Response to Reviewer Comments and Changes Incorporated in the Revised Manuscript

Improving Energy Efficiency and QoS of LPWANs for IoT Using Q-Learning Based Data Routing Transmission over Cognitive Small World WSN

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We are thankful to the Editor, Reviewer 1, Reviewer 2 for spending their precious time and providing positive and constructive comments on our manuscript. Addressing these comments has helped improve the paper. We have addressed the Reviewer's concerns against each point. We have highlighted the changes in the revised manuscript in blue as journal format allows it. All the grammatical and typographical errors have also been meticulously corrected in the revised manuscript. Please note that Reviewer's comments are italicized while the author's reply is in normal font.

Response to comments of Reviewer 1

Comment 1: *Many technologies can be used to improve the QoS and energy-efficiency problems, why Q-learning is selected? what is the core strength of Q-learning in practice?.*

Reply: REPLY-1

Comment 2: *I recommend the authors to list the used symbols with a table and avoid to use abbreviates in the figures.*

Reply: REPLY-2

Comment 3: *Where the Q-Learning algorithm will be deployed? I think some references about edge learning should be discussed to clarify this problem. Maybe "EdgeLaaS: Edge Learning as a Service for Knowledge-Centric Connected Healthcare" and "Service Popularity-Based Smart Resources Partitioning for Fog Computing-Enabled Industrial Internet of Things" are helpful.*

Reply: REPLY-3

Response to comments of Reviewer 2

Comment 1: *The authors present a routing framework for IoT-based LPWAN. The proposed schemes consider energy-efficiency and evaluate the scheme along multiple metrics such as energy consumption, data latency, interference, and bandwidth utilization. The efficacy of proposed scheme is evaluated both simulation as well as real field data. Given the urgent need to designing power-efficient solutions for IoT-enabled LPWAN, the considered topic is timely, and the routing scheme developed in this work has intellectual merit. However, there exists few issues that need to be addressed before the paper can be accepted for publication.*

Reply: We would like to thank the reviewer for the time spent reviewing the manuscript. We thank the reviewer for positive and constructive comments on the importance of the work. In this work, a cognitive small world WSN is developed by adding new links between a selected fraction of nodes and the sink at various time instants. The selection of node-sink pair for new link creation is in cognitive manner. At different time instants varying new links are created in the network which utilizes the node and network characteristics. Proposed method utilizes several network and node characteristics such as hop count between node-sink pairs, geographical distance between nodes-sink pairs, and nodes betweenness and centrality measure. A self organizing network with small world characteristics (SWC) features is developed by considering the aprior knowledge of used parameters at the gateway at various time instants. Figure 1 illustrates the cognitive small world WSN development at various time instants (τ_1, τ_2) utilizing node and network characteristics. Therefore, the development of a self organizing network with SWC is the cognitive feature considered in the

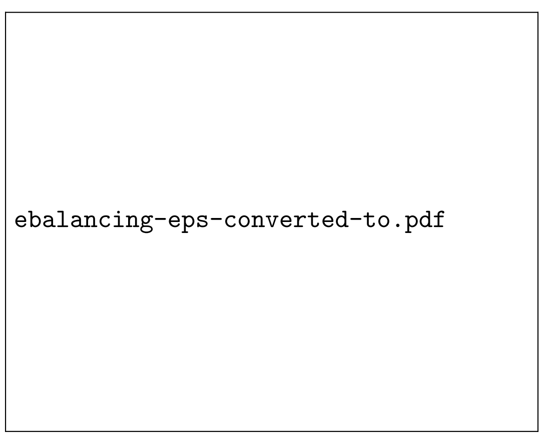

Figure 1: Figure illustrating small world characteristics (SWC) introduction in a conventional WSN at various time instants. Black dots represent sensor nodes. Conventional links are denoted in black. Long links (red or blue links) are created to introduce SWC into the network. Long links of same color (red or blue) are created at various time instants for the development of cognitive small world WSN.

system model. The necessary changes have also been incorporated in the revised manuscript in Section V.

Comment 2: *Though as claimed the probabilistic approach is taken to add a link, the results are not provided to show the effect.*

Reply: Yes, the Reviewer is correct that the probabilistic model is used to add a link in the network. The results are now illustrated in the performance evaluation section corresponding to probabilistic model of link addition. Results obtained using proposed probabilistic model of link addition is also compared with conventional multi-hop data transmission method, direct data transmission model, heuristic model of link addition, and LEACH protocol. Significant gains are obtained in terms of data latency and network lifetime using proposed method when compared to existing methods of link addition. Low-latency and increased network lifetime illustrates the advantages of adding new links using proposed method.

Comment 3: *Introduction of new links will certainly reduce the APL but at the cost of increased interference and complexity in deciding what links to use. More discussion is needed to discuss the drawbacks of such an approach.*

Reply: We would like to thank the Reviewer for commenting on occurrence of interference phenomena and complexity analysis for deciding what links to be used. Yes, the Reviewer is correct that addition of new links causes interference phenomena. However, in this work, it is considered that the new links are established between selected fraction of nodes and the sink. It is also considered that no new link is created between node-pairs. Therefore, the interference phenomena is avoided in this work by considering these assumptions. In our previous work [1], a frequency selective algorithm for new link introduction is proposed wherein additional links are created between node-pairs.

In this work, Dijkstra algorithm [2], [3] is used for data transmission over the network. Dijkstra algorithm considers both conventional and the new links with modified link energy cost for data transmission. Therefore, the complexity in selecting the link for data transmission is similar to conventional methods. This is because at each iteration of data transmission link energy is updated in a cognitive manner over the network.

The necessary changes have also been incorporated in Section V of the revised manuscript. The references used in the aforementioned discussion are listed below.

[1] O. J. Pandey and R. M. Hegde, "Node localization over small world wsns using constrained average path length reduction," Ad Hoc Networks, vol. 67, pp. 87-102, 2017.

[2] U. Brandes, "A faster algorithm for betweenness centrality," Journal of mathematical sociology, vol. 25, no. 2, pp. 163-177, 2001.

[3] Skiena, S.: "Dijkstra's algorithm", Implementing Discrete Mathematics: Combinatorics and Graph Theory with Mathematica, Journal of mathematical sociology, 2001, 25, (2), pp. 163-177.

Comment 4: *It appears that number of iterations is very linear to initial energy. Why? Comment on this. In an energy-balanced network, typically the overall power is increased. Is it the case here (with addition of links)?*

Reply: Yes, the Reviewer is correct that number of iterations is linear to initial energy. However, it is not completely linear with initial energy. In some cases like using heuristic method under simulation condition after the initial energy of 0.25 J the network lifetime increases very slowly. On the other hand in case of real WSN testbed using heuristic method, a similar phenomena is also noted. A linear relation between initial energy and network lifetime is noted because as the initial energy of sensor nodes increases, due to improved energy balancing a drastic increase in network lifetime is obtained. This phenomena is observed because of utilization of proposed probabilistic model of link addition and novel routing algorithm. Additionally, the addition of new links utilizing proposed method leads to overall power increased, in the energy-balanced network.

Comment 5: *On a minor note, the words such as "ln" and "if" within the equations (6)/(11) should not be in italic.*

Reply: We thank the Reviewer for this comment. The necessary changes are incorporated in the revised manuscript in Section III and Section IV.

Response to comments of Reviewer 3

Comment 1: *The reviewer has the following suggestions. Provide more reasons that the small world phenomena can be applied for WSN. [40] is not specific for WSN.*

Reply: We would like to thank the Reviewer for the time spent reviewing the manuscript. Yes, the Reviewer is correct that [1] is not specific to wireless sensor network (WSN). However, in [1] the concept of small worlds is investigated in the context of spatial graphs that tend to be much more clustered than random networks and have much higher path length characteristics. WSN is also a network with similar characteristics. Therefore, small world phenomena can be introduced in WSN to improve the network performance. Also in [1] it is mentioned that, "Multi-hop wireless networks-including ad hoc and sensor networks-are spatial graphs, where the links are determined by the radio connectivity, which is a function of distance, among other factors. Hence, we expect that such networks, by their own nature, do not lend themselves to small worlds. We also expect high clustering in wireless network due to the locality of the links, since many of a node's neighbors are also neighbors of each other. Also, due to this locality we expect the average path length for such networks to be high as compared to random networks."

In [1], the authors conducted further experiments on spatial graphs in the context of multi-hop wireless networks, and investigate the applicability of the small world concept to these networks. Their investigation took a practical perspective in which they tried to utilize small worlds in designing efficient protocols for ad hoc and sensor networks. In particular, they briefly propose a novel contact-based architecture for resource discovery in large-scale ad hoc and sensor network. In such architecture, their goal is to reduce the number of queries during the search for a target node or resource.

There are many other works where the concept of small world phenomena is introduced in WSN to improve the network performance in several context. For instance, in [2-4] small world characteristics are introduced in WSN utilizing wired shortcuts. It leads to improved energy efficiency of a WSN. In these works, wires act as short cuts to bring down the average hop count of the network, resulting in a reduced energy dissipation per node. In [5-7], a model to design heterogeneous sensor network topologies with small world features based on the Kleinberg model is proposed. The proposed model considers the data communication flow in this kind of network to create network shortcuts toward the sink node in a way that the communication between the sink and the sensor nodes is optimized. The shortcuts are created toward the sink node, with a few powerful sensors, the network presents better small world features and the latency is reduced in the data communication when compared with the original Kleinberg model. In [8], the authors tried to show that it is possible to model a WSN as a small world network by using multiple sink nodes to emulate the long edge required in small world networks. It is illustrated that introduction of small world characteristics in such a manner leads to improved localization and routing across the network. In [9], [10], it is shown that due to spatial nature of the wireless networks, achieving small-world properties remains highly challenging. Motivated by the benefits of small-world networks, the authors propose a self-organization framework for wireless ad hoc networks. In [9], [10], the authors investigate the use of directional beamforming for creating long-range short cuts between nodes which is also applicable for WSN. In [11], [12], the results obtained are illustrating that the detection and estimation performance is largely dependent on the topological properties of the networks, such as the average path length, the clustering coefficient and the degree distribution, indicating that the network topology indeed plays an important role in distributed detection and estimation. Therefore, in [11], [12], small world characteristics are introduced in the WSN such that the qualities of detection and estimation are optimized. In order to reduce the data transmission cost over WSNs, small world phenomena is introduced in [13]. In [14], the authors investigate the design of heterogeneous sensor network based on the small world models. The authors designed the network using two well-known Newman-Watts and Kleinberg small world models. The simulation results showed that both models are able to create a sensor network with small world features. However, as the Newman-Watts model does not consider the distance, the created shortcut reduces more the path length, and consequently, data communication latency compared to the Kleinberg model. On the other hand, the Kleinberg model is able to reduce the energy consumption when a power control algorithm is applied. Introduction of small world characteristics into scale-free WSN leads to improved energy-saving performance of the network [15]. Existing over-the-air programming (OAP) protocols do not enable the reprogramming of a subset of the sensor nodes in a WSN. In [16], the authors propose a multicast-based over-the-air programming protocol that considers a small world infrastructure (MOAP-SW). The small world model is used to create shortcuts toward the sink in the communication infrastructure of sensor networks. The end points of these short cuts are more powerful nodes, resulting in a heterogeneous WSN. Simulation results show the feasibility of the protocol regarding the number of messages transmitted, the energy consumption and the time to reconfigure the network. In general, it may be unfeasible to have a synchronization hardware in each sensor. In [17], the authors propose a heterogeneous WSN model based on small world concepts to improve synchronization algorithms for wireless sensor networks. In [18], the authors propose a Greedy Model with Small World properties (GMSW) for heterogeneous sensor networks in Internet of Things (IoT). The proposed method results in improved network robustness and latency. In [19], the authors propose topology planning methods that efficiently exploit the expensive long-reach transmission facilities to add the small-world property to the network. The authors show that these methods are practical, cost-effective and efficient since they are appropriately tailored based upon the network realities, such as topology and channel fading. How to design an energy efficient network model to achieve the balanced utilization of node energy and prolong the lifetime is an important challenge for the research of WSNs. WSNs with small world characteristics are constructed in [20] based on the hybrid mode, which can be divided into the stage of topology optimization, small world model construction and energy dynamic balance. Our previous works [21-23] result in improved node localization in WSNs utilizing small world characteristics. The references used in the aforementioned discussion are listed below.

[1] Helmy, Ahmed, "Small worlds in wireless networks." IEEE Communications Letters 7, no. 10 (2003): 490-492.

[2] Chitradurga, Rohan, and Ahmed Helmy, "Analysis of wired short cuts in wireless sensor networks." In Pervasive Services, 2004. ICPS 2004. IEEE/ACS International Conference on, pp. 167-176. IEEE, 2004.

[3] G. Sharma and R. Mazumdar, "Hybrid sensor networks: A small world," in Proc. ACM Int. Symp. MobiHoc, May 2005, pp. 366-377.

[4] G. Sharma and R. R. Mazumdar, "A case for hybrid sensor networks," IEEE/ACM Transactions on Networking (TON), vol. 16, no. 5, pp. 1121-1132, 2008.

[5] Guidoni, Daniel L., Raquel AF Mini, and Antonio AF Loureiro. "On the design of heterogeneous sensor networks based on small world concepts." In Proceedings of the 11th international symposium on Modeling, analysis and simulation of wireless and mobile systems, pp. 309-314. ACM, 2008.

[6] D. Guidoni, R. Mini, and A. Loureiro, "On the design of resilient heterogeneous wireless sensor networks based on small world concepts," Computer Network-Special Issue Resilient Survivable Networks, vol. 54, no. 8, pp. 1266-1281, Jun. 2010.

[7] D. L. Guidoni, R. A. Mini, and A. A. Loureiro, "Applying the small world concepts in the design of heterogeneous wireless sensor networks," IEEE Communication Letters, vol. 16, no. 7, pp. 953-955, 2012.

[8] Chinnappen-Rimer, Suvendi, and Gerhard P. Hancke. "Modelling a wireless sensor network as a small world network." In Wireless Networks and Information Systems, 2009. WNIS'09. International Conference on, pp. 7-10. IEEE, 2009.

[9] Agarwal, Rachit, Abhik Banerjee, Vincent Gauthier, Monique Becker, Chai Kiat Yeo, and Bu Sung Lee. "Achieving small-world properties using bio-inspired techniques in wireless networks." The Computer Journal 55, no. 8 (2012): 909-931.

[10] A. Banerjee, R. Agarwal, V. Gauthier, C. K. Yeo, H. Afifi, and F. B.-S. Lee, "A self-organization framework for wireless ad hoc networks as small worlds," IEEE Transactions on Vehicular Technology, vol. 61, no. 6, pp. 2659-2673, 2012.

[11] Aldosari, Saeed A., and José MF Moura. "Distributed detection in sensor networks: Connectivity graph and small world networks." In Signals, Systems and Computers, 2005. Conference Record of the Thirty-Ninth Asilomar Conference on, pp. 230-234. IEEE, 2005.

[12] Liu, Ying, Chunguang Li, Wallace KS Tang, and Zhaoyang Zhang. "Distributed estimation over complex networks." Information Sciences 197 (2012): 91-104.

[13] Asif, Waqar, Hassaan Khaliq Qureshi, and Muttukrishnan Rajarajan. "Variable rate adaptive modulation (VRAM) for introducing small-world model into WSNs." In Information Sciences and Systems (CISS), 2013 47th Annual Conference on, pp. 1-6. IEEE, 2013.

[14] Araujo, Renan Pereira, Fernanda Sumika Hojo De Souza, Jo Ueyama, Leandro Aaparecido Villas, and Daniel Ludovico Guidoni. "On the Analysis of Newman & Watts and Kleinberg Small World Models in Wireless Sensor Networks." In Network Computing and Applications (NCA), 2015 IEEE 14th International Symposium on, pp. 17-21. IEEE, 2015.

[15] Duan, Ying, Xiuwen Fu, Wenfeng Li, Yu Zhang, and Giancarlo Fortino. "Evolution of Scale-Free Wireless Sensor Networks with Feature of Small-World Networks." Complexity 2017 (2017).

[16] Maia, Guilherme, Andre LL Aquino, Daniel L. Guidoni, and Antonio AF Loureiro. "A multicast reprogramming protocol for wireless sensor networks based on small world concepts." Journal of Parallel and Distributed Computing 73, no. 9 (2013): 1277-1291.

[17] Guidoni, Daniel L., Azzedine Boukerche, Horacio ABF Oliveira, Raquel AF Mini, and Antonio AF

Loureiro. “A small world model to improve synchronization algorithms for wireless sensor networks.” In Computers and Communications (ISCC), 2010 IEEE Symposium on, pp. 229-234. IEEE, 2010.

[18] Qiu, Tie, Diansong Luo, Feng Xia, Nakema Deonauth, Weisheng Si, and Amr Tolba. “A greedy model with small world for improving the robustness of heterogeneous Internet of Things.” Computer Networks 101 (2016): 127-143.

[19] Tadayon, Navid, Amir Ehsani Zonouz, Sonia Aïssa, and Liudong Xing. “Cost-effective design and evaluation of wireless sensor networks using topology-planning methods in small-world context.” IET Wireless Sensor Systems 4, no. 2 (2014): 43-53.

[20] Geng, Peng, Yan Liu, and Jie Yang. “A Dynamic Energy Balance Method for Wireless Sensor Networks with Small World Characteristics.” In Proceedings of the Fifth International Conference on Network, Communication and Computing, pp. 287-291. ACM, 2016.

[21] Pandey, Om Jee, Ashutosh Kumar, and Rajesh M. Hegde. “Localization in wireless sensor networks with cognitive small world characteristics.” In Communication (NCC), 2016 Twenty Second National Conference on, pp. 1-6. IEEE, 2016.

[22] Pandey, Om Jee, and Rajesh M. Hegde. “Node localization over small world WSNs using constrained average path length reduction.” Ad Hoc Networks 67 (2017): 87-102.

[23] Pandey, Om Jee, Akshay Mahajan, and Rajesh M. Hegde. “Cooperative localization in small world wireless sensor networks.” In Communication Systems and Networks (COMSNETS), 2017 9th International Conference on, pp. 391-392. IEEE, 2017.

Comment 2: *Give some physical meaning of Eq. (3), especially for function f.*

Reply: Equation (3) (Equation (1) in the revised manuscript) [1], [2], is given by

$$L_{rand}(N,p) \sim \frac{N^{1/d}}{K} f(NKp), \tag{1}$$

where f is a universal scaling function and is given by

$$f(u) = \left\{ \begin{array}{ll} \text{const}, & \text{if } u \ll 1 \\ \ln(u)/u, & \text{if } u \gg 1 \end{array} \right\}$$

and each node has at least K neighbors. Probability of link addition is denoted by p, and is given by

$$p = \frac{\text{\# links added}}{\text{\# possible links - \# links existing}}. \tag{2}$$

Newman, Moore, and Watts (2000) have calculated the form of the scaling function $f(u)$ for the one-dimensional small-world model using a mean-field method that is exact for small or large values of u, but not in the regime in which u $\simeq 1$, obtaining

$$f(u) = \frac{4}{\sqrt{u^2+4u}} \tanh^{-1} \frac{u}{\sqrt{u^2+4u}}. \tag{3}$$

They also solved for the complete distribution of path lengths within this mean-field approximation. The scaling relation (3) has been confirmed by extensive numerical simulations [3], and series expansions [4]. Equation (3) tells us that although the average path length in a small-world model appears at first glance to depend on three parameters— p, K, and N - it is in fact entirely determined by a single scalar function $f(u)$ of a single scalar variable. Note that both the scaling function $f(u)$ and the scaling variable $u = pKN^d$ have simple physical interpretations [1], [2]. The variable u is two times the average number of random links (shortcuts) on the graph for a given p, and $f(u)$ is the average of the fraction by which the distance between two nodes is reduced for a given u.

The necessary changes have also been incorporated in the revised manuscript. The references used in the aforementioned discussion are listed below.

[1] Albert, Réka, and Albert-László Barabási. "Statistical mechanics of complex networks." Reviews of modern physics 74, no. 1 (2002): 47.

[2] Barrat, Alain, and Martin Weigt. "On the properties of small-world network models." The European Physical Journal B-Condensed Matter and Complex Systems 13, no. 3 (2000): 547-560.

[3] Newman, Mark EJ, and Duncan J. Watts. "Renormalization group analysis of the small-world network model." Physics Letters A 263, no. 4-6 (1999): 341-346.

[4] Newman, Mark EJ, and Duncan J. Watts. "Scaling and percolation in the small-world network model." Physical review E 60, no. 6 (1999): 7332.

Comment 3: *The problem is formulated as a mixed integer programming problem. The authors may use other existing algorithm to solve such a problem. What is the advantages of the proposed algorithm? Simulations may be conducted.*

Reply: Yes, the Reviewer is correct that the problem is formulated as a mixed integer programming problem. Mixed integer problem formulation deals with mathematical optimization problems with two types of variables: variables taking values in an integer domain, and variables taking values in a continuous domain [1-2]. The mathematical optimization model in this problem involves both discrete and continuous variables that must satisfy a set of equality and inequality constraints, and that must be chosen so as to optimize a given objective function [1-2]. Mixed integer optimization problems naturally appear in many contexts has led to an increased interest in the design of strong algorithms for different variants of the problem [3-4]. It should also be noted that while there might be the temptation to resort to simpler optimization approaches such as simulated annealing, mixed integer programming provides a rigorous and deterministic framework, although it is not always the easiest one to apply. On the other hand, many mixed-integer problems that were regarded as unsolvable few years ago are currently being solved to optimality with reasonable computing requirements due to advances in algorithms and increased computer power. Finally, the problem formulation for mixed integer programming problems has often a very large impact in the efficiency of the computations, and in many ways still remains an art for the application of these techniques. However, a better understanding of polyhedral theory and establishing firmer links with symbolic logic may have a substantial effect on how to systematically formulate mixed-integer problems. The references used in the aforementioned discussion are listed below.

[1] Kahjogh, Behnam Ojaghi, and Greg Bernstein. "Energy and latency optimization in software defined wireless networks." In Ubiquitous and Future Networks (ICUFN), 2017 Ninth International Conference on, pp. 714-719. IEEE, 2017.

[2] Kurt, Sinan, Huseyin Ugur Yildiz, Melike Yigit, Bulent Tavli, and Vehbi Cagri Gungor. "Packet size optimization in wireless sensor networks for smart grid applications." IEEE Transactions on Industrial Electronics 64, no. 3 (2017): 2392-2401.

[3] Grossmann, Ignacio E. "Mixed-integer optimization techniques for the design and scheduling of batch processes." (1992).

[4] Grossmann, Ignacio E., Ignacio Quesada, Ramesh Raman, and Vasilios T. Voudouris. "Mixed-integer optimization techniques for the design and scheduling of batch processes." In Batch processing systems engineering, pp. 451-494. Springer, Berlin, Heidelberg, 1996.

Comment 4: *Give some reasons that the energy cost function is chosen as Eq. (25)(26)(27). If the different function is selected, what's the result? How does the function affect the solution?*

Reply: In this work, different energy cost function are selected for energy cost assignment to the links. For instance, firstly an inverse energy cost is assigned to each link such that

$$c_{ij}(n\tau) = \frac{1}{E_j(n\tau)},\ \forall (i,\ j) \in \{\mathcal{E} \cup \mathcal{L}\}\,, \tag{4}$$

where, $E_j(n\tau)$ is the residual energy of j^{th} node at time instant $n\tau$. Inverse energy cost assignment to each link reduces the usage of nodes which have low residual energy. It results in improved network lifetime when compared to conventional energy cost assignment. When the data is transmitted from node i to node j, node j should have high energy. Because, if node j has low energy, transmission of data through this node leads to further loss of its energy and node j dies out very fast. There exist many paths between the node and sink when data is transmitted through multi-hop. Hence it is desirable to have data transmission through that path which has relatively higher energy nodes. The inverse cost function does not change more rapidly when the energy of the nodes changes. This change is more rapid using proposed exponential-sine cost function. In proposed method we assign energy costs using an exponential-sine function. This method leads to a high energy cost assignment to the links associated with low residual energy sensor nodes. The cost function used in this method is given by

$$c_{ij}(n\tau) = \exp\left(\frac{1}{\sin(\pi - \frac{\pi}{4}\frac{E_j(n\tau)}{E_j(0)})}\right),\ \forall(i,\ j) \in \{\mathcal{E} \cup \mathcal{L}\}, \tag{5}$$

where $c_{ij}(n\tau)$ is the cost assigned to link between nodes i and j at $n\tau$ time instant. This cost function is called as exponential-sine cost function. The inverse cost function does not change more rapidly when the energy of the nodes changes. This change is more rapid using proposed exponential-sine cost function. Therefore, the performance of proposed energy cost assignment is better when compared to inverse energy cost assignment.

A small energy change corresponding to a node leads to drastic change in exponential-sine cost function when compared to the inverse cost function. As a result, exponential-sine cost function is favorable than the inverse cost function for assignment of link energy cost. Exponential and sine functions are among those functions where small changes in variable can cause large changes in function values. We combine these two kinds of functions and construct an exponential-sine cost function as

$$f(x) = \exp\left(\frac{1}{\sin x}\right). \tag{6}$$

In the interval $(\frac{\pi}{2}, \frac{3\pi}{4})$, the exponential-sine cost function does not increase as rapidly as the independent variable but it increases faster than the independent variable in the interval $(\frac{3\pi}{4}, \pi)$. Thus, it is reasonable to map nodal residual energy to $(\frac{3\pi}{4}, \pi)$ than to $(\frac{\pi}{2}, \frac{3\pi}{4})$. Therefore, if

$$x = \sin\left(\pi - \frac{\pi}{4}\frac{E_j(n\tau)}{E_j(0)}\right). \tag{7}$$

Then the exponential-sine cost function for the proposed model is given by

$$c_{ij}(n\tau) = \exp\left(\frac{1}{\sin x}\right) = \exp\left(\frac{1}{\sin(\pi - \frac{\pi}{4}\frac{E_j(n\tau)}{E_j(0)})}\right). \tag{8}$$

In the performance evaluation section, results obtained are illustrating improved network performance using proposed energy cost assignment when compared inverse cost assignment.

Comment 5: *Comparison of complexity analysis (other existing protocol or algorithm) is needed.*

Reply: We thank the Reviewer for this comment. Addressing this comment has helped improve the paper. The time complexity of mixed integer programming problem is high, because it is a NP-complete problem. The time complexity of mixed integer programming problem increases drastically with number of sensor nodes in the network. Therefore, to obtain optimal solution in reduced time an efficient heuristic need to be used. In this work, the optimization problem is solved using linear programming relaxation as an alternate to the exact solution of mixed integer programming. Integer variables of the mixed integer problem are treated as continuous variables herein. Linear programming problems can be solved in polynomial time,

Table 1: Time complexity analysis for obtaining solutions using linear programming-relaxation (LP-R) and simulations. Results are obtained over simulated WSN testbed with sensor node's initial energy equal to 0.5J.

			Average Time (s)	
Bytes used	Lifetime difference %	Data latency difference %	LP-R	Simulations
300	1.3721	0.6541	6452	10803
400	1.6890	0.7141	6893	11247
500	2.0067	0.8448	7094	11790

however, the linear programming-relaxed solutions do not necessarily result in integral solutions. Linear programming-relaxation results in approximate to the optimal solution with low time complexity. In this work, results are also obtained using simulations. The time complexity of simulations is high with poor approximate results to the optimal solution. In this work, both linear programming-relaxation solutions and simulation solutions are obtained. A comparison between time complexity is illustrated in Table 1. For instance, a 2.0067% improved network lifetime and 0.8448% improved data latency is obtained using linear programming-relaxation when compared to simulations. The time complexity is 7094 seconds and 11790 seconds respectively using linear programming-relaxation and simulations. This result is obtained over simulated WSN testbed with an initial energy of 0.5 J for sensor nodes. An improved results are also noted over real WSN testbed when linear programming-relaxation is used over simulations. The solution times of linear programming-relaxation solutions are significantly lower than the solution times of the simulations.

The necessary changes have also been incorporated in the revised manuscript in the performance evaluation section.