# Efficiency Impairment of Sensor Area Coverage Protocols under Realistic Physical Layer Conditions

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*Abstract*— **Most of existing works about sensor networks focus on energy management. Already proposed solutions often consist in balancing energy consumption by taking advantage of the redundancy induced by the random deployment of nodes; some nodes are active while others are in sleep mode, thus consuming less energy. Such a dynamical topology should not impact the monitoring activity. Area coverage protocols aim at turning off redundant sensor nodes in order to constitute a set of active nodes that covers as large an area as the whole set of nodes. In this paper, we focus on localized algorithms that require 1-hop knowledge only to allow nodes to choose their activity status. The unit disk model is the most commonly used assumption; if a node emits a message, any node within its communication range receives it while any node outside the disk does not. In this article, the impact of a realistic radio channel on area coverage protocols for wireless sensor networks is studied. It is shown that a non-binary reception probability can lead to very different results for protocols that could though provide great performances with the unit disk model. An optimization of a protocol to keep increasing the network lifetime once a realistic energy consumption model is considered is also provided.**

***Keywords:*** ***Wireless sensor networks, area coverage protocol, physical layer, channel modeling, power consumption.***

## I. INTRODUCTION

Distributing sensor nodes so that environment becomes a physical database appears realistic and affordable since recent advances in micro-electromechanical systems (MEMS), digital electronics, and wireless communications enable the development of low cost, low power, multi functional sensor devices [1]. These devices can operate autonomously to gather process and transmit information about the area they are deployed on. 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, their self-organization should provide full monitoring and pertinent data collection so that further heavy computation and analysis tasks could be achieved by external powerful computers. Energy is the most critical resource considering the irreplaceable batteries of the sensor nodes. In order to increase their lifespan, these objects are allowed to turn into sleep mode as long as they are not required for the local surveillance task. Indeed, monitoring redundancy induced by a random deployment can be used to switch off some nodes. The ensuing issue consists in allowing these nodes to decide themselves whether to turn off or not while preserving full area coverage. Several centralized and distributed approaches have already been proposed in literature but often lead to large information propagation throughout the whole network in order to update every node. Localized solutions have significantly lower communication overhead since no global view of the network is required. In this paper, fully localized protocols only are considered because of their scalability: they can be applied in sensor networks of any size and density. In a localized protocol, each node makes its activity status decision solely based on decisions made by its communication neighbors. Several solutions already provide full coverage of a target area by a set of active sensors. However, most of them exploit the unit disk model relying on two axioms: i) each node has a fixed communication range and no message can be directly transmitted to a node further than this distance ii) each message received by any node located in the unit disk is error-free. Such axioms don't hold with a realistic physical layer. Yet, ensuring coherent activity decisions necessarily requires the nodes to have valid neighbor information (messages can be received or not depending on whether the emitter is far, and so reliable, or not).

This paper assesses the impact of a realistic radio channel by introducing a packet error rate depending on the signal-to-noise ratio. After introducing some radio channel models and presenting some existing solutions to the area coverage problem, experimental results show how area coverage protocols can behave under realistic physical layer assumptions. We finally observe that power consumption models also remain simplistic and that one existing protocol can be further optimized to considerably increase the network lifetime with its activity scheduling.

## II. PRELIMINARIES AND EXISTING WORKS

### *A. Channel modeling*

In the majority of current studies about multi-hop networks, models used to characterize the wireless channel remain simplistic. Indeed, the communication zone is generally considered as a unit disk, where packets are error-free transmitted while not any packet can ever be received outside. This simplistic model is called the unit disk graph model. Generally, the channel is simply defined by a path loss function. In this case, the received signal level depends on the distance between the transmitter and the receiver. Let this distance be referred to as *d*. The signal level so decreases according to the law $K/d^{\alpha}$. The parameter $\alpha$ stands for the path loss exponent and depends on the environment (typical values are between 2 and 6, $\alpha=2$ for free space propagation). That is the randomness of the radio link communication is not modeled, which does not reflect reality. Besides the path loss, the radio channel response must be considered, to correctly model the wireless propagation. The simplistic model is the Gaussian channel or AWGN (Additive White Gaussian Noise). Furthermore, two really different effects may be observed over different time scale. The first one, named *shadowing*, reflects the power fluctuation which is mainly due to the propagation environment (obstacles, building…). A formal model used for shadowing predicts the received power to be "log normally" distributed around its mean value. The second phenomenon represents the rapid fluctuation of the signal power. It is essentially induced by the multi-path propagation. With this fast fading, the received signal is Rayleigh-distributed or more generally Rice-distributed [3]. Note that selective fading, occurring when the channel is time dispersive, is not considered herein.

Recently, several research works concerning the connectivity and the capacity of multi-hop networks have been interested in the impact of a more realistic physical layer. In [4, 5, 6], the radio channel (fading, shadowing…) is modeled by modifying the shape of the communicating area. A statistical variation is added and follows a "log normal" distribution around the mean power defined by the path loss model. For example, on Fig.1, nodes 4 and 0 would be able to communicate while node 1 would be isolated. However, in these works, once the path loss law is modifed, a threshold is again applied, and the communication range of every node is calculated. Therefore, each of two nodes in range will always be able to send and receive messages from each other. This hypothesis of a reception threshold is justified by the information theory. Indeed, obtaining a PER (Packet Error Rate) which tends to a step function is always possible provided that an ideal (but long) channel code is applied. Therefore, depending on the chosen channel coding, the law of PER, according to the transmission distance, stiffens and gets closer to a step function (see figure 2). However, an infinite length code would be necessary to really reach the threshold model. We so have to consider that packets can always be lost. Packet retransmission may appear as a way to raise the laws of PER. Meanwhile, this is still equivalent to a not optimized channel coding.

Let us note that for small-sized packets (that is generally the case for sensor networks), the direct coding turns out to be more effective than the retransmission from an energy efficiency point of view [7, 8]. The correct reception of a packet requires that the number of transmission errors is always lower than the capacity of the channel code used. With an AWGN channel, the error rate is directly bound to the signal to noise ratio *SNR*. Every node has a probability to correctly receive a message. This probability tends towards 1 with $SNR \rightarrow \infty$. With a realistic model, neither a threshold nor a communication range can be correctly defined. Instead, we consider a reception probability law according to the distance. The shape of the PER curve depends on the channel model applied and the radio transmission (packets-size, modulation, coding…).

Let us now to estimate the impact of this receive probability. An AWGN channel model is first introduced into two existing area coverage protocols, using probabilities presented on fig. 2. These curves represent the PER of a 30 data bits packet, transmitted with a BPSK modulation (Binary Phase Shift Keying), in an AWGN channel and a free space path loss model ($\alpha$=2), with or without error-correcting code. The considered error-correcting code is BCH(n,k) (which stands for Bose-Chaudhuri-Hochquenghem, n being the length of the code and k the number of detectable errors). The transmission power, following the used coding, is adapted so that an error probability of 0.5 is always obtained at an arbitrary fixed distance *d = 10.*

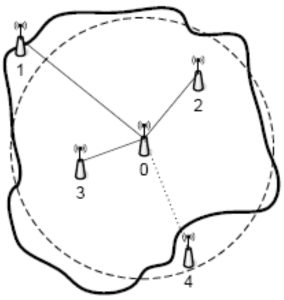


Figure 1. Modified communication graph

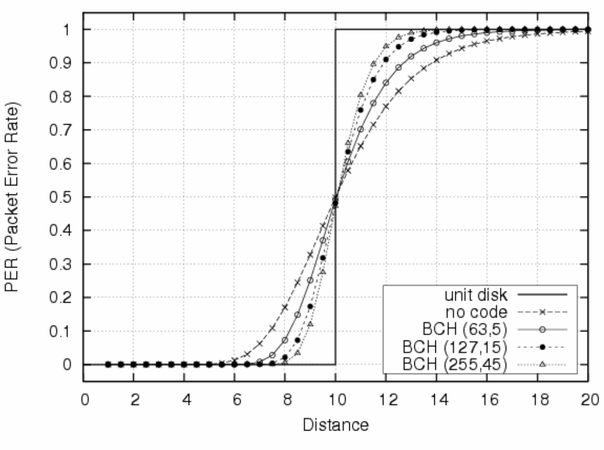


Figure 2. Packet error rate
BPSK modulation, AWGN channel, packet length:30 bits

### B. Area coverage issue

#### 1) Formulation

Any node of a sensor network is able to sense its environment. In this paper, the sensing area of a sensor node is modeled as a disk. The area covered by the whole network is composed of every sensing disk of the nodes. Area coverage protocols aim at turning off some redundant nodes being not useful for global coverage. Instead of relying on a central entity able to determine the activity status of each sensor device, nodes use only local information to choose their activity status.

#### 2) *Assumptions*

Before any activity, sensor networks must be deployed. The deployment can be either deterministic or random, depending on the application. We assume nodes to be randomly deployed and static, while having the same computational capabilities. It is also assumed that devices are time-synchronized ([9] for a survey and [10] for details) so that activity decisions can occur in rounds. Most existing algorithms assume that sensor nodes know their respective positions. The same assumption is made in this paper since positioning issue has already been addressed in literature (see [11]). Sensors are distinguished by their position, and otherwise have no identities. They can be distinguished by assuming that they have a random number generator, and that neighboring sensors always select distinct random numbers.

#### 3) *Existing works*

A comprehensive literature review of existing solutions for sensor area coverage problem, including centralized, distributed, and localized solutions, is described in [12]. Two algorithms are herein described. Both implement a localized approach and are close in their assumptions Then, we also mention some existing works that have already reconsider the unit disk model assumption.

Tian and Georganas [13] proposed a solution for sensor area coverage in synchronous networks where sensing and transmission ranges are equal. At the beginning of each round, each node sends a *hello* message that contains its position. This is the neighbor discovery phase. Then, once nodes are aware of their neighborhoods, each selects a random time-out interval. At the end of it, a node *u* evaluates the coverage provided by its neighbors. This is the decision phase. If its own coverage area is fully covered by its neighbors and then feels useless for global monitoring, it decides to switch in sleep mode. It so sends a withdrawal message so that its active neighboring nodes remove it from their neighbor table. If *u* is only partially covered, it remains active without sending any message. The process repeats periodically to allow for changes in monitoring status. This scheme has been extended in [14] with a generalized coverage evaluation scheme. This solution is named TGJD in the remaining of the paper.

This solution is studied along with the solution presented in [15]. This protocol does not require any neighbor discovery phase since only activity messages are sent. Each node sets a random timeout at the end of which it decides to be active or not. It can compute the coverage that is provided by its neighbors and can then decide to turn into sleep mode without sending any activity message. Such a message is sent if the node decides to be active so that nodes with a longer timeout will be aware of this node once they consider their status. This solution is named positive-only, further noted as PO.

Both these solutions drastically reduce the number of active nodes while preserving the whole coverage of the monitored area. Results have been provided using the unit-disk communication model. Some works have already introduced a realistic physical layer to observe the impact on network layer protocols. In [16], authors show that some routing protocols fail to achieve good performances since their basic idea (minimizing the hop count to reach the destination) can become counterproductive. Indeed, as the unit-disk model suggests forwarding the message to the neighbor closest to the destination, the message has a low reception probability at far distance. Therefore, retransmissions are needed and the expected hop count is so increased. In this paper, we show that area coverage protocols can also be very sensitive to the use of a realistic physical model.

## III. IMPACT OF A REALISTIC PHYSICAL MODEL

Networks are simulated with nodes randomly deployed over a 50*50 square area. Density represents the average number of sensor nodes that are within a communication area. All nodes have the same sensing and theoretical communication radii. Energy levels decrease according to the power consumption model. This is detailed in section III.B.

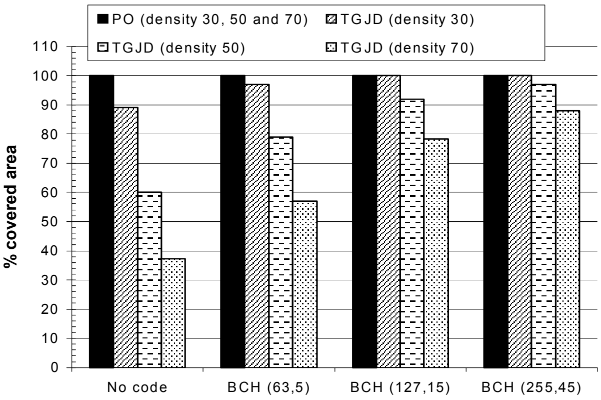
### A. *Area coverage maintenance*

Once protocols are applied on a wireless sensor network, the active nodes set should cover an area as large as the initially monitored surface. As long as unit disk graphs are simulated, both TGJD and PO fully preserve area coverage with a low percentage of active nodes (see table I) [13, 15].

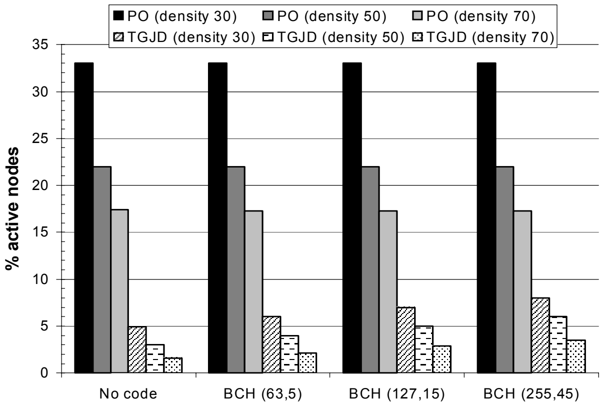
TABLE I. MODELISATION WITH UNIT DISK

| | **Density 50** | | **Density 70** | |
|---|---|---|---|---|
| | ***Active nodes (%)*** | ***Coverage (%)*** | ***Active nodes (%)*** | ***Coverage (%)*** |
| TGJD [13] | 12 | 100.0 | 8.4 | 100.0 |
| PO [15] | 22 | 100 | 17.4 | 100.0 |

Meanwhile, once a realistic physical layer is simulated, these performances can not be maintained by TGJD. Let us observe the consequences on both phases of TGJD algorithm. First, the neighbor discovery phase is impacted by this assumption change. Some *hello* messages may not be correctly received. Then, neighbor tables could get incomplete. This is not a problem as long as they are not wrong. However, during the decision phase, not receiving a withdrawal message implies that the corresponding node is not removed from the neighbor table, which therefore gets wrong. The consecutive decision can so be false regarding to the neighborhood. The direct consequence is the appearance of coverage holes over the target area since some nodes decide to be passive while they are not fully covered anymore. Figure 3(a) shows that, with non coded messages, coverage percentage falls as low as 60% at density 50 (and respectively 88% and 37% at density 30 and 70). This can also be observed on figure 3(b); the number of active nodes is in accordance with the covered area (the more wrong decisions, the less active nodes). If messages are not coded, TGJD induces less than 5% of active nodes, which is not sufficient to cover as large an area as the whole set of nodes. Meanwhile coding the messages improves the performances of TGJD. *Hello* and withdrawal messages are better received, thus reducing the number of wrong decisions. However, there is always a non-negligible probability that a message is not received by a node, thus leading to wrong decisions. This is why TGJD never achieves full coverage with a realistic physical layer. Furthermore, the size of the so introduced codes must considerably be increased to bring the PER closer to the one of unit disk model (nearly 90% of coverage when messages are coded in BCH(255,45)). Meanwhile, full coverage can never be ensured. Moreover, in addition to increasing the collision probability, having larger messages also induces much higher energy cost, which is inappropriate to sensor networks.



(a) Covered area



(b) Active nodes

Figure 3. Active nodes and maintained area coverage with a realistic channel.

Figure 3(b) shows the number of active nodes that TGJD and PO induce, for density 30, 50 and 70. We can observe that more nodes remain active with PO. This allows PO to still guarantee full area coverage, whenever messages are coded or not. Indeed, if a positive message is not correctly received, no wrong decision is taken simply because activity decisions are made solely based on the received messages. By this way, coding the transmissions does not much impact the number of active nodes, as observed in Figure 3(b). Indeed, as only one message is sent by a node, and as the packet error rate is fixed at 0.5 for a distance equal to the theoretical communicating range, nearly the same amount of messages is received by a node. Note that neighbor tables of PO may be incomplete due to bad receptions but they can never contain neighbors that are not active. In other words, these neighbor tables can never be false regarding the real neighborhoods of nodes. The exception to this statement is the case of a node failure after it has announced its activity. Yet, this node could announce predictable failures such as low battery level for instance. Meanwhile, this message may also be lost and this is why this case is devastating for all protocols. It could only be avoided with shorter table refreshment periods and so shorter rounds.

### B. *Evaluating energy consumption*

Most of area coverage protocols aim at reducing the number of active sensors, which is very often considered as the prime criterion to formulate energy consumption. Therefore, communication costs are rarely taken into account while energy costs related to wireless transmission can not be neglected. Indeed, most of existing sensor devices consumes energy accordingly to the following formula [17]:

$$Send_{cost} \approx Receive_{cost} = k * Sensing_{cos}$$

with $10^{-}<\psi k\psi<\psi 100$, depending on what sensors should sense (humidity, noise, temperature, etc.). We want to show that metrics used in existing protocol evaluations may not reflect the reality of sensors communicating over a wireless link. In other words, minimizing the number of active nodes is not as energy-efficient as minimizing the transmission costs.

Therefore, sensing activity is not as expensive as the wireless transmissions. For instance, TGJD algorithm induces one *hello* message and a withdrawal message from nodes that decide to be passive. Hence, as more nodes wrongly decide to be passive once a realistic radio channel is introduced, TGJD generates even more withdrawal messages and so more overall energy consumption. The additional number of sleeping nodes can not compensate the energy lost to send withdrawal messages that moreover prevent this protocol from maintaining full area coverage. PO has a very low communication overhead. A message is sent if and only if the node decides to be active. With a non ideal channel, more nodes get active but there are still less sent messages than with TGJD since it requires at least one *hello* message from each node. Note that, assuming the worst case when all nodes decide to be active, PO implies at most one message per node. Thus, PO should provide more energy savings than TGJD.

Meanwhile, energy costs have an impact on the protocol implementation. Without considering energy consumption due to carrier sense, we evaluated PO by introducing sending and receiving costs. Figure 4 represents the network lifetime for four different energy models. The network lifetime is the time during which the network remains connected. Here is the meaning of the legend of the Figure 4:

- *No protocol* corresponds to the case where all the nodes are always active. Because of the monitoring activity, each node losses one battery unit (all start with an initial battery level fixed at 100).
- *Monitoring cost only:* PO is basically simulated. Each node listens to activity messages during its random timeout. At the end, of its timeout, a node decides to be active if its discovered neighbors fail to fully cover its area. Active nodes loose one battery unit while energy levels of sleeping nodes remain unchanged.

- *All costs:* Until now, power consumption was only related to the activity status. In the "*All costs"* case, both transmitting and receiving costs (which include message coding and decoding costs) are considered. Note that computation costs were not included because of their high dependency degree with the application.
- *Optimized Carrier Sense:* all costs are still considered but PO has been optimized to save more energy. As the number of sent messages can not be decreased, we decided to modify the decision process in order to reduce the number of received messages; neighbor tables are updated after each message reception and sensors turn into sleep mode as soon as they are fully covered.

Then, in very dense networks, a node may already be fully covered at the beginning of its timeout and so, it could stop listening to activity messages. Therefore, it will save much energy by simply turning into sleep mode before the end of its random timeout. This can be observed on Fig. 4 as the network lifetime is nearly twice longer with an optimized PO protocol, compared to the basic PO simulated with the "*All costs"* case.

Such an optimization of the protocol could not be applied to TGJD since nodes must listen to all withdrawal messages during the decision phase. Stopping listening to the medium before the end of the timeout could imply missing some withdrawal messages and so having similar troubles as those exposed in previous section (coverage loss and higher communication overhead due to too many sleeping nodes).

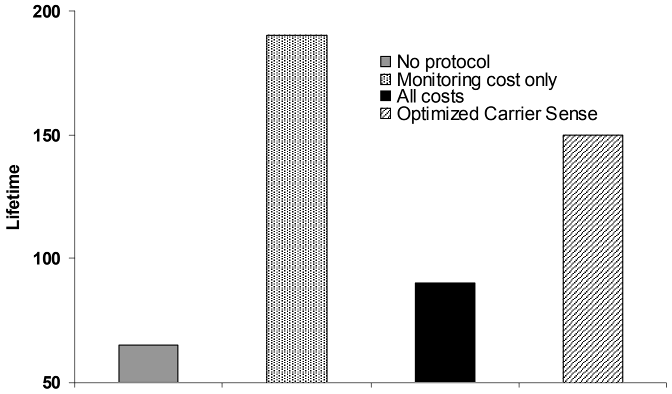


Figure 4. Impact of physical layer on network lifetime

## IV. CONCLUSION

In this paper, the performances of area coverage protocols under realistic physical layer conditions are evaluated. Once a realistic radio channel is introduced, coverage is not fully maintained by TGJD protocol. The randomness induced by the radio link considerably impacts its performances. Considering a probabilistic loss of message in the communication zone has a huge impact on protocols based on withdrawal messages. As nodes decisions rely on negative information from neighbors, any bad reception potentially induces a wrong decision. As we aim at providing coherent global behaviors from simple local and correct decisions, these protocols do not fit in our requirements. As PO is resistant to message loss, we observed here that it was also able to guarantee full coverage of the target area once the unit disk model was not used anymore. This joint work also led us to slightly modify the implementation of the protocol in order to reduce energy costs due to message receptions.

Future works will consist in investigating the connectivity preservation. We aim at extending the work presented in [15] by introducing a local probabilistic connectivity criterion. A sensor node could turn into sleep mode if and only if it is fully covered by a set whose probability of connectivity is above a given threshold.

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