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Performance Evaluation of EADQR Across Various Path Loss Models Through Propagation Analysis

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***Abstract*—Wireless Sensor Networks (WSNs) play a vital role in Internet of Things (IoT) technology by facilitating data collection and transmission through small wireless sensors. Path loss, influenced by environmental factors, significantly impacts WSN performance, affecting communication range and sensor reliability. This emphasizes the importance of considering path loss in WSN design and optimization. The proposed work aims to evaluate a sink-led decentralized routing system designed to enhance network longevity and minimize energy consumption under various propagation loss models. The methodology employs an energy-aware model to select initiator nodes, creating multiple paths and reducing redundancy. For improved quality of service, the system picks a forward relay node based on factors like remaining energy, the quality of the radio link between adjacent nodes, and proximity to the sink node. A fuzzy logic-based decision-making process is used to identify the most optimal path among the multitude of possible pathways. The research seeks to demonstrate the impact of path loss on crucial network metrics, such as end-to-end delay, hop count, energy usage, and the number of active nodes in a WSN topology. Simulations provide a comprehensive understanding of the impact of path loss on key network metrics. Computational outcomes, derived from Received Signal Strength Indicator (RSSI) values for near-surface wave propagation, showcase that the Energy Aware Data Centric Query Driven Receiver initiated (EADQR) protocol excels in scenarios characterized by substantial environmental clutter, as represented by the clutter factor and HATA suburban models. The energy-aware strategy mitigates path loss and energy depletion, thereby prolonging the operational lifespan of the network.**

***Keywords*—fuzzy logic, propagation channel, Signal Strength Indicator (RSSI)**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) consist of clusters of sensor units that interact wirelessly, forming intricate networks [1]. These systems have gained substantial favour across professional and scholarly spheres alike and find application in a plethora of contexts, spanning from scrutinizing infrastructural integrity and streamlining industrial processes to monitoring ecosystems and upholding security protocols. As the implementation of WSNs proliferates, there is an increasing demand for studies grounded in real-world contexts [2].

In hierarchical clustering, sensor nodes form clusters, and a cluster head is chosen to send data to the sink and establish inter-cluster communication paths [3]. However, the limited energy of the cluster head can run out during operations, posing challenges for recharge or replacement. This can lead to network disruption and reduced lifespan [4]. Non-hierarchical routing addresses this by effectively conserving energy and boosting the network's longevity. Its decentralized data forwarding eliminates a single failure point. Many current routing protocols for packet transmission, primarily centered on the network layer, often face challenges regarding energy optimization [5, 6]. This highlights the necessity for a dependable, energy-saving routing structure to enhance the effectiveness of WSNs. A new framework, EADQR, for non-hierarchical WSNs, which integrates a multi-faceted optimization strategy, is introduced. This aims to prolong the network’s lifespan while also reducing the energy expenditure in WSNs using fuzzy inference.

One crucial aspect of planning and deploying WSNs is the propagation model, which describes how radio signals interact with the environment and physical elements [7]. By understanding the characteristics of radio channels, including attenuation and warping, it is possible to compute the predicted received signal intensity level [8].

However, wireless channels are susceptible to interference, noise, and other factors impacting signal quality. Additionally, the communication environment influences the fading characteristics of the signal [9]. Therefore, simplistic or idealized propagation models may fail to effectively anticipate the link quality and range of WSNs in challenging conditions [10].

To ensure accurate predictions of connection quality and coverage in WSNs, an effective propagation analysis that is tailored to the specific environment and terrain is essential. Wireless networks are used in numerous sectors,

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and one of the main barriers is achieving a high data rate, which requires a larger bandwidth [11]. The propagation channel plays a critical role in determining the performance limit of any wireless system. A comprehensive understanding of transmission characteristics is essential to introduce new technologies successfully. While field test beds can be used to evaluate system performance, they can be challenging and time-consuming [12, 13]. Therefore, simulation tools are commonly employed to quickly simulate and assess new protocols. However, the accuracy of simulation results heavily relies on the selected propagation models [14].

This research paper aims to empirically analyze the EADQR routing protocol's performance through the application of various propagation loss models and quantitative assessments. The study evaluates the protocol's effectiveness under various signal propagation frameworks and analyses the influence of path loss on critical performance metrics [15]. These metrics are vital for the conception and optimization of wireless communication systems, as they offer valuable insights into signal interaction with environmental factors and obstacles essential for designing and optimizing wireless communication systems [16]. The study underscores the significance of employing accurate and credible propagation models in designing and analysing WSNs.

The remainder of the document is structured as follows: Section II presents an exploration of the associated suggested practical investigations. Delving deeper, Section III elucidates diverse path loss configurations and their empirical assessment. Moving on, Section IV offers an intricate exposition of the envisaged EADQR routing protocol. Section V analyses the performance of EADQR. This is followed by the discourse of the study’s revelations in Section VI. Lastly, Section VII encapsulates the culminating observations and conclusion.

II. LITERATURE REVIEW

It is worth mentioning that propagation models are classified as either deterministic or empirical [17]. Empirical models rest upon practical data collection and a statistical analysis founded on equations, all aimed at comprehending the behaviour of signals. Deterministic models, on the other hand, are founded on research into propagation phenomena as well as a comprehensive grasp of the surroundings wherein the network operates. They might be as simple as models that merely take node proximity into account or as complicated as models that take multipath fading into account.

By utilizing an efficient propagation model specifically designed for Wireless Sensor Networks (WSNs), this study aims to address the data transfer issue in WSNs [18]. A semi-deterministic path loss propagation model for WSNs in distant settings such as woodlands, jungles, and open dirt roads is the focus of the research, intending to increase its accuracy. The study utilizes WSNs nodes for measurement experiments, gathering radio signal strength information from open dirt roads, forests, and jungles and feeding that information into the Adaptive-Network-Based Fuzzy Inference System (ANFIS)engine as training input to improve the semi-deterministic model’s accuracy.

In an effort to enhance the communication functionality of space-air-ground integrated connections, an extended strong learning machine technique is presented to mitigate substantial path loss induced by adverse weather conditions[19, 20]. The approach includes gathering weather-related information through IoT-enabled sensors and inputting it into the advanced extreme Machine Learning Model (ELM) to forecast the decrease in communication caused by rainy weather. This data is then used to select the most suitable data transmission link and enhance satellite routing performance. The ELM algorithm anticipates communication interruptions caused by weather, thus improving communication efficiency.

To overcome the criticality of reliable wireless links for smart grid operations, as well as the constraints imposed by available resources and regulatory authorities on network design, a Propagation loss model for Neighbourhood Area Networks (NANs) in smart grids is proposed [21] taking into account the impact of various factors such as frequency, distance, and building penetration loss on signal strength. A path loss model with a focus on penetration loss for inside-to-outside communication in smart grid ecosystems validates the proposed model using measured data from a smart grid testbed. The study’s findings demonstrated that the proposed model is accurate and can be used to predict signal strength in NANs in smart grids.

Wireless communication systems have faced a persistent problem of signal quality degradation and signal strength decrease due to the decline in transmission power of electromagnetic waves when traversing obstacles and encountering multipath propagation atmosphere, particularly in urban areas with a high density of obstacles and population [20].

Path loss can occur due to various factors such as reflection, diffraction, absorption, and free space loss. However, due to variations in urban infrastructure, local landscape profiles, and weather conditions, path loss predictions can differ significantly between different propagation models. Thus, an accurate estimation of path loss is crucial for determining frequency assignments, identifying base station coverage areas, ensuring fair electric field efficiency, performing obstruction analysis, and adjusting transmit power levels.

III. PATH LOSS MODEL

The wireless channel pertains to the transmission and reception of electromagnetic waves through the transmitting and receiving antennas and the path along which the waves propagate [22]. The utilization of radio waves to transmit signals is a fundamental aspect of radio channels, primarily employing space waves, comprising of direct, refracted, scattered, and composite waves. A path loss model is a collection of mathematical equations that depict the radio attributes and calculate the signal strength decrease through theoretical modelling or real-world measurements [23]. The channel models utilized include the free space channel model, okumura hata urban and suburban model, walfisch ikegami model, and clutter factor mode. These models focus on specific aspects of signal propagation, such as primary attenuation in free space, the impact of urban structures, or the influence of clutter and obstacles.

A. Free Space Model

A widely adopted propagation model is the free-space model constructed upon the Friis transmission formulation [24]. This formula in Eq. (1) posits that in an ideal setting, power is dispersed evenly across the spherical expanse covering the antenna, with no obstacles blocking the line of sight between the antenna and the receiver.

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{1}$$

where, P_t represents the power output of the transmission, P_r represents the power received, G_t and G_r represent the transmitter and receiver antenna gain respectively, L represents the system loss which is always equal to or greater than 1 and λ is the signal's wavelength.

B. Okumura-Hata Model

The Okumura-Hata Model is a widely used path loss propagation model for mobile communication applications [25]. It is derived from measurements taken in Tokyo by Okumura and a mathematical model developed by Hata. This model applies to frequencies between 150 MHz and 1500 MHz and assumes transmitter heights between 30 m and 200 m, receiver heights between 1m and 10m, and distances between the transmitter and receiver of 1km to 10km. The model considers the varying level of urbanization, with two main categories: urban areas with tall buildings, trees and more obstacles in the covered area.

$$PL_{urban}(db) = 69.55 + (26.16\ logf) - (13.82\ loght) - A(hr) + ((44.9 - (6.55 \times loght)) \log d) \tag{2}$$

Suburban areas with some obstacles in the covered area but not heavily congested.

$$\begin{aligned} PL_{suburban}(db) = {} & 69.55 + (26.16\ logf) \\ & - (13.82\ loght) - A(hr) \\ & + ((44.9 - (6.55 \times loght)) \log d) \\ & - 2(log\frac{f}{28})^2 + 5.4 \end{aligned} \tag{3}$$

where, $A(hr)$is antenna correction,f is carrier frequency in MHz, ht signifies the elevation of the transmitting antenna in meters, hr indicates the altitude of the receiving antenna, d represents the span between Tx and Rx in Km.

C. COST 231 Walfisch-Ikegami Model.

The Walfisch-Ikegami model is a widely used prediction tool for determining the strength of radio waves as they travel through urban environments [26]. This model is handy for designing wireless systems in urban areas, such as public safety communications, transportation, and other applications that require reliable communication.

$$PL_{wi} = L_{fs} + L_{rts} + L_{msd} \tag{4}$$

where, L_{fs} denots free space path loss,
L_{rts} denotes diffraction and scatter loss from roof top to street,
L_{msd} denotes multiscreen diffraction loss.

$$L_{msd} = -18log_{10}(1 + H_{base}) + 54 + 18log_{10}(d) + (-4 + 1.5((f/925) - 1))log_{10}(f) - 9log_{10}(B) \tag{5}$$

$$L_{fs} = 32.45 + 20log_{10}(d) + 20log_{10}(f) \tag{6}$$

$$L_{rts} = -16.9 - 10log_{10}(w) + 10log_{10}(f) + 20log_{10}(H_{mobile}) + L_{ori} \tag{7}$$

L_{ori} is given as

$$L_{ori} = -10 + 0.354\theta \ \text{ urban environment} \tag{8}$$

$$L_{ori} = 2.5 + 0.075(\theta - 35) \ \text{ suburban environment} \tag{9}$$

D. Clutter Factor Model

The analysis incorporates the planar earth model, which accounts for both the direct ray and the ground-reflected ray detected by the receiver, as described by Eq. (10) [27]. The path loss model is defined as:

$$PL_{CF}(db) = (\ 40 \log d) - (20 \log ht) - (20 \log hr) \tag{10}$$

where, ht represents the elevation of the transmitting antenna in meters, while hr signifies the altitude of the receiving antenna, the variable d denotes the separation distance between the sender and the recipient, quantified in meters.

IV. EADQR ROUTING PROTOCOL

The non-hierarchical sink-initiated routing protocol, EADQR, aims to optimize energy consumption in WSNs [28]. The protocol incorporates an optimized route selection mechanism, as illustrated in Fig. 1.

To minimize excessive redundancy, we employ a judicious energy-aware framework. This framework selectively identifies initiator nodes from the set of 1-hop nodes. ensuring that only specific nodes initiate actions with their neighbouring nodes directly associated with sink nodes, thereby facilitating the formation of multiple paths.

EADQR establishes multiple routes between the sink and source nodes by selecting candidate nodes for the forward relay. The selection process of the forwarder takes into account factors such as the residual energy of each sensor, link quality indicators, and forward headway toward the sink.

The path formation begins with the sink node. Initially, the initiating node selects a relay node from its 1-hop neighbouring nodes. If the originating node is among these neighbors, a direct path is formed. If not, the initiating node selects the next hop based on those neighbors located within the source node's search area, prioritizing the one with the highest FNode Value.

$$F_{node}\,(SN_a\,,SN_b) = RE_b + CQI\,(SN_a\,,SN_b) + (1/d_{(SN_b,S_{dn}}) \tag{11}$$

The remaining energy of the sensor node is denoted as RE_b, and the link quality between SNa and SNb is represented by $CQI\,(SN_a\,,SN_b)$.

To ascertain the most suitable transmission path among the available routes, a data dissemination protocol that employs fuzzy logic for enhanced energy efficiency is applied. This protocol leverages routing-centric parameters to make intelligent decisions and ensure energy-efficient data transmission

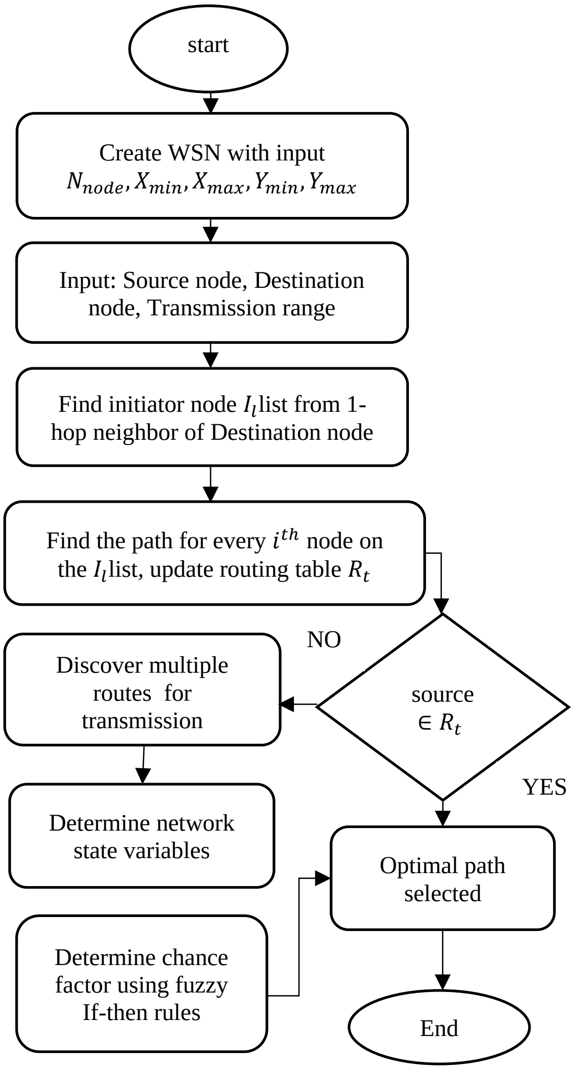

Fig. 1. EADQR flow chart.

V. PERFORMANCE ANALYSIS OF EADQR ROUTING PROTOCOL

This section meticulously assesses the performance of the Energy-aware Destination-initiated Query-Driven Routing Protocol (EADQR) through MATLAB simulations, comparing it to a spectrum of well-established routing algorithms, namely Ad Hoc On-Demand Distance Vector (AODV) [29], Destination-Sequenced Distance Vector (DSDV) [30], Zone Routing Protocol (ZRP) [31], and Energy-Efficient Distributed Routing (EEDR) [32]. The objective is to evaluate the unique characteristics and effectiveness of the protocol in terms of adaptability and reliability across various performance metrics.

TABLE I. COMPARATIVE ANALYSIS OF ROUTING PROTOCOLS

Parameters **Protocols**	**DSDV**	**AODV**	**ZONE**	**EEDR**	**EADQR**
Time in ms	98.2678	30.8263	19.2732	15.088	0.8745
Hops	302367	95147	7400	1300	441
Energy Consumed (mJ)	1×10^8	2.92×10^7	2.62×10^6	4.78×10^5	1.52×10^5
No of Alive Nodes	23	38	24	86	99
No of Dead Nodes	77	62	76	14	1
Lifetime Ratio	0.3001	0.6032	1.3588	11.9053	99.16
Network Lifetime	0.3475	0.3482	0.1631	0.202	5.8674
Throughput	0.2563	0.8172	1.2978	3.6592	38.9505
Residual Energy (mJ)	1.15	1.75	1.03	4.15	4.82
Packets Delivered	1.07	1.08	1.09	1.10	5.52
Packets Dropped	30.56	20.48	15.36	5.4	5.44
PDR	0.9474	0.966	0.9756	0.9935	0.9984

The table presents performance metrics for several routing protocols in a network, including DSDV, AODV, ZRP, EEDR, and EADQR routing protocol. Here are some key insights:

DSDV exhibits the highest time delay among the protocols, indicating relatively slower data transmission. In contrast, AODV shows intermediate delay, while ZRP, EEDR, and EADQR protocols offer progressively faster data delivery.

The routing protocols vary significantly in terms of hop count. DSDV requires the highest number of hops, suggesting a more complex routing path. Conversely, the EADQR routing protocol demonstrates the lowest hop count, implying a more direct and efficient route.

DSDV consumes the most energy, while AODV and ZRP consume less energy. EEDR and EADQR protocols are the most energy-efficient, with the EADQR protocol being the most energy-conserving.

EADQR protocol boasts the highest lifetime ratio and the most extended network lifetime, indicating its superiority in terms of network longevity. On the other hand, ZRP has the shortest network lifetime.

EADQR protocol delivers the highest throughput, signifying efficient data transfer capabilities. AODV and ZRP also exhibit relatively good throughput.

EADQR routing protocol maintains the highest remaining energy, showcasing its energy management efficiency.

EADQR routing protocol outperforms other protocols by delivering the highest number of packets with minimal packet drops. DSDV has the highest packet drop rate, impacting its overall packet delivery reliability.

The EADQR achieves the highest PDR, indicating a highly reliable packet delivery performance. Other protocols, such as AODV, ZRP, and EEDR, also demonstrate strong PDRs

In summary, the EADQR Routing Protocol stands out as a compelling option due to its exceptional attributes in energy efficiency, network durability, packet delivery, and reliability.

VI. SIMULATION RESULTS AND DISCUSSIONS

The EADQR protocol is implemented across diverse path loss models to assess its performance in various environments. The evaluation of performance is conducted using specific simulation parameters outlined in Table II. MATLAB is the chosen simulation tool for this purpose. The network comprises of 100 nodes that are deployed within a 100 m × 100 m topology area, with their random placement following a specified distribution [33].

The protocol is executed with varying spacing between transmitter and receiver, wherein each node possesses a predetermined transmission range and initial energy level. We examined the effectiveness of these propagation models at the specified operating frequency of 2.5 GHz in urban and suburban settings. Additionally, we accounted for the varying distance between the transmitter and receiving antenna for various terrain types, ensuring a thorough evaluation of the model's applicability.

TABLE II. NETWORK PARAMETERS

Parameters	Value
Tx Range	45 m
Source Node	31
Destination Node	45
Tx Energy	18 mj
Amplification Energy	12 mj
Attn Factor	1
Initial Energy	5000J
Span	100×100 m
Data Packet	1000 Kb

Delay is the difference in time from the first control packet sent to the last control packet received. Fig. 2 shows a delay comparison of considered path loss models for the proposed EADQR routing method. The HATA-Urban model exhibits a maximum delay of 0.35ms with an increase in delay as distance increases. The Free Space experiences the lowest delay, followed by Cost 231-Walfish-Ikegami, Clutter Factor, and HATA-Suburban path loss models.

Fig. 3 presents an analysis of the proposed routing protocol EADQR performance for the considered path loss models. It is noticeable that the HATA-Urban model drops maximum packets with a consistent increase in the drop as the distance between the transmission and reception increases. The best models for the routing protocol are Free space and Clutter Factor, with the least packet drops between transmission and reception.

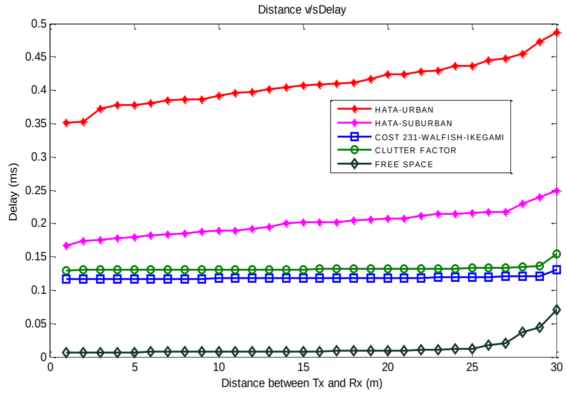

Fig. 2. Distance vs. delay comparison.

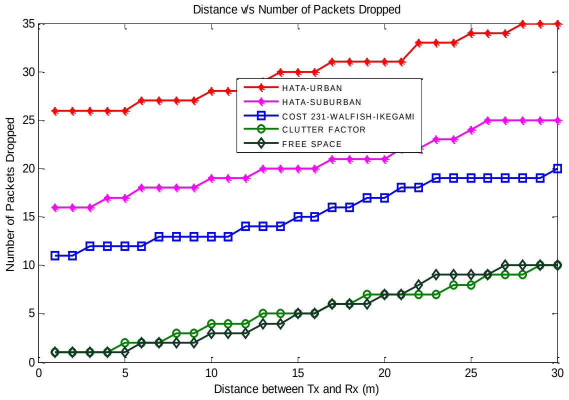

Fig. 3. Distance vs. number of packets dropped comparison.

The residual energy can be found by summing up the depleted energy from each node. Fig. 4 explains the performance analysis of path loss models for the routing protocol EADQR. The HATA-Urban path loss model has the lowest residual energy, while Free space has the highest. The Cost 231-Walfish Ikegami has higher residual energy at a more downward distance, and the energy depletes as the distance increases.

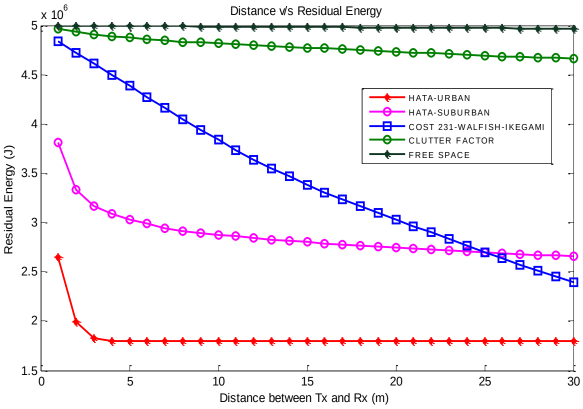

Fig. 4. Distance vs. residual energy comparison.

Time taken is the time it takes for a packet to be transmitted from the sending node to the receiving node and for an acknowledgment to be received back at the sending node. Fig. 5 exhibits each path loss model's time in the trans-reception considering the EADQR routing protocol. The HATA-Urban, Cost 231-Walfish Ikegami, and Free space exhibit faster execution of node trans-reception at 0.01ms while the HATA-Suburban and Clutter Factor take around 0.1ms.

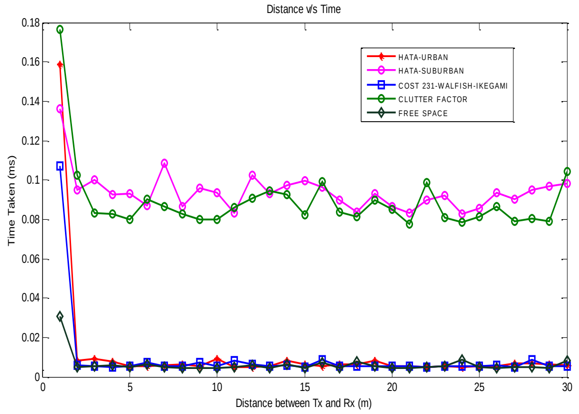

Fig. 5. Distance vs. time taken comparison.

Energy consumption includes the energy utilised in data transmission, data reception, and data processing at both the source and destination nodes. Fig. 6 depicts the electrical energy consumed by each path loss model, the Free Space consumes the least energy, followed by the Clutter Factor and Cost 231-Walfish-Ikegami consuming 0.1×10^6mJ of energy. The HATA-Suburban path loss model consumes energy of around 0.9×10^6mJ for the trans-reception of packets. In comparison, the highest energy is consumed by the HATA-Urban model of 1.6×10^6mJ, with increase in energy consumption as the distance increases.

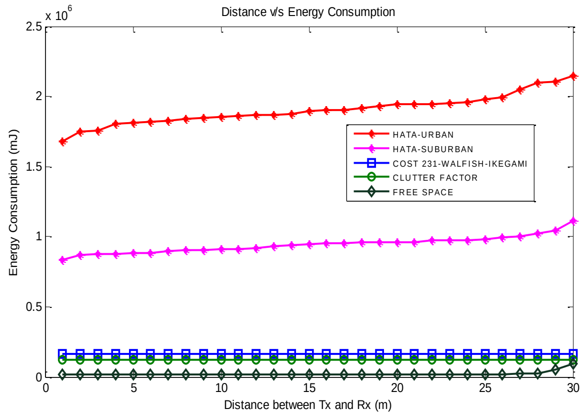

Fig. 6. Distance vs. energy consumption of pathloss models for EADQR.

Network lifetime refers to the duration for which a network can operate effectively and efficiently before node begin to fail or require replacement. It is an important metric for evaluating the performance and reliability of a network. Fig. 7 demonstrates the network lifetime of considered pathloss models for EADQR routing protocol. The Free Space has the highest network lifetime, steadily dropping as distance increases. All the other models suffer network downtime poorly.

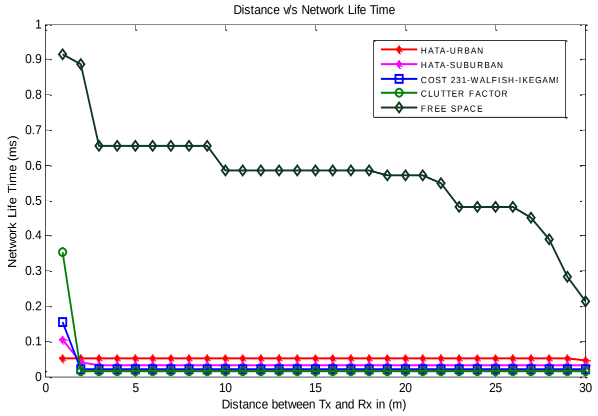

Fig. 7. Distance vs. network lifetime of pathloss models for EADQR.

The path loss between transmission and reception nodes in a network refers to the signal strength reduction between the transmitter and receiver in a wireless communication link. Fig. 8 shows that the Free Space, Cost 231-Walfish-Ikegami, and HATA-Urban experience maximum path loss while HATA-Suburban and Clutter Factor exhibit the least path loss for EADRQ routing protocol. The accuracy of path loss models is evaluated by comparing the predicted RSSI values.

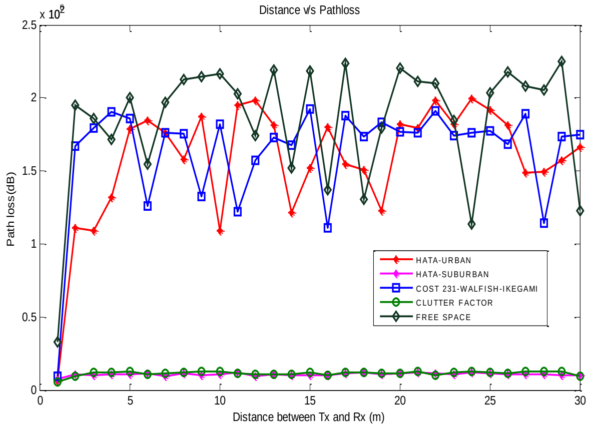

Fig. 8. Distance vs. pathloss comparison.

VII. CONCLUSION

Path loss is a critical parameter that demands for meticulous consideration when assessing wireless sensor network protocols. The Practical measurement and evaluation of wireless protocols across diverse environmental conditions pose challenges. Path loss models facilitate the theoretical evaluation of wireless communication protocols, enabling an analysis of their characteristics in distinct environments. The work focuses on the propagation performance of the EADQR routing protocol for the considered path loss models, namely HATA-Urban, HATA-Suburban, Cost 231-Walfish-Ikegami, Clutter Factor and Free Space, across various pivotal network topologies with varying distance between transmission and reception. The HATA-Urban path loss model exhibits the highest values for maximum Delay, maximum Number of Packets dropped, maximum Energy Consumed, and maximum path loss. Among the models, Free Space demonstrates the highest residual energy. Both

HATA-Suburban and Clutter Factor experience the maximum time for trans-reception of packets. In terms of network lifetime, Free Space exhibits the longest duration. In conclusion, as Wireless Sensor Networks are increasingly deployed in heterogeneous environments, from dense urban landscapes to forested terrains, the efficiency of the EADQR Routing Protocol demonstrates optimal performance, especially when applied with the clutter factor model. This model adeptly captures the extensive environmental clutter, underscoring its potential as a keystone for optimizing WSNs in diverse settings. We anticipate the practical deployment of EADQR in varied environments to gain more tangible insights into the robustness of the protocol.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Conceptualization by Mohamed Najmus Saqhib and Lakshmikanth S; methodology conceptualized by Mohamed Najmus Saqhib; Mohamed Najmus Saqhib did formal analysis; writing—original draft preparation was done by Mohamed Najmus Saqhib; under the supervision of Lakshmikanth. S. All authors had approved the final version.

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