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Cost and Collision Minimizing Forwarding Schemes for Wireless Sensor Networks

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***Abstract*—The paper presents a novel integrated MAC/routing scheme for wireless sensor networking. Our design objective is to elect the next hop for data forwarding by minimizing the number of messages and, at the same time, maximizing the probability of electing the best candidate node. To this aim, we represent the suitability of a node to act as the relay by means of locally calculated and generic cost metrics. Based on these costs, we analytically model the access selection problem through dynamic programming techniques thereby devising the optimal access policy. We subsequently derive a contention-based MAC and forwarding scheme, named Cost and Collision Minimizing Routing (CCMR). Both analytical and simulation results are given to demonstrate the effectiveness of our technique by comparing its performance against state of the art solutions.**

I. Introduction and Related Work

Forwarding algorithms for WSNs should be *simple*, as sensor nodes are inherently resource constrained. Moreover, they should also be *efficient* in terms of energy consumption and quality of the paths that are used to route packets towards the data gathering point (referred to here as sink). The trend in recent research is to select the next hop for data forwarding locally [1]–[6] and without using routing tables. Such a localized neighbor election is aimed at minimizing the overhead incurred in creating and maintaining the routing paths. Usually, nodes are assumed to know their geographical location. Such a knowledge can be exploited to implement on–line routing solutions where the next hop is chosen depending on the advancement towards the sink. However, in addition to the maximization of the advancement, other objectives, such as the maximization of residual energies, should be taken into account. [1]–[6] are *localized routing algorithms* (LRAs), where nodes only exchange information with their one–hop neighbors. This local information exchange is essential to achieve scalability, while avoiding the substantial communication costs incurred in propagating path discovery/update messages.

GeRaF [1] is an example of geographical integrated MAC and routing scheme where the forwarding area is subdivided into a number of regions, whose priority depends on the geographical advancement provided by the nodes therein. The next hop is elected by means of a channel contention mechanism, where the nodes with higher priority contend first. This has the effect of reducing the number of nodes which simultaneously transmit within a single contention, whilst increasing the probability of electing a relay node with a good geographical advancement. The authors in [2] propose Contention Based Forwarding (CBF). In their scheme the next hop is elected by means of a distributed contention. CBF makes use of biased timers, i.e., nodes with higher advancements respond first to contention requests. The value of the timers is determined based on heuristics. A similar approach is exploited in [3], where the authors propose the Implicit Geographic Forwarding (IGF) scheme. This technique accounts for biased timers as well. Response times are calculated by also considering the node's residual energy and a further random term. Advancements, energies and random components are encoded into cost metrics. The random term improves the performance when multiple nodes have similar costs. In [4] the authors improve the performance of LRAs by presenting the concept of *partial topology knowledge forwarding*. Sensors are assumed to know the state of the nodes within their communication range (called *knowledge range* in [4]) only. Their goal is to optimally tune, based on the local topology, the communication range (local view) at each sensor in order to approach globally optimal routing. Reference [5] proposes the MACRO integrated MAC/routing protocol. This is a localized approach relying on priority regions as [1] by, in addition, exploiting power control features for improved energy efficiency. A common denominator among these forwarding schemes is that they are all based on some sort of cost metrics, which are locally computed, and take into consideration the goodness of a node to be elected as the relay. Costs are often calculated by accounting for the progress towards the sink, but other factors such as residual energy and transmission power are also considered [7]. We however observe that the next hop election is achieved by means of cost–aware heuristics which are not optimal.

In this paper, we present an original forwarding technique which couples the desirable features of previous schemes, such as the local nature of the next hop election and the definition of suitable cost metrics, with *optimal access policies*. Specifically, we consider a sensor network where traffic flows from the nodes to the sink. Assume the forwarding process is at a generic node and this node has a number of active neighbors. Our objective is to elect the next hop among them by maximizing the probability that MAC contention successfully chooses the best node in the set. The next hop should be picked efficiently (in terms of both access time and energy consumption), while accounting for the goodness of the choice, where goodness represents geographical advancement, energy level, state of the queue, link quality, etc. The goodness of the node choice is captured by a cost, normalized in $[0,1]$, that is associated with each node in the network. This cost may be dynamically varying and is calculated on demand by the candidate relay nodes. In the contention to be the relay, routing and channel access are integrated. In fact, the contention is driven by the node costs,

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which also account for routing aspects such as the advancement towards the sink. Based on these costs, we formulate the access selection as a dynamic programming optimization problem. Subsequently, we find the optimal access policy and we use it to derive a contention-based MAC and forwarding scheme, named Cost and Collision Minimizing Routing (CCMR). We finally show the effectiveness of our solution by means of extensive and detailed simulation results, where we compare CCMR against previous algorithms [2], [3] while considering realistic cost metrics. Our approach can be seen as a generalization of [1], [5], [6] as contentions are carried out by considering cost-dependent access probabilities instead of geographical [1] or transmission power-aware [5] priority regions. Moreover, we optimize the access mechanism jointly over multiple access slots, rather than focusing on heuristic strategies for single slot contentions as was done in [6]. Also, as our solution provides a method to locally and optimally elect the next hop for a given knowledge range (transmission power), we note that it can be readily coupled with previous work [4]. We further observe that our forwarding scheme is designed to be reactive to the network dynamics and to elect the next hop with extremely low overhead. For these reasons, we integrated routing with a contention based MAC not requiring time synchronization. A comparison with schedule based MACs such as S-MAC or TRAMA [8], [9] is not addressed here due to both space constraints and their different optimization criteria. This study is left for future investigation.

The paper is structured as follows. The analytical framework, including the cost model and the characterization of the optimal access policy, is presented in Section II. In Section III we derive a complete cost-aware forwarding technique exploiting the optimal policy. Section IV presents simulation results and Section V concludes the paper.

II. Analytical Framework

A. Cost Model

In this section, we introduce a simple analytical cost model that we adopt to design our scheme. In doing so, we explicitly account for the correlation ρ among costs, as this parameter affects the optimal channel access behavior the most. In the next subsections, such a cost model is used to derive the optimal access policy and to design an integrated channel access/routing protocol. In Section IV simulation results are given to demonstrate the validity of the approach in the presence of realistic costs, depending on geographical advancements and energy levels.

Let us consider a generic set $\mathcal{S}_N$ of N nodes, where we refer to c_k as the cost associated with node $k \in \mathcal{S}_N$. In order to model the cost correlation, we assume that c_k is given by $c_k = \overline{c} + \gamma_k$, where $\overline{c} \in [0, 1]$ is a cost component common to all nodes, whereas γ_k is an additive random displacement uniformly distributed in $[-\alpha\overline{c}, \alpha(1 - \overline{c})]$, $\alpha \in [0,1]$, and independently picked for every node k. For instance, $\alpha = 0$ corresponds to the fully correlated case as all node costs collapse to $\overline{c}$. On the other hand, $\alpha = 1$ gives the i.i.d. case ($\rho = 0$) as the costs of every pair of nodes in $\mathcal{S}_N$ are uncorrelated. Intermediate values of α lead to a correlation $\rho \in (0, 1)$. The correlation coefficient between any two nodes $r, s \in \mathcal{S}_N$ is $\rho_{r,s} = (E[c_r c_s] - E[c_r]E[c_s])/(\sigma_r \sigma_s)$ where $\sigma_s^2 = E[(c_s - E[c_s])^2]$. It can be verified that:

$$\rho_{r,s} = \frac{(1-\alpha)^2}{(1-\alpha)^2 + \alpha^2} \,. \tag{1}$$

Note that there is a one-to-one mapping between α and ρ as Eq. (1) is invertible. Also, for a given $(\alpha, \overline{c})$ pair, all costs fall in the interval $[c_{min}, c_{max}]$, where $c_{min} = \overline{c} - \alpha\overline{c}$ and $c_{max} = \overline{c} + \alpha(1 - \overline{c})$, thus the cost set can be specified in terms of either $(\alpha, \overline{c})$ or (c_{min}, c_{max}). Moreover, by specifying α and $\overline{c}$ or, equivalently, c_{min} and c_{max}, we only know that all costs are *uniformly* and independently distributed in the subset $[c_{min}, c_{max}] \subseteq [0, 1]$, which means that our cost model has maximum entropy. In fact, for a given $(\alpha, \overline{c})$ pair there is maximum uncertainty for the actual position of the costs in $[c_{min}, c_{max}]$. We finally observe that finding an optimal policy by considering this cost model makes sense from both a practical and a theoretical point of view. From a practical standpoint, this model requires only two parameters to statistically characterize the costs by accounting for their correlation. This is especially useful in sensor networks due to their inherently limited resources. From a theoretical point of view, we note that maximum entropy also corresponds to the worst case in terms of performance. In fact, any other distribution able to track the cost correlation would lead to a more precise statistical description of the costs.

B. State Space Representation and Problem Formulation

Let us consider the next hop election problem for a given node in the network. Such an election is performed by means of MAC contentions which usually consume resources in terms of both time and energy. Broadly speaking, our goal is to elect the relay node by maximizing the joint probability that a node wins the contention and it has the smallest cost (or a sufficiently small cost) among all active neighbors. The formal problem statement is given at the end of this subsection. Here, we refer to this election strategy as *optimal*. According to our scheme, the node sends a request (REQ) addressed to all nodes in its active (or forwarding) set, which is composed of all active neighbors providing a positive advancement towards the sink. Upon receiving the REQ, the active nodes in this set transmit a reply (REP) by considering a slotted time frame of W slots. Specifically, each node picks one of these slots according to its cost and uses it to transmit a REP to the inquiring node. The first node sending a REP captures the channel so that the nodes choosing a later slot refrain from transmitting their REPs.

To model the above scheme and find the *optimal* slot election strategy under any cost correlation value, we proceed as follows. For each node we account for a cost and a token, the latter being a number which is randomly picked in $[0, 1]$ at every contention round. Tokens are used to model cost-unaware access probabilities [10]. In more detail, when costs are fully correlated ($\rho = 1$) the nodes should pick the access slots by only considering their tokens, as their costs are all equivalent by definition. In this case, the aim of the algorithm is to select any node in the forwarding set by maximizing the probability of having a successful contention; the solution reduces to the

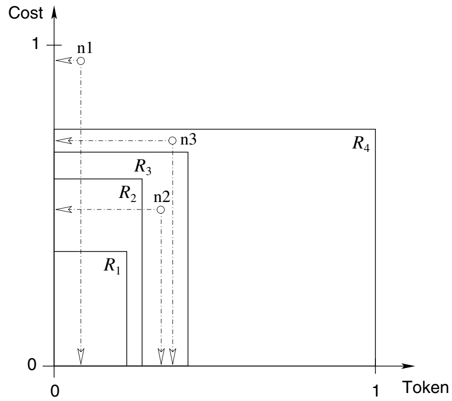

Fig. 1. Example of access regions and nodes representation for $W = 4$.

one in [11]. On the other hand, when costs are completely uncorrelated ($\rho = 0$), tokens must be disregarded and the slot selection should be made on the basis of the node costs only. Finally, if the cost correlation is in $(0, 1)$, both costs and tokens should be taken into account in the selection of the access slot. In addition, in order to simplify the problem formulation, access probabilities can be expressed in terms of access intervals as we explain next. For illustration, consider the case where $\rho = 1$, i.e., only tokens are accounted for in making access decisions. In this case, at any given node and for a given slot, accessing the channel with a given probability p is equivalent to accessing the channel if the token is within the interval $[0, p]$. When $\rho = 0$, the same rationale can be used for the costs, by defining intervals in the cost space. In the most general case ($\rho \in (0, 1)$) we can define rectangular *access regions* spanning over both costs and tokens. For the sake of explanation, we illustrate the concept by means of the example in Fig. 1, where we plot an access slot selection example for $W = 4$ slots. A formal treatment is given in Section II-C. The active set is composed of the 3 nodes n1, n2 and n3 which are plotted in the token-cost space by means of white filled circles. We associate the access regions R_1, R_2, R_3 and R_4 with the access slots $1, 2, 3$ and 4, respectively. Note that $R_1 \subset R_2 \subset R_3 \subset R_4$; this property holds in the general case, see Section II-C. For the slot selection, each node picks the access slot corresponding to the smallest region containing its (cost, token) pair. Specifically, in the first slot none of the nodes can access the channel. In fact, R_3 is the first region containing a node, n2 in our example, which therefore sends its REP in the third slot. Note that according to our slot selection strategy, n3 would be allowed to transmit its REP in slot 4. However, it refrains from transmitting the REP in this slot as it senses the ongoing communication of node n2. In this example a single node (n2) accesses the channel and this is the node with the minimum cost in the active set. We observe that collisions (multiple nodes select the same slot) are possible. Moreover, although it could also be possible that the winner of the contention is not the node with the minimum cost, our solution is aimed at minimizing the probability of occurrence of this event.

The problem to be solved can be formulated as follows. For a given active set $\mathcal{S}_N$, characterized by the number of nodes N therein and their cost correlation ρ, and for a given number of contention slots W, our objective is to find the sequence of access regions $R_1, R_2, \dots, R_W$ maximizing the joint probability that a node wins the contention and has a sufficiently low cost. The term "sufficiently low" means that the absolute value of the difference between the cost of the winner and the minimum cost in the set is smaller than or equal to a certain parameter $\varepsilon \in [0, 1]$ that we use to define the optimality criterion. In more detail, if $\varepsilon = 0$ we aim at electing the node with the smallest cost in $\mathcal{S}_N$, whereas if $\varepsilon \in (0, 1]$ we relax our optimality requirement. We mathematically formulate and solve this problem in subsection II-C.

C. Optimal Access Schedules: Analysis

We represent the generic access region $R_i, i \in \{1, 2, \dots, W\}$ by means of a cost-token pair (c_i, t_i), where $c_i, t_i \in [0, 1]$. With (c_i, t_i) we understand that the region R_i is identified by the two intervals $[0, c_i]$ and $[0, t_i]$ for the cost and the token spaces, respectively. We observe that, as tokens are uniformly and independently drawn in $[0, 1]$, the only fact that counts for the optimization over the token space is the length of the token interval. For the costs, our assumption is also correct as we aim at electing a node with a small (possibly the smallest, see later) cost in the active set $\mathcal{S}_N$. Moreover, we observe that $R_1, R_2, \dots, R_W$ is an *increasing sequence*. With this term we mean that if $R_i = (c_i, t_i)$, $i \in \{1, 2, \dots, W-1\}$, the region associated with slot $i+1$ must be $R_{i+1} \supset R_i$, i.e., (c_{i+1}, t_{i+1}) should comply with one of the following three cases: 1. $c_{i+1} > c_i$ and $t_{i+1} = t_i$, 2. $c_{i+1} = c_i$ and $t_{i+1} > t_i$, 3. $c_{i+1} > c_i$ and $t_{i+1} > t_i$. In fact, if $R_i = (c_i, t_i)$ and no node accesses the channel in slot i, it does not make sense to have $R_{i+1} = R_i$ as in this case no node will access the channel in slot $i+1$ as well, and this is trivially inefficient. To proceed with our analytical formulation we introduce the following definitions:

Definition 1: consider an active set $\mathcal{S}_N$ of N nodes and a constant $\varepsilon \in [0, 1]$. We define node $k \in \mathcal{S}_N$ as ε-optimal if $c_j \geq \max(0, c_k - \varepsilon)$, $\forall\ j \in \mathcal{S}_N$, $j \neq k$, i.e., if none of the remaining nodes has a cost strictly smaller than $c_k - \varepsilon$.

Definition 2: We say that slot i is **silent** if no node chooses this slot and that there is a **collision** if two or more nodes pick the same slot i. In addition, we say that a node **wins** in slot i if it is the only sensor picking this slot and all previous slots $1, 2, \dots, i-1$ were silent. Finally, we say that a given contention round is **successful** according to a given $\varepsilon \in [0, 1]$ (optimality criterion) if there is a node that wins in any slot in $\{1, 2, \dots, W\}$ and this node is ε-optimal.

Note that the following analysis is conditioned on the values α (ρ), the number of nodes in the active set N and the common cost component $\bar{c}$. For readability, we do not explicitly state these conditions. In order to get to the recursive expression of the probability of a successful event, we introduce the following quantities by considering the cost model in Section II-A:

i) Probability $P_T(t_a, t_b)$ that the token of a given node falls within the generic interval $[t_a, t_b] \subseteq [0, 1]$. This probability is given by $P_T(t_a, t_b) = t_b - t_a$.

ii) Probability $P_C(c_a, c_b)$ that the cost of a given node $k \in \mathcal{S}_N$ falls in the generic cost interval $[c_a, c_b] \subseteq [0, 1]$. We note that for node k, $P_C(c_a, c_b) = P\{\bar{c} + \gamma_k \in [c_a, c_b]\}$. Therefore $P_C(c_a, c_b) = \int_{c_a - \bar{c}}^{c_b - \bar{c}} f(\gamma)\ \mathrm{d}\gamma$, where $f(\cdot)$ is the probability density function (pdf) of the random cost displacement γ_k. $f(\gamma)$ equals $1/\alpha$ for $\gamma \in [-\alpha\overline{c}, \alpha(1-\overline{c})]$ and zero otherwise. By solving the above integral we obtain the following close form expression:

$$P_C(c_a, c_b) = \begin{cases} 1 & \alpha = 0 \\ & \text{and } \overline{c} \in [c_a, c_b] \\ [\min(c_b, c_{max}) & \\ -\max(c_a, c_{min})]\alpha^{-1} & \alpha \in (0,1] \\ & \text{and } c_b \geq c_{min} \\ & \text{and } c_a \leq c_{max} \\ 0 & \text{otherwise}, \end{cases} \quad (2)$$

where $c_{min} = \overline{c} - \alpha\overline{c}$ and $c_{max} = \overline{c} + \alpha(1-\overline{c})$, see Section II-A.

iii) We now calculate the probability $P_{\text{noTX}}\{R_i\}$ that none of the nodes transmit in slots $1, 2, \ldots, i$ (region R_i). The cost and token intervals associated with R_i are $[0, c_i]$ and $[0, t_i]$, respectively. $P_{\text{noTX}}\{R_i\}$ is found as follows:

$$P_{\text{noTX}}\{R_i\} = [1 - P_T(0, t_i) P_C(0, c_i)]^N , \quad (3)$$

where N is the number of nodes in $\mathcal{S}_N$, $P_T(\cdot)$ and $P_C(\cdot)$ are defined in i) and ii) and we used the fact that tokens and costs are independent by construction.

iv) In the following, we focus on the probability $P_{\text{noTX}}\{R_i|R_{i-1}\}$ that none of the N nodes access the channel in a given slot i given that no node transmitted in slots $1, 2, \ldots, i-1$. By using Bayes' formula we can write:

$$P_{\text{noTX}}\{R_i|R_{i-1}\} = \frac{P_{\text{noTX}}\{R_i\}}{P_{\text{noTX}}\{R_{i-1}\}} , \quad (4)$$

where we used the fact that region R_i contains region R_{i-1} and therefore if R_i is empty R_{i-1} must also be empty.

v) We now consider the event that the generic slot i is successful. In particular, we refer to S_i as the event that a single node transmits in slot i, that its cost is ε-optimal and that no nodes transmitted in slots $1, 2, \ldots, i-1$. The probability of this event is referred to as $P\{S_i\}$ and is found by means of the following integral:

$$\begin{aligned} P\{S_i\} &= N\Bigg[\int_0^{c_{i-1}} P_T(t_{i-1}, t_i)\xi(c, N-1) f_{\text{cost}}(c)\, \mathrm{d}c \\ &+ \int_{c_{i-1}}^{c_i} P_T(0, t_i)\xi(c, N-1) f_{\text{cost}}(c)\, \mathrm{d}c\Bigg] . \end{aligned} \quad (5)$$

In the above equation we integrate over the cost region $[0, c_i]$ by splitting this integration interval in $[0, c_{i-1}]$ and $(c_{i-1}, c_i]$. In both terms we use the cost pdf $f_{\text{cost}}(c)$ to account for the fact that the node transmitting in slot i (the winner of the contention) has cost equal to c. Considering the first integral, $P_T(t_{i-1}, t_i)$ gives the probability that the token of this node falls in $(t_{i-1}, t_i]$ so that the node is entitled to transmitting in slot i but not in slots $1, 2, \ldots, i-1$. For the second integral, we instead consider the probability that the token of the winner is in $[0, t_i]$ (term $P_T(0, t_i)$). In fact, the integration interval $(c_{i-1}, c_i]$ already accounts for the fact that the winner cannot pick a slot in $1, 2, \ldots, i-1$. The factor N is due to the N ways in which it is possible to elect a winner. Finally, the term $\xi(c, N-1)$, which appears in both integrals, returns the joint probability that the remaining $N-1$ users do not transmit in any of the slots up to and including slot i and their cost is larger than or equal to $c - \varepsilon$ (this ensures ε-optimality for the node transmitting in slot i). $\xi(c, N-1)$ is obtained as follows:

$$\Big[P_C(\max(0, c-\varepsilon), c_i) P_T(t_i, 1) + P_C(c_i, 1)\Big]^{N-1} , \quad (6)$$

where, for each of the $N-1$ remaining users, we account for the mutually exclusive cases where the cost of the node is larger than c_i (term $P_C(c_i, 1)$) and the case where the node cost is within $[0, c_i]$, is larger than or equal to $c - \varepsilon$ (this accounts for ε-optimality, see term $P_C(\max(0, c-\varepsilon), c_i)$) and the token is outside the interval $[0, t_i]$ (term $P_T(t_i, 1)$). By factoring out the common terms and writing $P_T(\cdot)$ as in point i), Eq. (5) can be simplified as follows:

$$P\{S_i\} = N\left[t_i \int_0^{c_i} \Psi(c)\, \mathrm{d}c - t_{i-1} \int_0^{c_{i-1}} \Psi(c)\, \mathrm{d}c\right] , \quad (7)$$

where $\Psi(c) = \xi(c, N-1) f_{\text{cost}}(c)$. To express the above equation in close form, we need to solve the following integral $I(x) = \int_0^x \Psi(c)\, \mathrm{d}c$. By considering that $f_{\text{cost}}(c) = 1/\alpha$ if $c \in [c_{min}, c_{max}]$ and zero otherwise and that $c_{min} \geq 0$, $I(x)$ can be rewritten as follows:

$$I(x) = \int_{c_{min}}^{\min(x, c_{max})} \xi(c, N-1)\, \alpha^{-1}\, \mathrm{d}c \quad x > c_{min}, \quad (8)$$

and $I(x) = 0$ for $x \leq c_{min}$. The calculation of $I(x)$ involves the following two cases: a) $c_{min} < x \leq c_{max}$ and b) $x > c_{max}$. For readability, we skip the tedious calculations for these two cases and we give the close form solution for $I(x)$ in Eq. (9) at the top of the next page. Finally, $P\{S_i\}$ is obtained in close form as follows:

$$P\{S_i\} = \begin{cases} N(t_i - t_{i-1})(1-t_i)^{N-1} & \alpha = 0, \overline{c} \in [0, c_{i-1}] \\ N t_i (1-t_i)^{N-1} & \alpha = 0, \overline{c} \in (c_{i-1}, c_i] \\ 0 & \alpha = 0, \overline{c} \notin [0, c_i] \\ N[t_i I(c_i) - t_{i-1} I(c_{i-1})] & \alpha \in (0, 1] . \end{cases} \quad (10)$$

Consider the first line of the previous equation. As $\alpha = 0$ all costs are equal and the optimization is carried out on the token space. Thus, the probability of having a winner is equal to the probability that one of the nodes has the token in $(t_{i-1}, t_i]$, as if it had the token in $[0, t_{i-1}]$ it could have accessed the channel in a previous slot ($< i$), and that the remaining $N-1$ users have their tokens in $(t_i, 1]$, i.e., they are entitled to sending their REPs in a later slot ($> i$). As above, N accounts for the number of ways in which it is possible to elect a winner. Similar considerations apply for the second and third lines of Eq. (10). Also, note that for $\alpha = 0$ ε-optimality is always verified as all costs are equal.

vi) We finally consider the last building block for our analysis which consists of the probability of having a successful reply in the generic slot i (R_i), given that all previous slots (R_{i-1}) are silent. We refer to this probability as $P_{\text{succ}}\{R_i|R_{i-1}\}$, which is readily found via Bayes' formula by considering the results in iii) and v):

$$P_{\text{succ}}\{R_i|R_{i-1}\} = \frac{P\{S_i\}}{P_{\text{noTX}}\{R_{i-1}\}} . \quad (11)$$

$$\begin{aligned} I(x) &= \Big\{[\min(x, c_{min}+\varepsilon, c_{max}) - c_{min}][k_1(k_2 - c_{min}) + P_C(c_i,1)]^{N-1} + \\ &+ \frac{[k_1(k_2 - \min(x, c_{min}+\varepsilon, c_{max}) + \varepsilon) + P_C(c_i,1)]^N - [k_1(k_2 - \min(x, c_{max}) + \varepsilon) + P_C(c_i,1)]^N}{k_1 N}\Big\}\alpha^{-1} \\ k_1 &= (1-t_i)\alpha^{-1} \\ k_2 &= \min(c_i, c_{max}) \end{aligned} \tag{9}$$

$$\varphi(i, R_{i-1}) = \begin{cases} \max\limits_{R_i \supset R_{i-1}} \; P_{\text{succ}}\{R_i|R_{i-1}\} & i = W \\ \max\limits_{R_i \supset R_{i-1}} \left[P_{\text{succ}}\{R_i|R_{i-1}\} \; + P_{\text{noTX}}\{R_i|R_{i-1}\}\,\varphi(i+1, R_i)\right] & i \in \{1,2,\ldots,W-1\} \end{cases} \tag{12}$$

Next, we derive the maximum probability that a single contention round is **successful** for a given optimality criterion ε. This probability is written as a function of the access regions, the number of nodes N in $\mathcal{S}_N$, the common cost component $\overline{c}$ and the cost correlation ρ. For a generic slot i, we define $\varphi(i, R_{i-1})$ as the maximum probability to have a successful reply in some slot in $i, i+1, \ldots, W$ given that all previous slots $1, 2, \ldots, i-1$ were silent and that the region associated with the last slot $(i-1)$ is R_{i-1}. This probability is found according to a dynamic programming formulation [12] as detailed next. For the last slot W, and for a given region R_{W-1}, $\varphi(W, R_{W-1})$ is found by maximizing over $R_W \supset R_{W-1}$ the probability of having a successful reply in the last slot given that all previous slots were silent ($P_{\text{succ}}\{R_W|R_{W-1}\}$). To find $\varphi(W-1, R_{W-2})$, we proceed by applying a backward recursion as follows. For a given (R_{W-2}, R_{W-1}) pair, the maximum probability of having a success in any of the last two slots ($W-1$ or W) is given by the probability of having a success in slot $W-1$ given that all previous slots were silent $P_{\text{succ}}\{R_{W-1}|R_{W-2}\}$ summed to the probability that slot $W-1$ is also silent, $P_{\text{noTX}}\{R_{W-1}|R_{W-2}\}$, multiplied by the maximum success probability in the last slot $\varphi(W, R_{W-1})$. $\varphi(W-1, R_{W-2})$ is found by maximizing the latter calculation over the feasible values of R_{W-1}, i.e., $R_{W-1} \supset R_{W-2}$. The same reasoning can be recursively written for each access slot by means of the optimality Equation (12). The maximum probability of having a successful round is finally given by $\varphi(1, R_0)$, where $R_0 = (0,0)$ by construction. The optimal access policy is given by the sequence of access regions $R_1^*, R_2^*, \ldots, R_W^*$ leading to $\varphi(1, R_0)$. In particular, the optimal policy specifies for each pair (i, R_{i-1}) an access region $R_i^* = (c_i^*, t_i^*)$ maximizing the right size of the optimality equation. Both the maximum probability that a single contention round is successful $\varphi(1, R_0)$ and the optimal access regions can be found by numerical approximation and recursive fixing techniques [12]. The results of these computations are discussed in the next Section II-D.

D. Optimal Access Schedules: Discussion of Results

As a first result, in Fig. 2 we show the probability $\varphi(1, R_0)$ of having a **successful** contention round using the optimal policy, by averaging over $\overline{c}$ (uniformly distributed in $[0,1]$). The parameters for this figure are $\varepsilon = 0$, $\rho = 0.5$. A perfect knowledge is assumed at the transmitter for the number of contenders N, the cost correlation ρ and $\overline{c}$. As expected, $\varphi(1, R_0)$ increases with an increasing number of access slots W: increasing W from 1 to 10 almost doubles the performance, whereas further increasing it ($10 \rightarrow 20$) only provides marginal improvements. Also, for a given W, the success probability quickly stabilizes ($N \geq 10$) to its asymptotic value. In our implementation of the scheme, we chose $W = 10$ to obtain a reasonable tradeoff between complexity and effectiveness.

In Figs. 3 and 4 we plot the optimal access regions for costs and tokens, respectively. Notably, the value of ρ does have an impact on the shape of the regions. In practice, the case $\rho = 0$ is the most selective in the sense that high costs, for any given slot, are penalized the most. Also, we observe that for $\rho = 1$ all costs are equal by construction and hence they should not affect the slot selection process. This is in fact verified in Fig. 3, where cost regions are all equal to one for $\rho = 1$. This concept can be remarked by looking at Fig. 4, where we plot the token regions t_i^* for the same system parameters. In this case, t_i^* are equal to one for $\rho \in [0, 1)$. This means that for these values of ρ the tokens do not influence the slot selection which is only driven by the costs. On the other hand, for $\rho = 1$, costs are no more relevant to the access policy. We finally observe that *token* regions t_i^* when $\rho = 0$ are equal to the *cost* regions c_i^* for $\rho = 1$. This suggests a sort of *duality* between costs and tokens in these two extreme cases.

By analyzing the obtained results for $\varepsilon = 0$ we found an interesting connection with the findings in [11], whose theory allows to find the optimal access probability for every slot when all costs are equal ($\rho = 1$). If N is the number of contenders, i is the generic access slot, and $N \geq 2$, we define $f_s(N)$ as: $f_1(N) = 0$ and $f_s(N) = ((N-1)/(N - f_{s-1}(N)))$ for $s \geq 2$. According to [11], the optimal value of the probability that a user selects i as its access slot is:

$$p_i^* = \frac{1 - f_{W-i}(N)}{N - f_{W-i}(N)}(1 - p_1^* - p_2^* - \cdots - p_{i-1}^*)\,. \tag{13}$$

Choosing the access slots according to the above p_i^*s leads to the maximization of the probability that a single node accesses the channel during a given contention round. Note that this distribution does not depend on the node costs ($\rho = 1$ in our framework). In fact, for $\rho = 1$ our problem reduces to the one considered in [11]. Hence, in this case our token regions t_i^* must lead to the same slot selection policy dictated by the p_i^*s

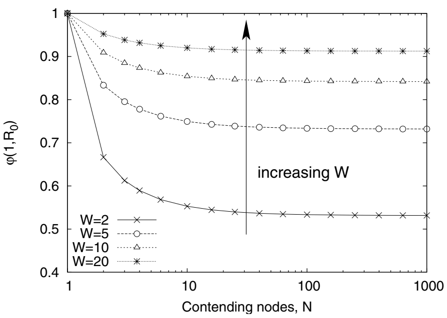

Fig. 2. $\varphi(1, R_0)$ as a function of N.

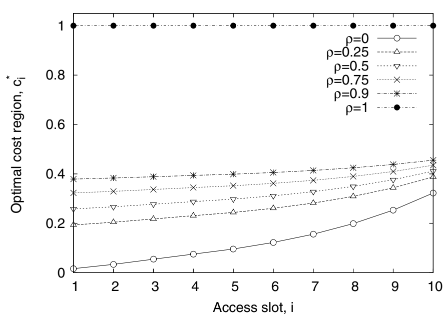

Fig. 3. c_i^* for $N = 10$, $W = 10$, $\bar{c} = 0.5$.

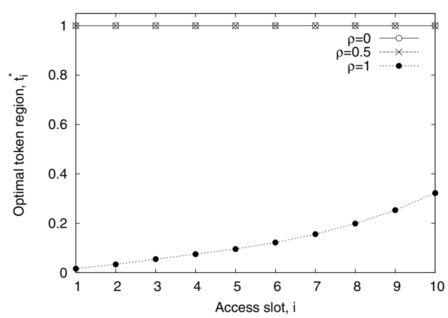

Fig. 4. t_i^* for $N = 10$, $W = 10$, $\bar{c} = 0.5$.

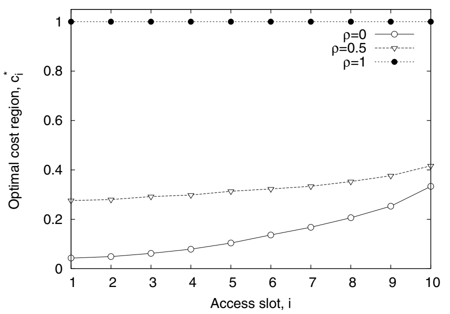

Fig. 5. c_i^* for $N = W = 10$, $\bar{c} = 0.5$, $\varepsilon = 0.1$.

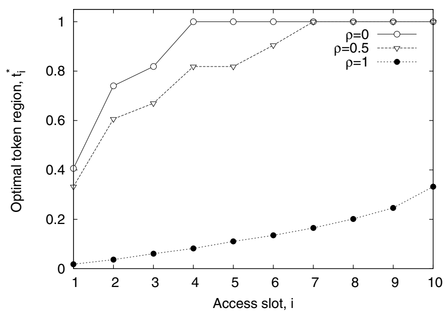

Fig. 6. t_i^* for $N = W = 10$, $\bar{c} = 0.5$, $\varepsilon = 0.1$.

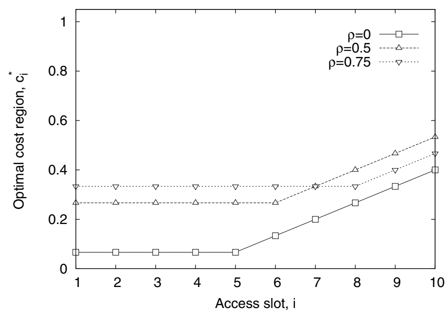

Fig. 7. c_i^*: quantized state space.

in Eq. (13). According to our scheme, a node picks the generic slot i if and only if its token is in $(t_{i-1}^*, t_i^*]$. The probability of such an event is $\pi_i^* = t_i^* - t_{i-1}^*$, and since $p_i^* = \pi_i^*$ for $\rho = 1$, we have $t_i^* = t_{i-1}^* + p_i^*$. This was validated in all our results. In addition, by recalling that t_i^* for $\rho = 1$ equals c_i^* for $\rho = 0$, we can claim that the p_i^*s also give the optimal cost regions for $\rho = 0$, i.e., $c_i^* = c_{i-1}^* + p_i^*$. Further, we note that for $\rho \in (0, 1)$ costs are simply re-scaled in $[c_{min}, c_{max}]$ (see cost model in Section II-A) and are distributed uniformly in this interval. As the difference between the two cases $\rho = 0$ and $\rho \in (0, 1)$ is only given by the size of the cost interval and not by the cost distribution which is still uniform, we infer that the optimal cost regions c_i^* for $\rho \in (0, 1)$ must be a re-scaled version of those for $\rho = 0$. Accordingly, for $\rho \in (0, 1)$ we must have that:

$$c_i^* = c_{i-1}^* + p_i^*(c_{max} - c_{min}) \,, \tag{14}$$

where $c_0^* = c_{min}$. Hence, for $\rho \in [0, 1)$ the c_i^*s can be calculated by means of Eq. (14), whereas $t_i^* = 1 \; \forall \, i$ (note that for $\rho = 0$, we have $c_{min} = 0$, $c_{max} = 1$, thus Eq. (14) still holds). Finally, for $\rho = 1$ we have that $c_i^* = 1 \; \forall \, i$ and the t_i^*s are obtained as $t_i^* = t_{i-1}^* + p_i^*$. p_i^* can be tabulated for a given W and for several values of N according to Eq. (13). This is a practical and exact method to derive R_i^* when $\varepsilon = 0$.

Now, we discuss the case where $\varepsilon > 0$ whose example results in terms of cost and token regions are reported in Figs. 5 and 6, respectively. As can be observed from these plots, for $\rho \in [0, 1)$ the optimal policy varies both c_i^* and t_i^* concurrently, i.e., the duality between costs and tokens and the result in Eq. (14) do not hold in this case. Finally, in Figs. 7 and 8 we report c_i^* and t_i^* when the cost/token space $[0, 1]$ is quantized in 20 equally spaced levels, by considering $\varepsilon = 0$, $N = 10$, $W = 10$ and $\bar{c} = 0.5$. This may be the case for resource constrained devices. In these settings, our analysis still holds by just re-defining the access regions R_i as a cost-token pair (c_i, t_i), where costs and tokens take values in discrete and finite sets composed of 20 points. As reported in the figures, now token regions are varied first, while keeping the cost region fixed. Subsequently, as the token regions t_i^* saturate to the maximum value (one), the optimal policy starts varying c_i^*. This behavior compensates for the lack of precision due to the state space quantization. We finally observe that $\varphi(1, R_0)$ decreases when regions are quantized. As an example, $\varphi(1, R_0)$ for $N = 10$, $W = 10$ is about 0.85 for a continuous state space, whereas it drops to 0.748 for $\rho = 0$ (best case) and about 0.592 on average.

The results that we discussed above highlight some interesting characteristics of the optimal policy and demonstrate the validity and the flexibility of our analytical formulation. In the next Section III, we consider the case $\varepsilon = 0$ by exploiting the result in Eq. (14) to devise an efficient cost- and collision-minimizing forwarding technique.

III. Cost and Collision Minimizing Routing

In this Section, based on the previously discussed results, we present an integrated channel access and routing scheme that we name as Cost and Collision Minimizing Routing (CCMR). Our cross-layer design relies on the definition of the costs, which are used in the channel access to discriminate among nodes. This is achieved by accounting for routing metrics, such as the geographical advancement, right in the cost calculation. Realistic cost models are presented in Section IV, where we report extensive simulation results to validate our approach.

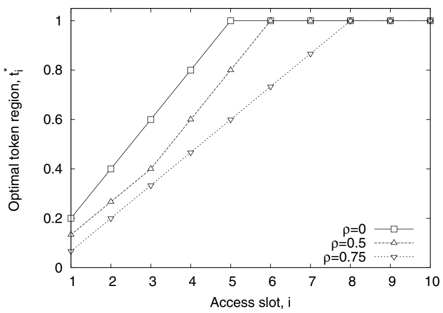

Fig. 8. t_i^*: quantized state space.

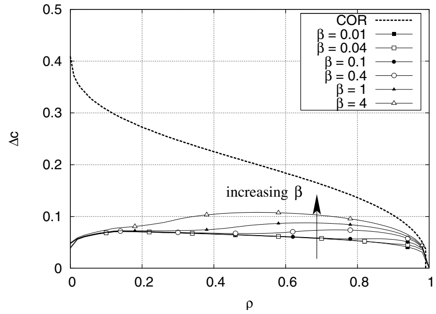

Fig. 9. Δc as a function of ρ.

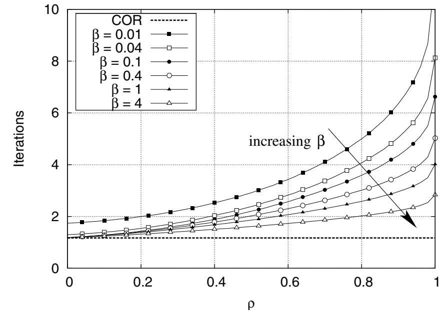

Fig. 10. Rounds needed to complete a contention.

Next, we outline our integrated scheme by considering the costs as given:

1) Consider a generic node n. The contention to elect the next hop works in rounds and ends as soon as a round is **successful**. At the generic round $r \geq 1$ node n sends a request (REQ) including its identifier and an estimate for the number of contenders N, and specifies a cost interval $[c_{min,r}, c_{max,r}]$, where $c_{min,1} = 0$ and $c_{max,1} = 1$. We detail how this interval is modified for $r > 1$ in point 3 below.

2) All active devices providing a positive advancement towards the sink contend for the channel. Upon receiving the REQ, at round $r \geq 1$, every node considers W access slots and calculates cost and token regions as follows. The node first computes a decay function $d(r) = r\beta/(r\beta + 1)$ depending on the round number r and on a constant $\beta > 0$. If $(c_{max,r} - c_{min,r}) > d(r)$, the c_i^*s are calculated by means of Eq. (14) and $t_i^* = 1 \; \forall \; i$, otherwise, $c_i^* = 1 \; \forall \; i$ and $t_i^* = t_{i-1}^* + p_i^*$ ($t_0^* = 0$), where p_i^* are as in Eq. (13) and $i \in \{1, 2, \ldots, W\}$. We refer to the cost region associated with the last slot W as $c_{W,r}^*$. Subsequently, using these access regions and its own cost the node picks a slot in $\{1, 2, \ldots, W\}$ according to the scheme in Section II and sends a reply (REP) in this slot.

3) Three cases can occur: a) all slots are **silent**. In this case, node n infers that none of the active nodes has cost in $[c_{min,r}, c_{W,r}^*]$ and starts round $r + 1$ by sending a new REQ, including the interval $[c_{min,r+1}, c_{max,r+1}]$, where $c_{min,r+1} = c_{W,r}^*$ and $c_{max,r+1} = c_{max,r}$. b) multiple nodes send their REP in the same slot so that a **collision** occurs. Node n assumes that at least two nodes have cost in $[c_{min,r}, c_{W,r}^*]$. Hence, the node sends a REQ including the new interval $[c_{min,r+1}, c_{max,r+1}]$, where $c_{min,r+1} = c_{min,r}$ and $c_{max,r+1} = c_{W,r}^*$. c) a single node responds to the REQ (**success**): node n sends the packet to this node, which subsequently replies with an acknowledgment and the contention is concluded.

Even though obtaining the regions may be computationally demanding, we note that for a given N and W pair, the scheme needs a unique p_i^* sequence (calculated by means of Eq. (13)). Cost and token regions are in fact a simple reshaping of the p_i^*s according to the limits of the cost intervals. According to our current implementation of the scheme, a very satisfactory set of look-up tables, for 50 values of N and $W = 10$ occupies less than 1 Kbyte of memory. This makes the scheme attractive for actual sensor devices.

The decay function $d(r)$ is used to tune the maximum number of contentions before considering the costs as fully correlated. That is, as the interval $[c_{min,r}, c_{max,r}]$ becomes sufficiently tight, access regions are calculated as in [11]. The parameter β is used as a knob to determine the decay threshold as a function of r. In Figs. 9 and 10 we plot the average distance between the minimum cost in the active set and that of the winner of the contention (Δc) and the average number of contentions to elect the next hop, respectively. The considered system parameters are $N = 10$, $W = 10$, $\varepsilon = 0$, $\overline{c}$ is uniformly distributed in $[0, 1]$. The performance of the scheme in [11] (COR) is reported for comparison. These results demonstrate that the algorithm is robust against ρ, is very effective in promoting low cost nodes, and has delay very close to the optimum (which is given by COR). Also, suitable trade-offs can be achieved by varying β.

We finally note that we assumed that collisions are detected with probability one and are always due to the transmission of REQ messages and that simultaneous transmissions always collide. We note, however, that in practice these assumptions may be incorrect due to, e.g., capture effect, parallel transmissions, channel errors, etc. In addition, we considered a perfect estimate of the number of contenders N. All these assumptions are removed in the results shown in the following Section IV.

IV. Simulation Results

The following results are obtained by means of the event-driven simulation tool presented in [13], which we complemented with PHY and MAC modules for sensor networking. Inter-user interference is accurately modeled through the calculation of the received Signal to Interference plus Noise Ratio (SINR) for each pair of nodes. Bit errors at the PHY layer are derived from SINR measurements, according to [8] (see chapter 5 and references therein). For the energy consumption, we adopt the model in [14], i.e., idle, reception and transmission modes consume 26.1 mW, 47.1 mW and 90.6 mW, respectively. Sensor nodes have a maximum transmission range and a bit rate of $R = 30$ m and $B = 38400$ bps, respectively. Both sensors and sink are uniformly placed within a square-shaped simulation area of side 100 m. In the results that we show next, we use our solution to deliver the data to the sink by exploiting geographical coordinates. Geographical forwarding is considered here to show the validity of the approach. However we stress that our scheme, through minor modifications, works over virtual coordinates as well, e.g., hop counts [6]. In fact,

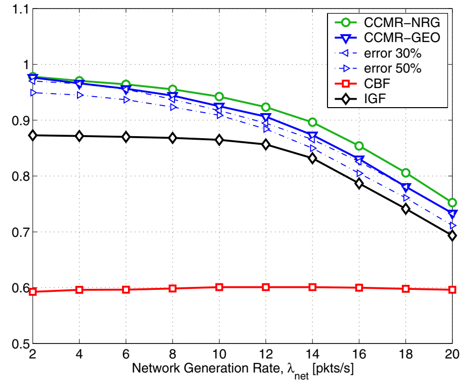

Fig. 11. Delivery rate vs. λ_{net}.

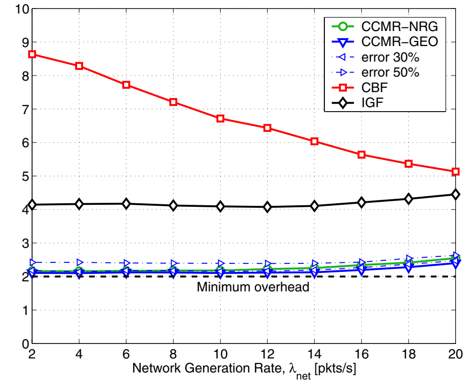

Fig. 12. Average protocol overhead.

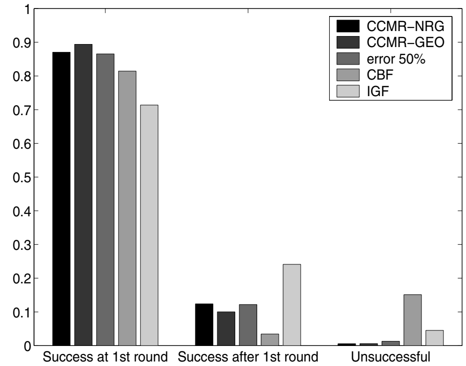

Fig. 13. Distribution of the contention outcome.

different topologies just translate into a different definition of the costs. We run extensive tests varying the number of nodes N_u from 25 up to 150, all of which generate traffic according to a Poisson process with intensity λ packets per second per node. We plot the performance as a function of the total packet generation rate $\lambda_{net} = \lambda N_u$.

In the following, we compare our Cost and Collision Minimizing Routing scheme (CCMR) against IGF [3], [15] and CBF [2]. In both schemes the nodes in the active set respond to the inquiring node by exploiting a timer-based approach. In particular, upon receiving a REQ each node replies after a time period which is calculated as a function of its cost. Costs are derived from the geographical advancement only [2] or by also considering the node residual energy [3]. The main difference between [2], [3] and our scheme is that in our approach nodes contend by jointly optimizing over a multi–slot frame, whereas in [2], [3] the response time is a continuous quantity calculated by means of heuristics. We consider here two versions of CCMR. The first, called CCMR-GEO assumes a cost model as in [2], i.e., the cost associated with the generic node n is calculated as $c_n = 1 - (a_n/R)$, where a_n is the geographical advancement provided by the node. In the second scheme, referred to as CCMR-NRG, c_n is calculated as $c_n = 1 - (a_n/R)(e_r/E)$, where e_r is the node's residual energy and E is the initial energy reserve. This is in line with the cost model in [3]. For both CCMR-GEO and CCMR-NRG we assume a decay factor $\beta = 2$ (see Section III) which gives a good tradeoff between cost and delay. All forwarding techniques are implemented on top of a standard Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) MAC where the channel is sensed before starting new contentions and nodes back off in case of colliding REQs.

Figs. 11-17 consider a network scenario with $N_u = 50$ randomly distributed nodes, all of which generate data traffic. This translates to an average of 7 active nodes in the forwarding area. The performance achieved for different values of N_u is discussed at the end of this section. All plots, in order to show the robustness of our approach, also include CCMR-GEO by considering erroneous estimates of the number of active nodes N. We do not report such curves for CCMR-NRGs as they revealed a nearly identical behavior. These estimation errors are accounted for by randomly drawing N from a uniform distribution defined in the interval $[N - \Delta N, N + \Delta N]$, where ΔN is computed as a percentage of the actual value of N (ΔN is 30% and 50% in our plots).

As a first result, in Fig. 11 we report the packet delivery rate, calculated as the total number of received packets divided by the total number of packets generated. In all cases CCMR obtains better performance than the other schemes, and at low λ_{net} it delivers almost all packets. CCMR-NRG performs slightly better than CCMR-GEO as energy aware costs allow the redistribution of the data flows, avoiding excessive congestion at specific nodes. Note that CBF suffers from a low delivery rate, even at low λ_{net}. This is due to the timer-based mechanisms adopted to respond to the REQs. In fact, in case the difference among the response times picked by multiple nodes is shorter than the time needed to complete the carrier sense operation, the REPs collide with high probability. In IGF, this problem is reduced thanks to the addition of a random quantity in the response times. In our solution, instead, slots are designed so as to allow for the completion of a full carrier sense operation. Note that this does not completely prevent collisions in CCMR, as sensors can still select the same access slot. However, after a collision event the scheme adapts its policy to avoid such an event in the subsequent round with high probability.

Fig. 12 reports the overhead, defined as the average number of REQs and REPs required to transmit a data packet to the relay. Note that CCMR is very close to the optimal performance (1 REQ and 1 REP): keeping the control traffic low is beneficial as this means improvements in terms of channel capacity (interference) and energy consumption. A further reduction of the overhead, not treated in detail here, would be obtained by transmitting back-to-back multiple packets to the winner of the contention. In Fig. 13 we show the percentage of packets successfully sent in one and multiple contention rounds, and the percentage of unsuccessful contentions (more than 7 failed attempts in a row). Further results on the contention are given in Figs. 14 and 15, plotting the probability of successfully electing a next hop and the associated average delay, respectively. Note that both IGF and CBF improve as λ_{net} increases as a higher traffic means a lower number of active nodes taking part in the contentions and, in turn, a lower number of collisions. The results in Fig. 16 show the number of packets delivered to the sink per second in steady state. This metric saturates for

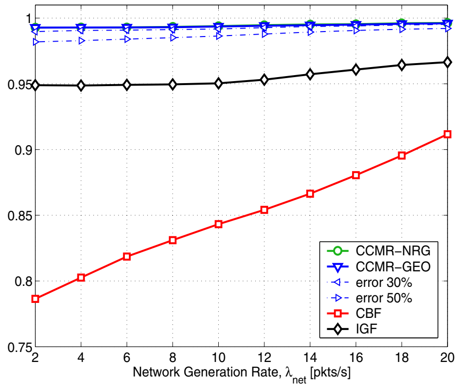

Fig. 14. Probability of a successful contention.

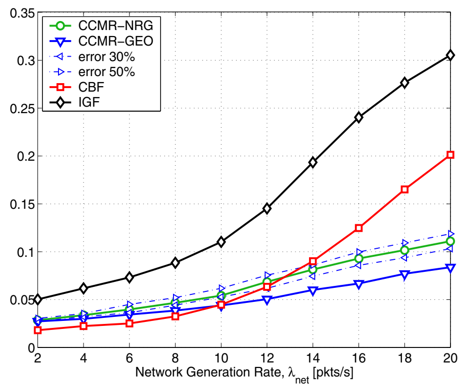

Fig. 15. Duration of the channel contention [s].

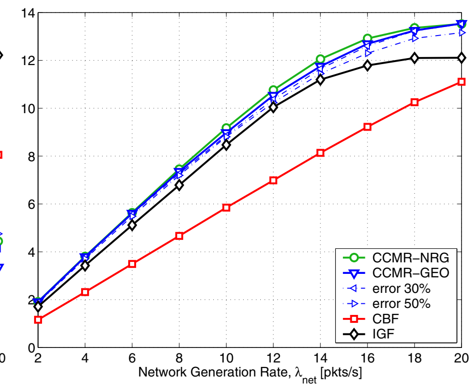

Fig. 16. Packets delivered to the sink per second.

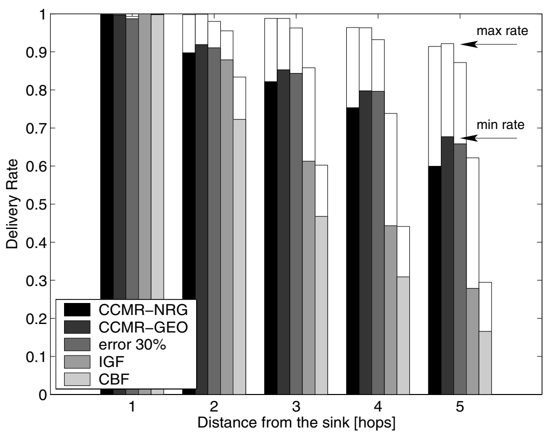

Fig. 17. Delivery rate vs. hop distance from the sink.

increasing λ_{net}. Although from this figure one might conclude that IGF and CCMR roughly lead to the same performance, by looking at the microscopic behavior of the schemes, it can be shown that this is not the case. To this end, in Fig. 17 we focus on the delivery rate as a function of the minimum number of hops separating the traffic sources from the sink. For each scheme, colored histograms are used to report the worst case performance, whereas white filled histograms indicate the best achievable delivery rate. Best and worst cases are found by varying λ_{net} from 1 to 20 pkts/s. Both versions of CCMR outperform the remaining schemes by leading to a weaker dependence of the delivery rate on the distance from the sink. Finally, we obtained the same plots for different values of the density (N_u), which show better performance for higher values of N_u and a roughly similar behavior for lower densities: note that CCMR properly adapts its access policy according to the size of the active set, whereas IGF and CBF do not. These results are not reported here due to space limitations.

V. Conclusions

In this paper we presented an original integrated channel access and routing technique for wireless sensor networks. We analytically modeled the next hop selection problem by finding the optimal policy by means of a dynamic programming formulation. Based on the optimal access policy, we subsequently designed a forwarding scheme, proving its effectiveness and comparing its performance against existing solutions. The scheme showed excellent performance as well as high robustness against errors in the estimation of critical parameters.

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