Ensuring K-Coverage in Wireless Sensor Networks under Realistic Physical Layer Assumptions

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Ensuring Area k-Coverage in Wireless Sensor Networks with Realistic Physical Layers

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***Abstract*— Wireless sensor networks are composed of hundreds of small and low power devices deployed over a field to monitor. Energy consumption is balanced by taking advantage of the redundancy induced by the random deployment of nodes. Some nodes are active while others are in sleep mode. Area coverage protocols aim at turning off redundant sensor nodes while preserving satisfactory monitoring by the set of active nodes. The problem addressed here consists in building k distinct subsets of active nodes (layers), in a fully decentralized manner, so that each layer covers the area. In our protocol, each node selects a waiting timeout, listening to messages from neighbors. Activity messages include the layer at which a node has decided to be active. Depending on the physical layer used for sensing modeling, any node can evaluate if the provided coverage is sufficient for each layer. If so, node can sleep, otherwise it selects a layer to be active. Here, we describe a localized area coverage protocol able to maintain an area k-covered under realistic physical layer assumptions for both sensing and communicating modules.**

I. Introduction

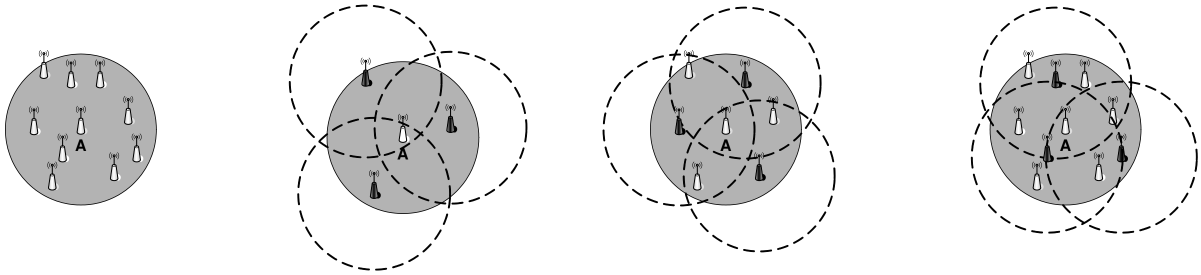
Acquiring information straight from the environment has become possible and affordable since recent advances in micro-electro-mechanical systems (MEMS), digital electronics, and wireless communications have enabled the development of lowcost, lowpower, multi functional sensor devices [1].

A sensor network is a set of nodes in which a battery, a sensing and a wireless communication device are embedded [2]. Densely deployed over hostile or remote environments, they should provide full monitoring and pertinent data collection so that further heavy computation and analysis tasks could be achieved by better equipped machines (usually called sinks). Once thrown over sensitive areas, the sensor nodes become one-use-only since their batteries can not be easily replaced or refilled. Energy is therefore the systems most important resource. In order to increase their lifespan, and the one of the constituted network, these objects are allowed to turn into sleep mode as soon as they are not required for the local monitoring task. Indeed, among the large number of nodes deployed over a given surface, only some of them are really needed for monitoring, depending on the application requirements. Redundancy can therefore be exploited by allowing redundant sensors to turn into a much less power-consuming passive mode. The ensuing issue consists in these nodes deciding themselves whether to turn off or not so that the whole area remains sufficiently covered according to the application requirements. Any physical point of the field needs to be monitored by at least one sensor. To increase reliability or security, coverage of any point by k sensors may be required. We also consider a key challenge in wireless sensor networks that consists in collected data to be as pertinent as possible. Such k coverage minimizes the risk of possibly missed event or false alerts.

We consider only fully localized protocols so that solutions can be applied in sensor networks of any size and density. Since no global view of the network is required, a significantly lower communication overhead is induced. Moreover, each node makes its activity status decision solely based on decisions made by its communication neighbors. Sensors are assumed to be time synchronized. Synchronization can be achieved by applying some network protocols (see [3] for a survey) or by sending a training signal from the base station or another entity (e.g. helicopter) which reaches all sensors (see [4] for details). We also assume, as in many existing works, that the static sensor nodes know their position, thanks to any efficient positioning algorithm (e.g. [5]).

We propose a localized area coverage protocol able to maintain an area k-covered. Most of existing protocols never show to what extent they can be resistant. Indeed, many solutions rely on clustering or distributed protocols with significant communication overhead and ideal link layer [6], [7]. Meanwhile, no study about the impact of channel randomness is ever conducted. As the unit disk model is often criticized for its lack of realism, we show that our protocol efficiently works under realistic physical layer assumptions for both sensing and communication modules.

In this paper, we present our contribution in section II by first detailing our localized protocol. After briefly describing the model we will use for the realistic physical layers, we will explain in section II-B our coverage evaluation scheme enhancement to handle non-unit disk sensing regions. Finally, in section II-C, we discuss the robustness of our solution when facing radio channel randomness. Conclusions of this work and future work are given in section III.



(a) A and its neighbors (b) Neighbors of layer 1 (c) Neighbors of layer 2 (d) Neighbors of layer 3

Fig. 1. Node A evaluates its coverage by sorting neighbors by order of activity layer

II. OUR CONTRIBUTION

In this section, we first detail our protocol which consists in evaluating the coverage of several distinct layers to enable k-coverage of the monitored area. We then describe how a realistic model for sensing can be handled through a simple coverage evaluation scheme enhancement. We finally show that our approach works efficiently once communications between nodes are subjected to the *lognormal shadowing* model.

A. A sensor area k-coverage protocol

Sensors are randomly deployed over a square area and activity is imagined in a rounded fashion. At each round, every node decides its status between either monitoring for the entire round or getting passive until the next decision phase. Every sensor is aware of required coverage degree, denoted as k. A node A can find smallest i so that ith layer of the area covered by that node is not fully covered by its neighbors. Then, if $i \leq k$, A decides to be active at layer i and sends a positive acknowledgment announcing its activity layer i and its geographical position. Otherwise, it decides to be passive and no message is sent. Fig. 1 shows that sensor A first evaluates the coverage provided by neighbors of layer 1 (black nodes on fig. 1(b)) before deciding to evaluate the coverage at layer 2 (Fig. 1(c)). Finally, as Fig. 1(d) shows that A is covered at all 3 layers, A takes its activity decision depending on its required coverage degree k. If $k > 3$, then A gets active at layer 4 and sends a positive acknowledgment. If $k = 3$, then A gets passive without sending any message. This solution is referred to as $positive - only$ protocol. In this example, we have modeled the sensing region of a node as a disk. This helps us to better illustrate the sensing coverage while focusing on the protocol itself. However, there is a need to design k coverage schemes that would be based on a realistic physical layer for sensing and communication.

B. Area coverage with a realistic sensing layer

Most of existing works define the sensing region of a sensor as a disk of range SR, centered at the node itself. Many coverage evaluation schemes have been proposed so that a node can decide whether it is fully covered or not. All of them strongly rely on the unit disk assumption and are based on calculating disk intersection points or portions of disk perimeters (see [8] and [9]).

In this paper, we apply the *lognormal shadowing* model [10] to model the probability that a node can sense a given physical point. We chose to use an approximated function $\mathrm{P_S}(x)$, described in [11] as follows:

$$\mathrm{P_S}(x) = \begin{cases} 1 - \frac{(\frac{x}{SR})^{2\alpha}}{2} & \text{if } 0 < x \leq SR, \\ \frac{(\frac{2SR-x}{SR})^{2\alpha}}{2} & \text{if } SR < x \leq 2SR, \\ 0 & \text{otherwise.} \end{cases} \quad (1)$$

In this formula, $\alpha \geq 2$ is the power attenuation factor which highly depends on the environment and x is the considered distance. This function assumes that the probability of relevant sensing for the range SR is always equal to $\mathrm{P}_S(SR) = 0.5$. Fig. 3 illustrates this function for $\alpha = 2$. The probability that a point P can be sensed by a node u depends on the distance between P and u.

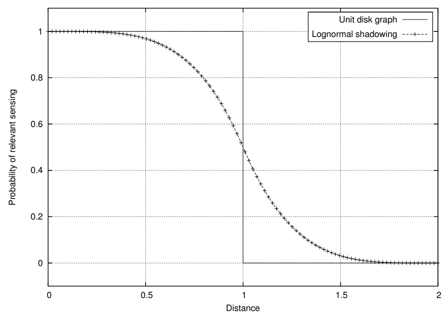
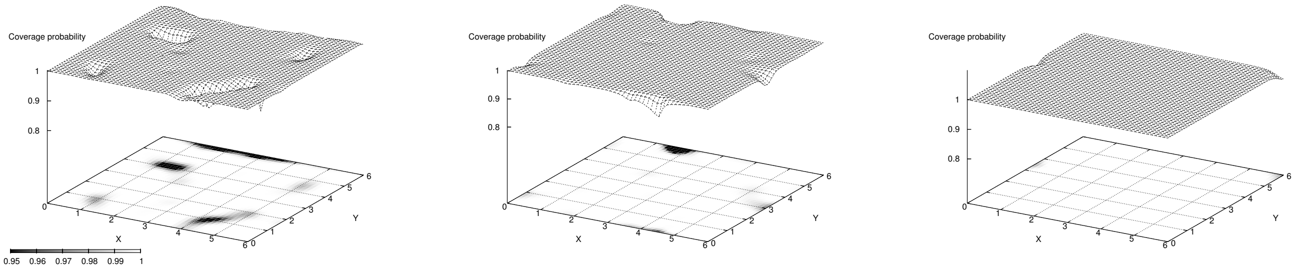


Fig. 3. $SR = 1, \alpha = 2$

To handle this realistic physical model for the sensing layer, we propose to simply enhance the coverage evaluation scheme. Each sensor selects a set of physical points, noted as S, whose size can be adjusted depending on the desired accuracy. We made it vary with the theoretical sensing range SR (e.g. once SR is fixed at 1, we observed that having 10 random points in S could provide enough accuracy). The geographical coordinates of these points are chosen according to a uniform random function. Then, for each point P from S, a node



(a) Coverage threshold = 0.1 (b) Coverage threshold = 0.5 (c) Coverage threshold = 0.9

Fig. 2. Coverage probability of a $6 * 6$ square area (density = 50, $k = 1$)

u computes the probability that P could be sensed by at least one of its neighbors. The neighborhood of a node is composed of the nodes from which the node has received a positive acknowledgment. It is noted as $N(u)$. This coverage probability, noted as $P_{coverage}$, can be obtained with the following formula:

$$\mathrm{P}_{\mathrm{coverage}}(P) = 1 - \prod_{i=1}^{|N(u)|} \overline{\mathrm{P}}_{\mathrm{S}}(d_i)$$

where d_i stands for the distance between the ith neighbor and P, and $\overline{\mathrm{P}}_{\mathrm{S}}(x) = 1 - P_{\mathrm{S}}(x)$. In other words, the probability that P can be sensed by at least one sensor is the inverse probability that P could not be sensed by any neighbor of u.

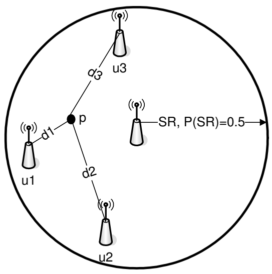


Fig. 4. Probabilistic coverage evaluation

Fig. 4 shows a sensor with three neighbors, noted as $u1$, $u2$ and $u3$, respectively at distance $d1$, $d2$ and $d3$ from P. The probability that P is covered is calculated with the following formula:

$$\mathrm{P}_{\mathrm{coverage}}(P) = 1 - \overline{\mathrm{P}}_{\mathrm{S}}(d_1) \times \overline{\mathrm{P}}_{\mathrm{S}}(d_2) \times \overline{\mathrm{P}}_{\mathrm{S}}(d_3)$$

Once the coverage probability of each physical point from S has been calculated, there are several ways of evaluating the coverage probability of the entire set S. It can be the minimal one among the set of physical points or the average of all probabilities. Considering the minimal probability was our first idea but this was too restrictive. Indeed, a single point with low coverage could force the sensor node to be active even if all other points were covered with high probability. Therefore, we decided to calculate the coverage probability of S as the average of every probability:

k	**Coverage threshold**	*Active nodes*	*Minimal $P_{coverage}$*
$k = 1$	0.2	4.0 %	0.57
	0.6	5.4 %	0.66
	0.9	9.1 %	0.84
$k = 2$	0.2	8.0 %	0.90
	0.6	10.7 %	0.96
	0.9	18.1 %	0.99
$k = 3$	0.2	11.9 %	0.99
	0.6	16.0 %	0.99
	0.9	27.0 %	0.99

TABLE I

INFLUENCE OF COVERAGE THRESHOLD AND COVERAGE DEGREE (k) WHEN RADIO MODEL IS UDG AND DENSITY = 50

$$\mathrm{P}_{\mathrm{coverage}}(S) = \frac{\sum_{i=1}^{|S|} \mathrm{P}_{\mathrm{S}}(P_i)}{|S|}$$

where $S = \{P_1, P_2 \ldots P_{|S|}\}$. Finally, each node has a sensing threshold and compares it to $\mathrm{P}_{\mathrm{coverage}}(S)$. If $\mathrm{P}_{\mathrm{coverage}}(S)$ is greater than the coverage threshold, then S, and its sensing region, is said to be covered.

We have conducted some experiments to test several coverage thresholds and the impact on the coverage of the area. All nodes apply this coverage evaluation scheme with the same coverage threshold and apply our k-coverage algorithm for $k = 1$. Fig. 2 shows a $6 * 6$ square area and the global coverage of the monitored area for three distinct coverage threshold values. Each sensor on average has 50 communicating neighbors, and sensing SR and communication CR ranges are both set to 1. In these experiments, the communication was assumed to follow the unit disk model, while sensing follows lognormal shadowing model. On these diagrams, the altitude of a point stands for its coverage probability. We have also drawn the projection of this altitude; the darker the surface, the lower the coverage probability. Each sensor first applies coverage threshold on the set S defined earlier (in this example, S is composed of 10 random points). Afterwards, it decides whether or not to sleep. If it becomes active, the coverage probabilities of nearby points increase, and diagrams show these increased values. After applying our positive-only algorithm by all nodes, we can observe the coverage of the area. As expected, the coverage threshold directly impacts the

k	**Coverage threshold**	*Active nodes*	*Minimal $P_{coverage}$*
$k = 1$	0.2	5.1 %	0.70
	0.6	6.5 %	0.79
	0.9	10.3 %	0.9
$k = 2$	0.2	10.0 %	0.97
	0.6	12.2 %	0.99
	0.9	20.3 %	0.99
$k = 3$	0.2	14.9 %	0.99
	0.6	19.1 %	0.99
	0.9	30.2 %	0.99

TABLE II

INFLUENCE OF COVERAGE THRESHOLD AND COVERAGE DEGREE (k) FOR LNS RADIO MODEL ($\alpha = 2$) AND DENSITY = 50

coverage probability of the physical points of the area. Indeed, Tab. I shows that when the coverage threshold is fixed at 0.6, the lowest measured coverage probability equals to nearly 0.7 while it reaches more than 0.9 (0.99 when the coverage degree is greater than 1) once nodes have a coverage threshold of 0.9. This means that our algorithm provides a high coverage probability of the monitored area. Tab. I also collects the percentage of active nodes for several coverage thresholds and coverage degrees. The higher the threshold is, the more active nodes there are since the coverage requirements are more strict. The coverage degree has a similar impact. More nodes must be active in order to cover twice or more the area (from 5.4 % at $k = 1$ to 27.0 % at $k = 3$ when the coverage threshold is fixed at 0.9). Logically, this increase of active nodes allows the area to be better covered. Therefore, the minimal coverage probability increases (from 0.66 % at $k = 1$ to 0.99 % at $k = 3$ when the coverage threshold is fixed at 0.6).

C. Overcoming the channel randomness

We are now attempting to show that our algorithm still performs well when a realistic physical layer is applied for communication. Realistic physical layers imply that two nodes have a probability to communicate with each other, that mostly depends on the distance between them. This induces some randomness in the wireless transmission and unstable neighborhood information. We have already shown in another contribution that the kind of algorithm we use would not be impacted in terms of coverage performances (see [12]). Indeed, missed positive acknowledgment from an active neighbor only implies reduced coverage of certain area and increased probability of receiving node to become active. Nodes therefore merely have incomplete tables of active sensor nodes. This can not lead to coverage holes. Meanwhile, more nodes will decide to be active since they have less information (e.g. with $k = 3$, we have 19.1% of active nodes instead of 16.0% with the unit disk model). Therefore, there is an even higher quality of coverage (the lowest measured coverage probability is 0.97 when the coverage threshold is fixed at 0.2, with a coverage degree equal to 2). Tab. II shows complete statistics that have been obtained with the lognormal shadowing model.

III. CONCLUSION AND FUTURE WORK

In this paper, we have presented a simple localized algorithm for providing area k-coverage. This protocol enables sensors in a wireless sensor network to self divide into k distinct subsets of active nodes. Activity decisions of sensors are made solely based on positive acknowledgments. Our protocol is able to handle channel randomness and is therefore a good candidate for use in real sensor deployments. We have shown experimentally that high minimal sensing probability is achieved even for low coverage thresholds.

We aim at introducing a connectivity criterion to ensure the connectivity of one or several activity layers, in order to achieve correct data gathering. Future work could so be dedicated to ensure high probability of k-connectivity with a realistic physical layer.

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