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Optimized Probabilistic Sink Node Deployment for Enhanced Performance in Wireless Sensor Networks

Abstract: - This paper presents an innovative mechanism to deploy sink nodes in Wireless Sensor Networks (WSN), which play an essential role in the gathering sensed data from sensor nodes across diverse applications. Our mechanism is different from existing mechanisms, which deploy sink nodes based on the residual status of buffer and energy of the sensor nodes. Instead, proposed mechanism's sink node deployment is decided based on the optimal probabilistic metrics related to buffer and energy status during data processing; aim to extend the network performance with respect to risk of buffer overflow and energy consumption. We analyse and validate the performance of the proposed work through simulation and compared the results with existing residual-based sink node deployment mechanisms. The results indicate the signification extension in the performance in terms of energy, packet loss and lifetime by mitigating bottlenecks at nodes. The work contributes to the improvement of WSN design and deployment mechanisms by significantly enhancing the performance and reliability of the network.

Keywords: Buffer Overflow, energy efficiency, energy consumption, network lifetime, network performance, Optimization, packet loss, sink node, Wireless Sensor Networks (WSN).

1. Introduction:

Wireless Sensor Networks (WSN) has been emerging as a vital technology, gaining significant attraction from researchers over the past few years. The network consists of wireless sensing nodes distributed in communications area, aim to sense, and gather the surrounding environmental information. Nodes having self-directed characteristic and gather data on parameters such as humidity, gravity, and temperature and then transmit this data to internet through sink node. This transmission occurs via single-hop or multi-hop manner based on the distance between transmitting node and sink node [3]. The characteristics of WSNs include self-organizing, infrastructure-free, and autonomous, makes it suitable for various applications.

One of the applications of WSNs is living and sleeping pattern reorganization in home environment [1]. In this application, sensing nodes having constrained resources such as limited energy with irreplaceable batteries, and constrained buffer and computational ability. The nodes deployed in this environment are heterogeneous i.e., variety of types, including cameras, RFID devices, and biosensors [4]. However, the similarity in them is constraints in terms of battery, memory, and computational ability. Nodes aim is to continuously monitor their

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surrounding environment and transmit the sensed data to internet through sink node, which may be static or mobile.

The performance and lifetime of the WSNs is analysed and extended by sensing coverage area offered by sensor nodes. Premature depletion energy of the sensor nodes during operation directly impacts on the sensing coverage area, lifetime of the network, and performance. Thus, energy efficient mechanisms are playing vital role to utilize available constrained energy of sensor nodes effectively and optimally. Further, effective placement of the sink node directly impacts on the network performance, as sensed data forwarded to internet through sink node. The nodes which are neighbour to sink node faces heavy traffic load and resource strain, creates the bottlenecks scenario in communication [2].

The work aims to address the sink node placement in WSNs, with the help of optimizing probabilistic values of buffer overflow and energy consumption during gathered data transmitting to sink node. The existing method deploys the sink node based on the residual status of buffer overflow and energy consumption. Work analyses and validates the performance of the proposed mechanism through simulation and compared the results with existing residual-based sink node deployment mechanisms. The results indicate the signification extension in the performance in terms of energy, packet loss and lifetime by mitigating bottlenecks at nodes. The work contributes to the improvement of WSN design and deployment mechanisms by significantly enhancing the performance and reliability of the network.

2. Literature Review:

In literature various works have been proposed to enhance the performance and lifetime of the Wireless Sensor Networks [5]. This enhanced performance is achieved using mobility-based mechanisms, which allow the dynamically adjust the sink node's position and referred to as mobile sink sojourn locations. Finding suitable location for sink node and adjusting sink node to that position plays an important role to receiving extended amount of data from sensor nodes, it further optimizes network performance in terms of network lifetime, network coverage and energy efficiency. Thus, strategic placement of sink nodes is an important considerable factor in WSNs to enhance the performance of the network, which requires the design and development of dynamic deployment mechanism that take not only take account of the residual buffer and energy status of surrounding nodes but also optimize the residual buffer and energy status [7-20].

In multi-hop communication, the neighbouring node to the sink receives extended amount of data from sensor nodes, if received data exceeds its handing capacity with respect to buffer and energy, packets get dropped and impact on network performance. This workload imbalance leads to network bottlenecks, impact on network performance in terms of scalability, energy efficiency, and network lifetime. To overcome the problem, dynamic sink node deployment mechanism developed with the help of considering sensor node residual buffer and energy status. This approach calculates the residual status of sensor nodes and adjusts sink node positions accordingly, accounting for living and sleeping pattern reorganization in home environments.

Existing literature presents various congestion control mechanisms to prevent buffer overflow in wired and wireless networks, yet these are not directly applicable to infrastructure-free networks like WSNs, where packet drops occur due to buffer overflow [6-21, 22]. An early congestion detection algorithm is needed to identify congestion at sensor nodes neighboring the sink, implemented at the network layer of the OSI model. This algorithm computes traffic load and adjusts sink node positions based on neighboring node buffer size.

Nodes in home networks operate on constrained batteries and energy depletion negatively impacts network performance and lifespan. To optimize network lifetime and performance, packet communication must minimize energy consumption, considering the node's state. Therefore, a node balancing process calculates remaining energy and residual packet capacity of sensor nodes, adjusting sink node positions based on neighboring nodes' packet processing capacity [23].

Home sensor networks feature a mobile sink node initially deployed randomly, requiring dynamic adjustments during communication phases. Sensor nodes compute their residual buffer status and packet processing capacity, transmitted to the mobile sink node, which verifies neighbouring node status and adjusts its position accordingly. The dynamic replacement of the sink node considers the distance between the sink node and sensor nodes.

Despite advancements in sink node deployment strategies, existing approaches often rely on static assessments of sensor node status, leading to suboptimal network performance and inefficiencies in energy utilization. Moreover, current techniques may not fully account for dynamic network conditions and the probabilistic nature of buffer overflow and energy consumption during packet processing.

The work introduces an innovative mechanism to deploy the sink node in Wireless Sensor Networks. Our mechanism is different from existing mechanisms, which deploy sink nodes based on the residual status of buffer and energy of the sensor nodes. Instead, proposed mechanism's sink node deployment is decided based on the optimal probabilistic metrics related to buffer and energy status during data processing; aim to extend the network performance with respect to risk of buffer overflow and energy consumption [24].

The major problem addressed in this work is determined the inadequate positioning of sink nodes inside WSNs, which causes the degradation in network performance in terms of energy efficiency, lifetime, and scalability. The prime objective addressed in this work as follows:

- The sink node placement detection in existing work led to suboptimal solution due to network dynamics and characteristics, as it is based on residual status of buffer overflow and energy consumption.
- The current mechanisms fail to effectively manage resources particularly energy and buffer, which leads to inefficient resource utilization and premature energy depletion.

The objective of the proposed mechanism is to improve the effectiveness of resources management and optimized strategies for deploying sink nodes in WSNs to improve the overall effectiveness and performance.

3. Optimized Probabilistic Sink Node Deployment:

Sink node deployment to appropriate location in WSNs is an important considerable issue. In this work, we design novel mechanism to compute the suitable location for sink node deployment using dynamic probabilistic metric. This metric computed based on factors such as buffer overflow and energy consumption during multi hop communication, through which we enhance the network lifetime and energy efficiency in WSNs [25].

3.1 Evaluation of Packet Dropping Probability due to Insufficient Buffer Size:

To compute the probability of the packet drop due to Insufficient buffer in WSNs multiple parameters need to be considered; such as node's buffer capacity, average packet processing time (Tp), incoming and outgoing packet transmission rates (R_{in} and R_{out}), total number of packets in the outgoing buffer Q, and duty cycle of the wireless link. We used the Little's Law and dynamic network conditions to compute the packet dropping probability due to insufficient buffer (P_{buffer}), and is shown in equation 1.

$$P_{buffer} = \left(1 - P(R_{out} \geq R_{in}) * P(Q = \mathrm{B} \mid R_{out} \geq R_{in})\right) \dots\dots\dots\dots\dots (1)$$

The value of P_{buffer} provides the probability of the packet being dropped due to insufficient buffer by considering network dynamics and buffer capacity. Here, the packet transmission rate exceeds the packet departure rate, and buffer reaches its maximum capacity then packet being dropped due to insufficient available space. This enables us to proactively adjust the position of the nodes in the network communication area. .

$$P(R_{out} \geq R_{in}) = 1 - P(R_{out} < R_{in}) \dots\dots\dots\dots\dots (2)$$

Equation 2, used to compute the probability of outgoing packet rate R_{out} exceeds or equal to the packet receiving rate R_{in}, which causes the buffer overflow. This probability is important to provide the solutions to reduce packet loss and maintain optimal network performance.

$$P(R_{out} < R_{in}) = R_{in} \times (B / T_p + T_t) \dots\dots\dots\dots\dots (3)$$

Equation 3 represents the probability of packet departure R_{out} is slower than the rate of packet arrival $rate\ R_{in}$, which is likelihood of maintaining a stable buffer and help to mitigate buffer overflow scenarios.

$$T_t = d \times min(R_{in}, C) \dots\dots\dots\dots\dots (4)$$

The equation 4 is used to determine the transmission time (T_t) for a packet, it computes by considering minimum value of the incoming rate R_{in} and buffer capacity (C). It helps to reduce the energy consumption and enhances the packet transmission by considering the packet size (L), distance between sender and sink node (d), and effective transmission rate ($min(R_{in}\ , C)$).

3.2 Calculation of Packet Loss Probability due to Energy Drain in WSNs

To compute the probability of the packet drop due to energy depletion in WSNs multiple parameters need to be considered; such as transmission power (P_t), reception power (P_r),, signal-to-noise ratio (SNR), and path loss. The Packet Loss Probability due to Energy Drain (P_{Ed}) is shown in equation 5, and it is computed with the help of signal-to-noise ratio (SNR), path loss, and total noise power.

$$SNR = (P_r \,/\, P_t)^\wedge 2 \dots\dots\dots\dots\dots (5)$$

$$Path\ loss = (D_0 \,/\, d)^\wedge - \alpha \dots\dots\dots\dots\dots (6)$$

$$Total\ noise\ power = (R_{in} \times L \times E_d \times T_d + \Sigma^\wedge 2) \dots\dots\dots\dots\dots (7)$$

$$P_{Ed} = 1 - (1 - (P_r \,/\, P_t)^\wedge 2 \times (D\_0 \,/\, d)^\wedge - \alpha) \dots\dots\dots\dots\dots (8)$$

Equation 5 is used to compute the signal-to-noise ratio (SNR) at the receiver and is used to determine the quality of the received signal. Equation 6 is used to determine the path loss based on the decline in signal strength with increasing distance. Equation 7 is used to determine total noise power with the help of processing load, energy consumption during transmission, and background noise. Equation 8 is utilized the normalize the energy usage during single packet transmission. These equations play an important role to determine the of energy efficiency and signal quality in WSNs. Further, they also used to determine the positioning of sink nodes to enhance network performance.

3.3 Integration of Probabilistic Models for Sink Node Deployment:

Now we are integrating both the probabilistic models i.e., probability of packet being drop sue to insufficient buffer and energy drain in WSNs. This integration enables us to determine most advantageous place for sink node deployment in the network, and further mitigate the packet loss due to buffer overflow and insufficient energy.

3.3.1 Algorithm for Sink Node Deployment:

To integrating both the probabilistic models, we design a mechanism to probability of packet being drop sue to insufficient buffer and energy drain in WSNs packet loss caused by buffer overflow and energy depletion.

Algorithm 1: Combined Value of Packet Drop Probability Calculation

Input: List of nodes (with$P_{buffer}\ and\ P_{Ed}$)), α, and β)

Output: List of selected nodes with the lowest combined ranks

1. Normalize the probability of packet being drop sue to insufficient buffer and energy drain $\left(P_{buffer}\ and\ P_{Ed}\right)$ with the help of min-max normalization algorithm. For each in i in the network compute the Normalized probability of (($P_{buffer}\ and\ P_{Ed}$))

2. Calculate the combined rank for each node using the formula: $R(P_{buffer}, P_{Ed}))) = \alpha \times P\_buffer\_nrm + \beta \times P\_(E\_d)\_nrm.$

3. Arrange the node based on their computed combined ranks.

4. Pic the node $k$which is having lowest combined rank.

5. Return the picked node

The algorithm enables the systematic way of determining the node which is having in better condition regarding buffer and energy, so that we can place the sink node neighbour to it. Thus, this approach enhances the network performance in terms of lifetime and energy efficiency. This comprehensive mechanism addresses the challenges associated with sink node placement for deployment in WSNs, providing a foundation for future research and development in the field of WSNs.

4 Results and Discussion:

We analyse and validate the performance of the proposed work through simulation and compared the results with existing residual-based sink node deployment mechanisms i.e., EMLP [1], namely Energy aware [6], Buffer aware [2] based deployment. The simulation parameters considered for performance evaluation are shown in Table 1. Simulation environment consists of 400 stationary sensor nodes and a single mobile sink node that is equipped with the Random Waypoint Mobility model to move inside the network. Each sensor node equipped with the 100 joules battery and 250 meters of radio transmission range for sensing the surrounding environment. Further, nodes are equipped with IEEE 802.11 MAC card for Ethernet connectivity.

The simulation duration is set to 1200 seconds. The sensing node produces a 512-byte packet as a Constant Bit Rate (CBR) traffic signal. The performance results are calculated as the mean of three scenario performances in the simulation section. Threshold values can be established during network initialization. Therefore, these settings are adjustable based on the network's sensitivity and intended use.

Table 1: Network model parameters

Parameters	**Standards**
Simulation Time	1200 s
Deployed Nodes	400
Used Layer	Logical Link
Protocol Used (MAC)	802.11
Mobility Type	Random waypoint
Network Layer Used	Distance Vector
Communication Methodology	Two-Ray Ground
Queuing Technique	Drop-Tail priority
Battery Power	100 joules
Traffic Model	Constant Bit Rate
Total Application Area	1000m x 1000m

The performance evaluation metrics are throughput, packet delivery, network lifetime, and remaining energy, and their results are shown in Figures [1-4].

In Figure 1, the mean throughput is depicted in proportion to simulation time. The data demonstrates that the present protocol's throughput is 10 packets per second, but the proposed study achieves a throughput of 20 packets per second. The significant improvement in throughput can be ascribed to the reduction in packet drop.

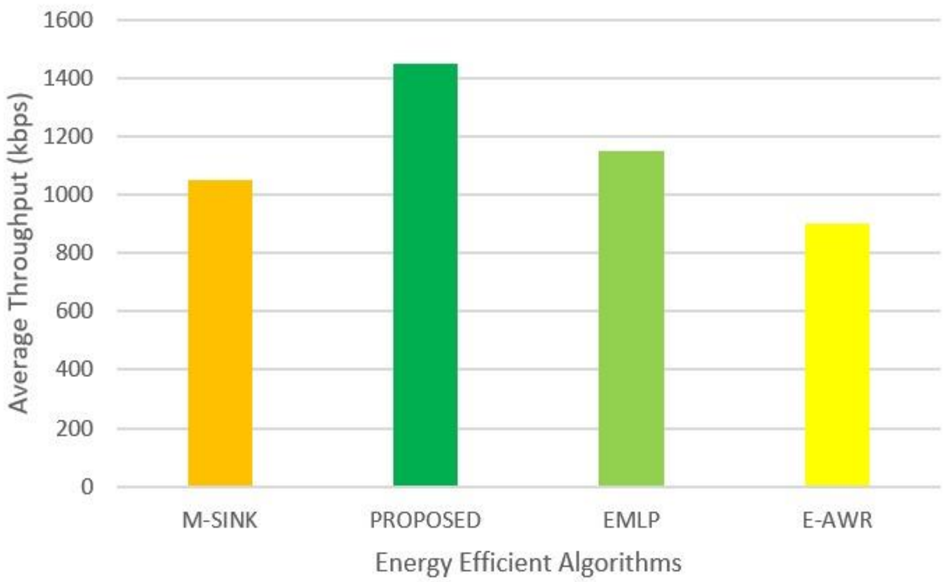

Fig. 1: Average comparison of throughputs for different approaches

Figure 2 depicts the comparison of the average packet delivery percentage between the current and anticipated works. The existing approach exhibits a packet delivery rate of 80%, whereas the suggested investigation achieves a higher rate of 95%, thus showcasing its effectiveness in reducing packet dropouts and network bottlenecks.

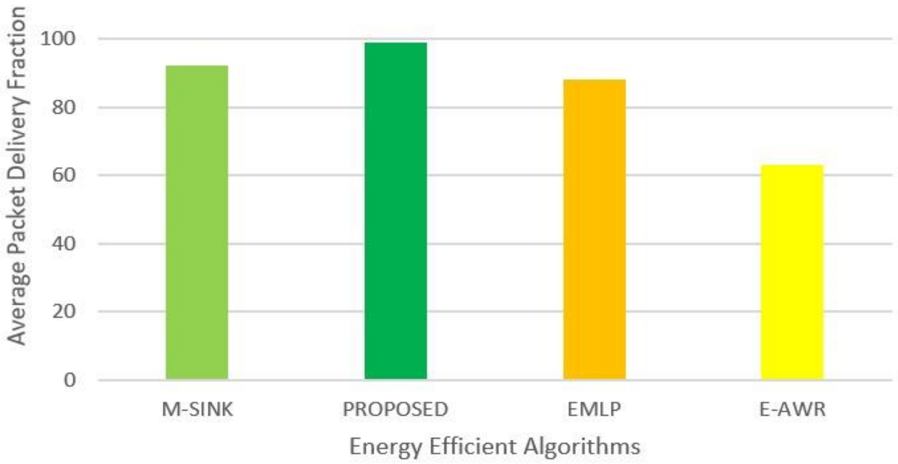

Fig. 2: Output performance of average packet delivery for different approaches

Figure 3 illustrates the comparison of network longevity between the proposed and existing techniques. The existing protocol sustains the network for a period of 5000 seconds, but the suggested innovation extends the network's availability to 7000 seconds, showcasing improved effectiveness and resilience.

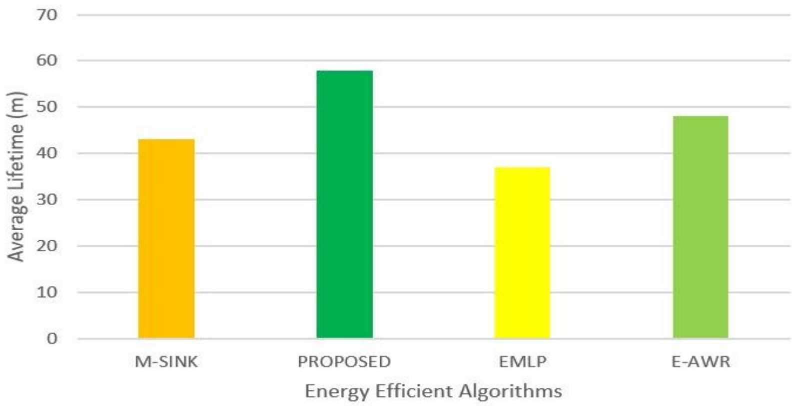

Fig. 3: Network lifetime comparison between proposed and existing work based on random mobility sink

Figure 4 illustrates the comparison of average remaining energy between the proposed and existing techniques. The existing protocol yields nodes with a leftover energy of 30 joules, but the suggested innovation extends the remaining energy of 50 joules, showcasing improved effectiveness in energy management.

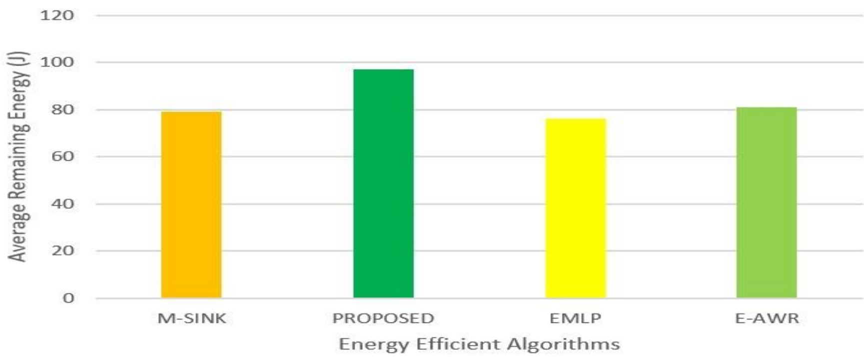

Fig. 4: Comparison of average remaining energy performance for different approaches

In conclusion, the simulation results of the proposed approach provide the strong evidence that it is suitable approach to determine the sink deployment location in WSNs, as it is provided extended performance in throughput, packet delivery, network lifetime, and remaining energy. The work contributes to the improvement of WSN design and deployment mechanisms by significantly enhancing the performance and reliability of the network.

5. Conclusion:

This work presented an innovative mechanism to deploy sink node in WSNs, which ply an essential role in gathering the sensed data from sensor nodes across diverse applications. Proposed mechanism is different from existing mechanisms, which deploy sink node based on the residual status of buffer and energy of the nodes. Instead, proposed mechanism's sink node deployment is decided based on the optimal probabilistic metrics related to buffer and energy status during data processing; aim to extend the network performance with respect to risk of buffer overflow and energy consumption. We analysed and validated the performance of the proposed work through simulation and compared the results with existing residual-based sink node deployment mechanisms. The results indicated signification extension in the performance in terms of energy, packet loss and lifetime by mitigating bottlenecks at nodes. The work contributes to the improvement of WSN design and deployment mechanisms by significantly enhancing the performance and reliability of the network.

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