On the Impact of the Death Criterion on the WSN Lifetime

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***Abstract*— Wireless Sensor Networks (WSNs) are sensor-based networks that are widely used in various critical applications and require the network to have a prolonged lifetime. However, these networks rely on battery-operated sensors that cause the network to be resource-constrained. Therefore, there is a continuous urge to efficiently exploit the network's energy, and henceforth, prolong the network lifetime. In this paper, we assess the impact of the death criterion on the network lifetime. We relate how the data from the different sensors are aggregated, which depends on the WSN application, to the death criterion. Additionally, we study the impact of the number of sensing cycles per network master on the network lifetime and energy efficiency for the different considered death criteria. Finally, the effect of the network master selection process, i.e. random versus planned, is examined to assess its effect on the network's energy efficiency.**

Keywords—WSN; death criteria; network lifetime; energy efficiency

I. Introduction

Wireless Sensor Networks (WSNs) retain sensors that are battery-operated. Typically, sensor nodes report measurements of certain phenomena to a sink node according to the WSN application. These different applications could be RADAR detection, agriculture monitoring, smart cities or many more [1]. This paper focuses mainly on monitoring electromagnetic (EM) pollution [2]; however, similar event detection applications could also be targeted.

One of the main challenges that WSN technology encounters is the energy consumption and the energy efficiency due to the use of battery-operated sensors. It directly affects the network lifetime, which is commonly defined as the time until the first node failure due to battery outage in the network [3-5]. This means that when one of the sensor's energy is below the specified threshold that allows it to send and receive data, then the whole network will be considered dead. This network lifetime definition obviously had a huge drawback on the network's energy efficiency as well as the network lifetime. The reason for that is that the death of one node within the network does not mean that the rest of the nodes are also incapable of correctly detecting the monitored event. Consequently, the amount of the remaining energy in the network is high due to the other sensors that still have enough energy to perform the required functions.

Henceforth, in this paper, our goal is to exploit and evaluate the energy efficiency of different definitions for the network lifetime. More specifically, we consider the cases in which the network lifetime is defined as at least one sensor is still alive, at least half the sensors are alive, and the legacy case which requires all the nodes to be alive to consider the network fully functioning. These three different death criteria suit the different WSN applications. Related lifetime definitions were discussed in [6]. However, they rely on mobile sensors, grid optimization and energy proficient clustering techniques. Moreover, several cluster heads exist in such networks, which are based on the LEACH algorithm [4, 7]. In contrast, our work considers the whole network as one cluster and relies on a single network master per round. This has already proven a prolonged network lifetime in [8, 9]. In this paper, we investigate the impact of the different network lifetime definitions on the wireless sensor network, while efficiently using the battery-operated sensors. These network lifetime criteria are re-evaluated assuming a predefined number of cycles per network master as opposed to [9]. Randomly choosing the sensor nodes that serve as network master during the operation cycles, versus [9, 10] which had an ordered circular selection of the network masters, is also studied. The reason for that is to investigate whether the particular choice of the network master has a significant effect on the network behavior, and accordingly, on the sensors energy or not.

The remainder of the paper is organized as follows. In Section II, we describe the network model. Section III presents the different evaluated death criteria. We evaluate their energy efficiency under different sensing cycle lengths and different network master selection approaches in Section IV and Section V, respectively. Section VI concludes the paper.

II. WSN System Model

A. System Architecture

The proposed definition of the network lifetime will be applied on the network architecture used in [9]. This implies a 100×100 m^2 area that is affected by four frequency polluters F1, F2, F3 and F4; each of them is placed on one side of the area [11]. A total of 100 sensors are uniformly distributed over the area in order to monitor different levels or different sources of electromagnetic radiations of the four polluters. A total of 25 sensors are associated with each frequency polluter as illustrated in Fig. 1. However, only 11 sensors that are closer to the polluter out of each 25 sensors report the violation, assuming that the polluter's radiation is only capable of covering half of the total area. Furthermore, the sink that aggregates and analyzes the data collected by the network masters (NMs) is located in the middle of the area. This position was proven in [10] that it utilizes the network's energy in the most efficient way, and hence, increases the network lifetime. The rest of the parameters are listed as follows:

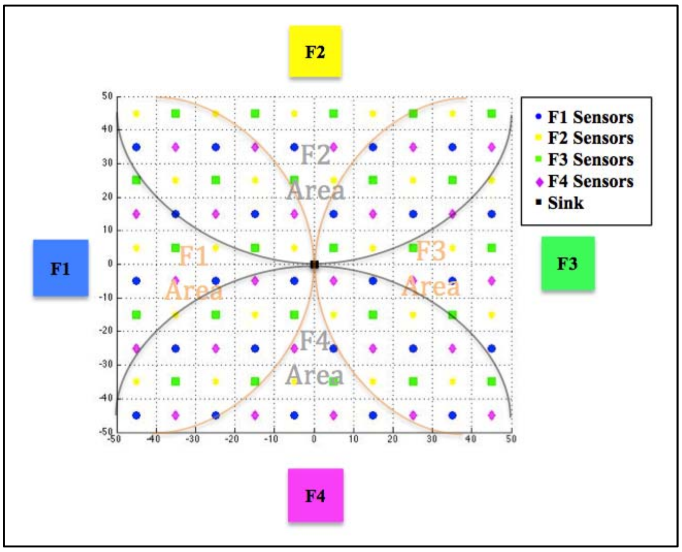

Fig. 1. Uniformly distributed 100 sensors in an area of 100 x 100 m^2 and surrounded by the four frequency polluters.

- Network size: 100×100 m^2
- Number of Sensors (N): 100 Sensors
- Initial Energy per sensor: 2J
- Transmitter/ Receiver Electronics (E_{elec}): 50 nJ/bit
- Transmitter Amplifier (E_{amp}): 100 pJ/bit/m^2
- Path Loss factor (n): 2
- Aggregation Energy (E_{agg}): 5 nJ/bit/Signal
- Data packet size sent by active nodes to NM (K): 64 bits
- Data packet size sent by the NM to the sink (K1): 512 bits
- Data packet size of sensing power levels (K2): 1 bit
- Sink location: field center
- Distribution: Homogeneous Density (Fig. 1)

B. Monitoring Electromagnetic Pollution

In order to easily analyze the effect of changing the network death criteria, the same monitoring process assumed in [9] will be adopted here. Every day, one of the frequency polluters Fi (starting with polluter F1) causes pollution during the last six hours of day. On the next day, F2 sends its violating radiations during the same time of the day and then F3 and F4 follow the same manner on the following days. This process repeats itself every four days starting with F1. Each hour of the day is considered to be one cycle and during these cycles a network master (NM) is chosen to collect the data from the sensors and send it to the sink. The criterion of choosing the NM during these cycles is acquired from [9]. It starts by the closest sensor to the sink and keeps moving in a circular pathway around the sink, while checking each sensor if it is suitable to act as an NM using a pre-calculated threshold for each NM. The threshold simply computes the required energy for each sensor to act as an NM, for one cycle, according to its distance from the sink and its distance to the remaining 99 sensors. A similar method of calculating the threshold for the NM is used in [8]. At the beginning of the process, the thresholds are calculated only once, at the sink, and hence, represent no running overhead. Such calculations rely on the information gathered about the sensors' locations. Later during the process of the monitoring system, the threshold for each NM is used to calculate the number of cycles during which each sensor will act as NM. The threshold is calculated as follows:

$$E_{threshold\_NMi} = E_{rx} \times N_S + E_{agg} \times K \times N_S + E_{prot} + E_{tx} \quad (1)$$

for $i = 1, 2, \ldots, 100$, where

$$E_{rx} = E_{elec} \times K \quad (2)$$

and

$$E_{tx} = E_{amp} \times K1 \times D^{n}_{NM\ to\ sink} \quad (3)$$

In Eq. (1), the N_s parameter is equal to the number of sensing nodes, which is 99 in this case, because the 100th is the NM. Furthermore, in Eq. (3), the $D_{NM\ to\ sink}$ is the calculated distance between the i^{th} NM and the sink.

Once the sensor's energy has reached the NM threshold, it will start acting as an ordinary active node and another sensor will be elected to be the NM of the following cycles and so on. When any of the active nodes reach the active node threshold, which is equal to the energy that allows a sensor to sense and send packets to an NM, the node will be considered dead. The functionality of the WSN depends on the percentage or number of active nodes. Hence, the network lifetime can be generally defined in terms of the number of cycles during which a minimum percentage of the sensors are active. In many previous works, that percentage was considered 100% [4, 8, 9 and 10]. In this paper, we assess various considerations for the WSN's lifetime and provide recommendations according to the underlying application of the WSN.

III. Network Death Criteria

As mentioned earlier, the death of one node was traditionally considered as an indicator that the whole network has stopped functioning. The disadvantage of such consideration is that it underestimates the network lifetime because with the death of only one sensor node, there is still remaining energy possessed by the rest of the nodes. This remaining energy could enable the network to sustain its activity for a longer time. Hence, it is more practical to view the network as functioning while multiple nodes become dead already. According to the number of dead nodes that can be tolerated without affecting the functionality of the network, multiple network death criteria can be identified. The different versions of the death criteria are driven from how much information is needed in the aggregation process of the different readings of the sensors, which sense the same phenomenon [12]. For instance, if aggregation is done based on ANDing all the measurements of all the sensors, the network lifetime is defined as the time to the first node failure since one node failure violates the AND rule. On the other hand, if aggregation is based on the OR rule, meaning at least one sensor is still alive and correctly reports the sensed phenomenon, then the network is considered alive. A compromise between the "AND" and "OR" rules is the majority rule. The majority rule implies that at least half the nodes sensing a given phenomenon are still functioning.

A. The AND Rule (All Readings Are Needed)

The first death criterion is the legacy one in which the network is considered dead when the first node that senses the intended phenomenon, EM violation in our case, dies. This criterion follows the decision of the logical "AND" rule. Figure 1 illustrates the network area divided into four zones, each with a specific polluter. For each polluter, there are 11 sensors within its pollution range that can sense the violation and send the packets to the network master. If one of the 11 sensors which are sensing the EM violation is dead, because it has reached the active node threshold, the whole area, and accordingly the whole network, will be considered dead. However, it is highly probable that the 10 other sensors might have remaining energy that could enable them to prolong the network functionality. In some critical applications that cannot tolerate the death of one node within the network, this criterion is the optimum, and solutions have to be sought to replace the dead node.

B. The OR Rule (At Least One Reading Is Needed)

The OR Rule is defined as having one sensor in the zone to report the violation even if the rest of the nodes in the area are considered dead. Herewith, the rule of the logical "OR" is applied. This technique is the most energy efficient one that is expected to prolong the network lifetime, since it consumes the sensor's energy at most. It might be needed in some WSN applications such as monitoring underwater pipelines [13], where the network is hardly accessible and the urge of prolonging its lifetime is highly needed.

C. The Majority Rule

The last death criterion would be the majority technique, where half or more of the sensors in the same area are required to be active, in order to be able to report a violation; otherwise the area will be considered dead.

The main advantage in the OR and majority criteria is that they make the network fault tolerant, because the reporting function of the network is not affected by the death of one or few nodes [14]. Since a WSN might be used in certain applications, where the network is placed under harsh conditions, the failure of one node or more could highly occur.

Additionally, they better exploit the total energy available in the network as compared to the AND case in which the network is considered dead while a lot of residual energy is still available. Therefore, these techniques are very application-dependent and their significance differs from one application to the other.

The three death criteria were simulated using MATLAB [15] and the previously explained system model. Figure 2 shows the death of each area according to each death criteria, and consequently, the corresponding lifetime of the network.

For example, the 1st group of points (at the bottom-left of the figure) shows the death of the 1st node in each area. Then the 2nd group of points (at the center of the figure) displays the death of 6 nodes, the majority, in each area. Finally, the last group shows the death of the last node in each area, using the OR rule. Note that, for the last group, the F1 area dies last, which means it can sustain a longer lifetime compared to the other areas. However, being the area with the highest lifetime does not mean that under all three death criteria, this area will necessarily have the highest lifetime. As shown in Fig. 2, the F1 area comes at the second place, when the AND rule is considered and comes at the 3rd place when the majority criterion is considered. The reason for that is due to the location of the sensors and the location of the network master in each cycle, which affect the energy consumption of each sensor differently. Hence, this graph is useful to illustrate the different death criteria at the same time. According to the application, one can choose the adequate death criterion.

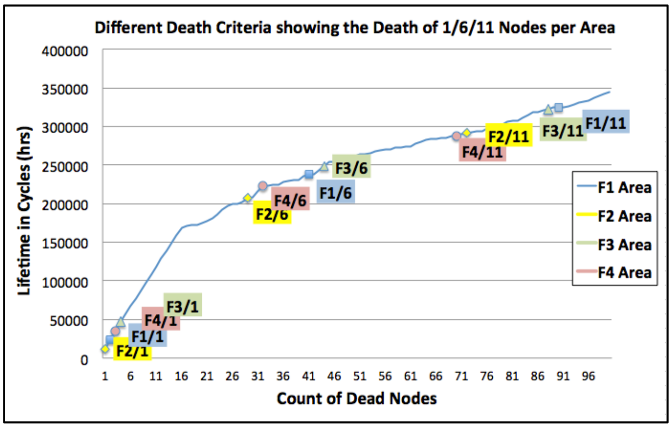

Fig. 2. The different death criteria are illustrated by showing the lifetime with respect to the number of dead nodes.

IV. Impact of the Number of Cycles Per NM

A. Selecting a Fixed Number of Cycles per NM

In the previous scenario, any sensor selected as an NM operates as an NM for a number of C_{NMi} cycles until it depletes its full energy by reaching the NM threshold, $E_{threshold\_NMi}$. At the beginning of the subsequent round, the next available sensor is chosen as the acting NM. Consequently, the number of cycles per NM is dependent on the sensor's energy and differs from one NM to the other. Formerly, an optimum number of cycles per round was investigated in [8] to elongate the network lifetime. However, the results obtained in [8] aimed to solve the drawbacks in [4, 7], and hence, are not applicable in the context of our model. Therefore, in the following, we study the effect of setting a predefined NM cycle count such that each sensor acts as an NM for a certain number of cycles irrespective of its residual energy. We focus on the following numbers of cycles per round:

1) *100 cycles per NM round*
2) *1000 cycles per NM round*
3) *10000 cycles per NM round*

Note that these numbers are chosen based on results from the previous section. It can be seen that the average number of cycles per NM, C_{NMi}, as obtained in the previous section, is around 10000 cycles. Hence, this number is chosen as the highest cycle count. Moreover, two other possibilities will be investigated by reducing the cycle count size by a factor of 10 and 100 cycles. The rationale behind such a change, as compared to the previous scenario, is that with smaller cycle counts, the sensor acting as an NM will not deplete the majority of its energy while acting as an NM and will have enough residual energy to act as a non-NM node for a longer number of cycles. This will also enable the rotation of the NM role more frequently, resulting in an even energy dissipation profile for all the sensor nodes.

In Fig. 3, the lifetime curves of each of the predefined number of cycles per round that were mentioned above are illustrated. For comparison, the lifetime curve obtained in Fig. 2 is shown and is labeled with Max Cycles/NM.

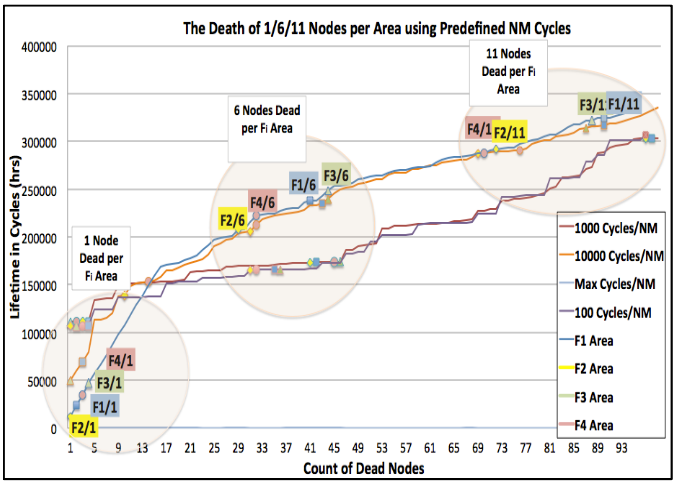

Fig. 3. Different lifetime curves that illustrate the different cycle number per NM.

Figure 3 implies that using the maximum number of cycles per NM technique, which is calculated according to each NM's energy consumption, results in a higher lifetime in most of the death criteria. However, if other lifetime definitions are adopted, the relative lifetime behavior will vary. For example, if an application requires the use of the AND aggregation approach in the network death definition, then definitely the maximum Cycle/NM scheme is not the best scheme in terms of network lifetime. On the contrary, all the other predefined cycles per NM curves achieve a higher lifetime during the death of the 1st Fi area. Henceforth, one can predict from Fig. 3, which is the best curve that prolongs the lifetime, that there still exist other aspects that should be taken into consideration, such as:

- Identifying the relevant death criteria according to the application requirement.
- With the definition of the network death criteria, a specific dead area Fi area could be determined ahead as well.
- Finally, there could be a tradeoff between maximizing the lifetime and exploiting the sensor's energy efficiently according to the application. When maximizing the lifetime is needed, then Fig. 3 will be sufficient to identify that. Otherwise, Figure 4 will be required to select the curve that mostly consumes the network's energy efficiently.

Therefore, the energy consumed by the four different lifetime curves should be investigated further.

B. Energy Consumption Comparison of the Four Scenarios

In order to get a deeper look into the energy consumption model of the network, two aspects will be investigated:

1) The Average Remaining Energy of the Four Scenarios: Figure 4 shows that using higher number of cycles per NM round, either through the maximum technique or through predefining the number of cycles per NM such as 10000 cycles, will result in an inefficient use of the network's energy. On the contrary, it could be obtained that 100 cycles per round and 1000 cycles per round achieve a lower remaining energy level compared to the other two scenarios. The reason for that is when a lower number of cycles per round is adopted, the location of the NM is changed more frequently which reduces the possibility of starving the nodes far from the NM for a long period of time. Avoiding this will prevent the sensors from exploiting their energy all at once.

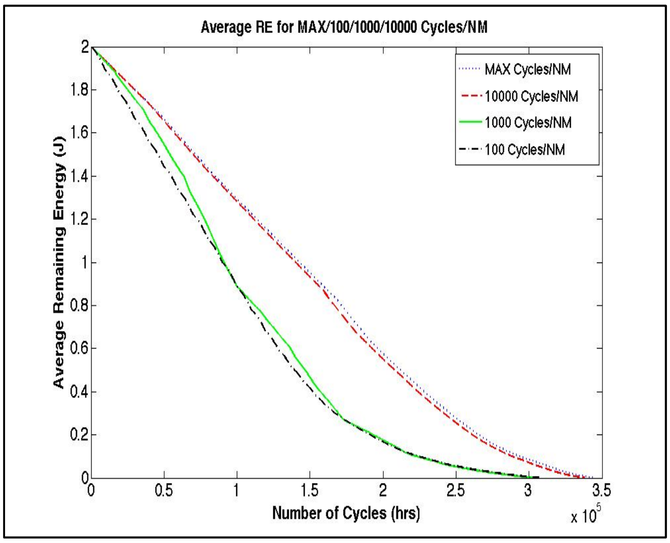

Fig. 4. Average remaining energy for the four scenarios using the ordered choice of NMs.

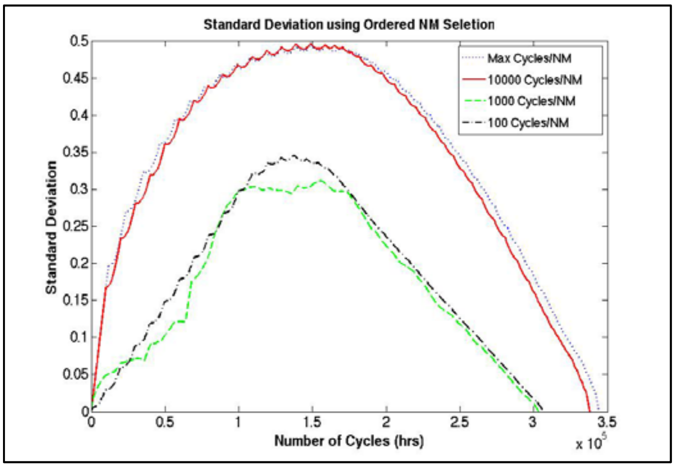

Fig. 5. Standard deviation curve of the remaining energy for the four scenarios using the ordered choice of NMs.

2) The Variance of the Remaining Energy of the Four Scenarios:

Figure 5 shows the standard deviation of the remaining energy of the sensor nodes versus the cycles of the network. The curves in Fig. 5 emphasize the observations from Fig. 4. These curves can be described as follows. At the beginning of network operation, all the sensors have the same initial energy. When the process starts, some of the nodes start to lose their initial energy faster than the other nodes. Hence, they reach a point where the difference in the remaining energy is too high, as some nodes are already dead, with a very low remaining energy, while other nodes still contain high remaining energy and are acting as network masters. Afterwards, the nodes with high remaining energy start to lose their energies. This is when the standard deviation decreases again. When the nodes become dead by reaching the specified threshold, the total remaining energy in the whole network will be almost the same. At this point the standard deviation curve will be approaching the zero level.

V. Impact of NM Selection Approach

As mentioned in the previous sections, the choice of the NM is in a circular order starting from the sensors near to the sink to those away from the sink. In order to make sure that the NM selection does not contribute in our findings, a random selection of the NM is investigated. It is expected that the behavior of the scenarios described in section IV would be independent of the NM selection, as they are not tied specifically to this system model and should be applied on any other application.

Figure 6 illustrates the four NM count schemes discussed in the previous section using random selection of NM. Each of the 100 sensors is randomly selected to serve as an NM during a period of rounds without a specific order.

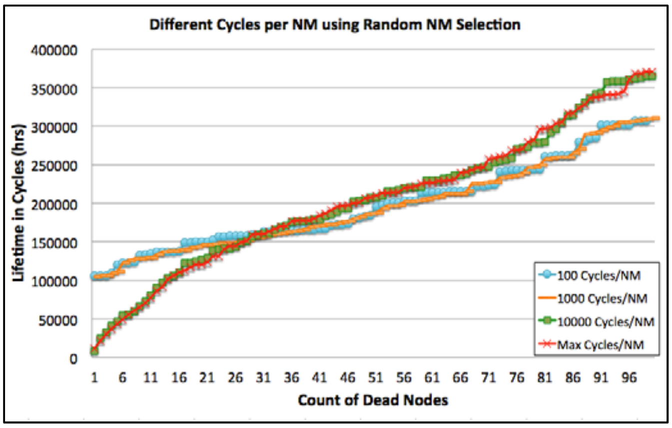

Fig. 6. Different lifetime curves that illustrate the different cycle number per NM using the random selection of the NM.

Despite the use of the random selection of the NM, the four schemes have similar behavior to that shown in Fig. 3. For example, the maximum scheme remains the highest with respect to total lifetime while the 10000 cycles per round comes next. Also the other two curves 1000 and 100 cycles/NM follow the same behavior as in Fig. 3. The only difference between Fig. 3 and Fig. 6 is the lifetime value for each curve. Figure 6 implies that a random selection of the network master results in a higher lifetime in general. The reason for that is that changing the location of the NM more frequently as previously mentioned in section IV causes the network not to exploit one specific area at a time and instead it averages over the whole network.

Figures 7 and 8 also show similar results compared to Figs. 4 and 5. The only difference between Fig. 4 and Fig. 7 is that in Fig. 7 the remaining energy is consumed more efficiently than in Fig. 4. Likewise, Figure 8 shows similar behavior of the standard deviation. Nevertheless, the main contribution of doing this experiment is to show that the previously discussed schemes behave independent of the system model assumptions, and henceforth, the whole system does not rely on a specific case and can be applied to various applications and scenarios.

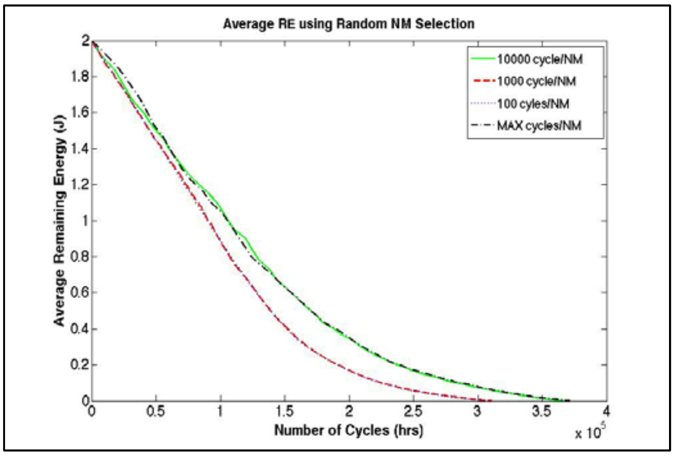

Fig. 7. Average remaining energy for the four scenarios using the random choice of NMs.

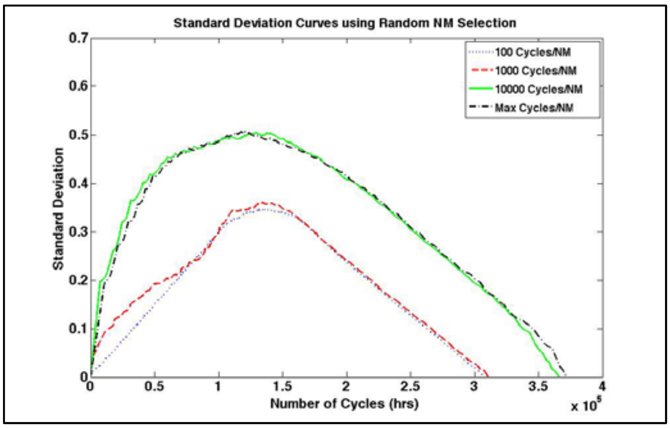

Fig. 8. Standard deviation curve of the remaining energy for the four scenarios using the random choice of NMs.

VI. Discussions and Conclusions

This paper has evaluated three different definitions of the network death criterion that are applicable to different WSN measurement aggregation techniques. Choosing between all these techniques is application-dependent, since every technique best fits certain WSN applications. We examined the impact of the different death criteria on the WSN lifetime. Furthermore, the impact of the number of sensing cycles is examined to show the difference between exploiting the NM energy to its maximum all at once, versus acting as NM several times and consuming the NM energy on separate intervals. Our results show that using a predefined low number of cycles per NM will result in a more efficient use of the network's energy. However, there is tradeoff here, since the network lifetime decreases when the predefined number of cycles is low.

Finally, we have studied the significance of the process for selecting the NM. Instead of the circular ordered path selection, we have considered random NM selection. This has proven that despite the change of the NM selection, the previous conclusions were not changed, which indicates that the proposed scenarios are not aligned with a specific system model, however can be implemented on other WSN applications.

In conclusion, it is very important to identify the targeted WSN application first and then decide whether the aim is to have a prolonged lifetime or to consume the network's energy efficiently. Accordingly, the various death criteria and NM count/selection approach illustrated in this paper could be very helpful in obtaining the most adequate conditions for the application, meaning choosing the number of cycles per NM master and the best death criteria to achieve the best fit for the desired application.

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