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Advancements in Mathematical Modelling for Estimation of Lifetime of Wireless Mobile Ad Hoc Networks

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ABSTRACT- This article proposes a comprehensive mathematical model along with reviews on various mathematical models used by the researchers to estimate the lifetime of Mobile Ad-hoc Networks (MANETs). Network lifetime is a crucial quality-of-service (QoS) metric, and researchers have defined it in multiple ways, including the time from network establishment to its failure or the average time until the network dies. Many models utilize the First Order Radio Model (FORM) to calculate energy consumption during data transmission and reception. There are different factors which influence network lifetime which include, energy consumption during data transmission and reception, battery capacity and discharge rate, energy consumption by the microcontroller, transceiver, and sensors in various modes (active, sleep, idle, etc.). The article also discusses existing mathematical models that are based on some of these factors. Further, a comprehensive mathematical model is proposed, integrating all relevant factors, offering a holistic approach for network lifetime estimation. Experimental evaluations suggest significant improvements in network lifetime and energy efficiency compared to conventional methods. Through this holistic approach, the study contributes to advancing the understanding and estimation accuracy of network lifetime in MANETs.

Keywords: Mobile Ad-hoc Network (MANET), Network Lifetime, Quality-of-Service (QoS), First Order Radio Model (FORM), Energy Consumption, Battery Capacity, Discharge Rate, Mathematical Model, Network Lifetime Estimation.

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1. INTRODUCTION

Mobile Ad hoc Networks (MANETs) represent a dynamic and decentralized form of communication infrastructure, characterized by mobile and battery-operated nodes. MANETs offer communication capabilities without relying on any fixed infrastructure or centralized control, making them suitable for various applications such as disaster relief, conference information exchange, and battlefield communication. However, MANETs face numerous challenges, including limited battery power, lack of centralized control, security concerns, and the need for efficient routing protocols.

Routing, in particular, stands out as a critical concern in MANETs due to their highly dynamic and dispersed nature. Traditional routing algorithms often prioritize selecting the shortest path between a source and destination, overlooking constraints such as limited bandwidth and battery power. Moreover, the mobility of nodes within MANETs can lead to network partitioning, necessitating frequent route rediscovery processes. These route discovery procedures introduce significant control overheads, resulting in increased power consumption and reduced node and network lifetimes. To address these challenges, it becomes imperative to develop energy-efficient routing algorithms tailored to the specific constraints of MANETs. Such algorithms must not only optimize for hop count but also consider factors like residual battery levels to prolong network lifetime.

Estimating network lifetime is crucial in mobile ad hoc networks (MANETs) for several reasons:

- *Resource Management*: MANETs typically consist of nodes with limited battery power. Estimating network lifetime helps in effectively managing these resources by predicting how long the network can sustain its operation before nodes start to fail due to depleted batteries.
- *Quality of Service*: Network lifetime is a key quality of service metric in MANETs. It directly impacts the reliability and availability of communication within the network. By estimating network lifetime, researchers and network administrators can ensure that the network remains operational for the desired duration, meeting the QoS requirements of various applications.
- Routing Optimization: Efficient routing is essential for maintaining connectivity in MANETs. Estimating network lifetime allows routing protocols to consider factors such as energy consumption and battery levels when selecting routes. Optimizing routing based on estimated network lifetime helps in prolonging network operation by reducing energy consumption and mitigating the risk of network partitioning.
- Application Suitability: Different applications deployed on MANETs have varying requirements in terms of network

lifetime. Estimating network lifetime enables application developers to assess whether the network can support their desired operations for the required duration. It also aids in selecting or designing appropriate protocols and algorithms to extend network lifetime for specific application scenarios.

- Network Planning and Optimization: Estimating network lifetime facilitates network planning and optimization efforts. By understanding how long the network can operate under different conditions, network planners can make appropriate decisions regarding node deployment, power management strategies, and protocol selection to maximize network longevity and performance.

Overall, estimating network lifetime is essential for ensuring the sustainable operation of MANETs, optimizing resource utilization, enhancing QoS, and supporting diverse application requirements in dynamic and resource-constrained environments.

The following is an outline of the main points made in this article.

- Review of mathematical models for network lifetime.
- Summary of the review.
- Factors considered for the proposed mathematical model.
- Proposed Mathematical Model.
- Effect of actual discharge current on energy consumption as per Peukert's Law.

2. REVIEW OF MATHEMATICAL MODELS FOR NETWORK LIFETIME ESTIMATION

Network lifetime is a crucial metric for evaluating the QoS in MANETs. Researchers have proposed various definitions for this metric. Authors in [1], define it as the duration between network establishment and termination of communication. While authors in [2], focus on the average time until network failure. Estimating network lifetime is essential for efficient resource management, ensuring reliable communication, and optimizing routing protocols.

A traditional approach for estimating network lifetime involves the First Order Radio Model (FORM) [3, 4, 5, 6]. This model calculates energy consumption during data transmission and reception. However, FORM has limitations such as it neglects energy consumed by sensing, processing, and coding, leading to underestimations of actual energy usage, as shown by A. Ahmad et al. [1].

Several studies explore factors impacting energy consumption and network lifetime. Authors in [4] propose a protocol that considers residual energy and distance from the base station to distribute workload and extend network lifetime. Similarly, [6, 7] highlight the influence of temperature and discharge current on battery life. They propose an equation for lifetime estimation considering battery capacity and current draw [7].
Researchers are continuously developing more comprehensive models. Fadi M. Al Turjman et al. [8] introduce redundant nodes to replace those causing link breakages, while S. Jothiprakasam et al. [9] consider energy consumption by microcontrollers, sensors, and transceivers. Abdelraouf Ouadjaout et al. [10] present hardware testbed experiments to compare network lifetime across different platforms.

M. S. Karyakarte et al. [11] propose a model that considers residual energy, minimum transmission energy, and FORM-based consumption. Wilawan Rukpakavong et al. [12] go a step further, including battery type, brand, self-discharge rate, actual discharge rate, age, and temperature in their model.

Sushabhan Choudhury et al. [14] demonstrate a ZigBee and Bluetooth-based data acquisition system for monitoring environmental parameters. Their work highlights the trade-offs between transmission range and hop count. Wilson T.H. Woon et al. [15] present a performance evaluation of the IEEE 802.15.4 standard, finding it suitable for low-rate applications. Hoang Anh Nguyen et al. [16] conduct an experimental study on actual node lifetime, focusing on battery brand and flash usage. Their findings suggest that flash writing can significantly impact power consumption in specific scenarios.

Load balancing schemes are another approach to extending network lifetime, as emphasized in [17, 18, 19]. These schemes use FORM to estimate energy consumption and choose routes based on factors like distance and signal strength. Mohamed Elshrkawey et al. [20] propose a modified LEACH algorithm for cluster head selection in sensor networks. Their approach considers residual energy, selection history, number of neighbors, distance to the base station, and average node energy to balance network load and prolong network lifetime.

Thus, we can summarize that the network lifetime is a vital aspect of MANETs. By understanding the various factors that influence it and utilizing the latest models and strategies, researchers and network designers can create more efficient, reliable, and long-lasting MANET deployments.

2.1 Summary of factors considered for the mathematical model to estimate of network lifetime

Table 1 summarizes the factors taken into consideration by different researchers to form a mathematical model for estimation of network lifetime.

Table 1. Factors considered for mathematical model of network lifetime

Reference Paper No.	Factors considered for mathematical model
[3], [4], [5]	1. Energy consumed in transmission and reception as per FORM
[7], [10]	1. Temperature 2. Full capacity battery voltage 3. Battery capacity loss 4. Energy consumed in transmission, reception, active, low and sensing modes

[8]	1. Energy consumed in transmission and reception 2. Total energy consumed 3. Initial energy available
[9]	Energy consumed by 1. sensor circuitry 2. microcontroller circuitry 3. energy consumed by radio transceiver
[11]	1. Residual energy 2. Energy consumed in transmission and reception 3. Energy required for transmission of single packet
[12]	1. Peukert's constant, age, temperature, self-discharge 2. Battery discharge rate

2.2 Factors considered for the proposed mathematical model

Conventionally, the lifetime of a node and thereby the network is decided by the existing battery capacity, 'Cb' and current consumption 'I' required by the node. Therefore, lifetime of a node/network is calculated by using *equation 1* as per [13].

$$Lt = \frac{Cb}{I^k} \tag{1}$$

Where Cb = existing/present battery capacity
I = current consumption required by the node
k = 1 is the Peukert's constant

From the literature review it is observed that FORM has been taken up by many of the researchers to implement the mathematical model. FORM considers node energy consumed by transmitter and receiver circuitry only. In addition to this, some researchers have considered energy consumed in other modes like active, sleep, processing, idle, sensing etc. along with residual battery level. A few researchers have considered Peukert's constant, age, temperature, self-discharge and discharge rate of the battery in their mathematical model. Neglecting battery characteristics such as age, temperature, self-discharge, and discharge rate can lead to inaccurate lifetime estimation as mentioned in [12]. Therefore, this research work has considered integration of all the major parameters in its mathematical model to calculate the accurate network lifetime. The following sections explain the equations of the terms considered while calculating the total energy consumption.

Therefore, the proposed mathematical model for network lifetime (NL) in this research includes all the factors *viz.*

- actual discharge rate of battery
- remaining battery capacity
- total energy consumed by
    - the microcontroller in different modes like active, sleep and sensing.
    - by the transceiver to transmit and receive the data packets.

This will help to estimate actual network lifetime or else a significant difference between the actual and calculated lifetimes would be observed.

2.3 Proposed mathematical model

A new model is proposed here for network lifetime (NL) as given by *equation (2)* which considers all the factors viz. actual discharge rate of the battery, remaining battery capacity, total energy consumption by the microcontroller for sensing, processing as well as in sleep, idle, active modes and by the transceiver for transmission and reception of data.

$$NL = \frac{BC_R}{EC_{Tot}} \text{ x } \frac{1}{DR_B} \tag{2}$$

- BCR = Remaining battery capacity
- by BC_R = Remaining battery capacity
- DRB = Actual discharge rate of battery
- by DR_B = Actual discharge rate of battery
- ECTot = Total Energy consumption by microcontroller and transceiver
- by EC_{Tot} = Total Energy consumption by microcontroller and transceiver

2.4 Effect of actual discharge current of rechargeable batteries on Energy Consumption according to Peukert's Law

Conventional applications with limited batteries often assume an ideal battery model, that is the remaining capacity decreases linearly with power consumption. However, real-world batteries exhibit non-linear discharge behavior, leading to performance degradation if ignored [22, 23].

To address this non-linearity, Peukert's Law provides a method to calculate a constant "k" that characterizes this behavior [21]. Notably, two key non-linear properties influence battery capacity and lifetime:

Rate-Capacity Effect: Accessible capacity decreases as discharge current increases [24].

Recovery Effect: Battery capacity partially recovers when discharge current decreases [24].

This constant, typically greater than 1 and dependent on battery brand and chemistry, is expected to be lower than 1.3 for NiMH batteries [25]. Peukert's Law [26] is given by *equation (3):*

$$k = \log_{\frac{C}{IH}} \left(\frac{t}{H} \right) \tag{3}$$

Where,
k = Peukert's constant, which is the dependent variable
C = Rated capacity in milliampere-hours (stated on packaging)
I = Actual discharge rate in milliampere (which will be measured)
H = Rated discharge time in hours
t = Discharge time in hours

Actual discharge current of the battery is calculated using the *equation (3)* which will be used to calculate the energy consumption and network lifetime. This will help to estimate accurate actual network lifetime reducing the difference between the actual and calculated lifetimes.

2.5 Experimental method

A hardware setup was built using the following components for the hardware implementation as it would give an affordable and comparable design option, to measure the actual network lifetime.

- Power source – Eveready 2100 mAh 1.2 V NiMH rechargeable battery
- Wireless Transceiver – 'Digi XBee' ZigBee RF module
- Microcontroller - Arduino Mega 2560

Figure 1 shows the Arrangement of coordinator, routers and end device in the hardware setup.

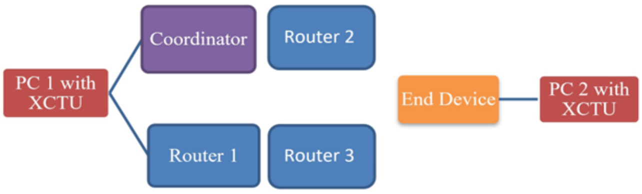

Figure 1. Arrangement of coordinator, routers, and end device in the hardware setup

The experimental setup depicted in *figure 1*, consisted of five devices: a coordinator, 3 routers viz. router 1, router 2, router 3, and the end device. All devices were configured in API mode for transmitting and receiving data frames during the experiment.

Coordinator and router 1 were stationary and connected to PC 1 using XCTU software. This setup allowed for defining the data frame and transmitting it towards the end device through the intermediate routers based on the chosen algorithm. PC 1 also served to monitor the number of transmitted data frames and corresponding acknowledgment frames. Meanwhile, PC2, equipped with XCTU, monitored the number of data frames received by the end device.

Four different MANET Communication Test Scenarios (CTS) as stated in *table 2* were considered for experimentation.

Table 2. MANET Communication Test Scenarios

CTS No.	Title	Description
1.	Static line of sight communication	All the nodes are stationary with a clear line of sight between all nodes. Distance between Routers R2 and R3 is fixed.
2.	Static with obstacle communication	All the nodes are stationary with an obstacle between source and destination nodes. Distance between Router R2 and R3 is fixed.
3.	Mobile line of sight communication	Source and destination nodes are stationary with a clear line of sight between all nodes. Routers R2 and R3 are mobile (average speed of 2.7 km/h). The distance between Router R2 and R3 is variable due to their mobility.
4.	Mobile with obstacle communication	Source and destination nodes are stationary with an obstacle in between them. Routers R2 and R3 are mobile (average speed of 2.7 km/h). The distance between Router R2 and R3 is variable due to their mobility.

2.5.1. Experimental evaluation

For comprehensive experimental evaluation, considering four different MANET scenarios following performance metrics viz. Packet Delivery Ratio (PDR), Network Lifetime, Throughput, End to End delay and Energy Consumption are calculated. *Equations 4 to 8* give the mathematical expressions for the performance metrics PDR, Network Lifetime, Throughput, End to End delay and Energy Consumption respectively.

$$\text{Packet Delivery Ratio (PDR)}(\%) = \frac{\#Rx_{packets}}{\#\ Tx_{packets}}\,x100 \qquad (4)$$

where $Rx_{packets}$ = Received packets
$Tx_{packets}$ = Transmitted packets

$$\text{Network Lifetime (Hours/seconds)} = (Ttx_{1st_{packet}}) - Trx_{last_{packet}}) \qquad (5)$$

where $Ttx_{1st_{packet}}$ = Time of transmission of 1st packet by source node

$Trx_{last_{packet}}$ = Time of reception of last packet by destination node

$$\text{Throughput (bits per second)} = \frac{\#Rx_{packets}}{\text{Network Lifetime}} \qquad (6)$$

$$\text{End to End Delay/Latency (sec.)} = (Ttx_{1st_{packet}} - Trx_{1st_{packet}}) \qquad (7)$$

where $Ttx_{1st_{packet}}$ = Time of transmission of 1st packet by source node

$Trx_{1st_{packet}}$ = Time of reception of 1st packet by destination node

$$\text{Energy consumption } (\%) = \frac{(B_{init} - B_{end})}{B_{init}}\ x\ 100 \qquad (8)$$

where B_{init} = Initial battery level
B_{end} = Battery level at the end of communication

Table 3 gives the observations for four MANET communication scenarios as listed in *table 2*. The observation table records – initial battery voltage, first and last packet transmission (*Tx*) and reception (*Rx*) times, number of *Tx* and *Rx* Packets, number of *Rx* Bits, network lifetime (sec.) and residual battery voltage.

Table 3. Observations for calculations of performance metrics in for four MANET communication scenarios

SN.	Parameters	CTS 1	CTS 2	CTS 3	CTS 4
1.	Initial Battery (V)	3.73	3.48	3.49	3.48
2.	First packet Tx time	19:30:12.110	10:37:45.207	9:49:21.435	10:30:40.200
3.	Last packet Tx time	13:66:13.348	22:47:22.131	9:49:24.445	21:32:20.131
4.	First packet Rx time	19:30:13.250	10:37:47.002	22:42:40.439	10:30:44.500
5.	Last packet Rx time	14:80:14.658	22:47:22.425	22:42:46.219	21:36:22.425
6.	No. of Tx Packets	8540	7640	7728	6295
7.	No. of Rx Packets	8468	7570	7644	6203
8.	No. of Rx Bits	1558161	1396341	1421241	1150520
9.	Network Lifetime (sec.)	58212	43560	46548	43560
10.	Residual Battery (V)	2.6	2.1	1.9	1.5

3. RESULTS

Observations were noted to measure network lifetime in all four test scenarios as given in *table 3*. Measured network lifetime is compared with that of the estimated lifetime which is calculated using *equation (1)*. The effect of initial battery voltage on network lifetime was also studied during experimentation.

3.1 Performance metrics for four CTS

Calculations of performance metrics for four CTS was done for the observations given in *table 3* using *equations 4 to 8*. *Table 4* shows the results of calculations of performance metrics for all the four CTS.

Table 4. Performance metrics for four CTS

S N.	Performance metrics	CTS 1	CTS 2	CTS 3	CTS 4
1.	PDR (%)	99.16	99.08	98.91	99.53
2.	Network lifetime (Hrs.)	19.5	12.1	12.93	11.2
3.	Energy Consumed (%)	30	40	46	57
4.	Throughput (bps)	26.77	32.06	30.53	26.41
5.	End to End delay (sec.)	01.14	1.80	3.01	4.50

3.2 Estimated network lifetime for four communication scenarios

Estimated network lifetime is calculated using *equation (1)* for four CTS. Network lifetime is measured through experimentation by transmitting packets from source to destination nodes for all communication scenarios. The difference between start time and end time that is the time at which the destination node stops receiving data packets is considered as network lifetime.

Graphs of estimated and measured network lifetime and Difference between estimated and measured network lifetime for four test scenarios are shown in *figure 2* and *figure 3* respectively.

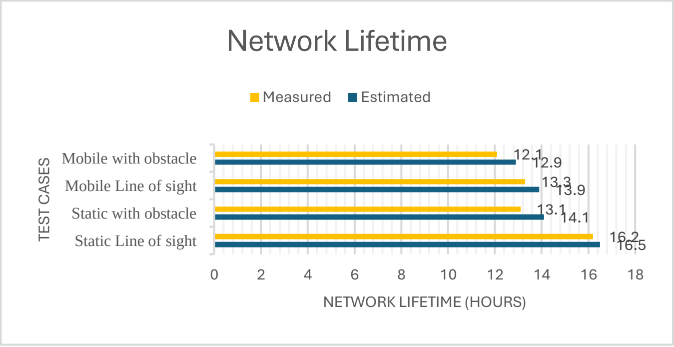

Figure 2. Comparison of estimated and measured network lifetime for four test scenarios

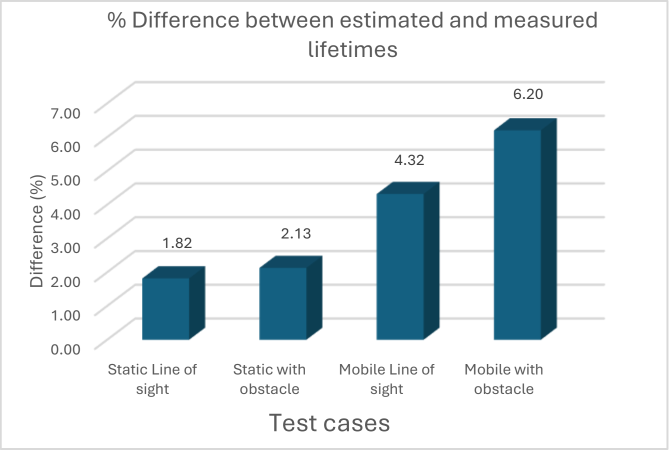

Figure 3. Difference between estimated and measured network lifetime for four test scenarios

3.3 Effect of Initial Battery Voltage on Network Lifetime

It is observed that the more the initial battery voltage the higher the network lifetime. Thus, it can be said that the network lifetime can be prolonged by using an algorithm which always selects the nodes with higher battery voltages. *Figure 4* shows the graph of initial battery voltage versus network Lifetime.

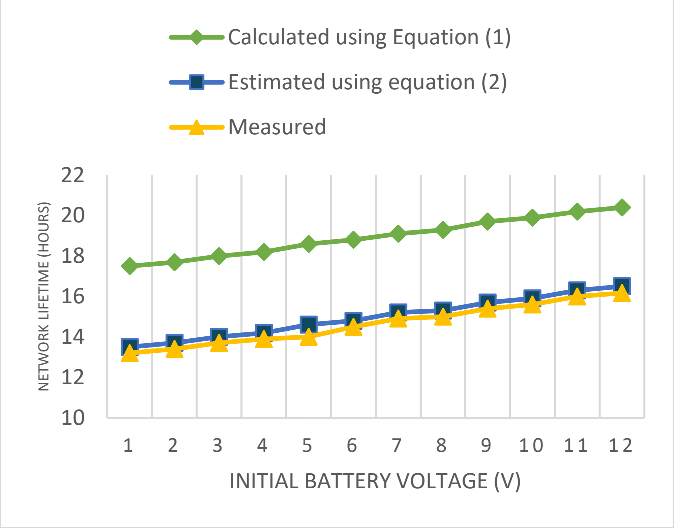

Figure 4. Effect of Initial Battery Voltage on Network Lifetime

4. RESULT DISCUSSION

From the Performance metrics for four CTS as given in *table 4*, it was observed that the communication performance is critically affected by the obstacles in the indoor and outdoor environment. These obstacles affect the received signal strength of the ZigBee transceiver that further deteriorates the data delivery and latency. Therefore, the PDR decreases with increasing obstacles, and it is minimum for CTS 4 among all the four CTS. Increased obstacles cause communication paths to break which requires re-initiating the route discovery process. This further increases energy consumption and end-to-end delay while reducing the throughput due to increased overheads in re-establishment of the communication sessions.

Figure 2 shows the graph of comparison of estimated and measured network lifetime for four CTS. It is observed that the network lifetime is highest in static line of sight without obstacle scenario. The difference between estimated and measured network lifetimes is 1.8%. When the nodes start moving and face obstacles as in the 4th test scenario (mobile with obstacle communication) more data packets are lost. Mobility of nodes causes breaking of paths which further leads to new route discovery and path establishments. This consumes more power making the batteries drain faster thereby reducing the network lifetime.

Figure 3 shows the graph that indicates the difference between estimated and measured network lifetimes for four test scenarios. It is seen that the average difference between estimated and measured network lifetimes is around 5%. The difference goes on increasing with mobility of nodes and in presence of obstacles.

Figure 4 shows the effect of initial battery voltage on network lifetime. It also gives the comparison of network lifetimes that are:

- Calculated using *equation (1)* which considers only the existing battery capacity and current consumption by the nodes,
- Calculated using *equation (2)* which considers all the factors viz. actual discharge rate of the battery, remaining battery capacity, total energy consumption by the microcontroller for sensing, processing as well as in sleep, idle, active modes and by the transceiver for transmission and reception of data.
- Measured during experimentation.

It is observed from the graph that the network lifetime calculated using *equation (1)* is quite higher than the measured lifetime. Whereas the difference between the network lifetimes estimated using proposed *equation (2)* and measured one are approximately similar with maximum average difference of 5%.

Thus, it is evident that the network lifetimes estimated using proposed *equation (2)* is more accurate and gives realistic values which will help the network planners to make appropriate decisions regarding node deployment, power management, and protocol selection to maximize network lifetime and performance.

5. CONCLUSIONS

While many studies on network lifetime use FORM, which focuses solely on energy used by transmit and receive circuits, others use consumption during sleep, idle, active, processing, and other modes. Traditionally, energy consumption models assume a linear decline in capacity with power use. However, Peukert's Law highlights the possibility for inaccurate results if the non-linear behavior of batteries is ignored. Therefore, our research incorporates not only energy consumption across various modes but also considers factors like residual energy and the battery's actual discharge rate. This all-inclusive approach provides a more realistic and reliable network lifetime estimation. Without which significant discrepancies between measured and estimated network lifetimes may lead to imperfect design decisions.

Experimental results show that the maximum average difference between the network lifetimes measured and estimated using proposed *equation (2)* and is 5% whereas it is almost 21% when estimated using *equation (1).*

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