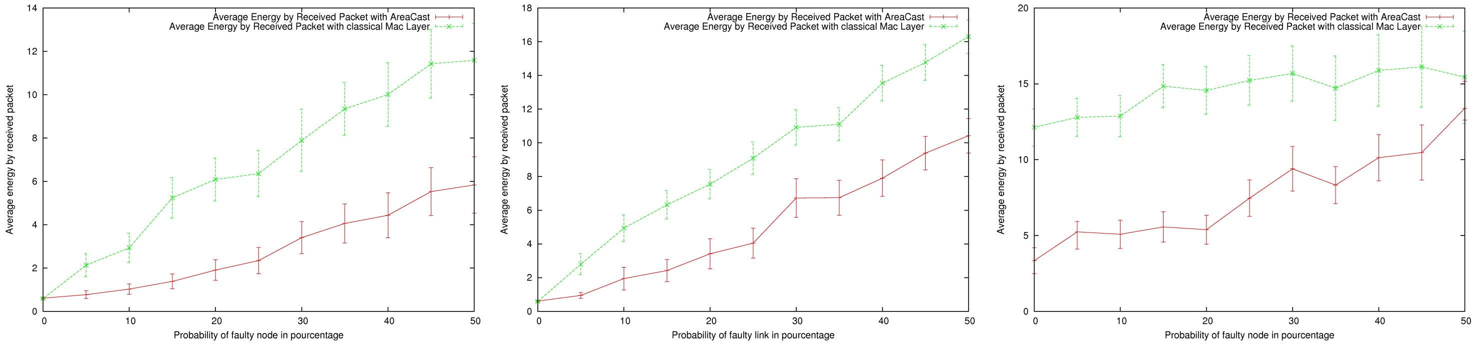
(a) (b) (c)

Figure 10: Protocol overcost in terms of total energy consumption: (a) against node failures; (b) against link failures; (c) against node failures in case of realistic propagation model

- By increasing the delivery ratio, AreaCast allows distant nodes to transmit their packets.

These phenomena are intensified in case of realistic propagation model.

On the one hand, because of overhearing, AreaCast has an energy consumption overcost. Nevertheless,



(a) (b) (c)

Figure 11: Energy consumption per received packet: (a) against node failures; (b) against link failures; (c) against node failures in case of realistic propagation model

this overhearing concerns a small part of the network nodes involved in the multi-hop routing. On the other hand, it minimizes the number of retransmissions and therefore the energy consumption. Moreover, with S-MAC, since dead nodes or faulty links lead to losing packets, this saves energy. As a result, the total energy consumption difference between AreaCast and S-MAC increases when the probability of faulty nodes or links increases (Fig. 10).

But when we study average energy spent per received packet, we note a clearly less important energy consumption. The gain is really important when the number of faulty nodes or links is high. This signifies that AreaCast is a good trade-off between energy consumption and network reliability (Fig. 11).

5 Conclusions and further work

In this article, we have proposed a MAC protocol enhancing the reliability under realistic signal propagation model and in presence of faulty nodes and links. The protocol uses information from routing layer to elect three *implicit relay* nodes within an area close to the *explicit relay* node. AreaCast protocol is especially designed to WSNs, where density is important and nodes are prone to failures. The communication *by area* dynamically avoids faulty nodes and unstable links. Note that the AreaCast protocol is independent of a given routing protocol. Our simulations show that, despite the increasing number of faulty nodes or links, the network is able to continue to deliver data packets to the sink while keeping a satisfactory energy-reliability trade-off.

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