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WSN Lifetime and Reliability Analysis From the Death Criterion Perspective

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ABSTRACT

Wireless Sensor Networks (WSNs) are widely used in numerous critical applications, and require the network to have a prolonged lifetime and high tolerance to failures. However, the battery-operated sensor nodes used in WSNs cause the network to be resource-constrained. On the one hand, there is a continuous urge to efficiently exploit the WSN energy, and hence, prolong the network lifetime. On the other hand, WSN node failures are not only attributed to battery drain. Node failures can be caused by hardware or software malfunctioning. In this article, the authors assess the impact of the death criterion on the network lifetime and reliability. It is related how the data from the different sensors are aggregated to the death criterion. Additionally, the impact of the number of sensing cycles per network master on the network lifetime and energy efficiency for the different considered death criteria. The effect of the network master selection process on the energy efficiency is also examined. Finally, the impact of the death criterion on the reliability of the WSN is evaluated.

KEYWORDS

Death Criteria, Electromagnetic Pollution, Energy Efficiency, Network Lifetime, Network Reliability, Wireless Sensor Network

1. INTRODUCTION

Wireless Sensor Networks (WSNs) are based on sensor nodes that are battery-operated. According to the application for which the WSN is designed, sensor nodes report measurements of certain phenomena to a sink node. WSNs have different applications including RADAR detection, agriculture monitoring, smart cities and many more (Waghmare, Chatur, & Mathurkar, 2016). This paper focuses mainly on monitoring electromagnetic (EM) pollution (Viani, Donelli, Oliveri, Massa & Trinchero, 2011); however, the findings of the paper are applicable to similar event detection WSN applications.

One of the main challenges faced by the WSN technology is the energy consumption and the energy efficiency due to the use of battery-operated sensor nodes. It directly affects the network lifetime, which is typically defined as the time until the first WSN node fails due to battery

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outage (Mahfoudh & Minet, 2008; Heinzelman, Chandrakasan, & Balakrishnan, 2000; Mamun, Ramakrishnan, & Srinivasan, 2010). Such a definition of the WSN death implies that when one of the node's energy falls below a specific threshold that allows it to send and receive data, then the whole network will be considered dead. This definition of the network lifetime had a huge disadvantage on the network's energy efficiency as well as the network lifetime. This is because the death of one node within the network does not imply that the remaining nodes are also incapable of correctly performing their task of detecting the monitored event. In other words, the other nodes in the WSN have an amount of energy that is high enough to allow the network to perform the required functions.

In this paper, our goal is to evaluate the energy efficiency and reliability of the different definitions of the network lifetime. More specifically, we consider the cases in which the network lifetime is defined as at least one sensor is still functioning, at least half the sensors are functioning, and the legacy case which requires all the nodes to be functioning in order to consider the network alive. These three different death criteria cover the different WSN applications. Other related WSN lifetime definitions were discussed in (Kaur & Singh, 2016). 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 (Heinzelman, Chandrakasan, & Balakrishnan, 2000; Heinzelman, Chandrakasan & Balakrishnan, 2002). In contrast, our work considers the whole network as one cluster which relies on a single network master per round. This has already been proven to result in a prolonged network lifetime in (Botros, Elsayed, Amer, & El-Soudani, 2009; Seoud, Nouh, Abbass, Ali, Daoud, Amer & Elsayed, 2010). In this paper, we evaluate the network lifetime criteria assuming a predefined number of cycles per network master as opposed to (Seoud, Nouh, Abbass, Ali, Daoud, Amer & Elsayed, 2010). We also study the impact of randomly choosing the sensor nodes that serve as network master during the operation cycles, versus (Seoud, Nouh, Abbass, Ali, Daoud, Amer & Elsayed, 2010; Nouh, Abbas, Seoud, Ali, Daoud, Amer, & Elsayed, 2010) which had an ordered circular selection of the network masters. The reason for that is to investigate whether the choice of the network master has a significant effect on the network behavior, and accordingly, on the sensors energy or not. Unlike (Nouh, Khattab, Soliman, Daoud, & Amer 2017), we analytically evaluate the impact of the WSN death criterion on the reliability of the networks against other types of hardware and software failures.

The remainder of the paper is organized as follows. In Section 2, we describe the network model. Section 3 presents the different evaluated death criteria. We evaluate their energy efficiency under different sensing cycle lengths and different network master selection approaches in Section 4 and Section 5, respectively. In Section 6, we analyze the impact of the death criteria on the network reliability against hardware and software failures. Section 7 concludes the paper.

2. WSN SYSTEM MODEL

2.1. Network Architecture

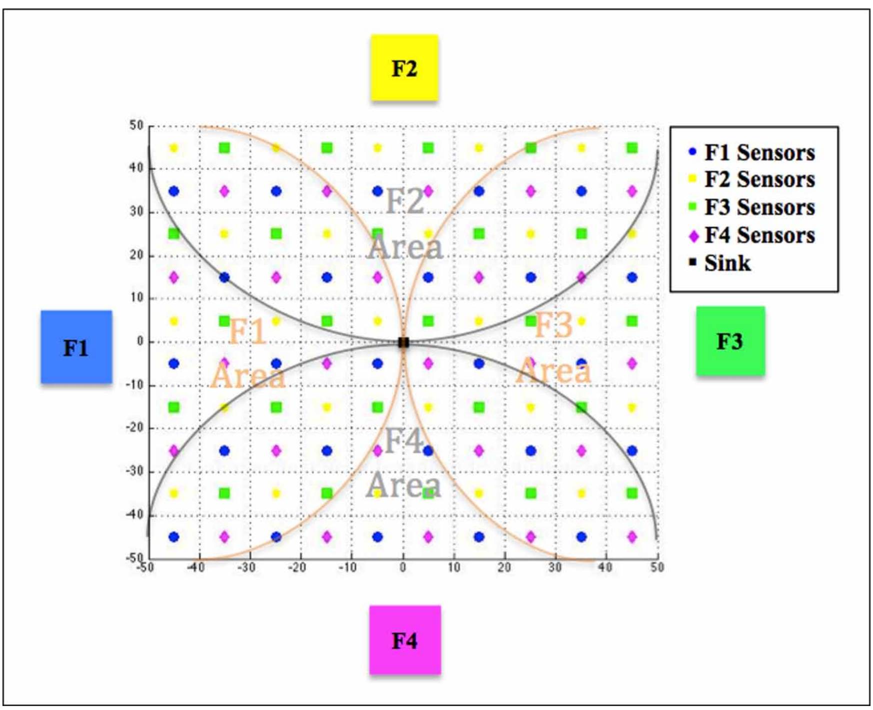
The different definitions of the network lifetime will be applied on the network architecture used in (Seoud, Nouh, Abbass, Ali, Daoud, Amer & Elsayed, 2010). More specifically, we consider a 100×100 m^2 area that is affected by four frequency polluters F1, F2, F3 and F4. Each of these frequency polluters is placed on one side of the area (Ioriatti, Martinelli, Viani, Benedetti & Massa, 2009). A total of 100 sensors are uniformly distributed over the area in order to monitor the levels of electromagnetic radiations of the four polluters. We associate 25 sensors with each frequency polluter as illustrated in Figure 1. However, only 11 sensors that are closest to the polluter out of each 25 sensors will be able to report the violation. This is because 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 center of the area. This position was proven in (Nouh, Abbas, Seoud, Ali, Daoud, Amer, & Elsayed, 2010) to utilize the network's energy in the most efficient way, and hence, increases the network lifetime. The rest of the parameters are listed as follows:

- Network size: 100×100 m^2
- Number of Sensors (N): 100 Sensors
- Initial Energy per sensor: 2 J
- 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 (Figure 1)

2.2. Electromagnetic Pollution Monitoring

In order to analyze the effect of changing the network death criteria, the same monitoring process assumed in (Seoud, Nouh, Abbass, Ali, Daoud, Amer & Elsayed, 2010) 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. 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. During each cycle, 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 a cycle is acquired from (Seoud, Nouh, Abbass, Ali, Daoud, Amer & Elsayed, 2010). It starts by the closest sensor to the sink and keeps moving in a circular pathway around the sink. Each sensor is checked if it is suitable to act as an NM using a pre-calculated threshold for each

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



NM. The threshold 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 (Botros, Elsayed, Amer & El-Soudani, 2009). 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 Equation (1), the N_s parameter is equal to the number of sensing nodes, which is 99 in this case, because the 100^{th} is the NM. Furthermore, in Equation (3), the $D_{NM\ to\ sink}$ is the calculated distance between the i^{th} NM and the sink.

Once the sensor node's energy reaches the NM threshold, it will act as an ordinary active node and another node 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% (Heinzelman, Chandrakasan, & Balakrishnan, 2000; Botros, Elsayed, Amer & El-Soudani, 2009; Seoud, Nouh, Abbass, Ali, Daoud, Amer & Elsayed, 2010; Nouh, Abbas, Seoud, Ali, Daoud, Amer, & Elsayed, 2010). In this paper, we assess various considerations for the WSN's lifetime and provide recommendations according to the underlying application of the WSN.

3. NETWORK DEATH CRITERIA

The death of a single node is commonly considered as an indicator that the whole network is incapable of functioning. The disadvantage of such an assumption is that it underestimates the network lifetime because even if only one sensor node dies, there is still remaining energy possessed by the rest of the nodes. Such remaining energy could enable the network to sustain its functionality for a longer time. Hence, it is more practical to view the network as functioning even if some nodes have already died. According to the number of dead nodes that can be tolerated without affecting the functionality of the network, multiple network death criteria can be defined. The different definitions of the death criteria are driven from the amount of information needed in the aggregation process of the different readings of the nodes, which sense the same phenomenon (Chen, Shu, Zhang, Liu & Sun, 2009). For instance, if aggregation is done based on ANDing all the measurements of all the nodes, 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, it means that the network is considered alive when at least one sensor is still alive and correctly reporting the sensed phenomenon. A compromise between the "AND" and "OR" rules is the majority rule. The majority rule implies that the network is not considered dead if at least half the nodes sensing the targeted phenomenon are still functioning.

3.1. AND Aggregation Rule (All Nodes Must Be Alive)

The first death criterion is the legacy one in which the network is considered dead when the first node that senses the targeted 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.

3.2. OR Aggregation Rule (At Least One Node Is Alive)

The OR rule is defined as having one node in the zone of each polluter to report the violation even if the rest of the nodes in the area are considered dead. Therefore, 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 (Benhaddou & Al-Fuqaha, 2015), where the network is hardly accessible and the urge of prolonging its lifetime is highly needed.

3.3. Majority Aggregation Rule (Half the Nodes Are Alive)

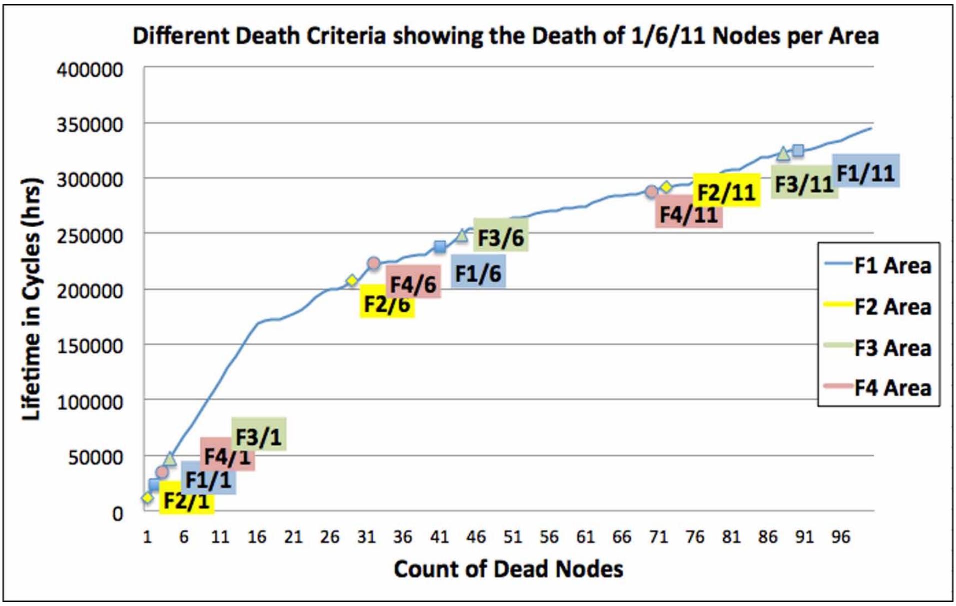
The other death criterion that we consider in this paper is the one based on the majority aggregation rule. In order to be able to report an EM violation, half or more of the sensor nodes in a given area are required to be active; otherwise the network will be incapable of detecting the violations in such an area.

Since WSNs might be used in certain applications, where the network is placed under harsh conditions, the failure of one node or more could highly occur. Thus, the OR and majority criteria are advantageous as they make the network fault tolerant, because the reporting function of the network is not affected by the death of one or few nodes (Manjunatha, Verma, & Srividya, 2008). Furthermore, they better exploit the total energy available in the network as compared to the AND rule in which the network is considered dead while a lot of residual energy is still available. Therefore, the different death criteria are very application-dependent, and their significance differs from one application to the other.

3.4. WSN Lifetime Under Different Death Criteria

First, we evaluate the performance of the aforementioned death criteria. The three death criteria were simulated using MATLAB (MATLAB, 2011) in the system model described in Section 2. Figure 2 shows the death of each area according to each death criteria, and consequently, the corresponding lifetime of the network. The 1st group of points (at the bottom-left of Figure 2) shows the death of the 1st node in each area. Then the 2nd group of points (at the center of Figure 2) displays the death of 6 nodes, i.e., 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 first polluter F1 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 Figure 2, the F1 area comes at the second place, when the AND rule is considered and comes at the 3rd place when the majority rule is used. This is attributed to location

Figure 2. The different death criteria are illustrated by showing the lifetime versus the number of dead nodes



of the nodes and the network master location in each cycle, which affect the energy consumption of each node differently.

4. IMPACT OF THE NUMBER OF CYCLES PER NETWORK MASTER

4.1. 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 completely depletes its 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. The optimum number of cycles per round was investigated in (Botros, Elsayed, Amer, & El-Soudani, 2009) to elongate the network lifetime. However, the results obtained in (Botros, Elsayed, Amer, & El-Soudani, 2009) aimed to solve the drawbacks in (Heinzelman, Chandrakasan, & Balakrishnan, 2000; Heinzelman, Chandrakasan & Balakrishnan, 2002), and hence, are not applicable in the context of our model. In what follows, 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:

- 100 cycles per NM round
- 1000 cycles per NM round
- 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} is around 10000 cycles as shown in Figure 2. 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 node 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.

Figure 3 illustrates the lifetime curves of each of the aforementioned predefined number of cycles per round. For comparison, the lifetime curve obtained in Figure 2 is shown and is labeled with Max Cycles/NM.

Figure 3 implies that using the maximum number of cycles per NM, 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 for the network death definition, then 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 higher lifetimes during the death of the 1st Fi area. Hence, one can predict from Figure 3, which is the best curve that prolongs the lifetime, that there still exist other aspects that should be taken into consideration, such as:

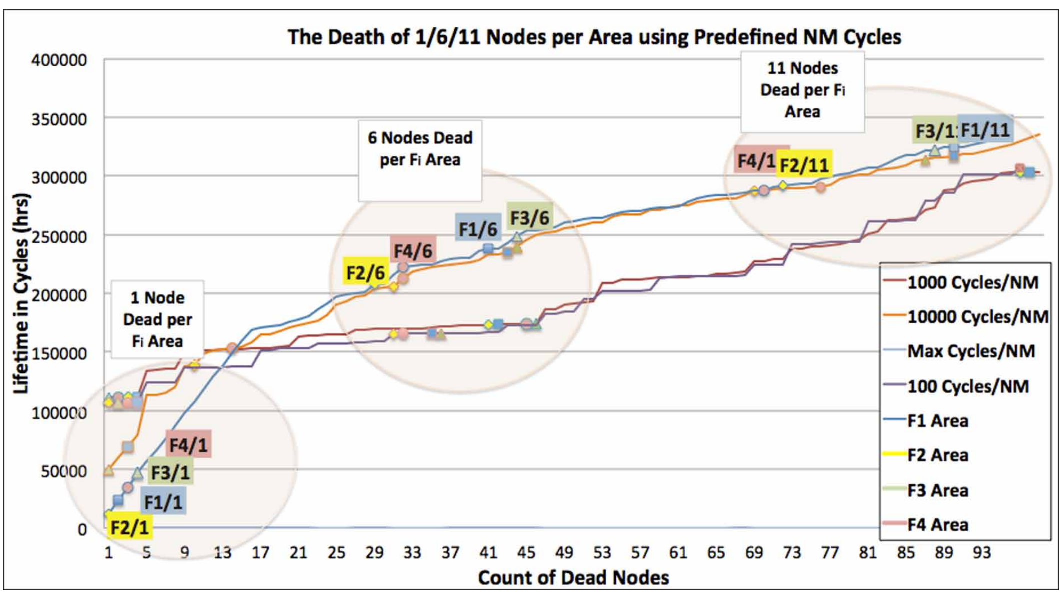
- Identifying the relevant death criteria according to the application requirement;
- A specific dead area Fi area could be determined ahead alongside the definition of the network death criteria;
- Finally, there is a tradeoff between maximizing the lifetime and exploiting the sensor's energy efficiently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

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

4.2. Energy Consumption Characteristics

In order to get a deeper look into the energy consumption of the network in the considered four scenarios, two aspects will be investigated.

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



4.2.1. The Average Remaining Energy

Figure 4 shows that using higher number of cycles per NM round, either through the maximum technique or through using a predefined number of cycles per NM such as 10000 cycles, will result in an inefficient use of the network's energy. On the contrary, using 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 that 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 nodes from exploiting their energy all at once.

4.2.2. The Variance of the Remaining Energy

Figure 5 shows the standard deviation of the remaining energy of the sensor nodes versus the cycles of the network. The curves in Figure 5 emphasize the observations from Figure 4. These curves can be described as follows. At the beginning of network operation, all the nodes 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.

5. IMPACT OF NM SELECTION APPROACH

As mentioned in the Section 4, 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 such NM selection procedure does not contribute to our findings, a random selection of the NM is investigated. It is expected that

Figure 4. Average remaining energy for the four scenarios using the ordered

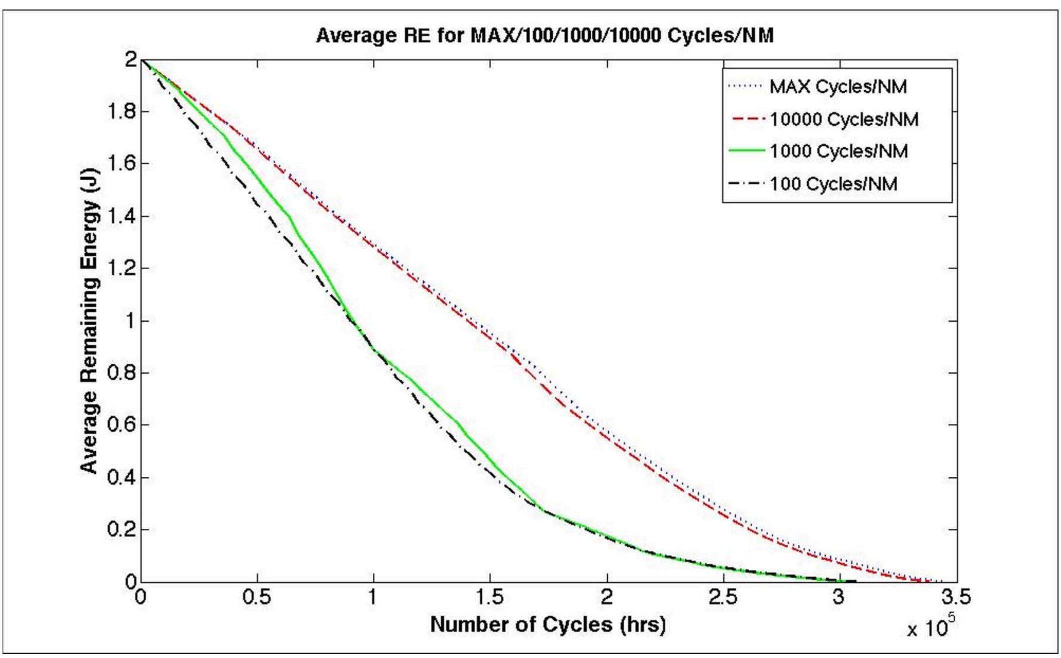
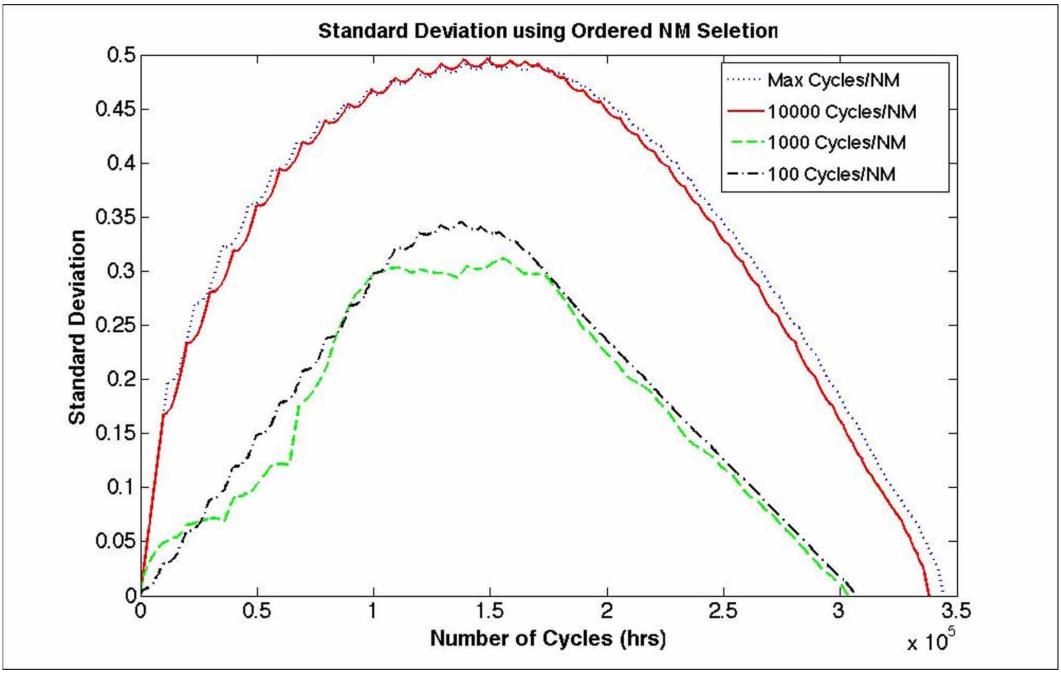


Figure 5. Standard deviation of the remaining energy for the four scenarios using the ordered choice of NMs



the behavior of the scenarios described in Section 4 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. Despite the use of the random selection of the NM, the four schemes have similar behavior to that shown in Figure 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 of 1000 and 100 cycles/NM follow the same behavior as in Figure 3. The only difference between Figure 3 and Figure 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 4 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 Figures 4 and 5. The only difference between Figure 4 and Figure 7 is that in Figure 7 the remaining energy is consumed more efficiently than in Figure 4. Likewise, Figure 8 shows a similar behavior of the standard deviation. Nevertheless, the main significance of this experiment is to show that the previously discussed schemes behave independently of the system model assumptions, and henceforth, the whole system does not rely on a specific case and works for various applications and scenarios.

6. RELIABILITY ANALYSIS

In the above discussion, all sensor nodes were assumed to be fully operational as long as their batteries had enough energy to complete the required tasks. If a sensor node experiences a hardware/software failure, the above calculations will no longer be valid. The following analysis obtains the probability that the WSN system will succeed in operating correctly for the entire lifetime calculated in the

Figure 6. Different lifetime curves illustrating the different cycle number per NM using the random selection of NMs

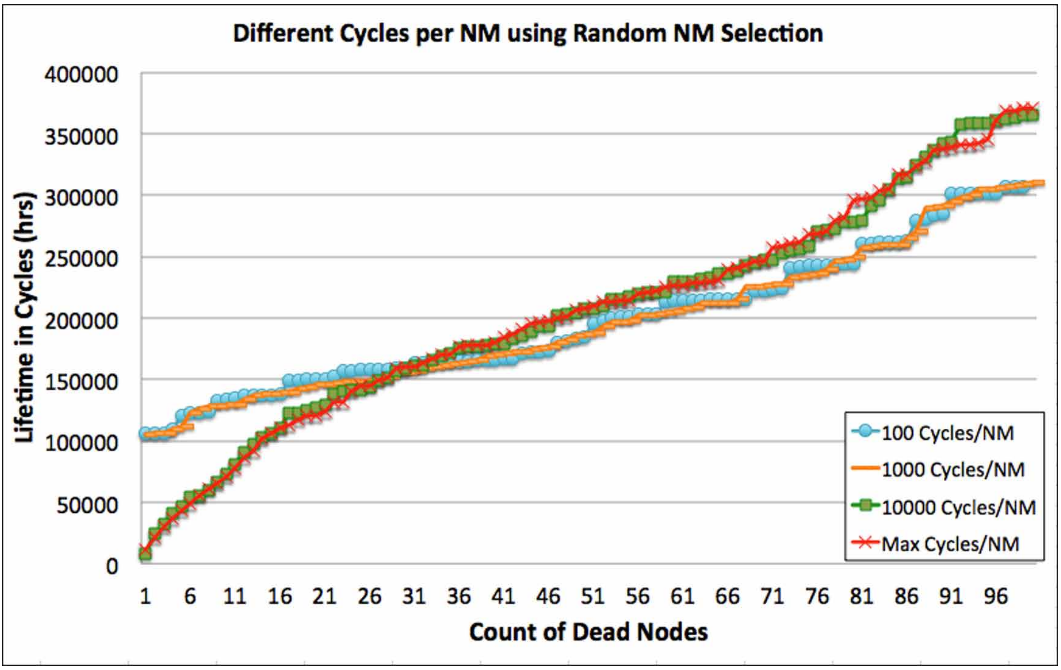


Figure 7. Average remaining energy for the four scenarios using the random choice of NMs

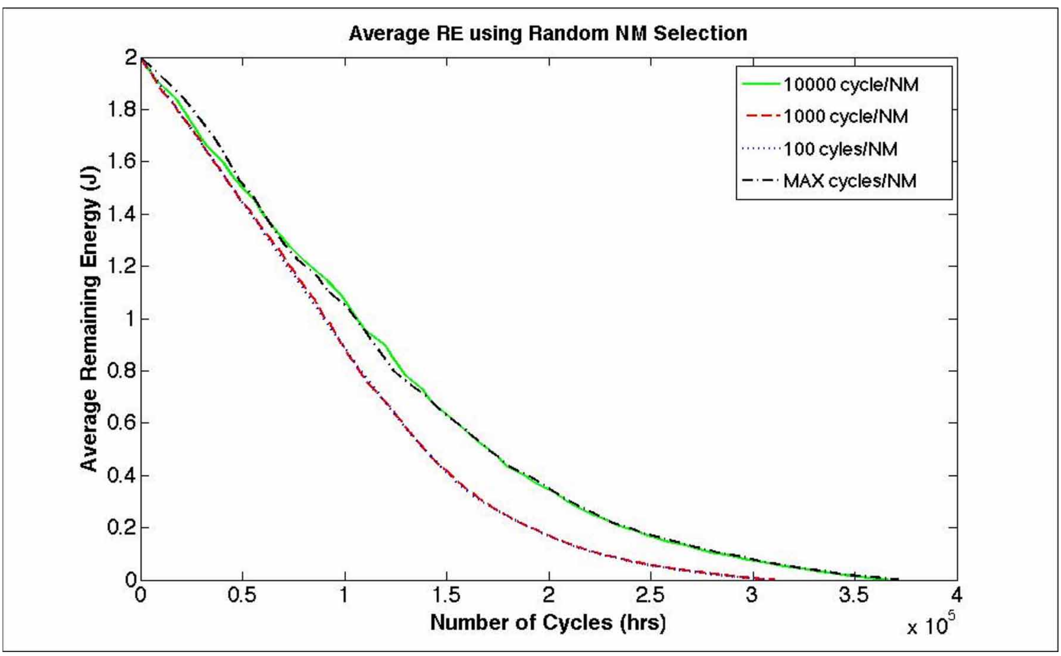
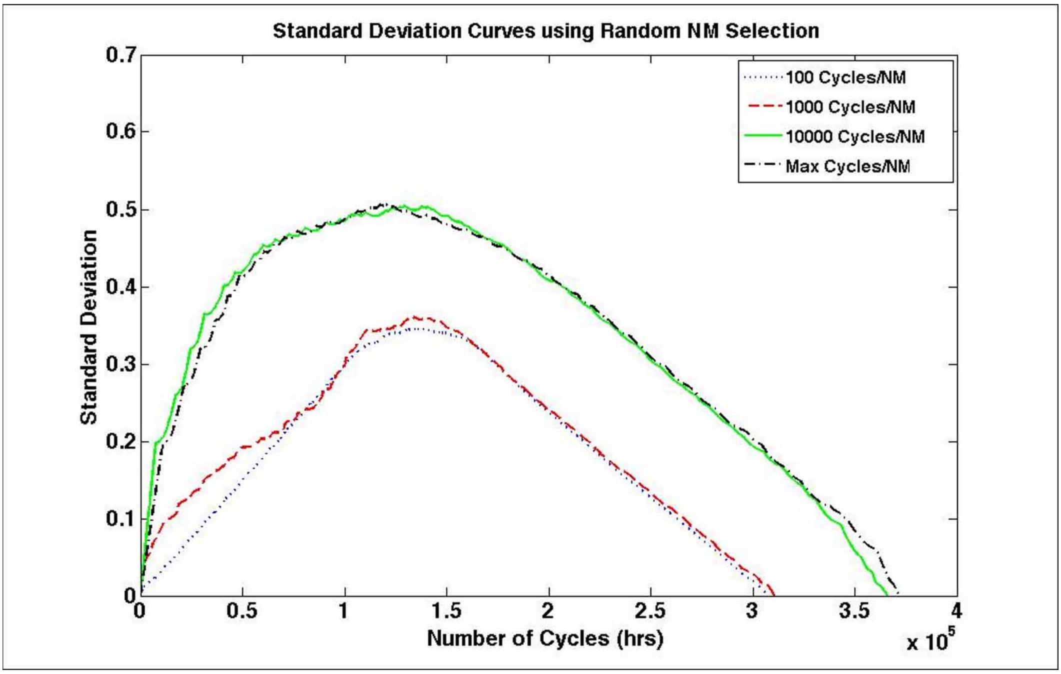


Figure 8. Standard deviation of the remaining energy for the four scenarios using the random choice of NMs



previous sections. We limit our analysis to the deterministic NM selection case developed in (Seoud, Nouh, Abbass, Ali, Daoud, Amer & Elsayed, 2010) in which the sensor nodes will fail in a certain order governed by the node locations.

We assume that all nodes in the WSN system are identical. Furthermore, let the failure rate of any of the sensors be λ_s. The time to failure is typically assumed to follow the exponential distribution (Siewiorek & Swarz,1998); therefore, the failure rate λ_s is constant.

6.1. Reliability Analysis of AND Rule

The system will cease to function properly as soon as the first sensor node (out of the 100 nodes) fails. For the system lifetime to be equal to the one calculated in Section 4, all sensor nodes must *not* have failed. In other words, if this lifetime is t_{and}, then all 100 sensor nodes must be operating correctly till time $t = t_{and}$. Let:

$$R_s\left(t\right) = e^{-\lambda_s t} \tag{4}$$

where $R_s(t)$ is the sensor node reliability, i.e., the probability that this sensor node is performing correctly at time t given that it was operational at time $t = 0$ (Siewiorek & Swarz,1998). It is important here to note that $R_s(t)$ has no relation to the amount of energy remaining in the node's battery. A sensor node failure in the context of $R_s(t)$ is due to a hardware/software failure. From a reliability standpoint, the WSN system is a "series" system; if any of the 100 sensors fails (hardware/software failure), the lifetime calculations in Section 4 above will no longer be valid. Hence:

$$R_{wsn}\left(t_{and}\right) = R_s^{100}\left(t_{and}\right) \tag{5}$$

$R_{wsn}(t_{and})$ is the probability that the WSN will function correctly up to its expected lifetime t_{and}. For a predetermined value $R_{wsn}(t_{and})$, the value of λ_s can be determined and the appropriate type (from a reliability point of view) of sensor nodes can be used in the system.

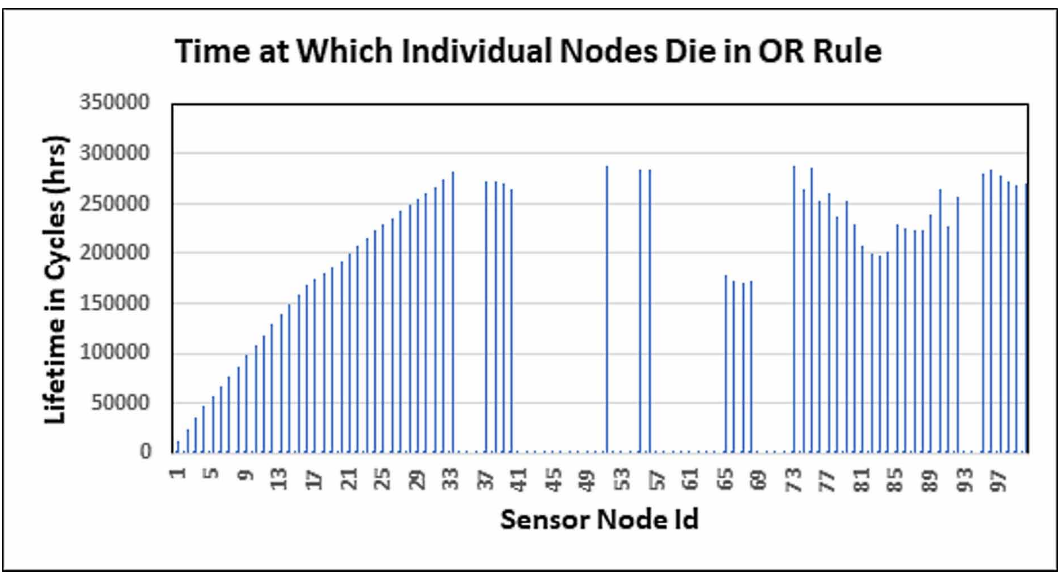
6.2. Reliability Analysis of OR Rule

In the OR aggregation rule, the WSN system reaches its expected lifetime t_{or} (as computed in Section 4) when all 11 sensor nodes measuring any one of the frequency polluters do not have enough battery energy to carry out their functions. The 11th sensor (for one of the four polluters) will not have enough energy at $t = t_{or}$. The other 10 sensor nodes measuring this same frequency polluter will have depleted their energy at $t < t_{or}$. For the sensor nodes measuring the other polluters, some will still be operating while others will not, as shown in Figure 9 in which the nodes with 0 lifetimes are those which are still operating, while the nodes with non-zero lifetime are those which stopped functioning. Let t_{or_i} be the time when sensor i (for any of the four polluters) does not have enough energy to operate correctly. For the calculations in Section 4 above to be valid, each sensor i must not have failed (hardware/software) before t_{or_i}. If it fails after that time (even before $t = t_{or}$), the lifetime calculated above will be valid. Let us divide the 100 sensors into two groups: (1) *Operating*: sensors which still have enough energy at $t = t_{or}$, 2) *LowBattery*: sensors which have depleted their energy at $t < t_{or}$. For the WSN to operate as predicted in Section 4, the "operating" sensor nodes must not fail (hardware/software) before $t = t_{or}$. Any sensor i in the "LowBattery" group of sensors must survive at least till $t = t_{or\_i}$:

$$R_{wsn}\left(t_{or}\right) = \left(\prod_{operating} e^{-\lambda_s t_{or}}\right)\left(\prod_{LowBattery} e^{-\lambda_s t_{or\_i}}\right) \tag{6}$$

Again, for a predetermined $R_{wsn}(t_{or})$, λ_s can be obtained and the appropriate sensors (from a reliability point of view) can be used in the system.

Figure 9. Time at which the individual nodes in Figure 2 die when OR aggregation is used



For the case of the Majority rule, the same reasoning and analysis can be used, but instead of waiting for the 11th sensor to fail, the system will cease to function as soon as one of the four polluters loses its 6th sensor.

7. CONCLUSION

This paper has evaluated three different definitions of the network death criterion that are related 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.

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.

Furthermore, we analytically evaluated the reliability of WSN for the different death criteria considered in the paper. Such analysis allows the WSN designer to choose the appropriate set of sensor nodes that can achieve a certain lifetime with a target level of reliability.

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, to consume the network's energy efficiently, or to be more reliable to failures. 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.

REFERENCES

Benhaddou, D., & Al-Fuqaha, A. (2015). *Wireless Sensor and Mobile Ad-Hoc Networks: Vehicular and Space Applications*. New York, NY: Springer. doi:10.1007/978-1-4939-2468-4

Botros, S. S., Elsayed, H. M., Amer, H. H., & El-Soudani, M. S. (2009). Lifetime Optimization in Hierarchical Wireless Sensor Networks. *IEEE 14th International Conference on Emerging Technologies and Factory Automation (ETFA)*, Mallorca, Spain. doi:10.1109/etfa.2009.5347016

Chen, Y., Shu, J., Zhang, S., Liu, L., & Sun, L. (2009). Data Fusion in Wireless Sensor Networks. In *Proceedings of the IEEE Second International Symposium on Electronic Commerce and Security*, Nanchang City, China. doi:10.1109/ISECS.2009.170

Heinzelman, W., Chandrakasan, A., & Balakrishnan, H. (2000). Energy- Efficient Routing Protocols for Wireless Microsensor Networks. In *Proceedings of the 33rd Hawaii International Conference on System Sciences (HICSS)*, Maui, HI. doi:10.1109/HICSS.2000.926982

Heinzelman, W., Chandrakasan, A., & Balakrishnan, H. (2002). An Application Specific Protocol Architecture for Wireless Microsensor Networks. *IEEE Transactions on Wireless Communications*, *1*(4), 660–670. doi:10.1109/TWC.2002.804190

Ioriatti, L., Martinelli, M., Viani, F., Benedetti, M., & Massa, A. (2009). Real-time Distributed Monitoring of Electromagnetic Pollution in Urban Environments. In *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, Cape Town, South Africa. doi:10.1109/IGARSS.2009.5417724

Kaur, T., & Singh, M. (2016). Lifetime Enhancement by Optimization of Grid Using Mobility and Energy Proficient Clustering Technique of Wireless Sensor Network. In *Proceedings of the International Conference on Computing for Sustainable Global Development* (pp. 1550-1555).

Mahfoudh, S., & Minet, P. (2008). Survey of Energy Efficient Strategies in Wireless Ad Hoc and Sensor Networks. In *Proceedings of the Seventh International Conference on Networking (ICN 2008)*, Cancun, Mexico. doi:10.1109/ICN.2008.55

Mamun, Q., Ramakrishnan, S., & Srinivasan, B. (2010). Selecting Member Nodes in a Chain Oriented WSN. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC'03)*. doi:10.1109/WCNC.2010.5506377

Manjunatha, P., Verma, A., & Srividya, A. (2008). Multi-sensor Data Fusion in Cluster Based Wireless Sensor Networks Using Fuzzy Logic Method. In *Proceedings of the IEEE Region 10 and the Third International Conference on Industrial and Information Systems*, Kharagpur, India. doi:10.1109/iciinfs.2008.4798453

MathWorks, Inc. (2011). MATLAB and Statistics Toolbox Release (2011b). Natick, MA, USA.

Nouh, S., Abbas, R. A., Seoud, D. A., Ali, N. A., Daoud, R. M., Amer, H. H., & Elsayed, H. M. (2010). Effect of Node Distributions on Lifetime of Wireless Sensor Networks. In *Proceedings of the IEEE International Symposium on Industrial Electronics (ISIE)*, Bari, Italy. doi:10.1109/ISIE.2010.5637472

Nouh, S., Khattab, A., Soliman, S. S., Daoud, R. M., & Amer, H. H. (2017). On the Impact of the Death Criterion on the WSN Lifetime. In *Proceedings of the IEEE International Conference on Electro Information Technology (EIT2017)*, Lincoln, NE. doi:10.1109/EIT.2017.8053328

Seoud, D. A., Nouh, S., Abbass, R. A., Ali, N. A., Daoud, R. M., Amer, H. H., & Elsayed, H. M. (2010). Monitoring Electromagnetic Pollution Using Wireless Sensor Networks. In *Proceedings of the IEEE 15th International Conference on Emerging Technologies and Factory Automation (ETFA)*, Bilbao, Spain. doi:10.1109/etfa.2010.5641288

Siewiorek, D. P., & Swarz, R. S. (1998). Reliable Computer Systems Design and Evaluation. Natick, MA: A K Peters.

Viani, F., Donelli, M., Oliveri, G., Massa, A., & Trinchero, D. (2011). A WSN- Based System for Real-time Electromagnetic Monitoring. In *Proceedings of the 2011 IEEE International Symposium on Antennas and Propagation (APSURSI)*, Spokane, WA. doi:10.1109/APS.2011.5997195

Waghmare, K. A., Chatur, P. N., & Mathurkar, S. S. (2016). Efficient Data Aggregation Methodology for Wireless Sensor Network. In *Proceedings of the International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)* (pp. 137-139). doi:10.1109/WiSPNET.2016.7566107

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