International Journal of Technology 10(2): 332-338
ISSN 2086-9614

A MATHEMATICAL MODELING APPROACH FOR OPTIMAL TRADE-OFFS IN A WIRELESS SENSOR NETWORK FOR A GRANARY MONITORING SYSTEM

Moses O. Onibonoje[1*], Adedayo O. Ojo[1], Temitayo O. Ejidokun[1]

[1]*Department of Electrical, Electronics, and Computer Engineering, Afe Babalola University Ado Ekiti, PMB 5454, Ado-Ekiti 340001, Nigeria*

(Received: June 2018 / Revised: November 2018 / Accepted: January 2019)

ABSTRACT

Wireless sensor networks can be deployed in the monitoring of granary systems and greenhouses. In ensuring the efficiency and reliability of such systems, optimal trade-offs should be guaranteed between the various considered constraints. This work has the important aim of translating the monitoring of the environmental factors that may influence the quality of stored agricultural grains into a mathematical model, in which optimal trade-offs are achieved between coverage efficiency, reduced costs and real-time monitoring. The intention is to mathematically model and optimize a developed distributed wireless sensor network system for quality bulk grains storability. The proposed model shows promise, as it attained optimal levels, with a coverage efficiency of 89% with minimum number of nodes.

Keywords: Granary; Modeling; Optimization; Sensor network; Trade-offs; Wireless

1. INTRODUCTION

Over the years, wireless sensor networks (WSNs) have developed into a very promising field of research, providing diverse and novel applications and solutions to various challenges (Hodge et al., 2015) Most of the systems in the environmental applications of such networks have been observed to have inherent limitations and challenges, which include uneven coverage; cost ineffectiveness; cumbersome operability; high installation costs; being prone to damage, hazards, non-recyclability and limited coverage; high maintenance costs; high node failure rates; energy constraints; and offline data collection (non real-time) (Onibonoje et al., 2016). Various models and schemes have either been proposed or developed to overcome many of these challenges (Li et al., 2016); for example, mathematical models can be applied to the deployment, topology control and design of WSNs (Erdelj et al., 2016).

Power consumption optimization in sensor nodes is a major problem in WSN application design and implementation (Shirazi & Morris, 2017; Onibonoje, 2019). In many applications, limited resources are used to satisfy quality of service (QoS) requirements, and also useful to increase system lifetime with minimum energy consumption. Many of the deployments are made in environments where energy replenishment is very difficult, but not impossible (Arioua et al., 2016). Wankhade & Choudhari (2016) proposed an election-based scheme for energy efficiency in WSNs. In his study, the assessment of nominating cluster heads by the coordinator depends upon the associated surplus energy, residual energy and the location of individual nodes. Moreover, the shortest path to reach the coordinating node is selected by the cluster head by using the congested link. Lajara et al. (2015) proposed an approach to finding an analytic

[*]Corresponding author's email: onibonojemo@abuad.edu.ng, Tel. +234-806-9531521
Permalink/DOI: https://doi.org/10.14716/ijtech.v10i2.2099

model to determine the charging state of the battery in wireless sensor nodes. The focus of their work was to derive modest models for accurately estimating the real state of batteries and accordingly evaluate the lifetime of the node.

A vital design issue in WSNs is energy consumption, with numerous data dissemination protocols and power management schemes specially designed for them. Protocols in WSNs are application-specific and depend on the application and network architecture; design emphasis has been placed on routing protocols which often differ. A classification of the different approaches of several possible routing protocols is presented (Zhao et al., 2017; Anasane and Satao, 2016).

Coverage control, as well as node localization, exist as basic problems in wireless sensor networks (Shamantha & Shirshu, 2016). Because of technical limitations, the detection capability of any sensor node is limited to a certain range. Use of a minimum number of sensor nodes to achieve coverage and connectivity requirements is an NP-hard problem. Wang (2011) formulated a mathematical model to calculate the number of nodes required to reach a specified coverage fraction, provided that some parameters are already determined. Hawbani et al. (2014) addressed coverage issues with the proposal of versions 1 and 2 of two grid-based algorithms, namely Grid Square Coverage. In addition, Hawbani & Wang (2013), provided a zigzag pattern-based algorithm for WSN coverage. The maximal and optimal coverage efficiency was reached by the algorithm when there was equality between the sensing range circumference for each node and the sum of its horizontal and vertical arc lengths.

There are also numerous WSN applications that necessitate mobility in sensor nodes. Conversely, security issues are increasing due to the mobility of sensor nodes in WSNs and their consequent susceptibility to numerous types of attacks (Ali et al., 2018). Key distribution and security in communication are the two emerging common issues in the authentication of mobile nodes in dynamic WSNs (Sarobin & Thomas, 2016). When sensor nodes move, there is always a requirement for repeated authentication from the central hub or other dedicated nodes (Deif & Gadallah, 2014). Pathak and Patil (2016) proposed an innovative protocol framework and a correlated mathematical model for key distribution and protected routing layer communication in mobile WSNs. On the basis of both static and dynamic situations, the model was applied to evaluate the performance of a diverse number of nodes, which eventually indicated that the framework was mainly suitable for dynamic WSN applications.

Mathematical models for specific wireless access in sensory networks were presented by Tymchenko et al. (2016). Their article reviewed and compared the special attributes of dedicated wireless sensor networks. The modules of the mathematical model for the prevailing dedicated wireless sensor network, which included signal propagation, communication graphs, and wireless channel models, were reviewed in the study. The study also explained the necessity for a topology control mechanism in WSNs.

The various current WSN models focus on addressing just one or two of the numerous challenges. However, achieving optimal trade-off between many objectives is presently a major challenge. Hence, the aim of this study is to present a mathematical model which represents a designed system that achieves optimal trade-off between the multi-objectives of environmental factors monitoring in WSNs. This is original work, with major applications in the modular storage systems of small-scale farmers and middle-level grain marketers. The novelty of the work contributes to the elimination of their inaccessibility to resourceful storage bins. The system can also be feasibly deployed for the effective monitoring of the existing large volume granary storage systems provided by governments in cities and major towns.

2. METHODS

Mathematical models are developed to translate real-world problems into mathematical solutions. A model cycle of such a scenario is shown in Figure 1, indicating the major goal of translating the monitoring of the environmental factors that may influence the quality of stored agricultural grain into a mathematical model, in which optimal trade-offs are achieved between coverage efficiency, reduced costs and real-time monitoring.

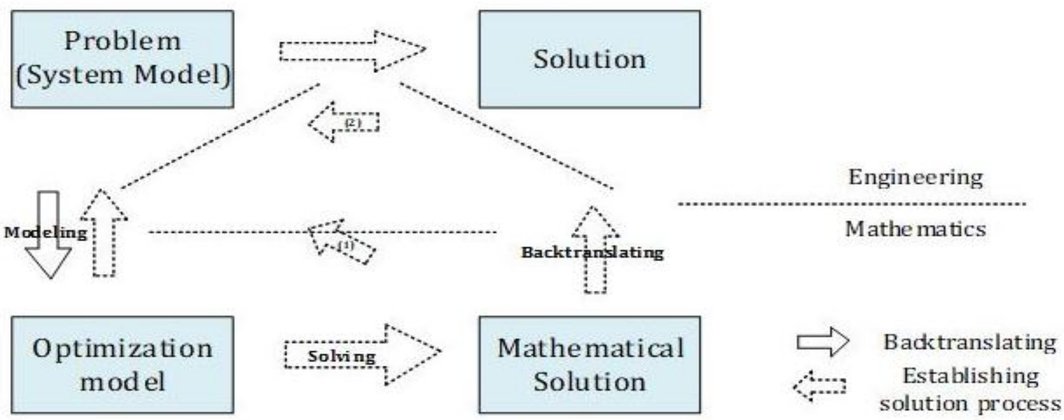

Figure 1 Mathematical solution to a real-world problem – modern applied mathematics in the problem-solving cycle (Eisenblatter et al., 2006)

The system model corresponding to the upper layer in Figure 1 would be an outcome of a comprehensive system analysis using all the engineering expertise available. The analysis develops an explicit understanding of the objective to be achieved, what the important parameters are, and what the key quality indicators of a solution are. The system model would be derived from sub-modeling the individual factors being considered for analysis; it could therefore be matched for optimization, but might not necessarily be optimized. Greener optimization models can be derived on the basis of typical data through further analysis of the system model.

The scope of the optimization model is the lower level illustrated in Figure 1. Powerful advanced optimization methods can preferably be used to solve this model. The relevant constraints in mathematical terms and optimization goals are stated by the optimization model - it is the sole reference during the optimization process. Aspects not implied by the model are not considered. One crucial aspect of the solution process is the solving of the optimization model, which is classified in the field of mathematical optimization. Optimization models can be distinguished according to the complexity of the objective function and the constraints; the simplest model type has a linear objective and linear equality, or inequality, constraints. Finding good solutions becomes more difficult with greater model complexities (e.g. by a quadratic or a generally convex objective function or by more complex constraints on the solutions). Therefore, the focus would be the reduction of the complexity of the model to ensure simplicity (Eisenblatter & Geerdes, 2006)

2.1. Optimal Trade-Offs

In optimizing the different objectives simultaneously, with possible conflicts in them, tradeoffs would be considered. Supposing the interdependence of the monitored parameters in a granary system is defined by:

$$J_1 = \|Ax + b\|^2 \text{ and } J_2 = \|Cx - d\|^2 \tag{1}$$

a sensible approach is to solve the optimization problem

$$\underset{x}{\text{minimum}}\ J_1 + \lambda J_2 \tag{2}$$

where λ > 0 is a fixed tradeoff parameter.

This problem is also equivalent to solving linear equations:

$$J_1 + J_2 = \|Ax+b\|^2 + \|Cx-d\|^2 = \left\| \frac{Ax+b}{\sqrt{\lambda}\|Cx-d\|} \right\|^2 \tag{3}$$

$$J_1 + J_2 = \|Ax+b\|^2 + \|Cx-d\|^2 = \left\| \left[\frac{A}{\sqrt{\lambda}} \right] x - \left[\frac{b}{\sqrt{\lambda d}} \right] \right\|^2 \tag{4}$$

This is an ordinary least squares problem, equivalent to solving

$$(A^T A + \lambda C^T C)x = (A^T b + \lambda C^T d) \tag{5}$$

In the analysis, the values for λ were chosen (log-spaced) to produce *n* points logarithmically.

i. For each λ value, x_λ was found, which minimizes $J_1 + \lambda J_2$.
ii. For each x_λ, the corresponding J_1^λ and J_2^λ were computed.
iii. J_1^λ, J_2^λ was plotted for each λ and the dots were connected.

This could therefore be modified to have more than one tradeoff parameter λ and be analyzed using a Pareto optimal analysis curve.

3. RESULTS AND DISCUSSION

Having carried out the mathematical modeling and the trade-offs for the wireless sensor network, a graphical representation of the comparison of the coverage area for three different nodes for a maximum of 100 square meters is presented in Figure 2. Using this model, it can be observed that the coverage area for the three nodes is approximately the same for durations ranging between 0 and 300 seconds. However, as the duration of operation increases to a range of between 350 and 1000 seconds, the differences in the coverage areas of the three nodes begin to widen. This is further evidenced by a difference of as much as 25 square meters in the coverage area between the two nodes covering the smallest and largest areas with a duration of 400 seconds.

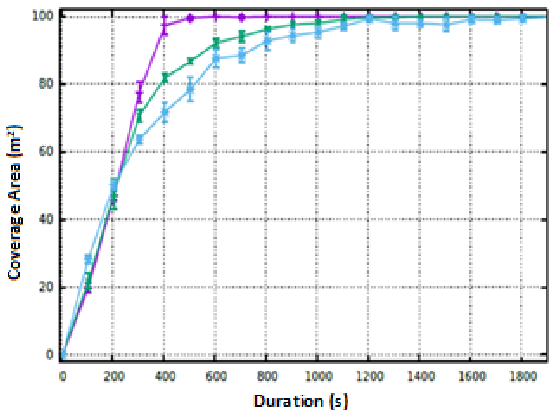

Figure 2 Comparison of the coverage areas of three node efficiencies over various time periods

However, with a duration of between 1000 and 1800 seconds, the difference in coverage area becomes less significant, as the three nodes tend to cover the same area (100 square meters). This unpredictable pattern in the distribution of the factors being optimized justifies the development of the mathematical model. The model eliminates the need for guesswork and will help network planners and designers to develop wireless sensor networks that perform optimally, reducing redundancy, and leading to informed decisions on what resources to trade-off, and to what extent.

The optimal relationship between the number of nodes, the coverage area and the corresponding redundancies was investigated and the results are shown in Figure 3. Redundancy gradually increased over the entire range considered. In general, it can be observed that the maximum coverage and total area also increased as the number of nodes increased.

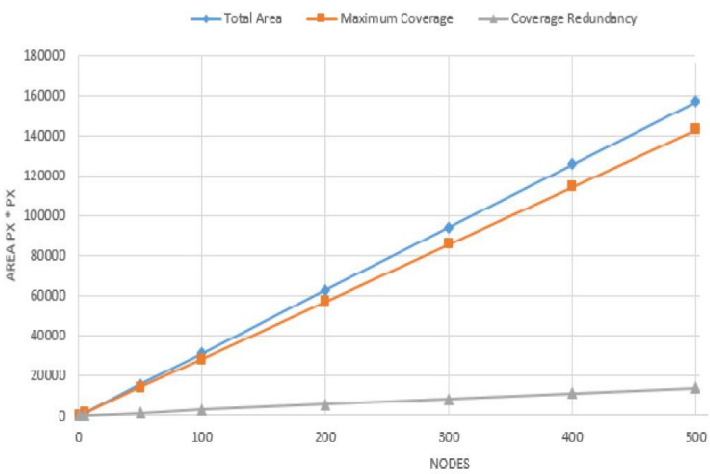

Figure 3 Optimal relationship between the number of nodes, coverage and redundancy

The difference between the total area and the maximum coverage becomes more pronounced as the number of nodes increases, becoming evident as the number of nodes reaches 400 to 500. One of the major goals of the mathematical modeling of optimization processes is to be able to rapidly understand the interrelationship between variables and quickly take trade-off decisions in order to maximize resources. Figure 4 shows a plot which portrays an overview of the optimization surface for the three nodes in terms of their duration of operation.

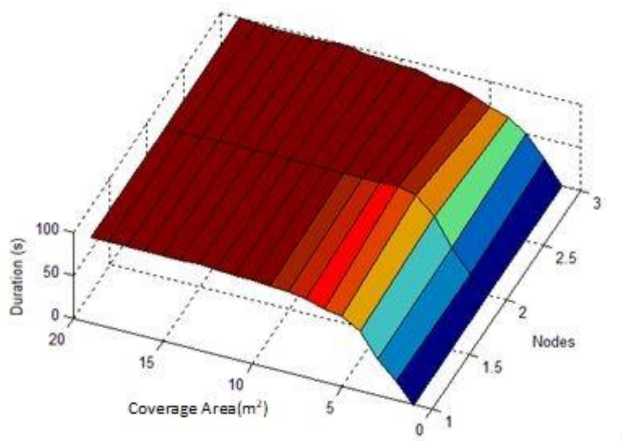

Figure 4 Overview of the optimization surface for the three nodes

These durations are encoded in different colors for easier visualization and interpretation. Dark blue signifies a short duration and the dark red colors indicate sensor nodes with longer durations of operation.

In summary, the derived mathematical model and optimization procedure were able to attain an optimal level, with coverage efficiency computed as 89%, in line with the method in Hawbani et al. (2013), and with a minimum number of nodes, thereby reducing costs, but still achieving a high degree of efficiency in terms of inter-node communication, resource management and overall granary monitoring operation efficiency.

4. CONCLUSION

The study has developed an optimized mathematical model for a granary monitoring system in a distributed wireless sensor network. It has achieved optimal trade-off between factors, such as coverage efficiency, cost and nodal failure.

The results demonstrate that maximum overall efficiency can be attained at a reduced cost, with adequate coverage with a minimum number of nodes within a distributed network. Application of the findings will help to make trade-off decisions during the deployment, design and implementation of such a system. This will eventually improve its accuracy, reliability and efficiency.

5. ACKNOWLEDGEMENT

We thank Mr. Temitayo Olowu for his support and contribution to the success of the work.

6. REFERENCES

Ali, S., Al Bulushi, T., Nadir, Z., Hussain, O.K., 2018. Improving the Resilience of Wireless Sensor Networks against Security Threats: A Survey and Open Research Issues. *International Journal of Technology*, Volume 9(4), pp. 828–839

Anasane, A.A., Satao, R.A., 2016. A Survey on Various Multipath Routing Protocols in Wireless Sensor Networks. *Procedia Computer Science,* Volume 79, pp. 610–615

Arioua, M., El Assari, Y., Ez-zazi, I., Oualkadi, A., 2016. Multi-hop Cluster-based Routing Approach for Wireless Sensor Networks. *Procedia Computer Science,* Volume 83(2), pp. 584–591

Deif, D.S., Gadallah, Y., 2014. Classification of Wireless Sensor Networks Deployment Techniques. *IEEE Communications Surveys & Tutorials*, Volume 16(2), pp. 834–855

Eisenblatter, A., Geerd, A.H., 2006. Wireless Network Design: Solution-oriented Modelling and Mathematical Optimization. *IEEE Wireless Communications,* Volume 13(6), pp. 8–14

Erdelj, M., Mitton, N., Razafindralambo, T., 2016. Robust Wireless Sensor Network Deployment. *Discrete Mathematics and Theoretical Computer Science*, Volume 17(3), pp. 105–130

Hawbani, A., Wang, X., 2013. Zigzag Coverage Scheme Algorithm and Analysis for Wireless Sensor Networks. *Network Protocols and Algorithm,* Volume 5(4), pp. 19–38

Hawbani, A., Wang, X., Husaini, N., Karmoshi, S., 2014. Grid Coverage Algorithm and Analysis for Wireless Sensor Networks. *Network Protocols and Algorithms*, Volume 6(4), pp. 1–18

Hodge, V.J., O'Keefe, S., Weeks, M., Moulds, A., 2015. Wireless Sensor Networks for Condition Monitoring in the Railway Industry: A Survey. *IEEE Transactions on Intelligent Transportation Systems,* Volume 16(3), pp. 1088–1106

Lajara, R.J., Perez-Solano, J.J., Pelegrí-Sebastia, J., 2015. A Method for Modeling the Battery State of Charge in Wireless Sensor Networks. *IEEE Sensors Journal*, Volume 15(2), pp. 1186–1197

Li, B., Wang, K., Shao, Z., 2016. Time-optimal Maneuver Planning in Automatic Parallel Parking using a Simultaneous Dynamic Optimization Approach. *IEEE Transactions on Intelligent Transportation Systems*, Volume 17(11), pp. 3263–3274

Onibonoje, M.O., Folorunso, O., Ajibade, A., Adeniji, K.A., 2016. An Integrated Approach to Automated Control for Air-conditioned Home Apartments using Wireless Sensor Network. *Indian Journal of Science and Technology*, Volume 9(40), pp. 1–9

Onibonoje, M. O., 2019. Design of a Power Optimization Module in a Network of Arduino-Based Wireless Sensor Nodes**.** *ARPN Journal of Engineering and Applied Sciences,* Volume 14(1), pp. 101–105

Pathak, G.R., Patil, S.H., 2016. Mathematical Model of Security Framework for Routing Layer Protocol in Wireless Sensor Networks. *Procedia Computer Science,* Volume 78, pp. 579–586

Sarobin, V.R.M., Thomas, L.A., 2016. Improved LEACH Algorithm for Energy Efficient Clustering of Wireless Sensor Network (WSN). *International Journal of Technology*, Volume 7(1), pp. 50–60

Shamantha R.B., Shirshu V., 2016. An Algorithmic Approach to Wireless Sensor Networks Localization using Rigid Graphs. *Journal of Sensors*, Volume 2016, pp. 1–11

Shirazi, M.S., Morris, B.T., 2017. Looking at Intersections: A Survey of Intersection Monitoring, Behavior and Safety Analysis of Recent Studies. *IEEE Transactions on Intelligent Transportation Systems*, Volume 18(1), pp. 4–24

Tymchenko, O., Zelyanovsky, M., Szturo, K., Tymchenko, O.O., 2016. Mathematical Models for Specialized and Sensory Networks of Wireless Access. *Technical Sciences*, Volume 19(2), pp. 129–138

Wang, A., 2011. Research on Mathematical Model in Wireless Sensor Networks. *International Journal of Digital Content Technology and its Applications*, Volume 5(5), pp. 180–186

Wankhade, N.R., Choudhari, D.N., 2016. Novel Energy Efficient Election Based Routing Algorithm for Wireless Sensor Network. *Procedia Computer Science*, Volume 79, pp. 772 –780

Zhao, H., Wang, C., Lin, Y., Guillemard, F., Geronimi, S., Aioun, F., 2017. On-road Vehicle Trajectory Collection and Scene-based Lane Change Analysis: Part I. *IEEE Transactions on Intelligent Transportation Systems*, Volume 18(1), pp. 192–205