1-hopMAC: An Energy-Efficient MAC Protocol for Avoiding 1-hop Neighborhood Knowledge

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Abstract— 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. Because of their dependence on scarce battery power, communication protocols need to be energy efficient. However, finding the optimal solution is challenging as it needs to consider the whole communication stack at once.

In this paper, we propose an approach that aims at optimizing jointly L2 (link) and L3 (routing) protocols. We design 1-hopMAC, a communication architecture grouping MAC and routing layers which avoids 1-hop neighborhood knowledge. 1-hopMAC can be combined, among others, with a geographic or gradient based routing protocols. We present an analytical study of energy consumption to point out the optimal configuration of 1-hopMAC.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are used in many application areas, ranging from defense and surveillance to health and intelligent homes [1], [2]. WSNs are composed of small sensor nodes capable of doing three complementary tasks: measuring a physical value, processing that value and communicating with other nodes using wireless technology.

A possibly large number of sensors are deployed inside the area that needs to be covered. In an surveillance scenario, upon sensing a feared event (*e.g.* the start of a forest fire) nodes send their alarms to a collecting node.

WSNs have witnessed a tremendous upsurge in recent years. From a networking point of view, these networks have very challenging constraints. First, there is no fixed infrastructure (*e.g.* an access point). Without such a centralized controller, nodes need to cooperate in a distributed manner. Furthermore, topology is subject to changes. Even with static nodes, new nodes can enter the network, and others can disappear because of battery exhaustion or failure. Finally, nodes communicate in a multi-hop way. As transmission power is finite, transmission range is limited. Intermediate nodes between out-of-reach nodes will serve as relaying nodes. Besides, WSNs have specific limitations in terms of processing power, available bandwidth, memory and embedded energy, mainly.

Whereas energy harvesting solution are under investigation [3], current sensor nodes [4] are powered by embedded batteries. The number of nodes can reach thousands, and deployment area can be dangerous. Human intervention on the nodes can therefore not be counted on. This is especially constraining regarding energy, as battery replacement is not possible.

Wireless sensors communicate in a multi-hop manner. Nodes use their local knowledge of the network to communicate globally with all nodes. Local knowledge typically refers to the knowledge of the nodes directly reachable by the node. If a node is directly reachable depends on the transmission range, which depends on several physical factors (distance, transmission power, antennas gains and radiation patterns, fading model and interferences, mainly). We call this set of nodes 1-hop neighbors; the 1-hop neighborhood also includes the node itself. Many routing protocols [5]–[8] have been designed to allow intermediate nodes to be used as relays for otherwise out-of-reach nodes to communicate. One important idea behind those protocols is the knowledge by any node of its 1-hop neighborhood.

1-one neighborhood knowledge traditionally involves periodic information exchange. These messages are called `Hello` packets. Using periodic `Hello` packets has two main drawbacks: (1) as the period between two consecutive `Hello` packets transmissions is not infinitely small, this knowledge is periodically out-of-date — at most of one `Hello` packet period — and (2) periodic message exchange is very costly in terms of energy. With a `Hello` packet scheme, even without useful information exchanged, batteries are rapidly depleted. By tuning the `Hello` packet period, trade off between updating interval and energy consumption is achieved.

To forward a message, a node chooses one node from its 1-hop neighbors and sends it the message. The latter node does the same and relaying goes on until the message reaches destination. To choose the most suitable 1-hop neighbor, a node may use a proactive or a reactive approach. In a proactive approach, the node maintains, through periodic exchange of `Hello` messages, a list of all its 1-hop neighbors with their corresponding metric values. Then, the node has just to pick from this list the neighbor with the best value. In a reactive approach, the node avoids periodic exchange of `Hello` messages; it asks its neighbors to send their metric values each time it needs to choose a relaying neighbor.

In lightly loaded networks, reactive approaches save more energy than proactive ones as they avoid the overhead of periodic `Hello` exchange. We build our solution on top of a reactive approach to circumvent the two main drawbacks

of the `Hello` message scheme: (1) we have an on-demand solution where out-of-date information is avoided, and (2) no energy is used for periodic messages. We obtain an energy efficient communication architecture by combining a three-way handshaking scheme with an energy-efficient MAC (Medium Access Control) protocol.

The remainder of the paper is organized as follows: we provide an overview of related work in Section II. In Section III, we describe our proposed protocol and 3 variants to the basic scheme. We perform an analytical study of energy efficiency on the variants and propose a communication architecture in Section IV. We conclude this paper and present future work in Section V.

II. RELATED WORK

This work has two goals: (1) propose a MAC protocol which can be easily combined with a routing protocol and (2) energy-efficiency.

In this paper, we use our election protocol in Geographic and Gradient Based Routing, which are promising routing schemes for WSNs. We point out that our election protocol has a broad range of applications (choosing the neighbor with most energy, with highest measured temperature . . .).

A. Geographic and gradient based routing

In routing protocols involving some sort of geographic forwarding [6], [9], a node elects its neighbor closest to destination to be the next hop node. Some protocols use gradient based forwarding [5], [8], [10], [11]. In this scheme, a given metric is attached to each node, such as the number of hops it is from destination.

WSNs pose many challenges regarding routing. They have specific characteristics, different from wired or wireless network with a central controller (*e.g.* access point in 802.11) [7]. First of all, it is not suitable to build a global address scheme due to the large number of nodes. Such a scheme involves global control packets for avoiding duplicate addresses, which seems poorly compatible with low bandwidth, energy constrained multi-hop paths. This makes IP-based protocols unsuitable for WSNs. Second, contrary to the traditional one-to-one scheme, communications in most WSN applications are many-to-one. This is because of multiple sources sending messages (*e.g.* sensed data) to a particular node called *sink*. Third, multiple close nodes may sense the same phenomenon and thus generate similar messages at the same time, which results in localized congestion. To avoid such a congestion, data aggregation is needed. Fourth, wireless sensors are constrained in terms of computational power, amount of available memory, bandwidth and energy. Energy constraints are a main challenge for designing a WSN communication architecture.

In [6], the authors propose GPSR, a geographic routing protocol for WSNs. In GPSR, each node is supposed to know its geographical position and that of its 1-hop neighbors. The node knows the positions of its 1-hop neighbors from the `Hello` messages they periodically send. In this scheme, a node chooses the closest node to destination from its 1-hop
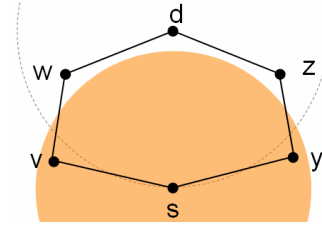

Fig. 1. Greedy forwarding fails at s. Right hand rule uses path s-y-z-d. Filled circle represents s's communication range. Nodes outside the dotted circle are further from d than s. Edges connect nodes able to communicate.

neighborhood as next-hop node, and forwards its data to it. Euclidean distance is used as a closeness metric. This simple approach fails in the case no node is closer to destination than the current node (Fig. 1). GPSR uses the right-hand rule to circumnavigate the void: node s draws an imaginary line from itself to final destination d, and rotates this line to the right, using itself as rotating center. The first node encountered is elected next hop. This way, path to destination is s-y-z-d.

Geographic forwarding needs position awareness. This assumes GPS-enabled nodes, which is an expensive solution. To tackle this problem, Gradient Based Routing (GBR) [12] assigns a *height* to each node. This height can for example be the number of hops to the sink. This is done during a gradient setup phase before runtime: (1) the sink node sends out a message containing *current height* of 0, (2) each node hearing this message puts its height to *current height*+1 and rebroadcasts this message with its height as current height [8]. It is supposed that collisions are avoided by some MAC scheme. Nodes are supposed to know their height and that of their 1-hop neighbors. During runtime, messages are sent by each node to their lowest 1-hop neighbor. This greedy approach (*i.e.* messages flow down the steepest slope) is very similar to greedy geographic forwarding. In this work, we address the problem of using the metrics once they have been set up. Studying energy-efficient metric setup mechanisms is considered future work.

Both routing protocols are very promising for WSNs as they require only local information for choosing network wide paths. No explicit self-organization phase is needed in geographical forwarding and [8] proposes a localized protocol for adapting height to changing topologies (node mobility, nodes arriving or dying). Those protocols nevertheless rely on `Hello` packets for 1-hop neighborhood knowledge, leading to poor energy efficiency. We propose a protocol which avoids 1-hop neighborhood knowledge, thus the use of periodic `Hello` packets.

B. Energy-efficient MAC protocols

Sensor network applications usually generate low traffic load so that the communication channel is expected to be idle most of the time. Therefore, idle listening is the most significant source of energy dissipation. Indeed, without any specific energy management, nodes waste a considerable amount of energy as they keep their radios on for large
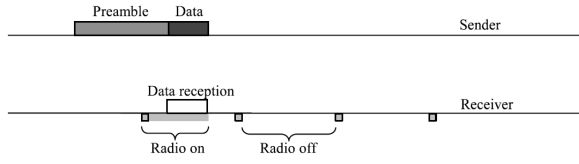
Fig. 2.   Preamble sampling technique.

Fig. 3.   MFP: avoiding reception of irrelevant preamble.

Parameter	Value
f_X	value of metric f at node X
f_{min}	minimum value of f
f_{max}	maximum value of f
f_{first}	smallest f among 1-hop neighbors
REQ	request message
ACK	acknowledgment for REQ
DATA	actual data message
T_{type}	duration, in seconds, of message of type type
P_t	power consumed when radio in transmission state
P_r	power consumed when radio in reception state
P_i	power consumed when radio in idle state
TR_X	time for the radios to be on in variant X
Δt	variation of backoff when f increases by 1
N	mean number of nodes in the 1-neighborhood, incl. sender
f_{thresh}	threshold to switch to 1-hopMAC$_{var3}$ (see IV)

TABLE I

VARIABLE USED THROUGHOUT THIS PAPER.

time intervals while listening to an idle channel. In energy-efficient MAC protocols for sensor networks, to mitigate idle listening, nodes sleep for long periods of time instead of being active permanently. These MAC protocols define a duty-cycle parameter to control the ratio of the activity period to the sleep period [13].

Duty cycles of 1% may substantially reduce energy consumption. However, if a node wakes up only at some chosen instants, there is a need for a method to detect transmissions of other nodes. There are two ways for making it possible for nodes to communicate without message loss due to a transmission to a node that is sleeping. The first approach used in protocols like SMAC [13], TMAC [14] and others, nodes synchronize on a common sleep/wakeup schedule by exchanging synchronization messages to set their sleep/wakeup schedule. The second way used in protocols like WiseMAC [15] and BMAC [16], does not fix a common schedule for sleep and wakeup periods to avoid synchronization overhead and to further reduce idle listening in low-rate data networks. Instead, each node chooses its own sleep/wakeup schedule independently of the others and a node transmits a preamble before each data frame which is long enough to make sure that all potential receivers will get their data. We call the second approach *preamble sampling* MAC (PS-MAC) [14].

Fig. 2 shows an example of a PS-MAC protocol operation. According to the duty-cycle parameter, nodes switch periodically their radios on to sample the channel. If a node finds the channel is idle, it goes back to sleep immediately. However, if it detects a preamble transmission on the channel, then it keeps its radio on until it receives the subsequent data frame. After receiving the data frame, the node goes back to sleep. To be effective, preamble transmission needs to be at least as long as the period between two consecutive instants of node wakeup. This way, a node makes sure that all potential receivers are awake during its preamble transmission and they get the subsequent data frame.

MFP [17] is a variant to PS-MAC which avoids receiving irrelevant preamble and data messages. The idea is to divide the preamble into a series of consecutive micro-frames. Each of these micro-frames contains the destination nodes address and the number of still to come micro frames before the actual data. After listening to a micro-frame, a node turns it radio off. Only if it is the destination for the data, the node turns its radio on again when the actual data is sent (see Fig. 3).

In [18], it is shown that preamble sampling techniques can yield ultra-low power MAC protocols and, under ideal conditions (scheduled message emissions, perfect synchronization),
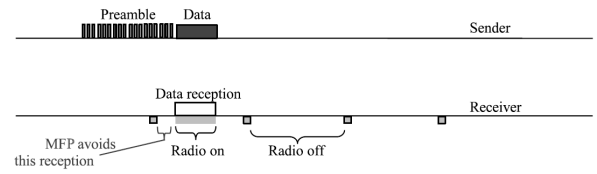
the resulting protocol is optimal regarding energy consumption. In this paper, we combine geographic and gradient based routing with a preamble sampling MAC protocol to obtain a energy-efficient communication architecture.

III. PROPOSED PROTOCOL AND VARIANTS

It this section, we start by giving the assumptions and models used; then, we present the basic 1-hopMAC protocol, together with 3 variants. We will call these variants 1-hopMAC$_{basic}$, 1-hopMAC$_{var1}$, 1-hopMAC$_{var2}$ and 1-hopMAC$_{var3}$, respectively.

A. Assumptions and model used

We consider that links may be unidirectional, and communication areas can be of any shape. We consider the nodes' radios cannot detect collision in the sense that they are not able to make the difference between collisions and transmission errors. This assumption is based on the fact that detecting collision, albeit feasible, requires dedicated algorithms and, due to the wireless nature of the communication links, is not always reliable. For instance, current wireless sensor radio chips (such as Chipcon CC1000 or CC2420) do not inform upper layers of message collision. We also assume that each node knows the deployment-dependent network density, *i.e.* N, the average number of nodes in its 1-hop neighborhood. All variables used throughout this paper – including the ones not presented yet – are listed in Table I.

f is generic and can be of any kind: number of hops or geographical distance to destination, residual energy, etc. Multiple nodes can have the same metric, and we assume all
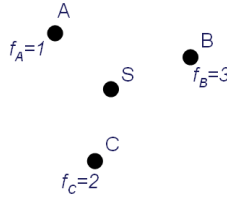
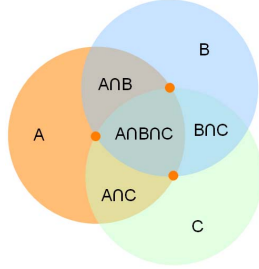Fig. 4.   The topology used during description.

Fig. 5.   Without handshaking, successful relaying node election is only possible if A B and C are within each others transmission range, i.e. in $A \cap B \cap C$. Transmission ranges are presented here as colored circles.

metrics can only be inside $[f_{min}, f_{max}]$. We will use the topology depicted in Fig. 4 when describing our protocol. Node S wants to send out a message to node A which has the lowest metric f_A. A is thus elected relaying node.

To extract our protocol's energy efficiency, we use an energy model. In this model, each node has three states Tx, Rx and $idle$, depending on whether the radio is in transmission, reception or idle state, respectively. We associate a power consumption to each state: P_t, P_r and P_i. We simplify this model by saying $P_t = P_r$ and $P_i = 0$. This way, energy consumption is proportional to the time radio is in transmission or reception state (radio is on). On actual sensors, the radio accounts for more than 90% of the overall consumed power [4], so other energy consuming parts (sensing, and computing, mainly) are not modeled here.

B. Not using handshaking

As a starting point, using only the most basic approach, S sends out a request message. On hearing this message A, B and C trigger a timer proportional to their metric and answer when this timer elapses. To have only one relaying node, all timers are aborted upon hearing the first reply. Nevertheless, nodes A, B and C may not hear each other. This could lead to three distinct relays. Successful timer abortion will only be possible if all nodes are within each others transmission range. Fig. 5 shows that this assumption is hard to reach. We therefore implement a protocol which involves handshaking.

C. 1-hopMAC$_{basic}$

A node sends out a request message received by its 1-hop neighborhood. Each neighbor will answer this request after a time proportional to its metric. The requesting node can then elect the most suitable node based on when it has received the answers.
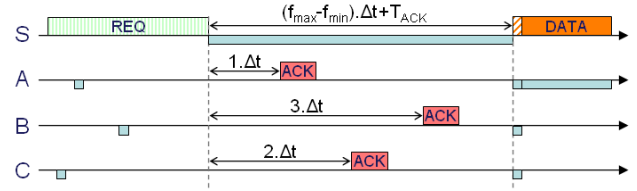

Fig. 6.   1-hopMAC$_{basic}$. Radio is in reception/transmission state when bloc appears under/above the line, respectively. When no bloc, the radio is in idle state.
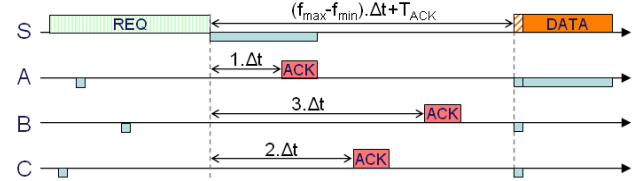

Fig. 7.   1-hopMAC$_{var1}$: reduce S's listening period.

We here present the basic 1-hopMAC protocol.

(1) S sends out a request message.

(2) A, B and C reply with an *ACK* message after a time proportional to $f_A - f_{min}$, $f_B - f_{min}$ and $f_C - f_{min}$, respectively. Δt is used here to convert a metric into a duration. Before sending out *ACK*, each node listens to the channel to make sure no other *ACK* is being sent. We hereby avoid collisions if nodes can hear each other's *ACK*s.

(3) S decides which node will be elected and sends out the message, including in its header the identifier of the node that should receive it (here A).

The resulting communication diagram is presented in Fig. 6. S starts by sending out its request *REQ*. This is done using the micro-frame preamble sampling MAC described in [17]. Each micro-frame contains the instant at which backoff timers can be started. When a node wakes up, it samples the medium for the minimal duration d and it knows when it has to start its timer. All nodes are thus synchronized at the end of the *REQ* message (the first vertical bar in Fig. 6). From this first synchronization point on, S listens to possible acknowledgment *ACK* messages. As f is bounded, no *ACK* messages will be sent after $\Delta t \cdot (f_{max} - f_{min})$. As all nodes know f_{max} and f_{min}, there is a second synchronization point. Right after second synchronization, S sends out a small header containing the next hop node it has elected. All nodes listen to this message, and go to sleep, except the elected node – here A – which receives the *DATA* message.

D. 1-hopMAC$_{var1}$: reduce S's listening period

After hearing the first ACK message, S knows which node will be elected as relaying node, so its radio can be turned off. This first variant is presented in Fig. 7.

E. 1-hopMAC$_{var2}$: avoid multiple ACK messages

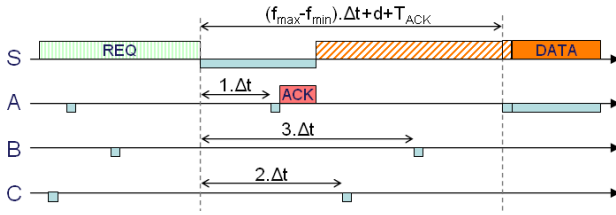After A's *ACK*, B and C's *ACK*s are useless. To avoid this, we can have S send out a "don't answer anymore"

Fig. 8. 1-hopMAC$_{var2}$: avoid multiple ACK messages.

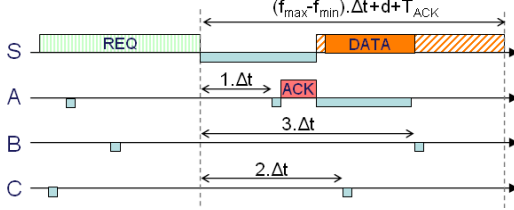Fig. 10. Avoiding collisions between multiple REQ messages.

Fig. 9. 1-hopMAC$_{var3}$: direct answer.

message from the moment it has received its first *ACK* until the second synchronization point. As all nodes listen to the channel right before sending an *ACK*, useless *ACK* messages will be avoided. This variant is presented in Fig. 8.

This variant is beneficial only when the extra power consumed by S to sent its "don't answer anymore" message is smaller than the energy B and C would have used to send their *ACK* message. We will study this threshold in detail in Section IV.

F. 1-hopMAC$_{var3}$: direct answer

As depicted in Fig. 9, it is beneficial to send the *DATA* message during the "don't answer anymore" message period. As with 1-hopMAC$_{var2}$, nodes B and C do not send useless *ACK*s. After having sent an *ACK*, A needs to listen to the medium. Indeed, S announces it has elected A right after receiving its *ACK*. A needs to stay in reception state to receive the message.

G. Handling collisions

In case f values are close to each other's, or equal, *ACK* messages can collide. Nevertheless, if nodes can hear each other *ACK*, collision is avoided as each node listens to the channel before sending an *ACK*. If not, collision probability is greater than 0. If f values are close to each other's – but not equal – this probability drops while increasing Δt. We tune Δt depending on an acceptable collision probability. [19] shows that determining an analytical value of the collision probability is not trivial. An analytical study on collision probability versus Δt will be presented in future work.

As with *ACK* messages, collisions between several *REQ* messages is possible. To minimize this probability, all nodes willing to send a message listen to the medium first. This way, as depicted in Fig. 10, B will only send out its *REQ* message when transmission from S has ended.
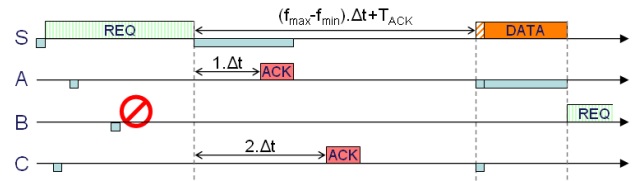
IV. ANALYTICAL STUDY

We have four variants of our protocol: 1-hopMAC$_{basic}$, 1-hopMAC$_{var1}$, 1-hopMAC$_{var2}$, 1-hopMAC$_{var3}$. In this section, by analytical study, we answer *which variant is more suitable in which case ?*

A. Times for the radios to be on

As described in section III-A, we approximate energy consumption of variant X by TR_X the cumulated time radios are on within the 1-hop neighborhood Eqs. (1)–(4). Remember that N is the number of nodes in the 1-hop neighborhood, including the sender, and that d is the minimal time needed by a node to sample the channel. For the sake of simplicity, we assume that the duration of the election message is equal to d the average duration of receiving one micro frame. In Eqs. (1)–(4), the items between square brackets correspond to the energy consumed by the sender, by the receiver, and by other nodes within sender's 1-hop neighborhood, respectively.

$$
\begin{aligned}
TR_{basic} \;=\; & \big[T_{REQ} + (f_{max} - f_{min}) \cdot \Delta t + T_{ACK} + \\
& d + T_{DATA}\big] \\
& + \big[d + T_{ACK} + d + T_{DATA}\big] \\
& + \big[(N-2)\big(d + T_{ACK} + d\big)\big],
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
TR_{var1} \;=\; & \big[T_{REQ} + (f_{first} - f_{min}) \cdot \Delta t + T_{ACK} + \\
& d + T_{DATA}\big] \\
& + \big[d + T_{ACK} + d + T_{DATA}\big] \\
& + \big[(N-2)\big(d + T_{ACK} + d\big)\big],
\end{aligned}
\tag{2}
$$

$$
\begin{aligned}
TR_{var2} \;=\; & \big[T_{REQ} + (f_{max} - f_{min}) \cdot \Delta t + d + T_{ACK} + \\
& d + T_{DATA}\big] \\
& + \big[d + d + T_{ACK} + d + T_{DATA}\big] \\
& + \big[(N-2)\big(d + d\big)\big],
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
TR_{var3} \;=\; & \big[T_{REQ} + (f_{first} - f_{min}) \cdot \Delta t + d + T_{ACK} + \\
& d + T_{DATA} + max\big(0; (f_{max} - f_{min}) \cdot \Delta t \\
& + d + T_{ACK} - (f_{first} - f_{min}) \cdot \Delta t \\
& - d - T_{ACK} - d - T_{DATA}\big)\big] \\
& + \big[d + d + T_{ACK} + d + T_{DATA}\big] \\
& + \big[(N-2)\big(d + d\big)\big].
\end{aligned}
\tag{4}
$$

B. Comparative analysis

We compare now above equations, looking for the protocol's variant which consumes least energy. We extract the following rules:

Rule 1: As $TR_{basic} > TR_{var1}$, 1-hopMAC$_{var1}$ should always be used instead of 1-hopMAC$_{basic}$.

Rule 2: We study $TR_{var2} - TR_{var1}$. 1-hopMAC$_{var2}$ should be used instead of 1-hopMAC$_{var1}$ only if:

$$f_{first} > \frac{f_{max} \cdot \Delta t + (2 - N)T_{ACK} + 2d}{\Delta t}.$$

We call the right hand part of this inequality f_{thresh}.

Rule 3: As $TR_{var2} \geq TR_{var3}$, 1-hopMAC$_{var3}$ should always be used instead of 1-hopMAC$_{var2}$.

We conclude that we should use 1-hopMAC$_{var1}$ or 1-hopMAC$_{var3}$, depending on the value of f_{first}.

C. Proposed communication architecture: 1-hopMAC

Swapping between 1-hopMAC$_{var1}$ and 1-hopMAC$_{var3}$ can be done dynamically. As all nodes know f_{max}, Δt, N, T_{ACK} and d, they calculate f_{thresh}. Any node with f higher than f_{thresh} uses 1-hopMAC$_{var3}$, others 1-hopMAC$_{var1}$. For a neighbor node, the difference is that it has to listen to the channel after having transmitted its *ACK*. S starts using 1-hopMAC$_{var1}$. If it receives the first *ACK* after $f_{thresh} \cdot \Delta t$, it switches to 1-hopMAC$_{var3}$.

Using this approach, we obtain a multi-mode protocol, where the decision on which mode to use is distributed and no signaling messages are necessary. By swapping between modes, we achieve energy efficiency.

V. CONCLUSION AND FUTURE WORK

This paper has presented a communication architecture grouping the MAC layer and some parts of the routing layer. Our proposition is easily usable with routing protocols such as geographic or gradient based routing, leading to an energy-efficient routing protocol. We took advantage of preamble sampling MAC layer techniques to make 1-hopMAC energy efficient. Without 1-hop neighborhood knowledge, we avoid the outdated data and the perpetual energy consumption induced by a `Hello` packet approach.

In this paper, we have proposed a basic version of 1-hopMAC, and three variants. An analytical study of energy consumption has lead to a communication architecture which dynamically switches between two variants, leading to energy efficiency.

As for future work, we plan to extract 1-hopMAC's energy efficiency through simulation, and look into lifetime increase by comparing it to other communication schemes. Furthermore, we would like to propose a rule to tune the value of Δt depending on the acceptable collision probability between *ACK* messages.

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