A Probabilistic Interference and Energy Aware Gradient Broadcasting Algorithm for Wireless Sensor Networks

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***Abstract*—This paper addresses the problem of robust transmission of sensed data through a vast field of small and vulnerable sensors towards a sink node. It introduces a routing algorithm called P-GRAB relying on a probabilistic gradient broadcasting framework. Our aim is to improve the GRAB algorithm by accounting for the energy expenditure and the potential of a node for creating interference in the forwarding decision of the algorithm. It is the forwarding stage of P-GRAB that differs from GRAB: once a node has the proper cost for broadcasting a packet, it decides to forward it with a given probability depending on its remaining energy level and its interference potential. We show by simulations that P-GRAB outperforms the GRAB algorithm by providing similar robustness but with much fewer forwarding packets and latency for packet delivery.**

I. INTRODUCTION

The reliable transmission of sensed data across large-scale wireless sensor networks (WSN) is of great interest nowadays. Recent technology offers low-cost and low-power chips that can be deployed for monitoring purposes in open fields. When a node senses some change in the environment, it advertises its data to one or several sink nodes. Due to the large scale of such networks, the transmission is multi-hop between the data source node and the sink. Therefore, the routing algorithms must provide robust end-to-end transmissions, which is even more important when nodes are deployed in an environment with severe operational conditions (e.g. high temperature, fire, humidity...). In such conditions, nodes are prone to an increased number of failures and the wireless transmission becomes less reliable.

Redundancy in the packet transmission increases robustness and can be achieved when packets travel on multiple paths in parallel. However, the more copies are sent through the network, the more energy for redundant transmissions is consumed and the sooner the network dies. There is a trade-off between the desired level of robustness and the life duration of the network. In this work, we target applications where the percentage of node failure is high due to severe working conditions. Therefore, single path approaches such as Directed Diffusion [1] or Rumor routing [2] are not suitable. In this case, the source-sink path easily breaks, which triggers a new flooding stage for route discovery.

Robustness is achieved through redundant transmissions, either by defining redundant source to sink paths [3] in the network or by allowing several nodes at a time to forward a packet based on given forwarding policies. Redundant source-sink pathes are constructed in braided multi-path routing algorithms [3], [4], which are multi-path versions of Directed Diffusion. In these works, N routes are reinforced after the flooding stage and maintained with either 'keep alive' packets [3] or by alternatively sending the data in a round robin manner on each path to reduce the route maintaining load [4].

The use of forwarding policies for individual nodes has been addressed in several recent works (cf. [5], [6], [7], [8], [9]) and are often referred to as gradient broadcasting algorithms. In these approaches, no routes are set prior sending data, only costs are assigned to nodes being equal to the minimum cumulative link cost to the sink node. When a sensor has some data to send, it broadcasts its data packet by assigning its own cost to the packet cost Q_p. The neighbor nodes *with costs smaller than the packet cost* Q_p decide to broadcast the packet or not, based on a set of forwarding rules. If the packet is broadcast, its cost Q_p is updated with the cost of the forwarding node. All the cost values of the network create a gradient field whose lowest value is located at the sink and all subsequent transmissions always 'roll down the hill' to reach the sink (cf. Fig1). When several sink nodes exist, several cost fields are determined. The cost field is either set up by an a-priori flooding stage [5], [10], [6], [8] or on-demand with a request / response packet exchange [9], [7]. The policy chosen to decide whether a node closer to the sink forwards or not a message impacts the robustness / energy trade-off and constitutes the heart of the protocol.

In this work, we present a new approach, P-GRAB, that accounts for the interference potential and the energy status of a node in the forwarding decision. The cost field is created as in the GRAB algorithm [6] but the data broadcasting decision follows a probability of forwarding. Our aim is to favor nodes lying in a less dense neighborhood to forward a packet in order to reduce the amount of collisions and to get a better message delivery ratio. Therefore, we assume that the sensors are static

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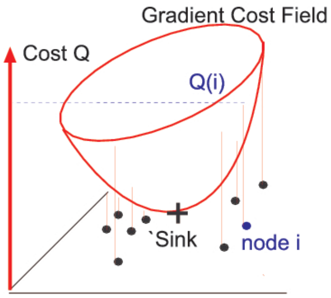

Fig. 1. Gradient cost field.

and know their location. We assign to each node a probability of forwarding that is determined as the product of a probability of interference avoidance component and a probability of life duration component. The probability of interference avoidance is determined based on a neighborhood density measure and the probability of life duration is proportional to the percentage of remaining energy. P-GRAB is compared in the simulations with a basic gradient broadcasting implementation and with the GRAB algorithm [6]. We show that P-GRAB outperforms the GRAB algorithm by providing similar robustness but with much fewer forwarding packets and latency for packet delivery.

This paper is structured as follows: Related work on Gradient Broadcasting is introduced in section II. Section III presents the P-GRAB algorithm and simulation results are provided in section IV.

II. GRADIENT BROADCASTING: BACKGROUND

The basic version of a gradient broadcasting algorithm can be found in [9] and in [5]. There is no additional policy and as long as a node is closer to the sink (i.e. has a smaller cost value than the packet cost), it forwards the packet. This approach triggers an important number of forwarding packets but in turns is the quickest one. Robustness is high but collisions occur at an important rate. Of course, a short term memory stores the identification of the previously transmitted messages to avoid re-transmitting twice the same packet. To reduce the forwarding load, implicit acknowledgement is implemented too: if a node is about to send a packet and notices that a copy of this packet with a smaller cost Q_p is currently being sent on the channel, it does not forward its own packet.

Maróti provides in [5] a global framework for such broadcasting algorithms referred to as 'Directed Flood-Routing Framework' where the decision policy of a node is modeled as a state machine. In addition to presenting the basic version, it proposes a 'Fat Spanning Tree' implementation where the state machine provides rules enabling the 1-hop neighbors of the nodes that belong to the shortest path from source to sink nodes to broadcast the packet. Such approach is more robust to failure than a regular shortest single-path routing protocol. However, he precludes that the spanning tree is constructed in an a-priori flooding stage which adds another expensive flooding step to the protocol.

Chen et al. [7] used the cost field in an different manner as they do not impose strict rules but a selection process of the node that forwards the packet. Their protocol, called Self-Selective Routing (SSR) uses a back-off delay and two broadcast packets to elect the node that forwards the data packet. All the nodes receiving a packet to forward from a node A start a back-off timer proportional to their cost. The closest node to the sink, node B, is the first to send its packet as its backoff is the smallest one. This packet is understood by the neighbor nodes of B as an implicit acknowledgement. To warn the neighbors of A that don't get the implicit acknowledgement from B, node A sends an explicit ACK packet upon reception of the data packet sent by B. This process is robust as paths adjust to failures. It also reduces drastically the number of forwarded packets. But the self-selection process increases the end-to-end delay and the radio layer can never be shut down which increases energy expenditure.

The GRAB algorithm has been proposed by Ye et al. [10], [6] to provide a robust routing algorithm based on the gradient forwarding algorithm concept. To reduce the overhead of multiple forwards, they propose to assign a credit to each data packet that is sent out by a source node. Each forwarding node determines if it has enough credit to broadcast the packet relatively to the distance to the source node. If there is enough credit left, the nodes broadcast the packet to reach a fixed number N_n of nearest neighbors through power adjustment. On the contrary, if credit is low, it only forwards to its nearest neighbor. This creates a forwarding mesh that can be adapted by the choice of the credit or the choice of the number of nearer neighbors. We implemented the GRAB algorithm as a benchmark for our P-GRAB protocol presented here after.

III. THE P-GRAB ALGORITHM

The GRAB algorithm is one solution for reducing the number of forwarding nodes by defining a forwarding mesh using a credit based approach. We compared the GRAB performance with the simplest version of a gradient broadcasting algorithm (referred to as Basic-GRAB) where a node forwards a packet if its cost is smaller than the packet cost (i.e. it is closer to the sink). We observed that GRAB needs less energy than Basic-GRAB for reliable environments. But to achieve the same robustness as the Basic-GRAB algorithm when the probability of node failure increases, GRAB spends as much energy as Basic-GRAB. Our aim is here to provide a gradient-based algorithm that: $i)$ Reduces the number of forwarding nodes when the network is reliable, $ii)$ Provides robust transmissions when the network becomes unreliable.

Let us define a probability of forwarding a packet P_{FW}. When a node n_i, based on its cost value Q_i, is allowed to forward a packet, it forwards the packet with probability P_{FW} defined as follows:

$$P_{FW} = P_{IA} * P_{LD} \tag{1}$$

Where:

- P_{IA} is a measure of the probability of interference avoidance.
- P_{LD} the probability of life duration of the node

A. The probability of Life Duration

P_{LD} is a function of the remaining energy in the node and the way the energy has been spent in the past. Each node knows the number N_F of already broadcasted messages, its initial energy $\mathcal{E}_{initial}$ and the remaining energy $\mathcal{E}_{remaining}$ in its batteries. Before forwarding a packet, the node can estimate how many packet transmissions it can still do with:

$$N_{EF} = \mathcal{E}_{remaining}/\mathcal{E}_F \tag{2}$$

Where $\mathcal{E}_F$ is the energy spent per packet broadcast $\mathcal{E}_F = (\mathcal{E}_{initial} - \mathcal{E}_{remaining})/N_F$. The probability of life duration P_{LD} is defined by:

$$P_{LD} = 1 - 1/(N_{EF} + 1) \tag{3}$$

B. The probability of Interference Avoidance

We define P_{IA} as $P_{IA} = 1 - P_c$, with P_c the probability of collision. A realtime estimation of the congestion may rely on a feedback procedure at the MAC level based on an RTS/CTS packet exchange. We consider that such MAC feature would drain too much power on the sensor nodes and thus we propose a simpler estimate based only on the geographical distribution of the nodes.

The denser the vicinity of a node is, the more likely the channel gets congested. We define here a relative measure of neighborhood density that considers the difference in size of a node's neighborhood relatively to the size of the neighborhoods of its 1-hop neighbor nodes. Let N_i be the number of neighbors of node n_i. A node v_j is a neighbor of n_i if the received power P_{ji} at location j from node n_i verifies $P_{ji} > P_{lim}$ with P_{lim} the sensitivity of a sensor. A node n_i can estimate the average discrepancy between its neighborhood size N_i and the neighborhood size of its neighbor nodes N_j for $j \in [1..N_i]$. This measures how much more (or how much less) sensors the node n_i is disturbing than its neighbor nodes. This average neighborhood discrepancy Δ_i of node n_i is defined by:

$$\Delta_i = \frac{\sum_{j=1}^{N_i}(N_i - N_j)}{N_i} \tag{4}$$

If $\Delta_i = 0$, the node distribution is uniform. If $\Delta_i > 0$ (resp. $\Delta_i < 0$), node n_i belongs to a denser (resp. sparser) neighborhood than its 1-hop neighbors.

To favor the forwarding of nodes that provide less interference to their neighborhood, we define a conversion function denoted f_{erfc} that assigns a probability P_{IA} to every value of Δ_i. This function relies on the the complementary error function $x \rightarrow \mathrm{erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^{\infty} e^{-t^2}dt$ that is scaled to fit to the set of Δ_i values. f_{erfc} is represented in Figure 2.

In this function, the parameter K ($K \geq 1$) spreads or shrinks the function. For small values of K, the nodes that yield high interference almost never forward a packet while nodes that belong to sparse neighborhoods almost always forward. For high values of K, P_{IA} is closer to a linear function of Δ_i.

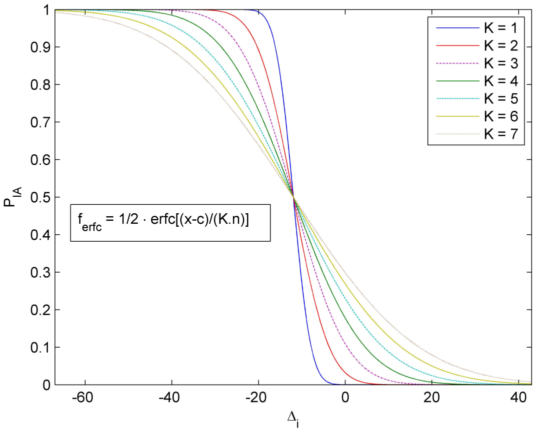

Fig. 2. Conversion function f_{erfc}.

IV. SIMULATION RESULTS

This section compares the performance of P-GRAB to the results obtained with GRAB and Basic-GRAB. Robustness, energy and end-to-end delay are assessed for a 1000-nodes network in a 500 × 500 meters area. Nodes are randomly distributed and simulation results are averaged over 100 runs. Each sensor follows the specifications of a MICA2 Mote [11]. For every run, 30 randomly positioned events are created, triggering about 30 +/- 5 messages.

All the protocols have been implemented with the OMNet++ simulator in a modified version of the SENSIM sensor network simulator presented in [12]. We enhanced the SENSIM simulator by adding a realistic radio layer model that accurately accounts for collisions originating from congestion and interference. In this layer, a node is able to completely demodulate a packet if and only if the Signal to Noise and Interference Ratio (SINR) is high enough during the whole packet reception duration. We also added a basic CSMA MAC layer to the simulator where a node sends its packet after a random waiting time. There is no feedback on local network congestion. Additional node failure is modeled with a uniform probability $p_f \in \{0, 0.4, 0.8\}$.

We have first investigated the effect of the spreading factor K of P-GRAB. The impact of K on robustness or delay is negligible, but it really modifies the energy consumption pattern. In Fig.3, it is for small values of K that we get the fewest number of forwarded messages without reducing the robustness of the algorithm. In this case, the conversion function is close to a simpler ramp model that can be easily implemented on a sensor node.

In Fig. 4 and 5, we compare the results of P-GRAB ($K = 2$) to GRAB and Basic-GRAB in terms of robustness (i.e. message success ratio), average end-to-end delay, total number of forwarded messages and energy (i.e. percentage of the initial available energy). We use the results obtained with GRAB for a credit factor $F_\alpha = 10$ as we get the most robust transmissions for this parameter. Standard deviation values are also presented on Fig. 4 and 5 for all the algorithms.

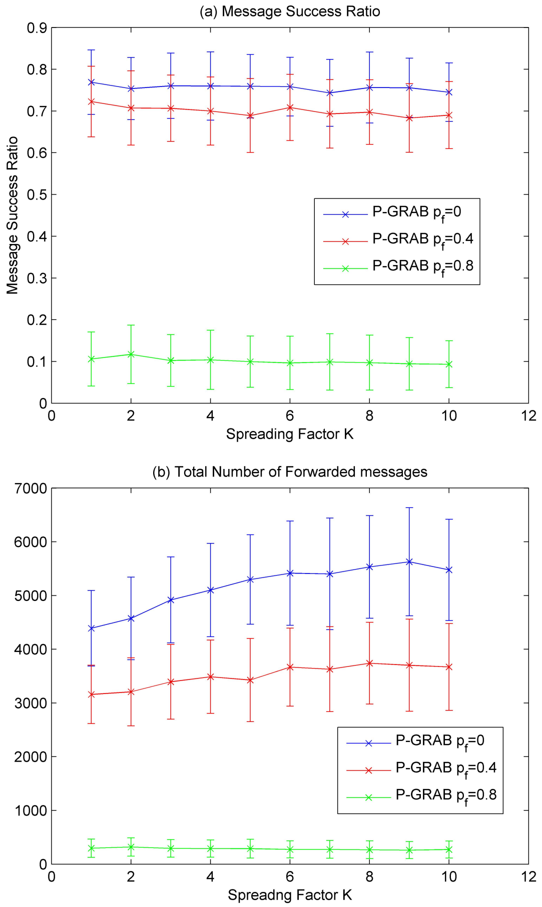

Fig. 3. Impact of the spreading factor K on the total number of forwarded packets (Top) and on the robustness (Bottom).

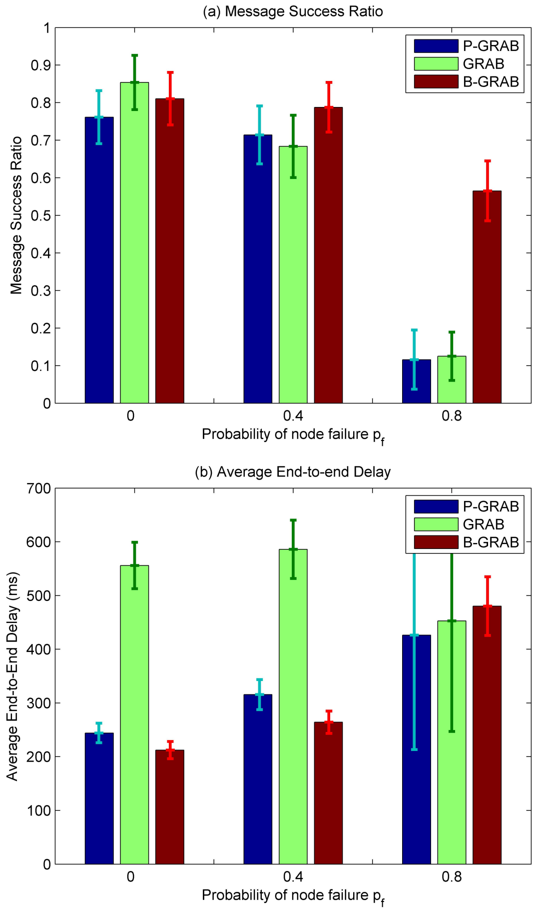

Fig. 4. Comparison of P-GRAB ($K = 2$) to GRAB ($F_\alpha = 10$) and Basic-GRAB for $p_f = \{0, 0.4, 0.8\}$. Performance metrics are: (a)- The message success ratio, (b)- The average end-to-end delay.

From Fig. 5 we see that P-GRAB outperforms GRAB and Basic-GRAB in terms of the total number of forwarded messages. It needs at least 30% less messages than GRAB and 50% less than Basic-GRAB. This decrease in redundancy still provides the same level of robustness as GRAB (Basic-GRAB is the most robust solution but also the most expensive one. It is presented here as a benchmark algorithm). In terms of the overall energy expenditure, P-GRAB uses about the same level of overall energy than GRAB when $p_f = 0$ even though it forwards much fewer messages. This is mostly due to the power adjustment feature of GRAB that limits the number of neighbors receiving a packet to 3 nodes. Such a mechanism triggers more messages but needs fewer transmission power when the network is reliable, resulting in a better overall energy performance. However, when the probability of node failures increases, transmission powers in GRAB have to be increased to compensate for the loss of density in a node's neighborhood. In this case, as shown in Fig.5, the decrease in the number of forwarded packets of P-GRAB is beneficial as it reduces the overall energy consumed and still guarantees the same level of robustness.

To illustrate this statement, the trade-off between energy consumption and robustness for both GRAB and P-GRAB is represented in Fig.6. The values obtained for $p_f = [0, 0.4, 0.8]$ are provided for both algorithms. When $p_f = 0$, we can clearly see that GRAB provides a better robustness/energy performance. But when the network gets unreliable, P-GRAB outperforms GRAB by providing solutions that need less energy than GRAB while still guaranteeing the same level of robustness. Accounting for the interference distribution in P-GRAB allows to efficiently reduce the number of packets transmitted without any loss in robustness.

In terms of delay, P-GRAB is almost as fast as Basic-GRAB and for low to middle probabilities of node failure, it outperforms GRAB resulting in about 50% improvement in latency. As the number of neighbors receiving a message in GRAB is much smaller than for P-GRAB (3 neighbors versus about 35 for P-GRAB), a message needs many more hops to transit in the network, resulting in a higher average delay to arrive at the sink. When addressing the performance metrics assessed here, we can state that P-GRAB outperforms GRAB as it provides as good robustness results as GRAB but reduces the energy expenditure and increases the network reactivity.

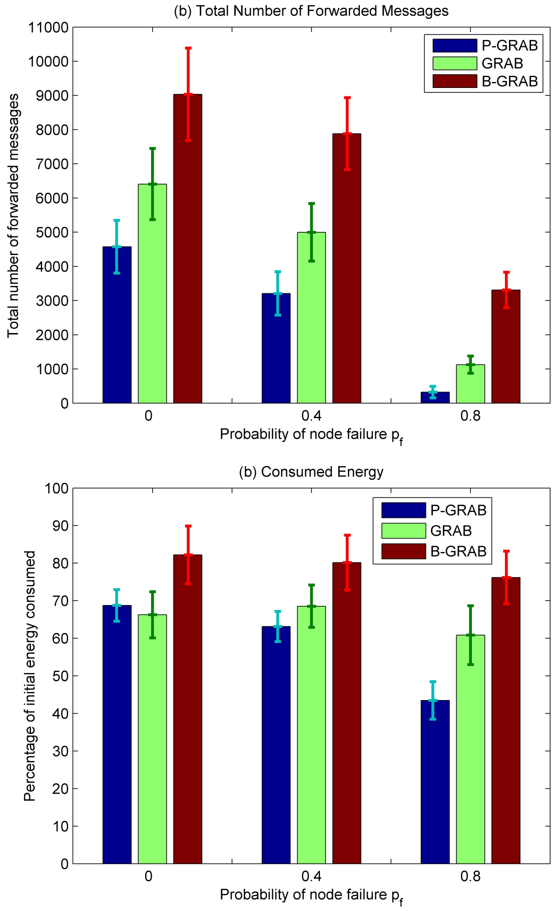

Fig. 5. Comparison of P-GRAB ($K = 2$) to GRAB ($F_\alpha = 10$) and Basic-GRAB for $p_f = \{0, 0.4, 0.8\}$. Performance metrics are: (a)- The total number of forwarded messages, (b)- The percentage of the initial energy spent.

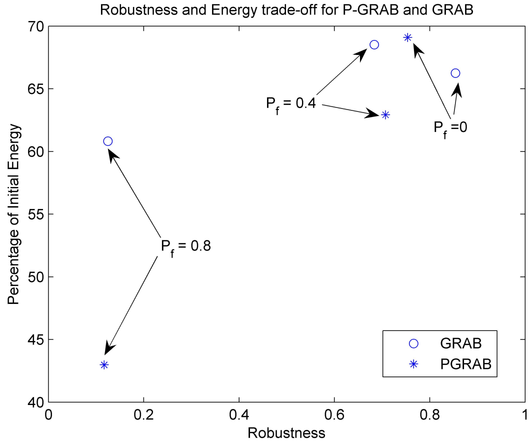

Fig. 6. Robustness and energy tradeoffs for P-GRAB ($K = 2$) and GRAB ($F_\alpha = 10$) for several values of $p_f = \{0, 0.4, 0.8\}$.

V. CONCLUSION

This work proposes a new probabilistic approach for gradient based routing algorithms in wireless sensor networks. The P-GRAB algorithm is proposed to enhance the GRAB gradient broadcasting algorithm. By defining P-GRAB, we aim to reduce the number of nodes forwarding messages. In P-GRAB, we have introduced a probability of forwarding that accounts for the potential of a node to create interference and also for the energy still available for transmission. Our simulation results confirm that P-GRAB outperforms GRAB in terms of energy savings and delay, while preserving the robustness property.

These results have been obtained for a predefined global value of the spreading factor K used in the definition of the probability of forwarding. This K value might not provide the best outcome for every node. In future work, we will investigate the problem of assigning the best spreading factor to each node of the network. Based on the congestion status of the channel, K can be adjusted to fine tune the probability of forwarding, using a distributed learning algorithm within a game theoretical framework.

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