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Original Article

An Energy-Efficient MAC Protocol for Linear Sensor Networks with Congestion-Aware Scheduling

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Abstract - *The distinctive linear topology of Linear Sensor Networks (LSNs) has made them a popular area of study because of the many useful applications they have found, including structural health assessment, pipeline monitoring, and border surveillance. Energy efficiency must be a primary design objective for LSNs due to the fact that, despite their potential, their performance is severely limited by the energy resources available to sensor nodes. In this research, Staggered Cooperative Forwarding MAC (SCF-MAC) is designed for LSNs, which improves data flow efficiency and reduces idle listening and collision overheads. A 2-Dimensional Discrete-Time Markov Chain (2D-DTMC) model is proposed in this research to accurately represent and alleviate network bottlenecks, especially in the vicinity of the sink node, where congestion is most probable. The system may optimize transmission plans and buffer management policies by modeling transitions based on both retransmission attempts and queue buildup. This reduces packet drops and improves Throughput. This grid-based state representation allows for more precise energy-aware MAC scheduling by capturing the nodes' probabilistic behavior in response to traffic load and link reliability. In several metrics, including Throughput, energy consumption, packet delivery ratio, and delay, SCF-MAC-2D-DTMC proves far superior to current state-of-the-art MAC protocols in rigorous discrete-time simulations. Longevity and dependability in linear sensor networks are improved by including the 2D-DTMC model into MAC protocol design, which leads to smarter and more adaptable channel access behavior.*

Keywords - *Linear Sensor Network, Medium Access Control, Collision Overheads, Markov Chain, Particle Swarm Optimization.*

1. Introduction

The evolution of the Internet of Things and artificial intelligence in the field of information technology has led to an accrescent growth of WSN-based applications. The core of a wireless sensor network revolves around sensors, which are miniature devices capable of sensing and storing vital environmental information [1]. The sensors' miniature size makes their deployment convenient and effective in physical environments, where human ingress and presence are not feasible at all times. The information collected by sensors is of vital importance as it can help in the prediction of natural hazards, maintain trans-border security, advancement in the health sector, climate-change pattern detection, etc. [2]. The data collected from several sensor nodes is processed and stored at a pivotal place, like Base Stations (BSs) or sink nodes, which helps in evaluating an environment effectively [4]. One of the major aspects of WSNs is how the sensors are deployed, giving birth to different types of topography. One such scenario in which the sensors are mainly linearly placed is known as a Linear Sensor Network. A linear sensor network is a type of WSN with several applications, such as Oil and gas pipeline monitoring, railroad monitoring, border monitoring, etc. [5]. A Linear Sensor Network based on the distance from the base station or sink node is divided into different grades. The classification of LSN based on hierarchy and topology is shown in Figure 1 [3].

LSNs use sensor nodes spaced out in a straight corridor rather than a curved one. This one-of-a-kind architectural configuration has revolutionized this approach to large-scale sensing and data collecting in linear environments, and it has become an essential part of the infrastructure for many environmental and industrial monitoring applications [6]. LSNs are so popular because they work so well with linear monitoring scenarios in the real world. Although LSNs are becoming more and more popular, there are a number of problems with them that affect how well they work and whether they can be used in the long run. Although the linear topology has its uses, it deviates significantly from conventional mesh or cluster-based sensor networks in terms of energy usage and communication patterns [7].

Due to the impracticality of replacing batteries frequently in distant or hazardous deployment areas and the restricted battery capacity of individual sensor nodes, energy efficiency has emerged as the primary problem in LSN design [8].

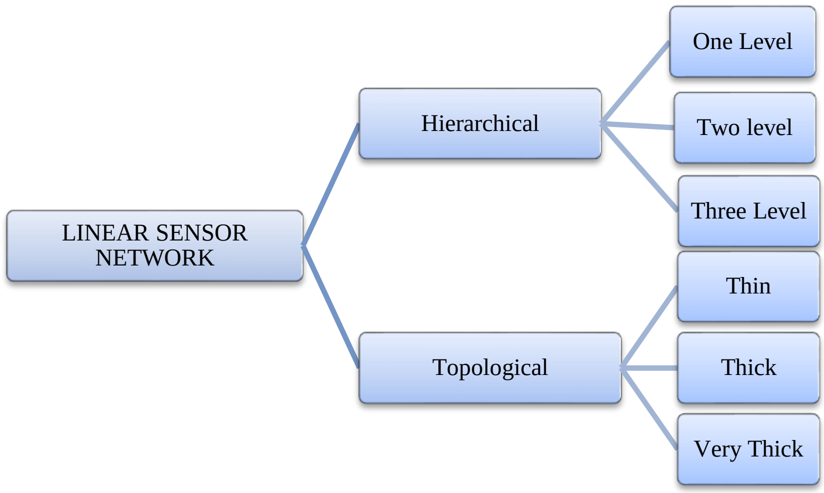

Fig. 1 Classification of linear sensor network

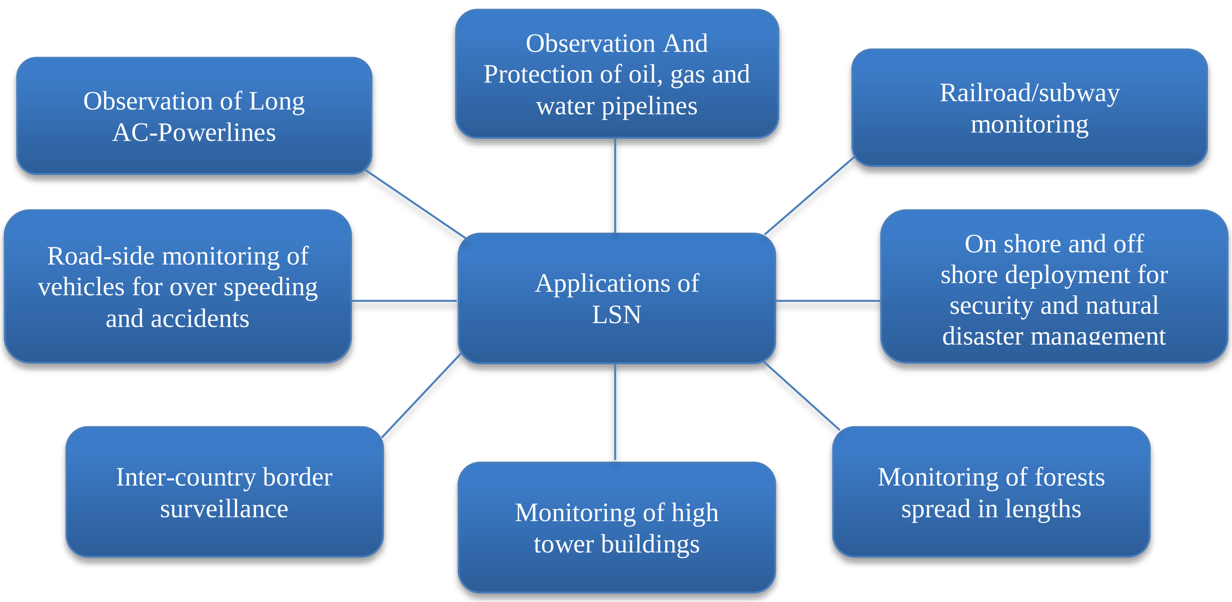

Fig. 2 Applications of linear sensor network

An uneven distribution of energy occurs in LSNs because, unlike traditional sensor networks, data from all upstream nodes must travel through downstream nodes before reaching the sink, a phenomenon known as the funneling effect. As a result, nodes in close proximity to the sink experience faster battery drain, which speeds up the process of network partitioning and shortens the operational lifetime [9].

Due to the linear topology, which causes bottlenecks in the network, especially close to the sink node, where all of the traffic converges, LSNs also have a high communication overhead. Network performance can be drastically reduced as a result of higher collision rates, packet drops, and communication delays caused by this convergence [10]. The unique communication patterns and traffic characteristics displayed by linear topologies are frequently ignored by traditional MAC protocols developed for general-purpose wireless networks [11].

A few major research gaps can be seen in the design of Medium Access Control (MAC) protocols specifically for Linear Sensor Networks due to issues related to linearity [1]. These issues/research gaps that need to be addressed in future works are discussed below:

a) How to overcome the limitation of restricted data transfer routes/paths due to linearity
b) The higher rate of packet drops and collisions occurs in grades that are closer to the sink node.
c) Sensor nodes face the energy-hole problem as they are battery-operated due to their proximity to the sink node.
d) To lay more emphasis on per-grade performance, as LSN exhibits heterogeneous performance based on grade level.

Despite having several issues associated with LSN due to its unique topography, many researchers have shown keen interest in designing an effective MAC protocol for LSN because of its vast application area (Figure 2 [3, 4]).

Strong mathematical models that account for the randomness of wireless communication, the interdependencies among nodes, and the effect of different network characteristics on performance are required due to the complexity of LSN behavior [12-14]. The complex behavior of nodes operating under different traffic loads and channel circumstances cannot be captured by traditional modeling methodologies, which frequently depend on oversimplified assumptions. Markov Chain modeling's potential for capturing the probabilistic behavior of communication protocols has been demonstrated in the context of wireless sensor networks. To properly characterize the complicated interactions in LSNs, however, the multi-dimensional state space may be too large for traditional single-parameter Markov models [15].

One major step forward in understanding how wireless sensor networks work is the incorporation of 2D-DTMC models into Linear Sensor Networks. The rationale behind using a multi-dimensional Markov Chain in modelling Linear Sensor Network behavior is to precisely predict different parameters. This way, incorporating DTMC helps assess optimal network configuration considering multiple scenarios like network congestion, residual energy, etc. The 2-Dimensional Discrete-Time Markov Chain model is shown in Figure 3.

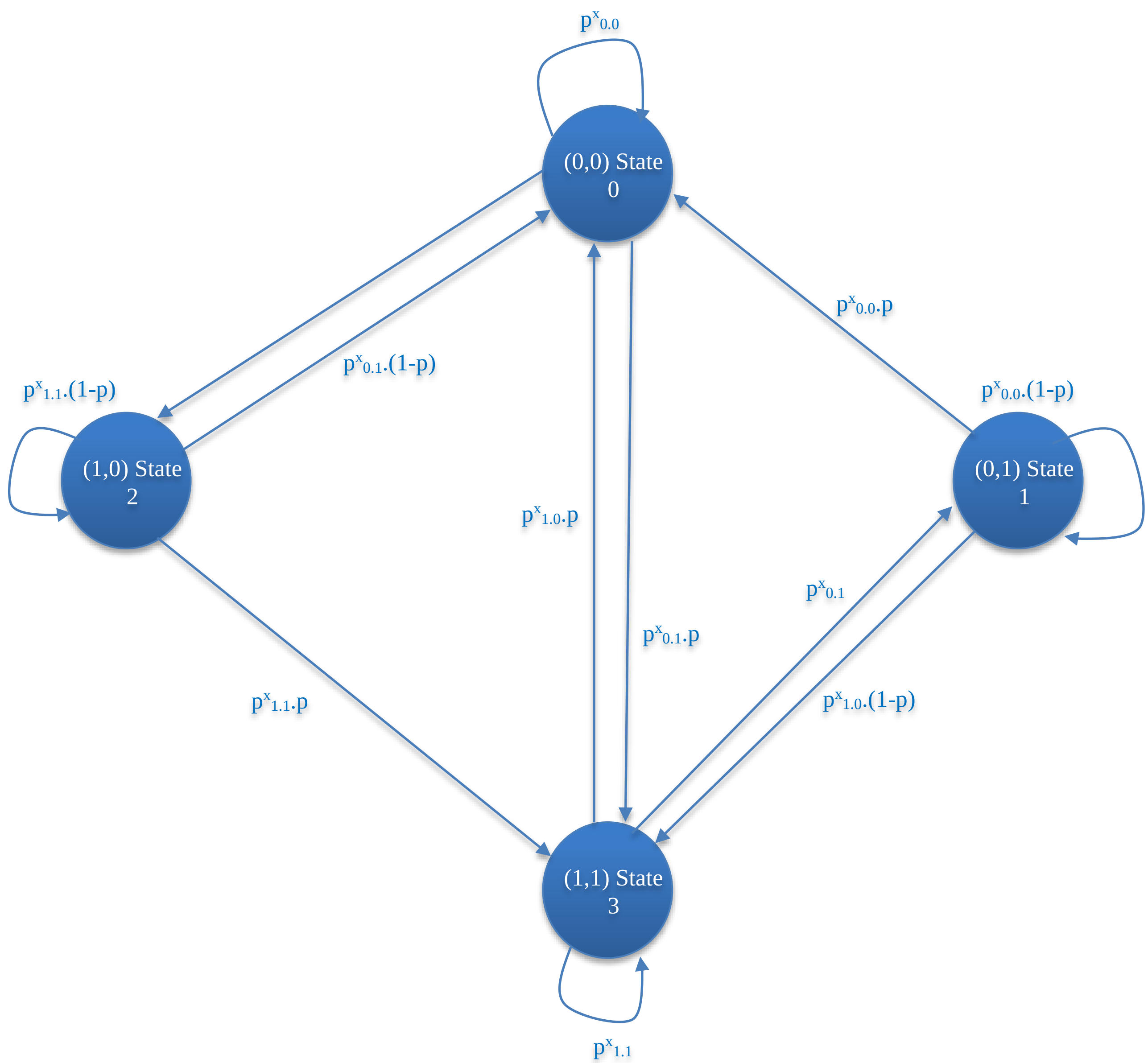

Fig. 3 2-Dimensional discrete-time markov chain

The major contributions of the proposed research work are:

- Development of a 2D-DTMC-based MAC Model for modeling the joint behavior of retransmissions (m) and queue length (n) per node.
- Congestion and Energy-Aware Transitions: Transition probabilities are adaptively modified using queue-based bias (W(m,n)) and residual energy-based load factor (τ(m,n)).
- Metric Derivation from Steady-State: Two key metrics—TPcong (congestion), TPenergy (energy usage loss)—are analytically derived from steady-state probabilities.
- A multi-objective Optimization algorithm is designed and optimized using Particle Swarm Optimization for improving overall network performance.

The rest of the paper is organized as follows: Section 2 discusses MAC protocols designed for Linear Sensor Networks and different Markov Chain models for modelling behavior. Section 3 provides the protocol layout and the proposed model. Section 4 provides a comparison with other MAC protocols achieved using extensive simulation. Section 5 is about the conclusion and future scope.

2. Related Work

2.1. Mac Protocols for LSN

A Medium Access Control protocol, named S-MAC, was introduced by Wei Ye et al. [1]. The protocol utilized the wake-up/sleep schedule concept to synchronously activate the nodes to transfer data packets. The nodes go into sleep mode once the data transmission is done, thus saving energy by reducing idle listening. S-MAC concentrates on improving overall network performance in terms of energy efficiency. However, less stress is laid on an individual's node behavior, which might result in high latency. This situation gets aggravated when the data is transmitted through multiple hops to the sink node. A new category of wireless sensor network was discovered by Immad Jawahar et al. [3] based on the arrangement or topography of sensor nodes. This new arrangement was named a Linear Sensor Network because sensor nodes were deployed in a linear fashion. Moreover, the LSN was further categorized into two classes based on the network's topography or hierarchy. The paper emphasized adapting the MAC protocol to overcome the specific issues, such as limited routes, early battery exhaustion, higher packet drop rate, etc., associated with linear networks.

A detailed analysis of the MAC protocol specifically designed for LSN, based on different parameters, is provided in Table 1. This helps in understanding the requirements better and developing protocols more efficiently.

The major issues related to the placement and working of LSN are described in [2]. The primary concern is to deal with the energy hole problem, which results in the early drainage of batteries in nodes closer to the base station or sink nodes. The paper also describes the

Challenges faced and diverse applications for the Linear Sensor Network. The paper gives a detailed overview of several real-world applications, such as trans-border security, high-voltage power line monitoring, and tunnel and pipeline surveillance.

Sudeep Varshney et al. [31] explore the key design challenges and emerging research directions in Linear Sensor Networks. The comprehensive analysis focuses on energy-efficient sensor node deployment techniques, specialized routing protocols, and methodologies targeted to enhance overall Linear Sensor Network lifetime. It further lays stress on critical parameters such as energy efficiency, reduced latency, network reliability, security, and fault tolerance, which are of paramount importance for any network architecture and protocol design tailored to Linear Sensor Network environments.

Hong Li et al. [32] proposed energy-efficient node placement strategies for linear wireless sensor networks by integrating two schemes: one optimizes node spacing for a fixed number of nodes, and the other determines optimal node density for a given spacing. The study finds that energy consumption is influenced by spacing and data relay load. Simulations show these approaches outperform uniform placement by balancing load and extending network lifetime. Radosveta Sokullu et al. [16] proposed LINE-MAC, which is an access mechanism explicitly designed to overcome the challenges and issues faced in LSN implementation. The two major challenges associated with LSN are ensuring reliable source-to-destination data packet transmission and tackling the packet drop rate efficiently. The protocol handles both issues by incorporating two novel parameters, "packetLimit" and "preACK".

LC-MAC, designed by Chen Fang et al. [19], is a synchronous duty-cycling-based MAC protocol designed for linear WSNs. It utilizes a super SYNC frame to successfully coordinate multihop transmissions, allowing the sensor nodes of adjacent grades to wake, receive, and forward packets sequentially. Extensive simulations demonstrate that LC-MAC significantly reduces end-to-end delay as compared to S-MAC while preserving energy efficiency and Throughput.

2.2. Markov Chain Models for Modelling Behavior

Interference and time-varying fading can cause packet losses on the communication lines that link wireless control system components. The wireless control network is examined here with loss of packets on both the sensor-controller connection and the controller-actuator link. A. Impicciatore et al. [15] represented the connections between sensing and actuators as FSMCs, or finite-state Markov channels.

Table 1. The MAC protocol specifically designed for LSN, based on different parameters

Protocol	Type	Technique used	Simulator	Pros	Comparison
1. LINE-MAC [2014][16]	Asynchronous, Duty Cycling	Preambling (PreAck, Packetlimit), Low Power Listening (LPL)	Castalia	Improved PDR, Reduced Latency	AREA-MAC
2.SA-MAC [2018][17]	Synchronous, Duty Cycling	Pipelined Scheduling, Selective Awakening based on grade, DTMC	Discrete Simulations	Reduced collision, Improved Throughput, and Energy Efficiency	PRI-MAC
3. H-MAC [2018][18]	Synchronous	Hash-based priority scheduling, pipelined scheduling	MATLAB	Improved Throughput, packet loss probability, and Uniform performance	SA-MAC
4. LC-MAC [2011][19]	Synchronous, Duty Cycling	Location Detection Packet for position awareness, message passing for multihop burst forwarding	NS-2	Better traffic delivery, Energy Efficient	S-MAC-Adaptive
5. RDCPF-MAC [2020][20]	Synchronous, Staggered Scheduling	Topology optimization using redundant nodes, pipelining	OMNET++	Improved AEC, Reduced source-to-sink delay	DCPF
6. DIS-MAC [2009][21]	Novel Scheduling Channel Access Scheme	Directional Antennas. Differential Binary Phase Shift Keying (DBPSK) modulation scheme	Theoretical Evaluation	Collision-free, Stable and Reliable link establishment	IEEE 802.11 MAC with Rician fading
7. HP- MAC [2022][22]	Synchronous, Duty Cycling Pipelining	Packet queuing Scheme, Hashing-based Distribution scheme	MATLAB, DTMC Modelling	Enhances Network Scalability,	PRI-MAC, SA-MAC
8.L-CSMAMAC [2015][23]	Duty cycling with CSMA, Synchronous	Priority allocation, Message Passing Mechanism	C language, mathematical modelling	Alleviates hidden/exposed node issue, eliminates starvation	IEEE 802.15.4 and Ripple
9.LTDA-MAC [2019][24]	Asynchronous packet scheduling	Heuristic optimization technique, Genetic Algorithm (GA), Particle Swarm	MATLAB R2018b	Collision-free transmission, No clock synchronization required	STDMA-MAC

		Optimization PSO			
10. RL-MAC [2006][25]	Asynchronous	Markov's Decision Process, Reinforcement Learning for adaptive channel access	NS-2	Quality of Service, Less Message Interval Time	S-MAC
11.CA-MAC [2009][26]	Hybrid, Duty Cycling	Buffer evaluation through the threshold limit	OMNET++	Reduced Control packet overhead and latency	S-MAC, T-MAC
12.AEE-MAC [2011][27]	Hybrid	Aggregation of Sync & RTS Control Packet, Traffic-Priority Scheduling	NS-2	Improved Energy Efficiency	S-MAC
13. SD-MAC [2010][28]	Synchronous, Deterministic	Staggered transmission over a Dielectric Wi-Wi(wireless wire)link	OMNET++	Better Fault Tolerance	Hardware Prototype
14.MFT-MAC [2013][29]	Synchronous, Duty Cycling	Novel Control frame: PION for Multi-frame Tx	NS-2	Reduced Average End to End Delay, Improved Throughput	DW-MAC, R-MAC
15. BSC-MAC [2013][30]	Synchronous, duty cycling	Root or Source Node Detection Algorithm, control Frame	NS-2	Higher Throughput	AEEMAC, P-MAC

While sensing link mode observation is insensitive to delays of any kind, actuation link mode observation is impacted by a one-step lag. The optimal output-feedback control problem in this FSMC setting is solved as our main contribution in this article by comparing and contrasting two state estimation methods, the Luenberger observer and the current estimator. The author derived a separation principle for both cases.

Data is transmitted from the collection node to the destination node using a multihop route in wireless sensor networks, which are typically implemented in regions with rather severe natural settings. Consequently, the question of how to efficiently plan the transmission route is crucial. Noting that the unbiased grey Markov Chain model shares some problems with the unbiased grey model when it comes to parameter selection, this paper merges the two models to create an unbiased grey Markov Chain model. In order to make it better, Y. Liu et al. [14] employed the particle swarm algorithm. The author presented the mathematical model, calculation technique, and different parameters of this optimization process, and we show you how to put it into action using a flow diagram. Combining the particle swarm method with the unbiased grey Markov Chain model, the particle swarm unbiased Markov Chain model aims to address the drawbacks of the original model. The training and extensive simulations show that the particle swarm unbiased grey Markov, by incorporating optimized scheduling of nodes, provides better energy efficiency and network coverage output.

A novel network architecture called Wireless Powered Communication Network (WPCN) performance is majorly dependent on how effectively the scheduling is done. Therefore, A. Iwaki et al. [15] proposed an effective scheduling mechanism called "Harvest-then-Access". To model the network behavior, a Markov Chain model is used along with "Harvest-then-Access", which improves the WPCN network's overall performance. We find the best time interval for WET in a network using Harvest-then-Access by analyzing the data, which improves Throughput and makes devices more equitable. By contrasting the analytical and simulation outcomes, we can see that the suggested analytical model is valid.

As a standard metric, Packet Delivery Ratio (PDR) evaluates the dependability of routing algorithms in wireless networks. PDR is presented under the hopeful assumption that the topology has been fully established and that the nodes have begun transmitting packets. This is so even though sending packets requires nodes to join the network and maintain a connection at all costs. Particularly in mobile IoT applications, where disconnections happen often, this is a critical component of the routing protocols' overall dependability. However, suitable criteria that could assess the routing systems from this angle are lacking. B. Safaei et al. [33] presented attachability, a novel measure for assessing routing methods' capacity to aid mobile or stationary nodes in establishing and preserving network connections. The author developed a novel metric and estimated it using Markov Chain analysis and the sample frequency-based method. To test attachability, we implemented a mobile IoT infrastructure simulator and ran extensive experiments on several IPv6 Routing Protocols for Low-power and lossy networks (RPL) versions. From what we can tell, the routing algorithms' metrics and path selection strategies have a major impact on attachability. When it comes to Cognitive Radio (CR)-based Internet of Things (IoT) networks, spectrum sensing is a critical tool for finding unused spectrum. Due to their widespread use and adaptability, the Internet-connected device networks face steeplechases in terms of responsiveness, accuracy, and adaptability. In order to make good use of spectral gaps, CR aids in the dynamic allocation of unlicensed frequency bands to IoT devices. In order to study the rates of spectrum utilization in CR-based IoT networks, S. Surekha et al. [34] suggested a nonoperative game theoretic model for spectrum sensing. A utility function based on the rate of spectrum usage is derived from the 2-D continuous-time Markov Chain model, while a noncooperative game theory is used to design the spectrum access and utilization strategy.

3. SCF MAC Protocol

3.1. Network Layout

A unidirectional Linear Sensor Network (LSN) is considered, featuring a single sink node positioned at one end of the network. The network is structured into *grades* based on the hop distance, which is how far the sensor node is from the sink node. A node is categorized under grade *h* if it is *h* hops away from the base station, with the total number of grades denoted by *H*.

The network topology is dynamic to reflect real-time deployment scenarios, and it is non-homogeneous—each grade may consist of a different number of nodes. Figure 5 depicts the grade-based classification of nodes.

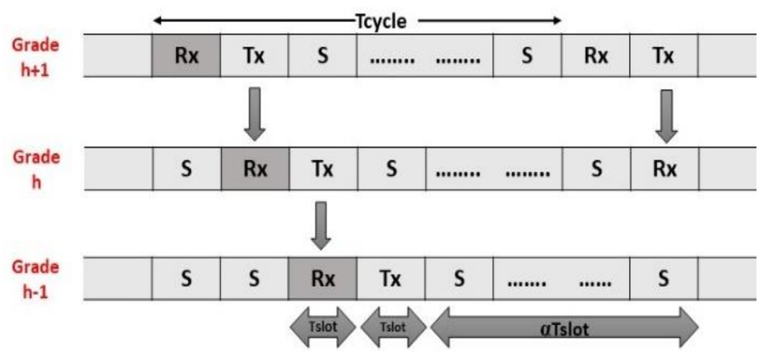

Fig. 4 Cooperative staggered scheduling cycle

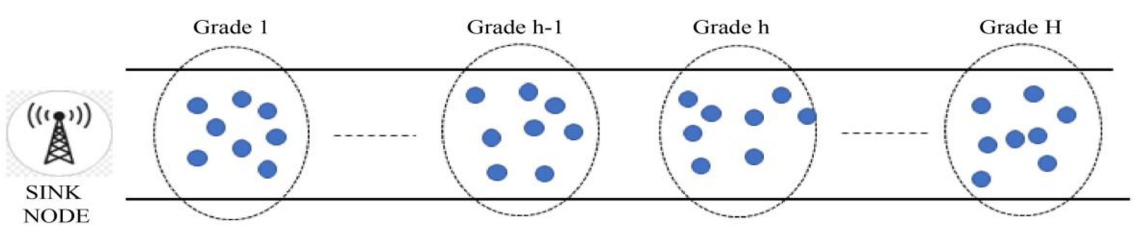

Fig. 5 Linear sensor network classification in terms of grades

During the initialization phase, nodes are assigned grades according to their transmission power and coverage range.

This structure restricts communication such that a node in grade *h+1* transmits only to a node in grade *h*. To enable efficient multihop data transfer, a pipelined scheduling scheme is implemented, allowing packets from the highest grade to reach the sink within a single time cycle. Pipelined scheduling operates by staggering the time cycle so that nodes in higher grades use their transmission slots concurrently with lower-grade nodes occupying their reception slots. This coordinated timing ensures smooth multihop communication across the network. The total cycle time, denoted as *Tcycle*, is divided into *n* time slots, each of duration *Tslot*, and is expressed as:

$$Tcycle = 2Tslot + \alpha\, Tslo$$

3.2. Analytical Model and Protocol Design

The proposed methodology is based on probabilistic modeling using a DTMC framework to minimize latency and energy consumption, reduce packet loss probability, and enhance overall network throughput.

Fig. 6 Two-dimensional DTMC framework

3.2.1. 2D DTMC Model for better Performance and Adaptability

To better represent and lessen network bottlenecks, particularly in the area of the sink node, where congestion is most likely; this research proposes a 2D-DTMC model. In this paradigm, the m^{th} retransmission count and the n^{th} node queue length are used to represent the current system state. Using this dual-parameter state modeling, a deeper insight can be gained into the network's dynamics and use that knowledge to regulate and predict where congestion will occur. By simulating transitions depending on queue buildup and retransmission attempts, the system may optimize buffer management strategies and transmission plans. As a result, Throughput is improved and packet losses are decreased. Accurate energy-aware MAC scheduling is made possible by this grid-based state representation, which captures the nodes' probabilistic behavior in response to connection dependability and traffic load. In exhaustive discrete-in time simulations, SCF-MAC-2D-DTMC outperforms state-of-the-art MAC protocols in parameters such as Throughput, energy consumption, packet delivery ratio, and delay. Adding the 2D-DTMC model to MAC protocol design makes channel access behavior smarter and more adaptive, improving Linear Sensor Networks' longevity and reliability.

Step 1: Grade-Based Nodes Distribution and Initialization

In order to model the distribution of nodes among different grades in a Linear Sensor Network, the Poisson distribution is utilized. This initialization process further helps in enhancing the adaptability of the 2D-DTMC framework. The following assumptions are made prior to the distribution:

Let G denote the number of grades in the LSN g∈{1, 2, …, G}: It denotes the current grade N_g: It is the actual number of nodes in grade g

$$P(N_g = k) = \frac{e^{-\lambda_g} . \lambda_g^k}{k!}$$

Here,

- $\lambda_g=\lambda_1 . e^{-\theta(g-1)}$: It is a grade-based exponential decay function, which is helpful in determining the expected number of nodes in grade g.
- θ : It is a decay rate parameter that controls how steadily the node density decreases as the grade number increases.

Step 2: State Space Construction: Retransmissions * Queue Length

The 2D-DTMC system state is defined as a tuple that contains 2 parameters, m and n, where m denotes the number of retransmissions and n denotes the node's queue length. In the context of the 2D-DTMC MAC model, the state space is simply the collection of all possible "situations" (or "states") your system can be in at discrete time steps. The state space definition is performed as:

$$SSpace = \sum_{i=1}^{K} \{(m,n) 0 \leq \mathrm{m} \leq \mathrm{MRT}, 0 \leq \mathrm{n} \leq \mathrm{MQS}\}$$

Where:

- m = number of retransmissions so far (from 0 upto some max MRT).
- n = current queue length at node i (from 0 upto max MQS).
- K is the total number of nodes.
- MRT is the maximum allowed retransmissions, and MQS is the maximum queue size.

This gives each node a two-dimensional grid of (m,n) states. Intuitively:

- Moving right in the grid (n→n+1) means the queue grew (new arrival).
- Moving down (m→m+1) means another retransmission was attempted.

Table 2. Transition matrix probability

Transition Type	(m,n)→(m',n')	Probability	Meaning
Queue growth	(m,n)→(m,n+1) n<MQS	$P_{arrival}(n) = \mu(i) = \lambda_g = \lambda_1 . e^{-\theta(g-1)}$	New packet arrival
Collision/ Retransmission	(m,n)→(m+1,n) n>0, m<MRT	$P_{collision}(m,n) = 1 - P_{success}(m,n)$	Queue state unchanged, Retry added

Successful Transmission	(m,n)→(0,n-1) n>0	$P_{success}$(m,n)= $\sum_{i=1}^{K} TP(m,n) \rightarrow TP(0,\ n-1) + \log_n(m+1))$	The queue length is reduced by 1, and the retransmission is reset.
Idle	(m,n)→(m,n)	No change	State remains the same

Step 3: Build Transition Matrix: P_{markov}

Define Transition Matrix

The state transition matrix of P_{markov} represents an N * N matrix in which P_{ij} states that the process transitions to state *j* at time *t* + 1 given that it is in state *i* at time *t*, for all *t*. The N*N state transition matrix can be expressed as:

$$P_{markov} = [P_{ij}]^{N}_{i,\ j=1}$$

Where:

- P_{markov}[i,j]=Pr{X_{t+1}=j| X_t=i}. It is the probability described as if the system model is in state i at time t, it will be in state j at time t+1. In our 2D–DTMC Model, "state i" represents (m,n) pair, and "state j" is some other (m′,n′) pair.
- N= |SSpace| =(MRT+1) ×(MQS+1).
- $\sum_{j=1}^{N} P_{ij}$ =1, ∀i=1,…, N, which means that "if the system is in state i, it must transition somewhere (possibly back to iii itself), and the probabilities of all those possibilities add up to 1."

Populating Transition Matrix: P_{markov}

The state transition probabilities for the |N*N| matrix are defined, such that for each (m,n) pair, there exists a transition to a feasible (m′,n′) pair. The possible transition probabilities are expressed in Table 2 at the end of this page.

Step 4: Calculate the Bias factor from the Q_{len} metric

Step 4 consists of two major steps in order to find a metric to adjust transition probabilities.

Defining Qlen Metric

If any new packets are added to the queue, there is a parameter that is updated as:

$$Qlen(i,n) = \sum_{i=1}^{K} [\omega(i).TP_{(m,n)\rightarrow(m,n+1)} . \psi(i) - \mu(i)] \ for\ n < MQS$$

Where:

- $TP_{(m,n)\rightarrow(m,n+1)}$ denotes the probability that, in a single time-step, node i transitions from queue-length n to n+1 (i.e., one new packet arrives).
- ψ(i)=$\left(1 + \gamma.\frac{\sum_{j\in N(i)} n_j}{|N(i)|\cdot MQS}\right)$
  It is the congestion propagation factor. Here, n_j represents the current neighbor node, and $|N(i)|$ is the total number of neighbor nodes of node i. It increases if the queue of neighbor nodes is almost full, which shows a high level of congestion. This means that if the neighbor nodes are congested, there is a likely higher possibility or risk that the current node will see rising traffic soon.
- $\omega(i) \in [0,1] = \left(\frac{G-g(i)}{G-1}\right)$
  Here, G is the total number of grades, and g represents the current grade. A grade-based weight prioritizes grades closer to the sink node over grades farther from the sink node. This is done as nodes (in lower grades) closer to sink nodes are more congested, as they have data relayed from higher grades along with data generated by the nodes themselves.
- μ(i) represents the packet arrival rate, and TP−μ shows whether the instantaneous arrival probability exceeds the average net growth.
- Positive Q_{len} → on average represents the risk of congestion.
- Negative Q_{len} → on average shows good Throughput.

Compute Bias Weight

Qlen becomes a network-wide measure that captures the net pressure to grow the queue at node i. It is used to define a bias weight for each state (m,n):

$$W(m,n) = \frac{1}{1 + Qlen(i,n)}$$

This indicates:

If $W(m,n) \approx 1$, *then this shows that the sensor node is lightly loaded*

If $W(m,n) < 1$, *then this shows that the node is congested*

Step 5: Load-Aware Fairness Scaling

A load-awareness scaling mechanism is introduced to preserve the overall energy of the system and avoid nodes that are already burdened due to multiple retries and high queue growth. This helps in ensuring that the NTPs are fairly adjusted on the basis of the energy used by a node.

Let each state be associated with a load balance factor defined as

$$\tau_{(m,n)} = \left(1 - \frac{E_{used}(m,n)}{E_{max}}\right).\left(1 - \frac{n}{MQS}\right)^{\alpha}.\left(1 - \frac{m}{MRT}\right)^{\beta}$$

Here, $E_{used}(m,n)$ is the total energy consumed by a node presently in state (m,n). Therefore, the load balance factor considers nodes with more residual energy, a smaller queue size, and having attempted fewer transmissions.

This indicates:

If $\tau_{(m,n)} \approx 1$, *then this shows that the sensor node has high residual energy*

If $\tau_{(m,n)} < 1$, *then this shows that the sensor node has less residual energy*

Step 6. Modified Transition Probabilities

The original state transition probability matrix is modified using bias weight W(m,n), τ(m,n), in order to discourage transitions to states with high queue-growth pressure.

$$\widetilde{TP}_{((m',n')\to(m,n))} = TP_{((m',n')\to(m,n))} \cdot W_{(m,n)} \cdot \tau_{(m,n)}$$

This way:

- W(m,n) discourages transitions into congested nodes.
- τ(m,n) encourages transitions into energy-efficient, lightly loaded nodes.

The multiplication of the transition matrix can disturb the row stochastic, i.e. the sum of the row must be equal to 1. Therefore, normalization is performed as:

$$\widetilde{TP}_{((m',n')\to(m,n))} = \frac{\widetilde{TP}_{((m',n')\to(m,n))}}{\sum_{(m,n)} \widetilde{TP}_{((m',n')\to(m,n))}}$$

Step 7: Steady-State Condition (SSC)

To find the long-run probability of being in each (m,n), solve the global balance, and therefore, the Steady State Condition (SSC) probability is calculated as

$$SSC_{(m,n)} = \sum_{(m',n')\in SSpace} SSC_{(m',n')} \times \widetilde{TP}_{((m',n')\to(m,n))}$$

$$\pi = \pi.\widetilde{TP}\ , \sum \pi_{(m,n)} = 1$$

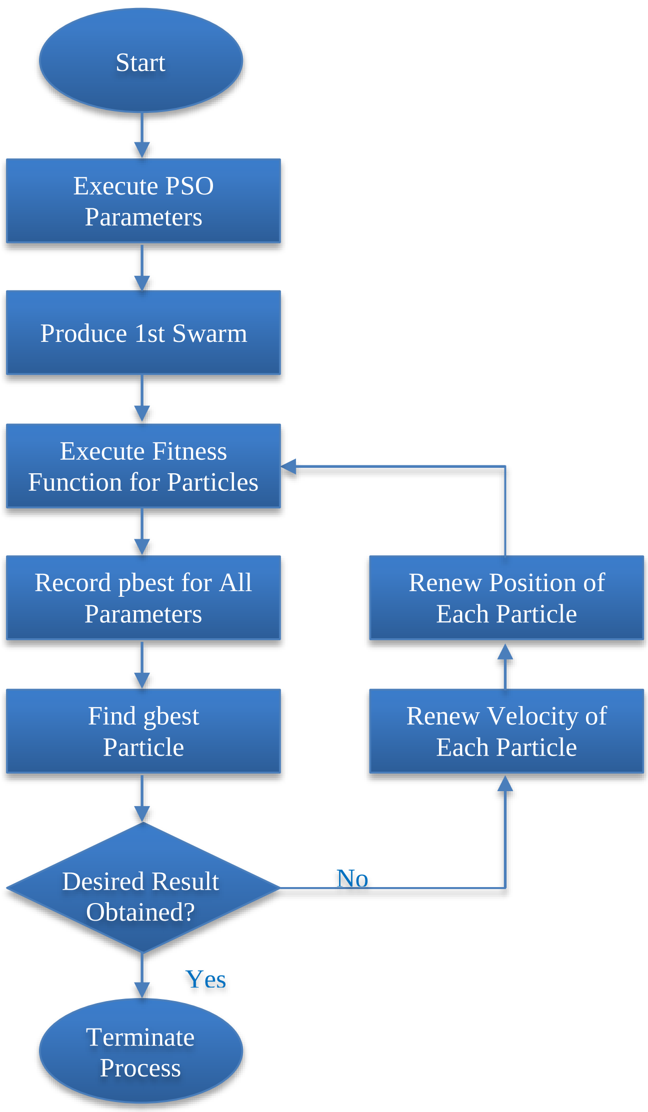

Fig. 7 PSO flowchart

Step 8: Risk Assessment Metrices
Congestion-Risk Prediction Metric

A high TPcong means a large fraction of the steady-state mass is at “dangerous” boundary states—i.e. nodes perpetually retrying or with maxed-out buffers. That signals a likely energy hole or sink-bottleneck.

Therefore, congestion reduction is performed to avoid bottleneck issues at the sink node. It is an aggregate congestion indicator built from steady-state probabilities.

$$TP_{cong} = \sum_{m-0}^{MRT}[\omega_m . SSC_{(m,MQS)}] + \sum_{n-0}^{MQS}[\omega_n . SSC_{(MRT,n)}] + \mu(m,n)$$

Where:

- $\omega_m = \frac{m}{MRT}$ It is a weight that grows linearly with the number of retransmissions.
- $\omega_n = \frac{n}{MQS}$, *is a* weight that grows with how full the queue is.

Energy-Hole Risk Prediction Metric

$$TP_{energy} = \sum_{m-0}^{MRT}\sum_{n-0}^{MQS}[SSC_{(m,n)}].\left(1 - \frac{E_{residual(m,n)}}{E_{init}}\right)$$

Where:

- $E_{residual(m,n)}$ Is the remaining energy of a node for being in state (m,n)
- E_{init} It is the initial energy of a node, which is at its maximum initially.

If $TP_{energy} \rightarrow 1$, this indicates that too many nodes are about to exhaust and are left with negligible energy.

If $TP_{energy} \rightarrow 0$ indicates that most of the nodes have not used much of their energy and are in a healthy state.

Step 9: PSO optimization

A machine learning based, metaheuristic algorithm like Particle Swarm Optimization can be used for our Linear sensor Network to optimize system parameters on the basis of metrices TP_{energy}, TP_{cong}.

The benefit of using PSO is that it is parallelizable, handles invalid states and works well in enhancing hybrid parameters or objectives. The multi-objective fitness function that needs to be minimized using PSO can be defined as:

$$\text{M\_Fitness}(x) = (\lambda_{cong} * TP_{cong}(x)) + (\lambda_{energy} * TP_{energy}(x)) + P_{penalty}(x)$$

Here,

- $\lambda_{cong} + \lambda_{energy} = 1$ are weights for normalization.
- x [α, β, γ, ω_m, ω_n, MRT, MQS] is a vector that defines parameters to be optimized.
- d |x| is defined as the particle dimension

4. Performance Evaluation and Numerical Results

4.1. Throughput

Two benchmark protocols, SA-MAC and PRI-MAC, were used to assess the throughput performance of the SCF-MAC protocol. Throughput is constantly higher with SCF-MAC regardless of the node density, as demonstrated in the graph. Its selective node activation mechanism, which boosts packet transmission efficiency and decreases needless channel contention, is responsible for this enhancement. By modeling the number of retransmissions and queue lengths with a 2D Discrete-Time Markov Chain (2D-DTMC), SCF-MAC is able to effectively handle congestion, particularly close to the sink node. Due to rising contention, the Throughput of all protocols gradually decreases with increasing numbers of nodes per grade. However, SCF-MAC maintains a more consistent and higher performance. Because of this, it is clear that it is suitable and robust for fairly dense Linear Sensor Network (LSN) settings.

$$Th(G) = \sum_{i=1}^{K} \mu(i). \sum_{(m,n \in Sspace)} SSC_i . TP_{(m,n)} \rightarrow TP_{(0,n-1)}$$

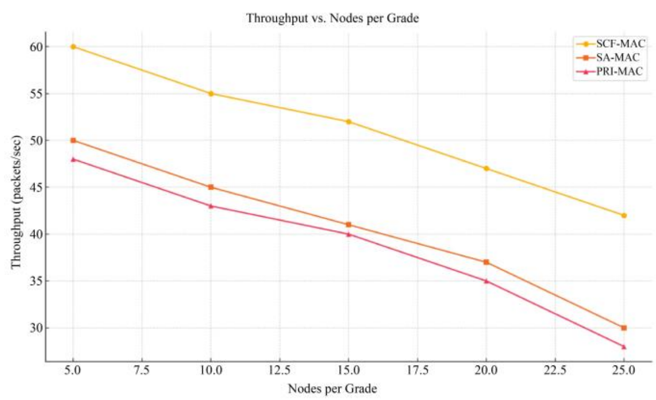

Fig. 8 Throughput vs. Nodes per grade

4.2. Packet Drop Probability

In comparison to SA-MAC and PRI-MAC, SCF-MAC clearly outperforms both in terms of packet drop probability. Both SA-MAC and PRI-MAC show a significant increase in packet drops as the number of nodes per grade grows, suggesting that they are susceptible to congestion and collision in dense network environments. The 2D-DTMC model informs SCF-MAC’s congestion control method, which allows it to keep packet loss to a minimum. SCF-MAC uses this model to make predictive modifications based on retransmission trends and queue buildup to avoid buffer overflows and missed packets. For sensor applications that are both time-sensitive and energy-constrained, the results show that SCF-MAC improves data delivery dependability.

$$P_{drop}^{(g)} = 1 - \left(1 - \rho_g\right)^{MQS} . e^{-\psi(g)}$$

Here, ρ_g Represents the traffic/load intensity, and $\psi(g)$ is the congestion amplification function.

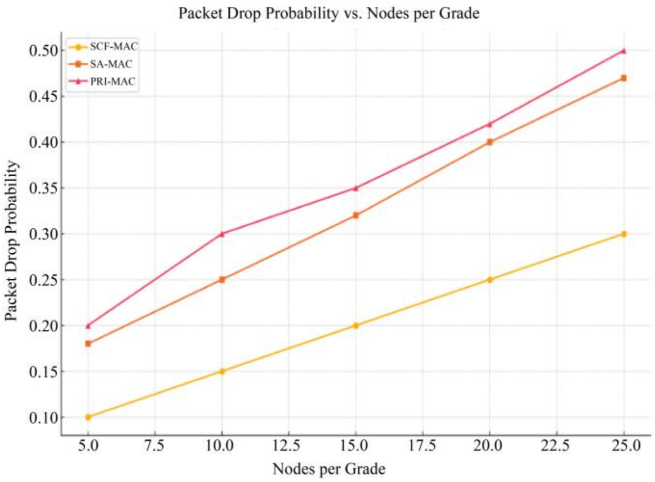

Fig. 9 Packet drop probability vs. Nodes per grade

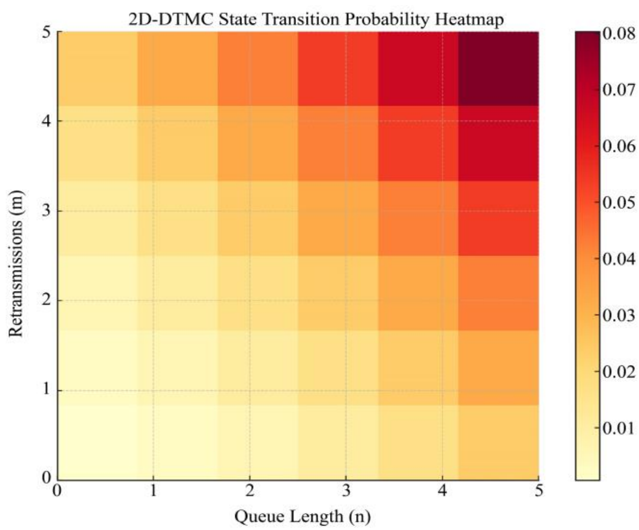

Fig. 10 2D discrete-time markov chain state transition heatmap

4.3. 2D-DTMC Heatmap

Each state in an LSN is represented by a tuple (m,n), where m is the number of retransmissions and n is the length of the node's queue. The 2D-DTMC heatmap graphically shows the probability of state transitions in this network. Based on transmission patterns in the past, this grid-based representation shows the probability of the network being in a given state. Low retransmissions and short queues correspond to low-congestion and efficient transmission modes, as shown in the bottom-left corner of the heatmap. On the other hand, states in the upper right corner have high retransmission rates and full lines, suggesting heavy congestion and possible bottlenecks.

Continuous monitoring, prediction, and response to these state probabilities is done via the SCF-MAC protocol using this 2D-DTMC model. Transmission priority is given to nodes in favorable situations, while nodes in high-probability congested states are deprioritized in terms of channel access. By distributing the traffic load more effectively across the network, this probabilistic congestion-aware decision-making method helps to reduce recurring collisions and retransmissions. The heatmap is a useful analytical tool for verifying this mechanism and proving that state probabilities are important for guiding scheduling and selective node awakening. Figure 10 shows the 2D Discrete-Time Markov Chain State Transition Heatmap levels.

$$Heatmap(m,n,m',n') = SSC_{(m,n)} \cdot TP_{((m',n') \to (m,n))}$$

4.4. Congestion

A comparison of SCF-MAC, SA-MAC, and PRI-MAC congestion levels over time slots is shown in Figure 11. The likelihood of the network being in a crowded condition, as determined by the 2D-DTMC model, is used to indicate the congestion level. All procedures start with modest congestion levels in the earliest time slots. Congestion levels on SCF-MAC have been steadily decreasing over time, whereas on SA-MAC and PRI-MAC, they have either stayed around the same or even increased. It is adaptive scheduling that takes into account real-time queue length, and retransmission monitoring is the reason for SCF-MAC's substantial reduction.

One of the major challenges faced in LSN implementation is the energy-hole problem, in which the nodes nearer to the sink are overburdened due to relaying of data packets from higher grades. This issue is dynamically resolved by SCF-MAC by modelling node behavior using 2-DTMC before accessing the medium.

On the other hand, other contemporary protocols, such as SA-MAC and PRI-MAC, do not offer this flexibility as they only use duty-cycling. The simulations show that the SCF-MAC deviates the packets to less congested nodes, thus reducing packet drop and latency. This graph illustrates the practical benefits of incorporating a 2D-DTMC model into MAC protocol design, namely in terms of congestion control prediction intelligence.

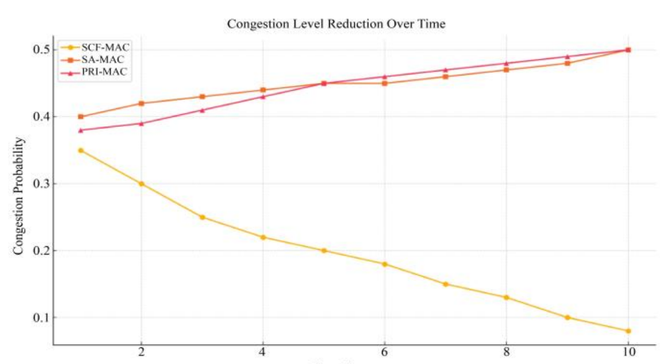

Fig. 11 Congestion reduction over time

$$TP_t = \sum_{m-0}^{MRT} [\text{ɯ}_m . SSC_{t(m,MQS)}] + \sum_{n-0}^{MQS} [\text{ɯ}_n . SSC_{t(MRT,n)}] + \mu(m,n)$$

5. Conclusion and Future Scopes

This paper proposes a novel MAC protocol for a wireless sensor network with linear topography. The duty-cycling mechanism of nodes can be adapted based on the node's behavior modelled using a Discrete Time Markov Chain. The state transition probability is adjusted based on two novel factors: - bias weight and load awareness. The dynamic nature of a linear wireless sensor network is accurately captured by modelling a node's behavior in terms of retransmission and queue length. Extensive simulations in MATLAB R2021a show that SCF-MAC outperforms other state-of-the-art protocols in terms of congestion, energy consumption, packet drop rate and latency. This is especially true under moderately crowded network settings. Heterogeneous node properties are prevalent in real-world deployments, but the protocol does not yet take them into consideration. It would be beneficial to further optimize the source-to-sink delay, as it is still relatively high. Potential future improvements could be implementing a TDMA technique close to the sink node to solve the energy-hole issue or using a multi-objective evolutionary algorithm to find the best number of nodes for each grade. In general, SCF-MAC is a huge step forward in designing MAC protocols for Linear Sensor Networks that are both energy-constrained and prone to congestion.

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