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New Sensing Model for Wireless Sensor Networks

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Abstract - ***The paper presents a new sensing model for Wireless Sensor Networks. This model, named Circular Sector Sensing Coverage, was first introduced by the authors at SENSORCOMM 09 conference. It uses circular sectors with variable central angles and radii. The purpose of the model is to minimize the energy consumption of the sensing itself, improving the energy balance of the sensor node (mote). This is especially relevant when the sensing is done remotely, by sending waves to detect intrusion or acquire data. Simulation of this model shows energy savings versus previously published schemes, suggesting the viability and the advantages of this new sensing model. However, no analytical model was yet developed. The present paper expands the scope of the previous one by adding background information about known sensing models, describing in greater details the algorithm used for simulation and by presenting new and significant simulation results. The obtained data confirms the advantages of this new sensing model. The possible implementation of such a WSN may significantly improve the energy-related performance of the WSN, allowing the development of new applications and improving the performance of existing ones.***

Keywords: Wireless Sensor Network; sensing models; sensing coverage; energy efficiency; circular sector

1. Introduction

The paper presents a new model of sensing coverage, supposed to achieve a better efficiency of energy utilization for remote sensing, by using an adaptable radii and angles algorithm. Coverage areas of circular sector shapes, adapted to the residual energy available, are used. The model was first introduced by the authors in [1]. The algorithm is intended to optimize the energy used for sensing, in order to extend the life of the sensor network. It does not assure a complete coverage of the area to be sensed - an NP-hard problem. Although an analytical model was not yet developed, the proposed model is interesting and efficient, and is presented as such to the wireless sensor networks community.

The Introduction section gives a succinct account of WSN-related problems, with emphasize on energy-efficiency related factors: placement and topology, management, coverage, lifetime.

Research in WSN is advancing at a fast pace, as can be seen in recent surveys of this topic - see [2][3]. Simultaneously, more and more actual deployments are implemented. One of the main problems facing WSN applications is the limited life span of the network. A typical node (mote) is powered by a battery, which is generally not field-replaceable. Also, energy harvesting was developed only as a proof-of-concept, and is not yet a viable option for real life implementations. A good survey of energy-related problems may be found in [4].

A typical mote has three energy-hungry subsystems: radio, processing and sensing unit. It is generally agreed that most of the mote's energy is required for communication ($\mathcal{E}_c$), followed by processing ($\mathcal{E}_p$) and, finally, sensing ($\mathcal{E}_s$). The total lifetime of the WSN is a function of their sum Σ, as shown in (1):

$$\Sigma = \mathcal{E}_c + \mathcal{E}_p + \mathcal{E}_s \qquad (1)$$

The energy needed for communication $\mathcal{E}_c$ has the same order of magnitude whilst the radio subsystem is transmitting, receiving or in idle state. To reduce the communication costs, two approaches were developed:

- Duty-cycling, i.e., putting the radio in a sleep mode and transmitting only when necessary. This imposes the use of a sleep/wake-up algorithm to coordinate their activities.
- Data-driven approaches, which decrease the amount of sensed data to be transmitted, by optimizing the sampling time, and using data fusion/aggregation/compression schemes.

The power consumption of the processing unit $\mathcal{E}_p$ is generally three-four times of magnitude less than $\mathcal{E}_c$. Finally, research has shown that the energy consumption of the sensing subsystem $\mathcal{E}_s$ may be significant, even greater than the energy consumption of the radio or processing subsystems [5]. The main factors are power hungry transducers and A/D converters, long acquisition time and the use of active sensors. The class of active sensors contains sensors that use active transducers, as sonar, laser or radar. They cover a dedicated sensing area, by sending out a probing signal. It may acquire data such as remote temperature, information about localization and tracking of moving objects, or simple binary intrusion detection.

Sensing is strongly related not only to energy-efficiency, but also to important problems such as area coverage and connectivity. Both problems may be viewed as a measure of quality of service in WSN. Maximizing coverage and ensuring network connectivity is a difficult task and many solutions were described [6][7]. The coverage of the sensed field is conditioned by an optimum deployment of the motes [8]. Various algorithms and approaches were proposed [9-16]. The lifetime requirements of mote deployment are related to their placement in the site to be surveyed [17]**.** A comprehensive theoretical presentation of the minimum-cost arrangement of the motes in order to achieve the wanted coverage lifetime may be found in [18]. Analytical methods use Linear Programming, Voronoi–diagram based heuristics or Delaunay triangulation in order to achieve an energy-efficient coverage. While the coverage problem is not solved for all cases and methods, good results have been obtained for particular cases. One of the best examples is described in [19] and [20].

The paper is organized as follows. In Section 2 we present various models of sensing area coverage, with emphasize on the disk model and his improvement, the variable radii circular model. The new Circular Sector Sensing Coverage (CSSC) model, which is a further improvement, forms the object of Section 3. The simulation environment for running the algorithm implementing this model is described in Section 4. Section 5 discusses the obtained results, while Section 6 proposes future research paths and concludes the paper.

2. Sensing Area Coverage Models

From a functional point of view, there are two kinds of sensing activities: local sensing and remote (or range) sensing. The first one relates to local measurements, while the late try to detect or measure a change of property of a distant location or range. A typical local measurement may be temperature, humidity, level of radioactivity, etc. in the immediate proximity of the sensor. A typical remote measurement may use ultrasound or a laser ray to detect an intrusion or to track the velocity of a moving object.

Remote measurements make use of physical characteristics of wave propagation. The time-of light method uses pulses of energy transmitted toward the target, and measures the time difference between the transmitted and reflected signals. Another method use the relative phase shift of these two signals. Lasers scanners may send continuous frequency modulated signals, varying linearly with time.

The results of the sensing may be deterministic or probabilistic data. For local sensing, the probabilistic factor is due to the precision range of the sensor. For remote sensing, the probabilistic model takes into consideration the inherent uncertainty of detections or measurements at increasing distance.

2.1 Disk model of sensing

This model defines the sensing area as a circle with radius $R_{s\_}$ for a sensor S_i, constant for every *i*. This sensing model is also known as the unit disk model [6][21].

It is generally accepted that the quality of sensing decreases nonlinearly with the increase of the distance, like in (2)

$$S(S_i, P) = \frac{\lambda}{d(S_i, P)^{\alpha}} \qquad (2)$$

where $S(S_i, P)$ is the sensitivity of the sensor s_i at point P, α and λ are parameters, and $d(S_i,P)$ is the distance between the sensor and the point where the measurement is done.

In the deterministic disk sensing model, sensing is done, with a given accuracy, in and only in the area of a disk with radius R_s, around sensor s_i. This is also called a binary sensing model.

In the probabilistic model, the probability of detection (or the accuracy of the measurement) varies as the distance between the sensor s_i, and the point at coordinates (x_i, y_i), $P(x_i, y_i)$ increases. Figure 1 illustrates the different sensing areas, while (3) defines the probability that a node will detect a point $P((x_i, y_i)$. The latest property is called the probabilistic coverage of $P(x_i, y_i)$, denoted $C_{x_i,y_i}(s_i)$.

Note that the quantity R_ε is a measure of uncertainty in detection , $R_\varepsilon < R_s$

$$C_{x_i,y_i}(S_i) = \begin{cases} 1 & if \quad R < R_s - R_\varepsilon \\ p & if \quad R \in [R_s - R_\varepsilon, R_s + R_\varepsilon] \\ 0 & if \quad R > R_s + R_\varepsilon \end{cases} \qquad (3)$$

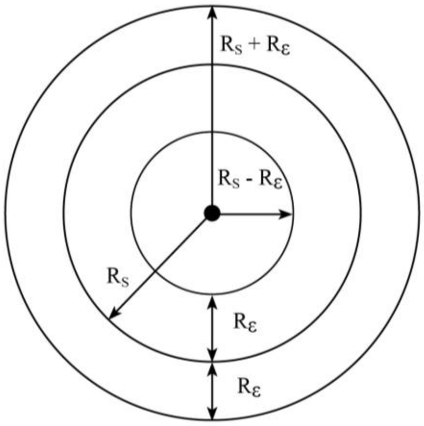


Fig.1 Probabilistic disk sensing model

Generally, p is evaluated as $p = e^{-\omega a^{\beta}}$, where $a = d(S_i, P) - (R_s - R_\varepsilon)$ while ω and β are empirical parameters that define the detection probability, when an object is situated at a certain distance from the node.

Due to the fact that a point $P(x_i, y_i)$ may lie in the sensing area of more than one node, the total is defined as in (4).

$$C_{x_i,y_i}(\chi) = 1 - \prod_{i=1}^{k}(1 - C_{x_i,y_i}(S_i)) \qquad (4)$$

where χ is the set of nodes whose sensing ranges cover the point $P(x_i, y_i), \quad \chi = \{s_i, i = 1,2,..., k\}$.

This model reflects the sensing behaviour of devices like ultrasound or infrared sensors.

2.2 Variable radii circular model

While the disk model of sensing is simple and the coverage may be relatively easily achieved by using an equal-spaced grid deployment in an obstacle-less environment, this model is not realistic and not energy-efficient. It is not realistic because the variance in sensor calibration and residual battery energy may substantially vary from sensor to sensor during their lifetime. It is not energy-efficient, because the overlapping of sensed areas with more than the necessary sensing radius R_s causes a waste of energy. Another argument is that a large sensing radius will increase the consumption of energy, due to the use of more sophisticated filtering and signal processing methods. The later operation is required to improve the signal-to-noise ratio, in order to achieve an energy-efficient confidence level.

Various models of variable radii circular sensing models were proposed, see [19][22]. They achieve an efficient coverage of the sensed area, while using centralized or local optimization algorithms. The basic idea is represented in Figure 2. It can be seen that by using different radii (R_1, R_2, R_3), the sensed field can be better covered, with less overlapping of sensed areas. Practical implementations/simulations use discrete values for radii.

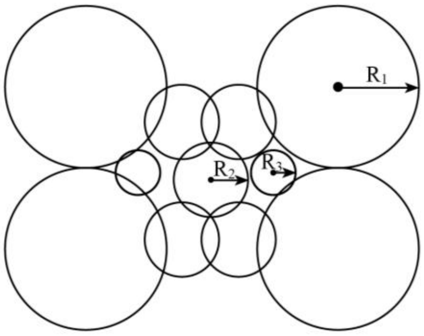


Fig. 2 Different sensing radii

It was shown [6] that this model, when compared to the disk model, presents a more energy-efficient behavior, especially in algorithms which try to solve the coverage problem, i.e., the sensing through all the monitored area. It allows for a more flexible and less redundant deployment policy, while ensuring an optimal approach of solving known coverage problems like

- Minimal exposure path, which is a measure of how well a sensed field is covered for detecting a moving target.
- Maximal breach path, defined as the highest observability path in a sensing field
- Maximal support path, which minimize the distance from any point to the closest sensor.

2.3 Other sensing models

In order to achieve even more energy-efficiency, and to accommodate real-life scenarios, other sensing models were proposed. A brief survey of the most significant ones is given below.

The irregular sensing range model is based on extending the variable radii circular model to a closed polygon. No better energy efficiency is achieved, the sensing range remaining the same. However, the analytical model facilitates a better simulation of the WSN, efficiently identifying fully covered sensors and discovering holes. Centralized or distributed algorithms are used to analyze the coverage problem [23].

Most of the WSN deployments are not truly two-dimensional, but in the majority of cases the height is small enough relatively to the length and width of the network. When simulating the behavior of such a terrestrial network, the third dimension (3D) of the motes may be safely neglected. This is not the case with the underwater, atmospheric or space deployment of WSN. The coverage and connectivity aspects of 3D networks was also researched, and the proposed solutions use generally Voronoi tessellation to partition the space in hexagonal prisms or rhombic dodecahedrons. [24]. These results have energy-related practical consequences. Consider using unmanned aircrafts for airspace surveillance, or underwater unmanned autonomous vehicles for ocean surveillance. Obviously, finding the optimal placement of vehicles, minimizing their number while guaranteeing total coverage of the space, makes a better use of the energy.

A possible approach to mitigate the coverage problem is based on redeploying mobile redundant motes to uncovered areas [25]. Nevertheless, obtaining location information in a GPS-less wireless mobile sensor network demands a lot of energy. This is due to heavy processing and extensive message exchanges. A number of algorithms were devised to alleviate these problems [26].

To be compared, each of the sensing models described in Section 2 would ideally have a complete analytical description. However, the majority of research papers relates to specific aspects, like coverage, connectivity, most exposed path, etc. The energy-effective aspect is generally taken in consideration mostly by presenting results of running simulations of these algorithms.

3. The Circular Sector Sensing Coverage (CSSC) Model

Our work proposes a new sensing model - the Circular Sector Sensing Coverage (CSSC) - based on circular sectors with variable central angles and radii. The sensing area is the portion of a circle enclosed by two radii and an arc, whose values are set after analyzing the data received from neighbor motes.

In Figure 3 an example of a possible partition of sensing areas between three neighbor sensors (S_j, S_k, S_m) is given. The sensed area between them is dynamically allocated as follows:

- Sensor S_j senses the area covered by the circular sector S_jAB, with radius R_1 and circular angle θ_1 (toward sensor S_k)
- Sensor S_k senses the area covered by the circular sector S_kAB, with radius R_2 and circular angle θ_2 (toward the sensor S_j), and the area covered by the circular sector S_kCD, with radius R_3 and circular angle θ_3 (toward sensor S_m)
- Sensor S_m senses the area covered by the circular sector S_mCD, with radius R4 and circular angle θ_4 (toward sensor S_k).

The same notation S_i is used for the sensor itself and its location. Observe the small overlapping areas between the intersections of circular sectors.

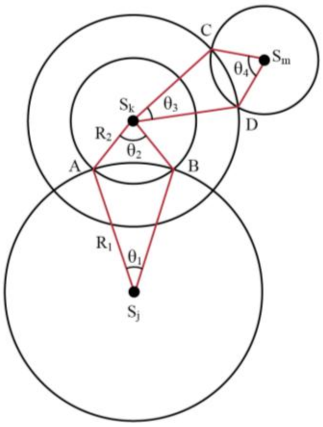


Fig. 3 CSSC model schematics - an example

The CSSC model is based on exchange of residual energy information between neighbor motes. The received data is used to calculate the parameters of the circular sectors covering the sensing areas. The goal is to maximize the coverage, while optimizing the energy consumption. Motes with more residual energy left in their battery may increase the sensing area toward a neighbor with less residual energy. The latest will correspondingly decrease the sensing area in the direction of the neighbor that helps him. The process is iterative, based on negotiations and subject to convergence conditions. It is periodically repeated during the lifetime of the WSN.

The following subsections describe the data exchanged by motes, the implementation of the proposed CSSC algorithm, and the visualization of the whole process.

3.1 Mote communication

In order to establish the sensing areas of each mote, they have to find their neighbors and send relevant information. Finding neighbors is done by broadcasting notification messages and assuming symmetric communication. After that, they send localization data and synchronization control commands. In the next stages, actual energy-related and sensing area information is exchanged. The relevant fields of such a packet contain sender and receiver ID, sender location, operation code, energy level and coverage percentages, maximum and actual coverage distance, supplementary parameters.

The purpose of the communication is to:

- receive enough data to calculate a variable called *StatParam*, used in simulation - See (5).
- notify neighbors about the current sensing area, decided as a function of the value of *StatParam*

$$StatParam = \frac{EnergyLeft}{\frac{CoverageConsum}{TimePeriod} \bullet CrntCoverage + 1} \qquad (5)$$

The variables are defined as follows:

- *StatParam* is the relative residual energy of the mote, function of the currently covered sensing area.
- *EnergyLeft* is the absolute value of the residual battery energy.
- *CoverageConsum* is the energy needed to sense the covered circular sector area.
- *TimePeriod* is the time interval between *StatParam* evaluation
- *CrntCoverage* is the area of the circular sensor where this mote does the sensing

If this value is greater (by a predefined threshold) than that of a neighbor node, the sensing area in his direction will be increased.

3.2 Area coverage algorithm

The algorithm used for the simulation of the CSSC model is described, skipping only minor details. The following steps are done for every mote:

Step 1

Broadcast and receive control messages from all sensors. Based on localization information, build a list of neighbors. A neighbor sensor is one which is situated closer than twice the maximum sensing distance (radius). The assumption is that the communication range is greater than the sensing one, and location information is available and part of the control message. Go to Step 2.

Step 2

Check the number of neighbors in the list. If no neighbors are found, use the *UnitDiskModel* of sensing, i.e., circular sensing with maximum radius, and apply the algorithm to the next mote. If only one neighbor is found, go to Step 3. If more than 1 neighbors are detected, order them according to their angular orientation: sort them beginning with the least angle (from 0), clockwise. Go to Step 3.

Step 3

For every neighbor, check if the maximum coverage distance was received. If not, ignore the neighbor till receiving this parameter. For all other neighbors, calculate the radicals, i.e., the intersection lines of their maximal radius sensing coverage circles. If radicals were found, select and retain only the relevant ones (i.e., those that are not hidden by other neighbors).

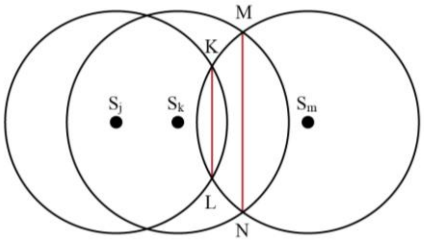


Fig. 4 Discarding radicals example

As can be seen in the example from Figure 4, the radical KL of motes S_j and S_m is situated in the sensing area to be covered by motes S_k and S_m. Consequently, radical KL will be discarded, while radical MN will be retained for further use. Go to Step 4.

Step 4

Calculate the *StatParam* values and compare them. Decide for each neighbor if you can help to preserve its energy reserve by increasing the covered sensing area in his direction. Communicate the changed radical to the neighbor. Do *Step 3* for all neighbors and go to Step 5.

Figure 5 gives an example, showing how two equivalent circular sector sensing areas (S_jPQ and S_kPQ) may be substituted by two asymmetric ones (S_jRS and S_kRS). This allows mote S_k to consume less energy, at the expense of mote S_j.

Step5

Eliminate overlapping of temporary calculated sensing areas for pairs of motes, using the results of the sort done in Step2. Do the sensing according to the newly defined circular sectors.

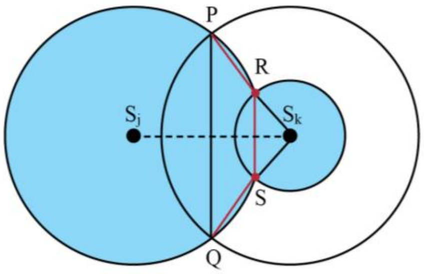


Fig. 5 Moving the radical example

Steps 1 to 5 are repeated periodically (in our simulation, every 5 minutes) for all motes. In order to avoid unnecessary changes, hysteresis was implemented when evaluating the differences of the *StatParam* values.

3.3 Visualization of the process

While running the algorithm described in the previous subsection**,** "housekeeping" calculations are taking place, to find and draw the current circular sectors. The results are used mainly to dynamically draw the sensing areas of the WSN on the screen. Furthermore, the obtained data is also used in energy calculations and as help to check the analytical model in work. These calculations doesn't affect the concept of the CSSC model, being based on specific geometric and programming implementations. The same results may be obtained using different procedures. While running interleaved with the computations needed to implement the CSSC algorithm, these calculations are done mostly during Step 4. Results from [27] were used for clipping arcs.

After eliminating the unneeded radicals, belonging to hidden neighbor motes (Step 3), a tentative temporary new radical, defining the boundary of circular sectors for two neighbor motes, is calculated (Step 4). A collection of intersection segments is saved for each pair of neighbor motes. The mote with the bigger sensing area will save three segments, while the mote with a smaller sensing area will save only one. Referring to Figure 5, mote S_j will save segments PR, RS, and SQ - while mote S_k will save only segment RS.

The next actions are needed to eliminate the ambiguity of areas which may be covered by different pairs of neighbor motes, i.e., they are overlapping. This is done by comparing the relative positions of the saved intersection lines, filtering them and even defining new ones.

Finally, the current circular sectors for the mote, illustrating the received sensing areas, is decided. In the example given in Figure 6, three circular sectors were obtained, with the following parameters:

$\theta_1=2\pi/3$, $_1$
$\theta_2= \pi/4$, r_2
$\theta_3= \pi/4$, r_3, and $r_1> r_2> r_3$

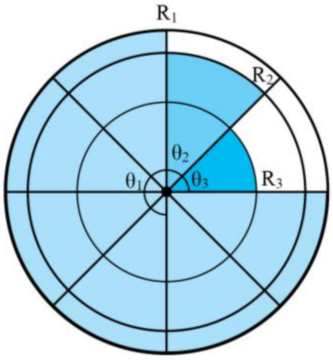


Fig. 6 Coverage example

It has to be noted that no complete coverage may be guaranteed for a given deployment and residual energy of motes. Conditions (6) and (7) hold for every mote:

$$\sum \theta_i \leq 2\pi \qquad (6)$$

where θ_i are the circular angles of the sensing circular sectors of a mote.

$$r_i + r_j \leq R_i + R_j \qquad (7)$$

where r_i , r_j are the current radii of neighbor motes S_i and S_j, while R_i , R_j are their maximum sensing radii.

The algorithm may be implemented centralized or as a distributed process, at each mote. The energy of processing overhead is obviously smaller than the energy used by emitting light, electromagnetic or sound waves.

4. Simulation

A dedicated simulation program was developed, based on .NET and GDI+ environments. For the simulation data, XML format was used. The simulator allows the programming of the following WSN coverage sensing models: disk unit (i.e., constant radius), circular (i.e., variable radii), and circular sector CSSC (i.e., variable radii and angles). It has the usual features: mote deployment methods, editing mote proprieties, save/import/export scenarios, logs, result analysis, GUI and viewing area, etc. The simulation may be checked in virtual real time, using an adjustable virtual clock, which allows specifying a desired running timeline.

The use of Opnet or ns-2 simulators was also considered. However, when weighting their advantages versus the flexibility of a purpose built dedicated simulator, the last solution was preferred. The main reason was the complexity of the CSSC model visualization.

Special care was given to chose the parameters of the simulation. Data from similar simulations were evaluated. The effects of routing protocols, which were not the object of this research, were minimized (by using single hop connections). A decision to not use, at this stage of the research, heterogeneous motes, was also taken. The planned testbed for WSN, to be built this year, also influenced the choices. During the simulation process, some of the settings and parameters were slightly changed, mainly to achieve better visualization.

The main parameters and data for the simulated network are given in Table 1.

Parameter	**Value**
Maximum number of motes	100 to 200
Sensed area	60m x 60m
Network type	Homogenous
Mote distribution	Normal/manual
Initial capacity of the battery	1-4Ah
Drain current	40mA
Routing algorithm	Single hop
Communication power/message - Tx	40mW
Communication power/message - Rx	5mW
Packet length (data and management)	1kB
Maximum sensing range	10m
Maximum sensing power (full circle, maximum radius)	20mW
Central angle increments	π/18
Radius increments	0.5m

Table1 Network and mote parameters

Typical timing parameters may be found in Table 2.

Parameter	**Value**
Location transmission	10s after start
First data transmission	30s after start
Data transmission intervals	10s
Neighbor motes negotiations interval	5s

Table 2 Timing parameters

The main metrics used are enumerated in Table 3.

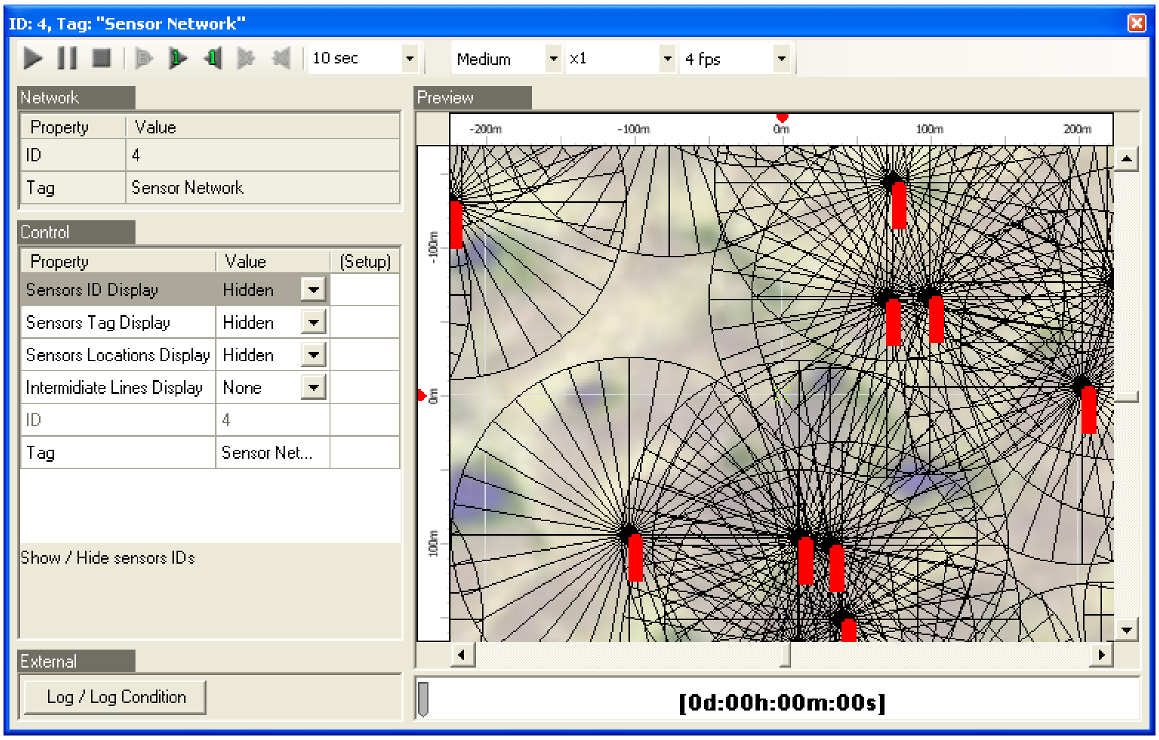
Metric	**Defined as**
Data reports	Quantity of data sent by all motes
Redundant data	Measurement already sent by neighbor motes
Application messages	Number of data messages
Management messages	Number of management messages
Number of motes	Current number of active motes

Table 3 WSN simulator metrics

For the purpose of simulation, all messages were defined as having the same number of bits.

The simulator may be relatively easy expanded to process new sensing models, mote parameters, running conditions, measurements, and visualizations. A typical screenshot, representing a partial view of the WSN area may be seen in Figure 7. It illustrates the initial phase of the algorithm. The weight of the red rectangles is proportional to the residual energy of the batteries.

The simulated scenario used a uniform random distribution of motes, while the virtual simulated time was 1000 hours. Three algorithms were implemented: unit disk, circular model, and circular sector (CSSC) model. A variable number of sensors were deployed (between 100 and 200), and performance differences were observed and will be discussed in the next section.



ID: 4, Tag: "Sensor Network"

10 sec | Medium | x1 | 4 fps

Network

Property	Value
ID	4
Tag	Sensor Network

Control

Property	Value	(Setup)
Sensors ID Display	Hidden	
Sensors Tag Display	Hidden	
Sensors Locations Display	Hidden	
Intermidiate Lines Display	None	
ID	4	
Tag	Sensor Net...	

Show / Hide sensors IDs

[0d:00h:00m:00s]

Fig. **7** Network View screen – partial initial field snapshot

5. Results

Extensive running of the CSSC algorithm were done. The results were compared to both the disk unit and the circular model. The life span of sensors, in various deployment situation and energy reserve/consumption assumptions were calculated during the simulations. The CSSC algorithm shows performance improvements of the lifetime of simulated WSNs.

Typical results are presented in Figure 8 and Figure 9. Although different number of motes were used in simulations, the graphs represent the minimum and the maximum number of motes only. Running of algorithms can be seen in two situations: deployment of 100 motes (Fig. 8) and 200 motes

(Fig. 9) in the same field. Both graphs plot the number of active motes, i.e., the motes with still residual battery energy as function of running time. As a consequence of the single-hop communication model adopted, the communication range is supposed to be always operational till the sink, and therefore the possible loss of the transmission connectivity is not an issue. It can be seen that the CSSC model is consistently more energy-efficient.

Interpreting the chart from Figure 9, it can be seen that after 1000 hours (simulated time), the WSN field utilizing the CSSC model had about twice more active nodes left, compared to the circular model. The CSSC model demonstrated, under the same conditions, a 50% increase in the number of active nodes also vs. the circular sensing model.

An interesting performance difference emerged from the simulations obtained by running 100 vs. 200 motes. The chart in Figure 9 shows shorter life-spans of WSN with 200 motes, compared to WSN with 100motes. The advantage of CSSC model, while observed, is less significant. A possible explanation may be the differences in the energy dissipation mechanisms required by the three sensing models. The energy-efficiency of the disk unit sensing model was not influenced by the number of motes, while the circular model was slightly affected and the CSSC model even more.

We have found a strong negative correlation between the density of motes in the WSN field and the energy-efficiency of the CSSC model. This model is less energy efficient for densely populated WSN fields. As can be seen in Fig. 10, a strong positive correlation exists between the motes density and the number of exchanged management messages. The presence of more neighbors in the sensing range of a mote implies an increased number of negotiations to establish the mutual optimal sensing areas. While this density decreases with time, it contributes to the energy consumption balance of the WSN.

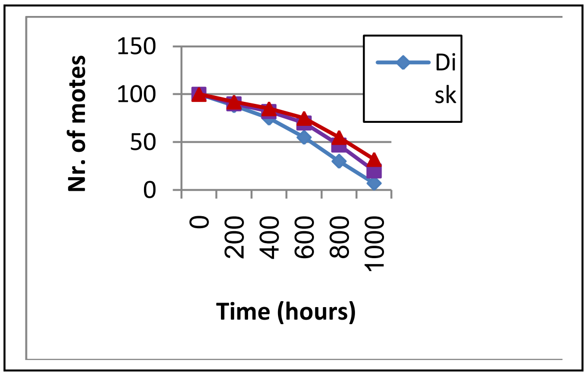


Fig. 8 Sensor field life – 100 motes

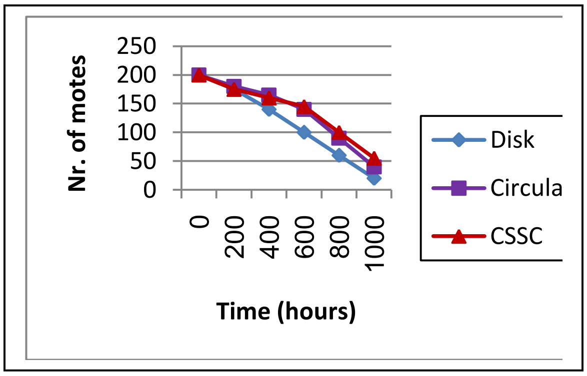


Fig. 9 Sensor field life – 200 motes

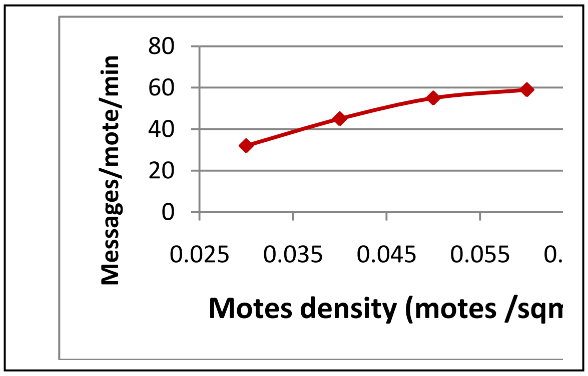


Fig. 10 Number of management messages (CSSC sensing model)

When varying the data transmission intervals, slightly modified simulation results were obtained. As expected, the maximum rate of 5s produced the greater energy consumption, while the minimum simulated rate of 15s presented a much more energy-efficient behavior. The results of these simulations are plotted in Figures 11(a), 11(b), and 11(c). They show the decrease of the number of remaining active motes vs. simulated time, when varying the data transmission intervals, for 100 motes initially in the WSN field. It may be seen that the relative performance of the three sensing models remains invariant, and no significant advantage of CSSC may be reported. At the beginning of the simulation, the increased energy consumption has no influence on motes depletion, due to the still enough existent residual energy.

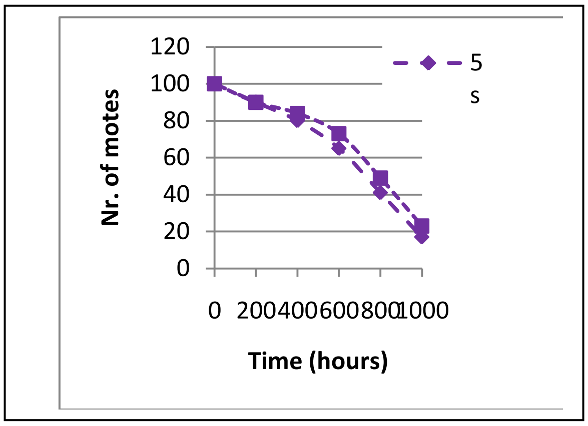


Fig. 11(a) Varying the data transmission intervals (5s to 15s) – Disk model/100 motes

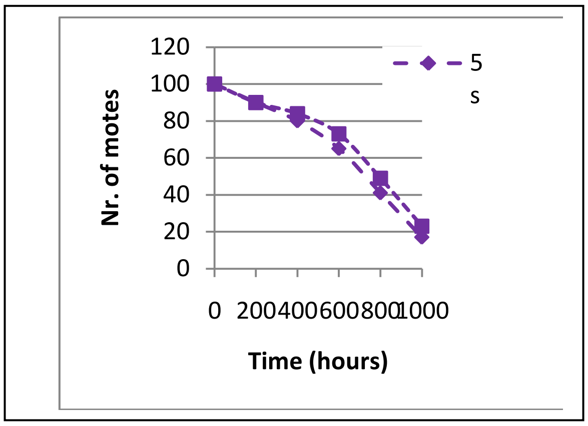


Fig. 11(b) Varying the data transmission intervals (5s to 15s) – Circular model/100 motes

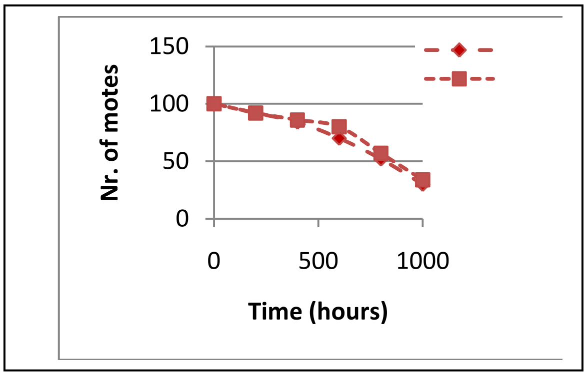


Fig. 11(c) Varying the data transmission intervals (5s to 15s) –CSSC model/100 motes

During the simulation runs, we also changed the rate of negotiation management messages between neighbor motes. For the disk model, where no management messages are used, obviously no performance change occurred. For the circular sensing model, the simulation showed a significant performance worsening when increasing the rate of these messages, as can be seen in Figure 12(a). The increased number of management messages exchanged between neighbor motes, in order to negotiate a possible change of the sensing radii, achieved an increased energy-consumption, resulting in a bigger depletion rate. Simulation showed that the expected improvement of the sensing energy needs was not achieved.

When decreasing the sensed data transmission rate beyond a certain value, a similar increase of the energy consumption was observed. This result is the consequence of using a not actualized and therefore less efficient set of sensing radii. Establishing an optimal rate is obviously needed. It have to be noted that (because of the one-hop communication model implemented) the simulation neglected data fusion scenarios, in which case the negative influence of increased data transmission rates may be alleviated.

A similar behavior was observed for the CSSC model. From Figure 12(b) it can be seen that the influence of varying the rate of the exchanged messages is even greater than for the circular model. The simulation used the same no. of bits for both models. Therefore, this result may be attributed to the following two factors:

- Increased processing time, calculating not only the radius, but also the value of the angle and the position of the arc.
- Less energy-efficient sensing optimization.

While the CSSC model is more energy-efficient than the circular model, it is also more sensible to timing considerations.

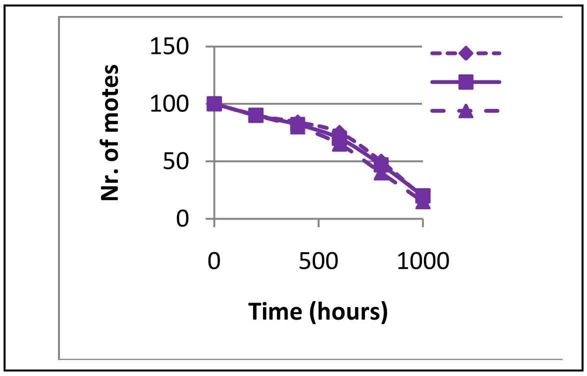


Fig. 12(a) Varying the neighbors' negotiation interval (2s to 12s) – Circular model/100 motes

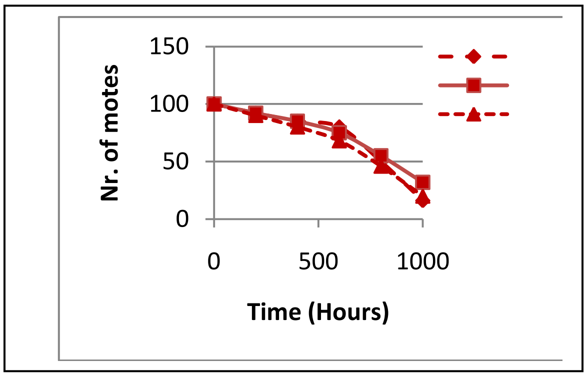


Fig. 12(b) Varying the neighbors' negotiation interval (2s to 12s) - CSSC model/100 motes

From the results of these simulations, it can be seen that the number of active motes remains constantly greater when using CSSC, if the rate of management messages is below a certain level. This level has to be found empirically for every specific WSN using this sensing model.

Comparing graphs for this worst-case scenario, as represented in Figure 13, it can be seen that for improperly chosen parameters, the energy-efficiency of the CSSC model may be even lower than that of the Circular model.

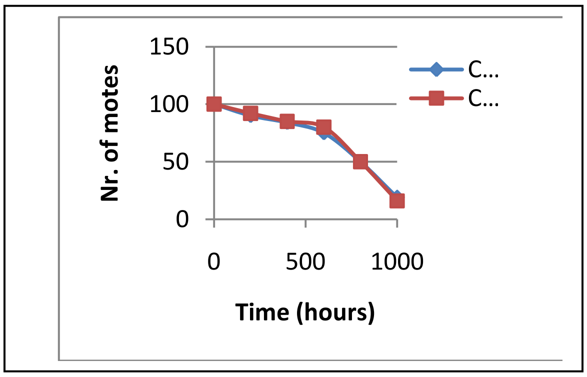


Fig. 13 Circular and CSSC sensing models – worst case scenario

Even if sometimes, at the beginning of the WSN activity, the use of CSSC model seems less energy-efficient than the circular model, toward the end of life-span of the networks it performs better. Significant improvements vs. the circular sensing model were obtained after 1000 simulated hours of sensing/transmitting. The simulation was stopped at this time interval, due to the fact that the remaining number of motes was not enough to effectively cover the sensed field. However, it has to be noted that the simulator has no facilities to check the connectivity of the covered areas. As such, although the lifetime of the WSN was obviously increased, it was not possible to accurately assess coverage data.

6. Conclusion and Future Work

A new model of sensing coverage for active sensors, based on circular sector sensing coverage – CSSC, was developed. The performance of this model was checked vs. previously published schemes, using a dedicated simulation program.. The results of the simulations showed energy savings, suggesting the viability and the advantages of this new sensing model. After 1000 hours of simulated sensing and data reporting, up to a 50% increase in the number of active motes was observed. The best performance, from an energy-efficiency point-of-view, was obtained in a sparsely populated WSN field, using a moderate rate of management messages.

The possible implementation of such a WSN may improve the energy-related performance of the WSN, allowing the development of new applications and improving the performance of existing ones. There are a lot of such applications, civilian or military alike, which implement some remote discovery, localization or tracking activities.

We want to stress again, that no analytical model exists yet for CSSC. However, it is a new sensing model, which as observed during simulations, shows energy-efficiency related performance improvements vs. other known sensing models.

Suggested future possible research topics include:

- Describing analytically the CSSC model.
- Minimizing the required communication overhead, to further increase the energy savings.
- Maximizing the coverage area, while using minimal energy.
- Studying the minimal exposure path, to check its behavior vs. other sensing models.
- Testing the connectivity of sensing areas, in a multi-hop communication environment.
- Researching the behavior of the model in a mobile WSN environment

At this stage, our work concerning the circular sector sensing coverage model CSSC concentrates on:

- Developing an accurate and complete analytical model.
- Defining the optimal rate of the management messages.

- Adding new metrics and functions to the simulator, for a more accurate modeling of sensing models and a deeper understanding of the behavior of the circular sector CSSC model.

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