Coloring based Hierarchical Routing Approach

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Abstract

Graph coloring was exploited in wireless sensor networks to solve many optimization problems. These problems are related in general to channel assignment. In this paper, we propose to jointly use coloring for routing purposes. We introduce CHRA a coloring based hierarchical routing approach. Coloring is exploited to avoid interferences and also to schedule nodes transmissions to sink. We provide an analytical and experimental study assessing the performance of CHRA in terms of end-to-end delay and energy consumption. In particular, we find that CHRA performs better than LEACH, a well established hierarchical routing protocol.

keywords: Wireless Sensor Network, Graph Coloring, TDMA scheduling, routing, optimization

1   Introduction

1.1   Context and motivation

Advances of wireless communication, micro-electro-mechanical systems (MEMS) and digital electronics have made wireless sensor networks (WSN) a popular research topic and promising technology for many fields. Indeed, WSNs have been envisioned in a large number of application domains [18, 13] like medical, military and environmental fields. WSNs are composed of a large number of autonomous nodes densely distributed within an area and sharing a wireless communication medium without the use of any infrastructure. Sensor nodes are made to operate autonomously to gather information about their environment and transmit it to a base station called sink. The intrinsic characteristics of sensor nodes like the limited transmission power, storage capacity and especially limited energy power impose several challenges. In fact, sensors are running on limited and typically non-renewable power supply since they are generally deployed in hostile or not

reachable areas. In view of the scarcity of energy, prolonging sensors lifetime is a main design challenge of these networks. Besides, radio communication constitutes also one of the major sources of energy dissipation. In such environments, as nodes share the same medium access, collisions and interferences caused by simultaneous transmissions of neighbors become very frequent especially in a dense network. Packets retransmissions caused by these collisions contribute to the energy depletion of sensor nodes. Contention based mechanisms, like CSMA/CA [9], aim to reduce probability of collisions. However, control packets overhead, active sensing of the medium and backoff algorithm typically performed in this context, are inefficient in terms of energy consumption. Minimizing transmission delay and assuring fairness are other important challenges. With contention based MAC (Media Access Control) algorithms, it is hard to assure these properties due to the recourse to the backoff algorithm and nodes competition to access the channel. Channel assignment techniques like TDMA, can be well suited in minimizing energy consumption [4] since nodes can turn off their transmitters or receivers, unless they are expecting to receive or transmit a packet. In this context, classical problems from graph coloring theory can be mapped to channel assignment in wireless sensor networks [14, 15, 11, 3]. For example, attributing a slot time to sensors nodes is equivalent to the assignment of distinguished colors to these nodes while respecting scheduling constraints. Several researches have been interested into applying graph coloring theory in wireless networks. Most of algorithm are investigating the so called distance d (in terms of hops) coloring, with $d \geq 2$. The aim is to assign to interfering nodes distinguished colors in order to assure a conflict-free communication. However, most existing work dissociate between collision free coloring-based scheduling and energy efficient routing.

1.2 Contribution

The objective of this paper is to study the possible gains in applying graph coloring in the context of routing in wireless sensor network. We propose CHRA (Coloring based Hierarchical Routing Approach), a hierarchical routing approach based on node 2-hop coloring. Within CHRA, we tackle *both* channel access issues by a TDMA like protocol, and routing by exploiting a coloring based virtual infrastructure. In this respect, CHRA does not dissociate between the two phases but addresses them simultaneously. We contribute both an analytical and experimental analysis assessing the performance of CHRA under different network circumstances. We find that depending on the properties of the coloring different trade-offs can be obtained both in term of end-to-end delay and energy consumption. We notice that these two objectives are conflicting with one another since to increase energy conservation nodes could even not send data at all. In opposite, more communication is likely to ensure better delay at the price of consuming more energy. We experimented three heuristics to construct the coloring structure and highlight their impact on routing. Besides, and independently of the considered coloring, we study the performance of CHRA against LEACH [8] a widely used hierarchical

protocol particularly known for saving energy and improving network lifetime. We find that CHRA outperforms leach and leads to lower energy consumption.

1.3 Related work overview

Routing protocols [12] in WSN can be divided into flat routing and hierarchical routing. With flat routing, all nodes have the same functionalities and execute the same tasks in the network. In this category, data transmission is performed hop by hop, e.g. [6, 10]. Flat routing is relatively not effective in large scale networks due to the limited energy resources. Hierarchical routing [2, 1] consists in building a virtual infrastructure based on clustering. Nodes are organized into clusters, where cluster-heads (CH) and members have to perform different tasks. Low-Energy Adaptive Clustering Hierarchy (LEACH) [8], is one of the pioneering hierarchical routing approaches for WSNs. In LEACH, each round is composed of two phases, a set-up phase to form clusters and a steady phase to data transmissions. The set-up phase operates in a randomized manner in an attempt to elect different CHs and to distribute energy consumption over nodes. Many versions of LEACH are proposed forming the LEACH family, e.g., LEACH-C [7]. Other algorithms based on LEACH try to improve the clustering process such as HEED [19] where CHs are elected based on their energy level and these CHs send the aggregated data to the sink in a multi-hop manner rather than single-hop manner of LEACH. DWEHC [5] build on HEED by trying to generate a balanced distribution of CHs, but CHs transmit their data to the sink in a single hop fashion. None of these protocols have considered the use of coloring to jointly manage channel access and routing to the sink.

1.4 Outline

In Section 2, we provide an overview of our routing approach as well as an analytical study of its properties. In Section 3, we report our simulation results assessing the performance of our approach. Finally, in Section 4, we conclude the paper and discuss future research directions.

2 Coloring based Hierarchical Routing Approach

2.1 Rationale

Hierarchical routing [2, 1] is based on the idea of assigning different roles to nodes depending on their status. Generally speaking, the virtual infrastructure for such routing is obtained after a clustering phase, where some nodes are elected to be cluster-heads (CHs) playing the role of collecting and aggregating data from neighbors, then sending it to a sink node. Two main issues are generally addressed in order to make such approach effective. First, collecting data into CHs have to avoid packet loss due to interferences and simultaneous transmissions. Second,

since CHs are more often active to route data to the sink, a scheduling mechanism has to make sure that CHs do not vanish quickly due to energy constraints.

This paper precisely aims at tackling the two previous issues by reducing and modeling them as a compound graph coloring problem. The main idea behind our approach is to design new hierarchical routing protocols over a coloring-based overlay structure. The properties of the coloring is then intended to both manage local transmissions occurring between nodes and their CHs, but also to reduce energy consumption when gathering data at the sink. This is to contrast with many previous studies where coloring is *only* intended to avoid local collisions. In the remainder, our goal is to gain new insights into how coloring-based network structures can serve to derive highly competitive protocols for routing purposes. Therefore, the distributed construction of the coloring it-self is out-of-scope of this paper and left as future work. As we will demonstrate, the properties of the coloring are directly linked to the performance of the routing in terms of network delay and energy conservation.

Throughout the paper, we shall make the following assumptions. Network connectivity is modeled by a unit disk graph, $G(V, E)$ where V represents the set of vertices embedded in the plane and E represents the set of edges. Each node is characterized by a transmission range R and an edge (u, v) in E exists between nodes u and v if u and v are within the transmission range of each other. Collisions and interferences are assumed to be caused by simultaneous transmissions of neighboring nodes or between nodes sharing the same neighbor. Hence, to handle collisions and interferences, we shall assume given a proper vertex coloring of G, where a node v is assigned a color different from any neighbor at distance 2. We suppose that time is divided into slots of equal length. We assume that nodes can aggregate data from their neighbors into a single packet of equal size. These assumptions are consistent with other studies, e.g. LEACH [8].

2.2 A coloring based routing algorithm (CHRA)

Our approach is based on a cyclic scheduling of nodes in order to route data. In fact, we divide the time line into *cycles*, where each cycle is divided into two phases as illustrated in Fig. 1. The first phase of each cycle is divided into λ *periods* devoted to collecting and aggregating data from neighboring nodes. The second phase is devoted to send the data to the base-station (the sink) as detailed in the following.

Each period of the first phase is divided into Δ time-slots, where Δ is the maximum number of colors implied by the coloring structure. We then map periods to colors in order to get a local scheduling of CHs. More precisely, at each period i, nodes having the color ($i \mod \Delta$) are elected cluster-heads for that period. Elected CHs announce their role to their neighbors and nodes receiving announcement message from a CH join its cluster. Respecting the TDMA scheduling defined by the coloring, nodes can sleep and wake up only in the corresponding slots to send their data to their CH. Nodes being not attached to any CH in a given period can simply sleep for the rest of the period thus saving energy. Notice that CHs are
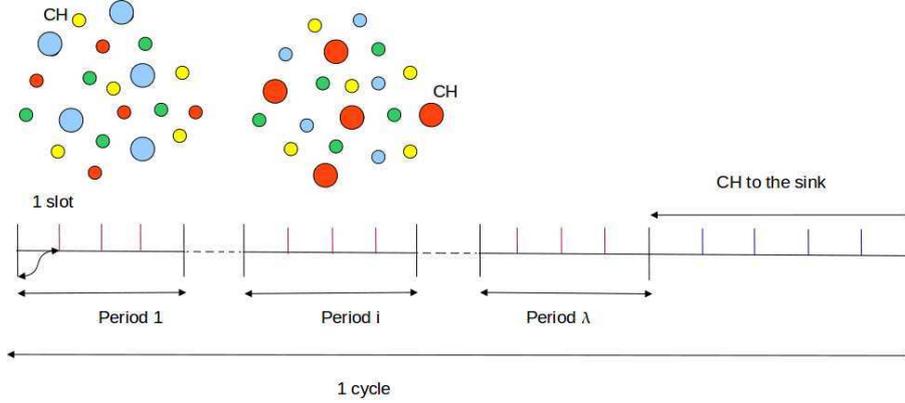
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Figure 1: Illustration of one cycle of CHRA.

different at each period and cycle over the available colors so that data collected in period i can be aggregated again at subsequent periods mapping different CHs, and so on until reaching the second phase of the considered cycle. It might also be the case that $\lambda < \Delta$, in which case at the very first period of the current cycle, nodes with the color following the one used during the last period (of the previous cycle), may declare their selves as CHs. In the second phase of our approach, aggregated data is simply to be sent to the sink. However, transmitting directly to the sink consumes energy. Therefore, we define a new scheduling in order to fairly distribute energy consumption over nodes. More precisely, for each cycle j, *only* nodes having color $(j \mod \Delta)$ are allowed to contact the sink. In this way, we cycle over the colors and do *not* choose the same nodes throughout different cycles. In order to enable data transmission to the sink, the second phase is divided into Δ' time-slots where Δ' is the maximum number of nodes with color $(j \mod \Delta)$.

Intuitively speaking, CHRA attempts to use the coloring structure to fairly distribute transmissions aver all nodes while in the meantime avoiding interferences. By playing with λ, which defines the length of a cycle, we postpone sending data to the sink, but we save energy. In the following, we give a more detailed analysis of this idea showing how the different parameters of our protocol, including the properties of the core coloring structure (Δ and Δ'), impact the performance of the routing, in terms of latency and energy.

2.3 Analysis of CHRA

Transmission delay A cycle in CHRA is composed of λ periods to collect data from neighboring nodes at CHs, followed by one period (second phase) to send data to the sink. Hence, the maximum delay introduced in one cycle is: $Delay_{cycle} = \lambda \cdot \Delta + \Delta'$. During a cycle, only nodes covered by one CH in at least one period i can transmit their data to this CH. Remaining nodes must wait until becoming

themselves CHs or being neighbors of some elected CHs at some period *i*. Eventhough, only some scheduled nodes at the second phase can transmit to the sink. However, we can ensure that the data from a node reaches the sink at most after Δ cycles, since then we have the guarantee that either the node transmits directly to the sink if it is elected in the second phase of one cycle, or a CH has aggregated and forwarded its data in previous cycles. Hence, the worst-case delay after which the data from a node in the network succeeds reaching the sink is:

$$Delay_{max} = \Delta \cdot Delay_{cycle} = \lambda \cdot \Delta^2 + \Delta \cdot \Delta' \tag{1}$$

We remark that the delay increases quadratically in Δ, and linearly in λ and Δ'. We can also impact the delay by playing with λ. For example, by taking $\lambda = 1$, we fall in the case where a cycle is composed of a unique period where some CHs collect data followed by a phase for sending data to the sink. As we will see, decreasing λ impacts negatively the energy consumed over nodes.

Energy consumed during a period of time T We start by the account of the energy consumed by a CH in one period of the first phase of CHRA. Since we assume a distance 2 coloring, CHs cannot share the same neighbors and so the number of members of a cluster is exactly the degree of the CH, denoted deg_{CH}. A CH can receive packets from its neighbors at the first phase and then it might send to the sink if its color is scheduled for the second phase. Hence, assuming that $\lambda \leq \Delta$, the energy consumed by a CH during a cycle is at most: $E_{CH} = deg_{CH} \cdot E_{CH_{rx}} + E_{CH_{tx}}$, where $E_{CH_{rx}}$ is the energy consumed to receive from neighbors members and $E_{CH_{tx}}$ the energy consumed to reach the sink. Following [8], the energy consumed to receive a packet can be computed as: $E_{CH_{rx}} = E_{elect} \cdot \ell$, where ℓ denotes the size of a packet and E_{elect} the electronic energy. The energy consumed by a CH to send a packet to the sink can be written as: $E_{CH_{tx}} = E_{elect} \cdot \ell + \varepsilon_{amp} \cdot \ell \cdot d_{CH,sink}^2$, where ε_{amp} denotes the energy of the amplifier $d_{CH,sink}$ is the distance the euclidian distance from the CH to the sink. Similarly, the energy consumed due to transmitting data from members in the same cluster to a CH can be written as: $E_{non-CH} = E_{elect} \cdot \ell + \varepsilon_{amp} \cdot \ell \cdot R^2$, where R is the maximum transmission range of nodes. Putting the pieces together, the energy consumed by a cluster is:

$$E_{cluster} = E_{elect} \cdot (deg_{CH} + 1) \cdot \ell + \varepsilon_{amp} \cdot (deg_{CH} \cdot R^2 + d_{CH,sink}^2) \cdot \ell \tag{2}$$

A node is re-elected to send to the sink after the rotation of the role of CHs over all the nodes and so over all the colors which means after at most Δ cycles. Thus, assuming that $\lambda \leq \Delta$, the total energy consumed by a cluster during a period of time T is at most :

$$E_{cluster_{tot}} = E_{cluster} \cdot \frac{T}{Delay_{cycle}} = E_{cluster} \cdot \frac{T}{\lambda \cdot \Delta + \Delta'} \tag{3}$$

By a routine verification, and summing over cycles, the maximum amount of energy consumed during a period T can be written as:

$$E_{tot} = \frac{\Delta' \cdot T}{\lambda \cdot \Delta + \Delta'} \cdot (E_{elect}(1+\delta) + \varepsilon_{amp}(\delta \cdot R_T^2)) \cdot \ell + \varepsilon_{amp} \cdot \ell \cdot \sum_{k=1}^{n} d_{k,sink}^2 \qquad (4)$$

where δ is the maximum number of neighbors in the vicinity of any node, and $d_{k,sink}$ the distance between any node $k \in \{1, \cdots, n\}$ in the network and the sink. We can remark that to reduce the energy consumption, one should increase the maximum number of colors Δ and/or the number of periods λ. In respect to Eqs. 1 and 4, we thus can conclude that Δ and Δ' (which are inherent to the coloring structure) as well as the length of a routing cycle λ, allows CHRA to exhibit different trade-off between reducing energy consumption and improving transmission delay, which are obviously two conflicting objectives going in opposite directions. For example, to reduce energy consumption, we can make λ so high, or we can manage Δ to be high (and Δ' low) so that very few nodes contact the sink directly, thus gaining energy but likely increasing delay.

3   Simulation Results

As discussed in the previous section, routing data with low energy consumption and optimized end-to-end delay is the main objective of our approach. To show its effectiveness, we conduct exhaustive simulations over several network topologies. In a first phase, we experiment the property of different distance 2 coloring heuristics on the performance of our CHRA protocol. From graph theory, it is well understood that the order in which nodes are assigned colors is crucial to minimize the number of colors. However, in HCRA minimizing the number of colors can only optimize the end-to-end delay, but it is likely to increase the energy consumption. In the following, we propose to evaluate different heuristics by playing with the order in which nodes are colored. The first strategy is a classical greedy heuristic coloring nodes iteratively in a *random* order. The second one assigns colors to nodes in a decreasing order of their *degree*. The last greedy heuristic assigns colors to nodes in an increasing order of their *distance* within the sink. These heuristics shall highlight the intrinsic performances that can be obtained by CHRA.

In a second phase of simulations, we compare the performances of our approach against LEACH [8]. LEACH is a state-of-the-art hierarchical routing algorithm which compares consistently to our approach from many perspectives, but differs in some others. In fact, LEACH uses randomized rotation and election of CHs. After election, these CHs announce themselves to neighbors. Each node decides to which cluster it wants to belong by choosing the CH that requires the minimum communication energy. Once all nodes are organized into clusters, CHs compute a TDMA schedule according to the number of nodes in their cluster. This schedule is broadcasted back to the node in the cluster. Respecting the received scheduling TDMA, nodes send their data to their CHs. Once a CH receives all

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the data from the nodes in its cluster, it aggregates it and transmits the compressed data to the sink. For all transmissions except intra-cluster transmissions, LEACH uses the CSMA/CA protocol. Inter-cluster interference is mitigated using different CDMA codes in each cluster chosen randomly by the cluster-heads.

Reported results were obtained using the OMNET++ simulator [17] for nodes randomly deployed, with the same transmission range and the same quantity of data to transmit in each round. In our simulations, the coloring is initially computed by the base-station and the scheduling it induces is communicated to nodes before starting data transmission and gathering. The simulation results are averaged over 30 simulation runs.

3.1 Intrinsic properties of CHRA

In this section, we aim to point out the impact of the coloring, on the performance of CHRA. We focused on the following measures: (i) the number of colors used for the two-hop node coloring (parameter Δ), (ii) the maximal number of cluster-heads which it corresponds to the maximal number of nodes having the same color (parameter Δ'), (iii) the end-to-end delay that is the worst case transmission delay that occurs from source node to the sink, and (iv) the network lifetime which is computed as the average over all sensors lifetime. A sensor lifetime starts when the node first boots and ends when its battery is depleted. We also concentrate on the impact of two network parameters which are the network size and the density of deployed nodes. The parameters considered in our simulation scenarios are resumed in Table 1.

Simulation area (m^2):	50*50; 70*70; 85*85; 100*100	Number of nodes:	100; 200; 300; 400
Transmission range (m)	10	Throughput	250000 bits/s
Node deployment:	Random	DATA packet size:	2000 bits
Coloring heuristics:	Random, Degree-based, Distance-based		

Table 1: Overview of experimental setting and simulation parameters.

Constant network density In Fig. 2, we draw a picture of the previous measures for the different coloring heuristics as a function of network size (between 100 and 400 nodes) and for CHRA running with a cycle of length $\lambda = 5$. In all runs, we managed the simulation area to obtain a constant network density of 0.11 independently of network size. The density of the network is crucial since it directly impact the quality of the coloring and thus of RCHA (the more the network is dense, the

(a) Number of colors (Δ)

(b) Maximum number of cluster-heads of the same color (Δ')

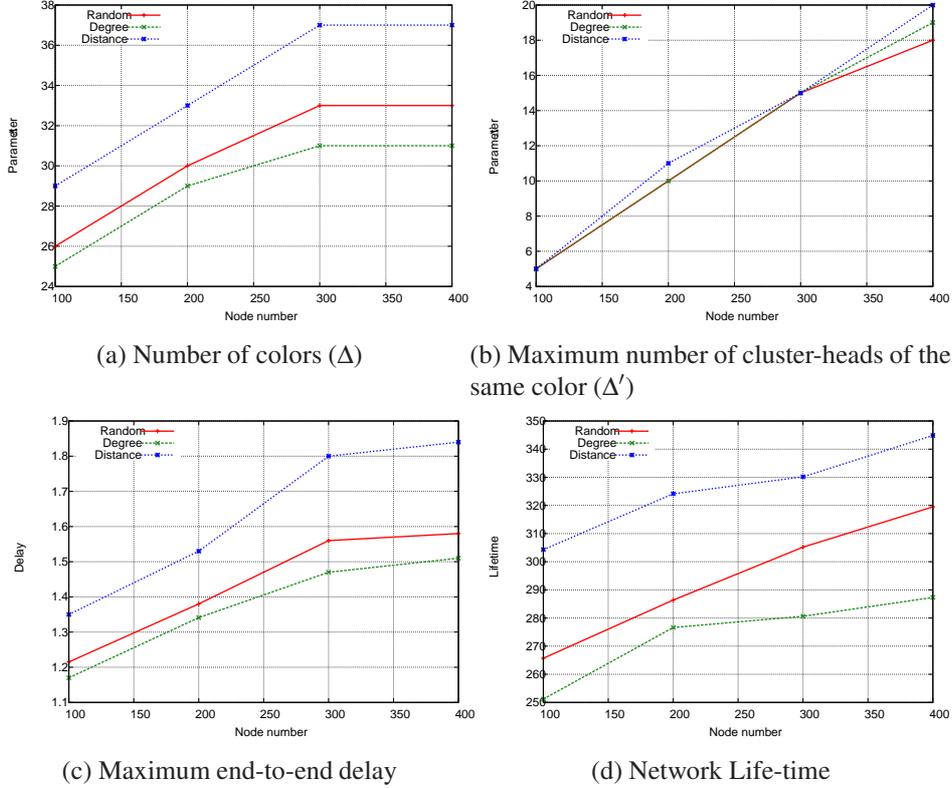(c) Maximum end-to-end delay

(d) Network Life-time

Figure 2: CHRA properties and performance according to coloring heuristic as a function of network size, and at a constant node density.

more colors are needed to resolve conflicts between neighboring nodes). Consistently with our analytical analysis, we can observe how the number of colors and the maximal number of CHs induced by the coloring-based scheduling correlates with the delay and the lifetime. We recall that delay is to be minimized and lifetime is to be maximized. Fig. 2c and 2d tell us that independently of network size none of the three heuristics is better in both objectives. While the distance (resp. degree) based heuristic produces the worst delay (resp. lifetime), it provides the best lifetime (reap. delay). It is to notice that the random heuristic produces balanced latency-energy trade-off.

Varying network density A second set of simulation was performed in order to study the impact of network density on CHRA. In Fig. 3, we show results for a network of 400 randomly deployed nodes while varying the simulation area to render different density. As one can clearly see, the number of colors increases with network density; this is without surprise since for a dense network, each node will have more neighbors in its vicinity. The maximal number of CHs also increases

(a) Number of colors (Δ)

(b) Maximum number of cluster-heads of the same color (Δ')

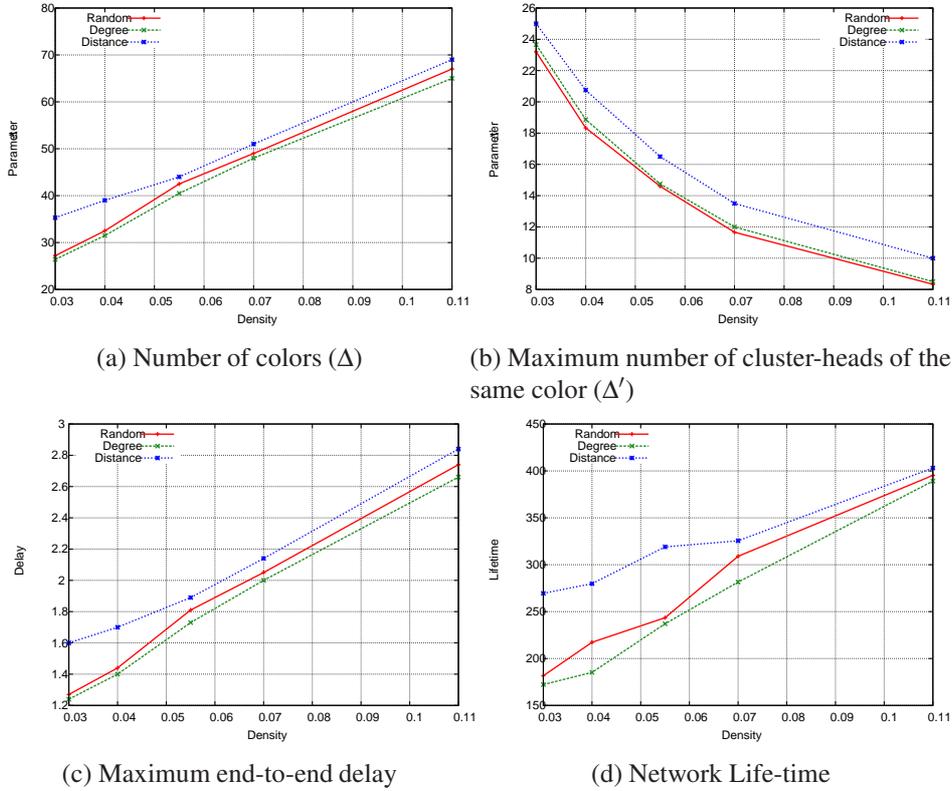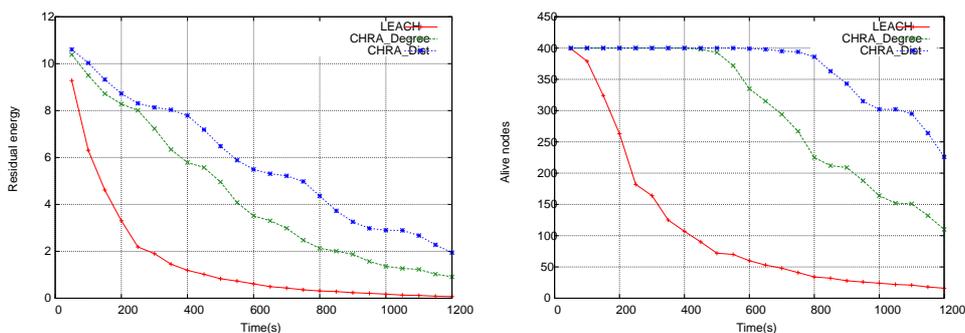(c) Maximum end-to-end delay

(d) Network Life-time

Figure 3: CHRA properties and performance according to coloring heuristic for 400 nodes and as a function of network density

consistently as network density decreases, since in a sparse network nodes are more scattered and the number of CHs is more important. As a direct consequence, the transmission delay increases with density independently of the coloring heuristics, since none of them is able to keep the number of colors constant, i.e., the duration of periods for sending data to CHs becomes unavoidably larger and the periodicity of sending to the sink becomes more important. Although the length of the period for sending data to the sink is reduced because the maximal number of CHs is reduced, this decrease is negligible compared to the delay induced by length of the first phase cycle of CHRA. This effect can be as well observed for the lifetime which increases with density.
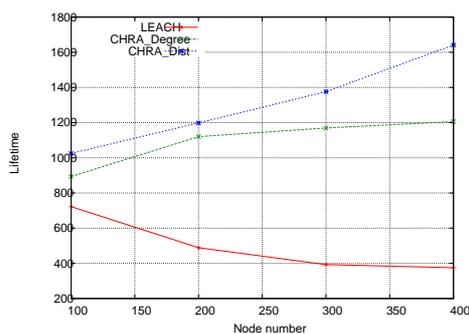
3.2 Comparison of CHRA with LEACH

Energy consumption In this section we compare our CHRA protocol with LEACH [8]. We first focus on the following metrics: (i) the residual energy of the network that is the average of remaining energy over nodes through time, (ii) the number of alive nodes through time, and (iii) network lifetime. In Fig. 4, we can see that compared

to LEACH, nodes remain alive for a longer time in CHRA; this is because a much less control packets have been exchanged before sending to the sink. In opposite to LEACH where randomization in choosing CHs may incur collisions and further control operations at each period, in CHRA clustering is computed deterministically and transmissions to CHs are optimized finely. Moreover, CHs send data to the sink following a deterministic TDMA scheduling whereas in LEACH CHs use CSMA/CA for sending data to the sink, thus risking collisions and contributing to consume more energy. We can also see that nodes die out faster with LEACH than CHRA (and this is independent of the coloring heuristic we are using). As a consequence, CHRA outperforms LEACH in terms of lifetime and independently of network size. We notice that the differences are more pronounced when increasing network size. As we adjust the simulation area to keep the same density, we are likely to have more nodes far away from the sink. In this case, LEACH fails managing the efficient election of CHs while CHs transmissions within CHRA is being automatically adjusted to save energy.

(a) Residual energy in of time (400 node network and density 0.11)

(b) Number of alive nodes in time (400 node network and density 0.11)

(c) Network life time as function of number of nodes (density 0.11)

Figure 4: Performance of CHRA *vs.* LEACH

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Coverage and Throughput In a second phase of our experiment analysis we focus on: (i) throughput, that is the average ratio of sent packets to the generated ones, and (ii) node coverage, that is the average number of nodes participating in the routing process during a period (Only nodes that participate in routing by sending packets to their CHs are counted). Node coverage gives an idea on how well CHs are well distributed to listen from neighbors. The more nodes are covered by CHs, the better is the performance since more data can be collected, aggregated and eventually transmitted to sink. Fig. 5 shows that CHRA performs better than LEACH. Nodes with same color in CHRA cannot be one hop neighbors nor share the same neighbors. This is to contrast with LEACH where CHs can even be neighbors and thus cover less nodes in the network. Tightly related to node coverage, the average throughput of CHRA is better than the one allowed by LEACH as can be seen in Fig. 5.
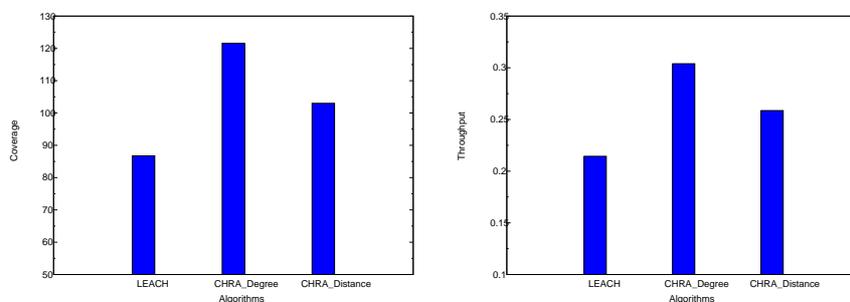

Figure 5: Coverage (Left) and throughout (Right) of CHRA *vs.* LEACH. Network size 400, density 0.11.

4 Conclusion

In this paper we presented CHRA a coloring based hierarchical routing approach for wireless sensor networks. We show that the performance of CHRA is tightly related to the number of colors used in the underlying coloring structure. Extensive simulation results with different parameter setting confirm our analytical finding. Comparing to LEACH, substantial improvements are shown in terms of energy consumption and network lifetime. We conclude the paper by two promising research directions:

- In our work, we focused on the gain one can obtain by routing over coloring in a cross-layer style. Future work should address the price of *initially* computing the coloring in a fully distributed manner. Since the greedy *random order* heuristic produced good performance, and many distributed algorithms were proved to be efficient in constructing coloring from scratch,

it is likely that simple distributed strategies taken from the literature can be deployed in a straightforward manner.

- CHRA highlights the fact that routing in sensor network can be modeled as a multi-objective problem when an external decider requires, depending on his priority or application constraints, a given trade-off in terms of delay and network lifetime. In this context, it would be interesting to provide a new modeling of hierarchical routing in WSN using well established tools coming from the operation research and combinatorial optimization fields [16], thus shortening the gap between theory and practice.

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