# M-JAW: Mobility-Based Jamming Avoidance in Wireless Sensor Networks

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***Abstract*—In this work, we study the problem of jamming avoidance for ensuring quality-of-service (QoS) in terms of the network lifetime and overhead in wireless sensor networks (WSNs). We propose a mobility model using *Single-Leader-Multiple-Followers Stackelberg game theory* to avoid the jamming affected region. In the proposed model, the centralized unit (CU) identifies the jamming affected region based on the locations of the affected nodes and acts as the leader. On the other hand, the jamming affected nodes act as followers and decide the mobility pattern, including the angle of movement, while minimizing the energy consumption and delay in packet delivery. A scheme, named M-JAW, for ensuring QoS, while avoiding jammers in WSNs, is proposed using the stated game-theoretic mobility model. Using M-JAW, the energy consumption of the overall network reduces by up to 20.36%, and the network overload reduces by 44.13–50.12%, which, in turn, increases the lifetime of WSNs.**

***Index Terms*—Quality-of-Service, Jammer, Mobility Model, Mobile Wireless Sensor Network, Stackelberg Game.**

## I. Introduction

WSNs are prone to various attacks [1]. Among them, *jamming* [2] is one of the important issues. A jammer [2] emits signals in the same frequency as the communication frequency of the deployed sensor nodes to restrict communication among them. This leads to the higher energy consumption of the sensor nodes [3], because of multiple unsuccessful packet re-transmissions. Consequently, the network lifetime gets reduced, as WSNs are energy resource-constrained. The effect of jamming is not permanent over the sensor nodes. Therefore, if the jamming affected nodes get out of the affected region or the jammer stops transmitting, the nodes start to behave normally.

In the existing literature, researchers studied different types of jammers such as one with single transmitter or another with multiple transmitters. Mpitziopoulos *et al.* [4] classified the jammers to be divided into four jamming categories – proactive or constant, deceptive, random, and reactive. In this work, we consider *proactive or constant* jammer [5] only. In other words, the jammers transmit continuously having random bit sequences. In the process, the jammer causes interference and keeps the wireless channel busy. Additionally, it corrupts the transmitted packets. In the existing literature [6]–[8], researchers proposed different jammer detection schemes. On the other hand, some of works focused on designing schemes to counter jamming. However, these proposed schemes are not implementable in real-life, because of high cost and limited energy. Mpitziopoulos *et al.* [4] surveyed the difficulties encountered with the proposed jamming avoidance schemes involving antenna polarization, direct-sequence spread spectrum, frequency-hopping spread spectrum, regulated transmitted power, ultra-wideband (UWB) technology, and directional transmission. However, in the existing literature, no mobility model is developed for countering jamming while taking strategies rationally. In other words, for jamming avoidance, no mobility model is proposed considering the stochastic decision of the jamming affected nodes, where the decision of each node is dependent on the environmental parameters and other jamming affected nodes.

We focus on ensuring QoS, in terms of the network overhead and lifetime, in the presence of jammers. In this work, we consider that all nodes are mobile. Initially, we detect the jammed zone with the help of a CU and propose a mobility model to avoid jamming while affecting the network lifetime minimally. The contributions of this work are briefly illustrated as follows:

a) The proposed scheme, named M-JAW, *ensures QoS* in terms of network lifetime and network overhead in the presence of jammers. M-JAW ensures jamming affected region identification with minimal energy consumption. In this process, the CU aims to detect the jamming affected area based on the received incremental flow-table updates.
b) In the next part of the proposed scheme, M-JAW, we propose a mobility model, named *Rational Mobility Model* (RMM), for jamming affected nodes to get away from the effects of jamming.
c) For RMM, we use the *Single-Leader-Multiple-Follower Stackelberg game*. The CU and the jamming affected nodes act as the leader and the followers, respectively. Accordingly, we propose a jamming avoidance algorithm based on the proposed RMM.

## II. Related Work

In the last few years, a lot of research work on jamming in WSN emerged, viz., [4], [6], [9]–[12]. Some of the existing literature are discussed in this Section. Garnaev *et al.* [12] studied jammer type identification using Bayesian game. In this problem, a dual linear programming problem, based on the jamming attack history, the nodes identify the type of attack

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and reduce the jamming effect. Aziz *et al.* [7] proposed a jammer type estimation scheme in LTE/LTE-A networks using a non-zero-sum repeated game.

Mamaghani *et al.* [13] proposed a time-switching architecture for bi-directional data-relay in the presence of jammers. Additionally, the authors also evaluated a closed-form performance metric with a high signal-to-noise ratio. He *et al.* [14] considered mobile relays in the presence of static nodes and intelligent jammer and designed the single and multi-commodity flow problem. The authors used spectral graph theory for maximizing network flow.

Nguyen *et al.* [15] proposed a jamming scheme to ensure privacy of the secondary users in the presence of multiple primary users by transmitting noise signals in cognitive radio networks. Amuru and Buehrer [16] studied an optimal jamming scheme with an additive white Gaussian noise channel. However, they did not propose any anti-jamming scheme.

Tague [17] studied that mobility affects the jamming attack. The authors proposed mobility control mechanism to achieve high performance. However, none of these works proposed any novel mobility model in a mobile sensor network. In the case of sensor networks, it is required to have some efficient mobility model which will be energy efficient, as sensor nodes are energy constrained in nature.

On the other hand, Misra *et al.* [8] studied the problem of jamming area identification. In Ref. [18], the authors proposed anti-jamming scheme with varying transmission power. Ma *et al.* [11] proposed a random mobility model for the jamming affected nodes in the presence of single jammer. Xu *et al.* [19] proposed a frequency multiplexing scheme for avoiding jamming. Ahmed and Faulkner [20] developed a hardware prototype to reduce the effects of a jammer. Mpitziopoulos *et al.* [21] studied a mobility scheme for jamming avoidance. However, these works do not consider the energy-constrained nature of the nodes. In addition, they fail to propose a novel mobility model for mobile WSNs.

In contrast to the existing literature, we aim to design a game-theoretic mobility scheme for ensuring QoS, in terms of network lifetime, in the presence of jammers in WSNs.

## III. System Model

We consider a wireless network consisting of multiple (a) *proactive jamming* nodes (JN), and (b) *normal* nodes (NNs). The jamming nodes are considered to be stationary and the normal nodes mobile in nature. Therefore, in the presence of a subset of active jamming nodes, the NNs use M-JAW to escape from the jamming region and ensure network connectivity. We define the bounds of M-JAW by outlining the *assumptions* below:

a) We consider a CU in the network, which ensures QoS in the presence of active jammers.
b) Each JN is static, behaves as a proactive jammer, and can block one frequency channel at a time.
c) Each NN is mobile and moves to a direction strategically, i.e., rationally, to avoid jamming affected region. In other words, while making the directional strategy, each jamming affected node takes into consideration the environmental parameters as well as the decision of other affected nodes.
d) The NNs are homogeneous in terms of communication range. In other words, they all have the same range.
e) The sender node, $S \in \mathbb{N}$, always has a packet to send.
f) The network is considered to be ideal, and the channels follow the free space model [22]. Hence, we argue that a packet can be lost, if and only if the sender node, $S$, or the forwarder node, $F$, where $S, F \in \mathbb{N}$, is within the communication range of a JN $J \in \mathbb{J}$.
g) Each node $n \in \mathbb{N}$ uses two different frequency channels – $CH_d$ and $CH_c$ – on a sharing basis. The channel $CH_d$ is used for sending data packets by the NNs. On the other hand, the channel $CH_c$ is used by the NNs and the CU for sending control packets. The CU uses $CH_c$ for communicating with the jamming affected nodes.

**Neighborhood Graph Formation:** We consider that, initially, when the NNs are deployed over the network, there is no active jamming node. Therefore, initially, each NN $n \in \mathbb{N}$ explores its neighbors $\mathcal{N}_n$ and populates the corresponding edges $\mathcal{E}_n$, where $\mathcal{E}_n = \{e^n_1, \cdots, e^n_{n-1}, 0, e^n_{n+1}, \cdots, e^n_{|\mathbb{N}|}\}$, and $e^n_n$ defines the edge between nodes $n$ and $i$, where $n, i \in \mathbb{N}$. Additionally, we express $e^n_n$ as follows:

$$e^n_n = \begin{cases} 1, & \text{if there exists an edge between nodes } i \text{ and } n \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

In M-JAW, we consider that the graph $G$ is formed by considering the available edges $\mathcal{E}_n, \forall n \in \mathbb{N}$ in the network.

**Relative Neighborhood Graph Formation:** In order to reduce the number of edges, we use the concept of *Relative Neighborhood Graph* (RNG) [23]. We consider that the graph having reduced number of edges is denoted as $G_{rng}$. Further, $G$ and $G_{rng}$ have the same number of vertices. However, the set of edges in $G$, i.e., $\bigcup_n \mathcal{E}_n$, is a superset of the edges in $G_{rng}$, which is denoted as $E_{rng}$. RNG formation is a distributed approach[1]. We consider that there are three nodes over the terrain – $p$, $q$, and $m$, as shown in Figure 1. We get $q, m \in \mathcal{N}_p$ and $p, q \in \mathcal{N}_m$. We evaluate $E_{rng}$ while satisfying the following constraint:

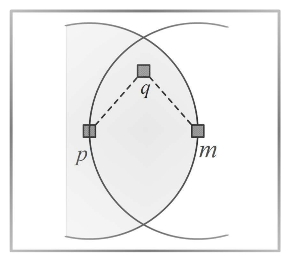



Fig. 1: Relative Neighborhood Graph Formation

$$E_{rng} = \{e^m_p \in \bigcup_n \mathcal{E}_n \mid \nexists q \in (\mathcal{N}_p \cap \mathcal{N}_m)\} \quad (2)$$

Thereafter, we estimate the quality of the available links or edges in $G(|\mathbb{N}|, E_{rng})$. In other words, we estimate the link quality of each edge $\{(p, q)\} \in E_{rng}$, where $d_{pq}$ denotes the Euclidean distance between the nodes $p$ and $q$, and

$$\max\ \{d_{pq}, d_{qm}\} \geq d_{pm} \quad (3)$$

**Lemma 1.** *The set of edges available in* $G(\mathbb{N}, E)$ *is a superset of the set of edges available in* $G_{rng}(\mathbb{N}, E_{rng})$*, i.e.,* $E_{rng} \subseteq E$.

*Proof.* In Figure 1, nodes $p$, $q$, and $m$ are within the communication range of one another. Therefore, in $G$,

$$\{(p,q),(q,m),(p,m)\} \in E, \quad \text{where } \{p,q,m\} \in \mathbb{N} \tag{4}$$

However, we find that:

$$\max \{d_{pq}, d_{qm}\} \ngeq d_{pm} \tag{5}$$

Equation (5) does not satisfy the constraint mentioned in Equation (3). Therefore, we conclude that $\{(p,m)\} \notin E_{rng}$. However, $\{(p,q),(q,m)\} \in E_{rng}$, as it follows the constraint given in Equation (3). Hence, we establish the fact claimed earlier, i.e., $E_{rng} \subseteq E$. □

**Lemma 2.** *RNG $G(\mathbb{N}, E_{rng})$ is a superset of the Minimum Spanning Tree (MST), i.e., $MST(\mathbb{N}, E_{mst})$.*

*Proof.* As shown in Figure 1, if node $q$ belongs to the intersection region of nodes $p$ and $m$, i.e., $q \in (\mathcal{N}_p \cap \mathcal{N}_m)$, we argue that $d_{pm} \notin E_{mst}$ as well as $d_{pm} \notin E_{rng}$.

On the other hand, $q \notin (\mathcal{N}_p \cap \mathcal{N}_m)$ and $d_{pm} \leq \max \{d_{pq}, d_{qm}\}$ are ample for considering $d_{pm} \in E_{rng}$. However, for MST, these conditions are *necessary, but not sufficient*, for considering $d_{pm} \in E_{mst}$. Therefore, we conclude that $MST(\mathbb{N}, E_{mst}) \subseteq G(\mathbb{N}, E_{rng})$. □

**Theorem 1.** *If there are $|\mathbb{N}|$ nodes deployed, RNG, i.e., $G_{rng}(\mathbb{N}, E_{rng})$, formed from the graph $G(\mathbb{N}, E)$, can have at least $(|\mathbb{N}| - 1)$ edges and at most $(3|\mathbb{N}| - 6)$ edges. Mathematically,*

$$(|\mathbb{N}| - 1) \leq |E_{rng}| \leq (3|\mathbb{N}| - 6) \tag{6}$$

*Proof.* In an MST consisting of $|\mathbb{N}|$ nodes, there must be $(|\mathbb{N}| - 1)$ edges. Additionally, from Lemma 2, we get that $E_{mst} \subseteq E_{rng}$. Therefore,

$$(|\mathbb{N}| - 1) \leq |E_{rng}| \tag{7}$$

According to Euler's Theorem [24], we have:

$$|\mathbb{N}| - |E_{rng}| + F_{rng} = 2 \tag{8}$$

where $|\mathbb{N}|$, $|E_{rng}|$, and $F_{rng}$ denote the number of nodes/vertices, the number of edges, and the number of faces, respectively, in a connected and planar graph, without having any edge intersecting with other edges. In an RNG, we need at least three edges to form a face. In between two faces, there exists a common edge. Therefore, we get:

$$3F_{rng} \leq 2|E_{rng}| \tag{9}$$

Hence, we can re-write Equation (8), as follows:

$$\begin{aligned} & 2 - (|\mathbb{N}| - |E_{rng}|) \leq \tfrac{2}{3}|E_{rng}| \\ \Rightarrow \quad & \tfrac{1}{3}|E_{rng}| \leq (|\mathbb{N}| - 2) \\ \Rightarrow \quad & |E_{rng}| \leq (3|\mathbb{N}| - 6) \end{aligned} \tag{10}$$

Therefore, from Equations (7) and (10), we have: $(|\mathbb{N}| - 1) \leq |E_{rng}| \leq (3|\mathbb{N}| - 6)$. □

**Link Quality Estimation:** For prioritizing the neighbor links, each node $n \in \mathbb{N}$ estimates the quality for each link $e_n^m \in E_{rng}$ based on the *Link Quality Estimation* (LQE) scheme, i.e., the *Triangle Metric* proposed by Boano *et al.* [25]. We estimate the link quality and predict the *Packet Reception Rate* (PRR), of each link $e_n^m \in E_{rng}$ based on the *Received Signal Strength* (RSS) and *Signal to Noise Ratio* (SNR). Using the *Triangle Metric* [25], we calculate the *window mean* of SNR and RSS, i.e., $\overline{SNR_{nm}^w}$ and $\overline{RSS_{nm}^w}$, over window size $w$, for each link $e_n^m \in E_{rng}$, while using the equations shown below:

$$\overline{SNR_{nm}^w} = \frac{\sum_{k=1}^{b_{nm}} snr_{nm}^k}{a_{nm}} \quad \text{and} \quad \overline{RSS_{nm}^w} = \frac{\sum_{k=1}^{b_{nm}} rss_{nm}^k}{a_{nm}} \tag{11}$$

where $a_{nm}$ and $b_{nm}$ denote the total number of packets sent and successfully delivered over the link $e_n^m \in E_{rng}$. $snr_{ij}^k$ and $rss_{ij}^k$ denote the SNR and RSS values for packet $k$ over the link $e_n^m$ while considering the radio-propagation path loss model [26]. Thereafter, using the Triangle Metric [25], the quality $\mathcal{LQ}_{nm}$ of the link $e_n^m \in E_{rng}$ is calculated as:

$$\mathcal{LQ}_{nm} = \sqrt{\overline{SNR_{nm}^w}^2 + \overline{RSS_{nm}^w}^2} \tag{12}$$

## IV. M-JAW: The Proposed Rational Mobility Model

In M-JAW, the interaction between the CU and the NNs is modeled using the Single-Leader-Multiple-Followers Stackelberg game. The NNs act as the followers and the CU acts as the leader. In M-JAW, initially, the source or destination nodes identify the presence of jamming nodes and informs the CU. Thereafter, each node updates its neighbor list on obtaining a request from the leader. The NNs inform the change in the neighbor list to the CU, based on which the leader decides the center of the jamming affected region and the optimal radius of the jamming affected area. On the other hand, each jamming affected nodes decides its mobility pattern after receiving the aforementioned information calculated by the CU. Thus, the proposed scheme, M-JAW, ensures the mobility-based jamming avoidance in WSN.

### A. The Justification for using Stackelberg Game

In M-JAW, we aim to model the interaction between the CU and the nodes. Additionally, we consider that the nodes decide their strategies distributively, i.e., non-cooperatively. Hence, it gives rise to a market scenario of individuals where their decisions are independent. Therefore, the presence of the CU is considered to ensure that the individuals can decide strategies, i.e., avoiding the jamming, based on the global information of the network. The strategy decided by each node gets affected by the information provided by the CU. Therefore, we argue that the Stackelberg game is well suited in this problem to model the interaction among the CU and the nodes.

### *B. Strategy of the Centralized Unit: Jamming Affected Region Identification*

In M-JAW, for introducing a strategic mobility model, initially, the jamming affected region needs to be identified by the CU, i.e., the leader, which acts as the coordinator. In order to identify the jamming affected region, we consider a scenario with a *sender node* $S$, a *destination node* $D$, and a set of forwarder nodes $\mathcal{F}$, where $\mathcal{F} = \{f_1, f_2, \cdots, f_n\}$, where $i \leq (|\mathbb{N}| - 2)$.

In this situation, we infer the presence of JN(s), if one of the following statements is true:

i) Destination node $D$ does not get any data packet for a `TimeOut` duration.

ii) Sender node $S$ does not get any `ACK` packet within a `TimeOut` duration.

Hence, we infer that a subset of *active edges*, as mentioned in Definition 1, is affected by jamming.

**Definition 1.** *We define an edge to be active if the edge connects the following pair of nodes:*

- *Sender node $S$ and Forwarder Node $n \in \mathcal{F}$*
- *Forwarder nodes $n, m \in \mathcal{F}$*
- *Forwarder node $n \in \mathcal{F}$ and Destination node $D$*
- *Sender node $S$ and Destination node $D$*

After detecting the presence of the jamming effect, the sender node $S$ or the destination node $D$ sends an `ERROR` message to the CU. Thereafter, the CU requests the NNs in the network to initiate the neighbor finding approach. After updating the neighbor list, a subset of nodes which detect a change in the neighbor list, informs the CU about the change in the neighbor list. Thereafter, the CU detects the set of jamming affected nodes, which is denoted by $\Delta\mathcal{N}$ based on the change in the neighbor list informed by the normal nodes. Thereafter, the CU calculates the jamming affected area.

The CU aims to obtain a convex hull of the jamming affected region. Hence, it needs to draw an circle with minimum area while ensuring that the jamming affected area is covered by the circle. The CU calculates the Euclidean distance $d_{nm}$ between each pair of nodes $n, m \in \Delta\mathcal{N}$. Thereafter, based on the maximum $d_{nm}$, which is denoted by $d_{nm}^{max}$, the CU considers a circle having a radius $r_c$ and center at a point $(x_c, y_c)$. We calculate $r_c$ and $(x_c, y_c)$ using the following equations:

$$r_c = \frac{d_{nm}^{max}}{2}, \;\; x_c = \frac{|x_n - x_m|}{2}, \text{ and } y_c = \frac{|y_n - y_m|}{2} \tag{13}$$

where $(x_n, y_n)$ denotes the Cartesian coordinates of node $n$.

### *C. Strategies of the Jamming affected Nodes: Mobility Model*

After getting $(x_c, y_c)$ and $r_c$ from the CU using the $CH_c$ channel, each node $n \in \Delta\mathcal{N}$ decides an angle $\theta_n$, and a velocity $\upsilon_n$. We note that $\theta_n$ and $\upsilon_n$ need to satisfy the following inequalities:

$$0 \leq \theta_n < \frac{\pi}{2}, \quad \forall n \in \Delta\mathcal{N} \tag{14}$$

$$0 \leq \upsilon_n \leq \upsilon_n^{max}, \quad \forall n \in \Delta\mathcal{N} \tag{15}$$

where $\upsilon_n^{max}$ defines the maximum velocity node $n$ can achieve, while assuming that the nodes are heterogeneous in nature. Each node aims to ensure that it is out of the jamming affected region, while consuming the minimum amount of energy. The strategic form of the utility function is denoted as $\mathbb{U}_n(\upsilon_n, \theta_n)$. Each component of the strategic form is discussed as follows:

i) $\theta_n$ defines the mobility direction, i.e., an angle with the X-axis, for each node $n$.

ii) $\rho_n(\theta_n)$ denotes the Euclidean distance to be covered by node $n \in \Delta\mathcal{N}$ in order to avoid the jamming affected region.

iii) $E_n^{res}$ defines the residual energy of node $n \in \Delta\mathcal{N}$ at the time of the jamming affected region detection.

iv) $r_c$, which is calculated by the CU, is the radius of the curve-fitted circle of jamming affected area.

v) $\alpha_n$ denotes the amount of energy to be consumed for moving an unit distance. Therefore, we consider that $\alpha_n$ needs to satisfy the following constraint:

$$\alpha_n > 0 \tag{16}$$

Additionally, each node $n$ needs to satisfy the following constraints to avoid the inter-node collision.

$$\frac{\upsilon_n}{\upsilon_{n'}} \neq \frac{\tan\theta_n}{\tan\theta_{n'}} \sqrt{\frac{1 + (x - x_n)^2}{1 + (x - x_{n'})^2}}, \quad \forall x \in \rho_n(\theta_n), \rho_{n'}(\theta_{n'}) \tag{17}$$

where $n, n' \in \Delta\mathcal{N}$ and are in same quadrant. Additionally, the nodes need to ensure that $\upsilon_n \leq \upsilon_{n'}$, $\forall n' \in -\boldsymbol{n}$, where $\rho_n(\theta_n) \geq \rho_{n'}(\theta_n)$.

We consider that the utility function $\mathbb{U}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ signifies the satisfaction of each node $n \in \Delta\mathcal{N}$, while considering that the node aims to reduce energy consumption due to mobility and packet loss, where $\upsilon_{-\boldsymbol{n}} = \{\cdots, \upsilon_{(n-1)}, \upsilon_{(n+1)}, \cdots\}$ and $\theta_{-\boldsymbol{n}} = \{\cdots, \theta_{(n-1)}, \theta_{(n+1)}, \cdots\}$. We define the utility function $\mathbb{U}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ of each node $n$ as the difference between the *revenue function* $\mathbb{R}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ and the *cost function* $\mathbb{C}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$. The revenue function $\mathbb{R}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ of node $n$ signifies the satisfaction of each node $n$ by moving from the jamming affected region. The nodes try to increase the revenue function, while losing some amount of energy due to mobility, and aim to ensure the normal communication in the presence of jamming nodes. We consider that $\mathbb{R}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ varies inversely with the distance covered $\rho_n(\theta_n)$. Moreover, the energy consumption $\alpha_n$ for moving per unit distance has an linear negative effect on $\mathbb{R}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$. Therefore, we define $\mathbb{R}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ as follows:

$$\mathbb{R}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}}) = 1 - \frac{\alpha_n \rho_n(\theta_n)}{2 r_c E_n^{res}}, \quad \text{where } n \in \Delta\mathcal{N} \tag{18}$$

On the other hand, $\mathbb{C}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ of node $n$ signifies energy consumption for transmission of packets which is lost due to jamming effect. We define the cost function $\mathbb{C}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ as the ratio of the amount of energy $E_n^{con}$ consumed due to movement and the residual amount of energy $E_n^{res}$ before the move.

We define $E_n^{con}$ of node $n$ as follows:

$$E_n^{con} = \left\lfloor \frac{t_n}{\mathtt{PTI}_n} \right\rfloor E_{Tx}\mathtt{PS} \tag{19}$$

where $\left\lfloor \frac{t_n}{\mathtt{PTI}_n} \right\rfloor$ defines the number of packets transmitted by node $n$ within a jamming affected area; $\mathtt{PTI}_n$ defines the packet transmission interval of node $n$; $E_{Tx}$ is the transmission energy consumption per bit [27]; and $\mathtt{PS}$ defines the packet size. Hence, $t_n$ defines the amount of time spent by node $n$ in the jamming affected region, and expressed as $t_n = \frac{\rho_n(\theta_n)}{\upsilon_n}$. Hence, we get:

$$\mathbb{C}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}}) = \left[ \frac{E_{Tx} \times \mathtt{PS}}{\upsilon_n \times \mathtt{PTI}_n} \right] \frac{\rho_n(\theta_n)}{E_n^{res}} \tag{20}$$

The first part of Equation (20), i.e., $[\cdot]$, is a constant which is define it as $\alpha$. Therefore, from Equation (20), we get:

$$\mathbb{C}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}}) = \Lambda_n \frac{\rho_n(\theta_n)}{\upsilon_n} \tag{21}$$

where $\Lambda_n = \frac{E_{Tx}\mathtt{PS}}{E_n^{res}\mathtt{PTI}_n}$.

**Lemma 3.** *$\Lambda_n$ satisfies the constraint — $0 < \Lambda_n < \infty$.*

*Proof.* The energy required to transmit one bit, i.e., $E_{Tx}$, is always greater than zero. Additionally, in any protocol, the size of a packet must be greater than zero. Therefore, we conclude that $\Lambda_n > 0$.

On the other hand, the denominator part of $\Lambda_n$ is also greater that zero, as $E_n^{res} > 0$ and $\mathtt{PTI} > 0$. Therefore, we conclude that $\Lambda_n < \infty$. □

Hence, using Equations (18) and (21), the utility function $\mathbb{U}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ of each follower $n$ is defined as follows:

$$\mathbb{U}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}}) = \left(1 - \frac{\alpha_n \rho_n(\theta_n)}{2r_c E_n^{res}}\right) - \Lambda_n \frac{\rho_n(\theta_n)}{\upsilon_n} \tag{22}$$

Therefore, in the presence of jamming node(s), each follower $n$, i.e., each NN $n \in \Delta\mathcal{N}$, tries to *maximize its utility function* $\mathbb{U}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ while satisfying the following constraints along with the constraints mentioned in Equations (14), (15), and (17):

$$\left.\begin{array}{r} \rho_n(\theta_n) \leq 2r_c, \quad 0 < \alpha < \infty, \\ 0 < E_n^{res} \geq [\Lambda_n \rho_n(\theta_n) + \alpha_n \rho_n(\theta_n)]. \end{array}\right\} \tag{23}$$

## V. Existence of Stackelberg-Nash Equilibrium

In M-JAW, each node $n \in \Delta\mathcal{N}$ decides their strategy in a distributed fashion, i.e., non-cooperatively. We define the generalized Stackelberg-Nash equilibrium (GSNE) [28], [29] of M-JAW in Definition 2. In a Stackelberg game, each follower decides his/her strategy non-cooperatively. On the other hand, the leader decides its strategy to ensure a high payoff of its own and the overall system. Therefore, the Stackelberg game cannot always ensure the presence of GSNE. Hence, we investigate the existence of GSNE in the context of M-JAW, in Theorem 2.

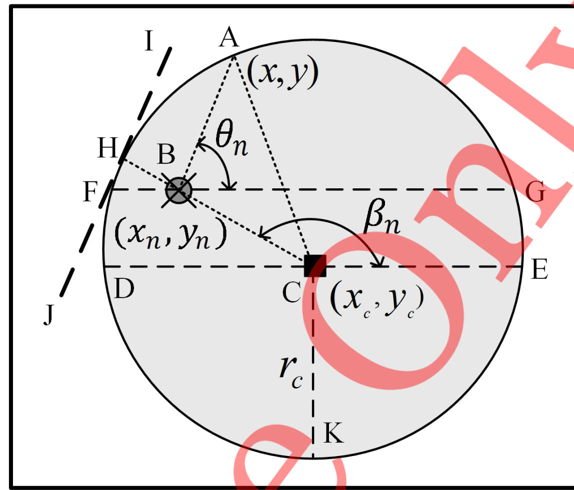



Fig. 2: The Direction Movement of an Affected Node

**Definition 2.** *We define the generalized Stackelberg-Nash equilibrium (GSNE) of M-JAW as the tuple $< \upsilon_{\boldsymbol{n}}^*, \theta_{\boldsymbol{n}}^* >$, where $\upsilon_n^*$ signifies the optimum velocity of the jamming affected node $n$ and $\theta_n^*$ denotes the optimum angle of mobility of node $n$, which satisfies the following inequality.*

$$\mathbb{U}_n\left(\upsilon_n^*, \theta_n^*, \upsilon_{-\boldsymbol{n}}^*, \theta_{-\boldsymbol{n}}^*\right) \geq \mathbb{U}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}^*, \theta_{-\boldsymbol{n}}^*) \tag{24}$$

**Theorem 2.** *Given the center $(x_c, y_c)$ and radius $r_c$ of the curve-fitted circle, there exists a GSNE, where each node $n \in \Delta\mathcal{N}$ satisfies the following inequality mentioned in Equation (24).*

*Proof.* We consider that the center of the curve-fitted circle is at point $C$ having coordinate $(x_c, y_c)$, and jamming affected node $n \in \Delta\mathcal{N}$ is at point $B$ having coordinate $(x_n, y_n)$. Thereafter, node $n$ moves with an angle $\theta_n$ towards point $A$ having coordinate $(x, y)$, as shown in Figure 2. The distances $\overline{AB}$, $\overline{BC}$, and $\overline{CA}$ are denoted as $\rho_n(\theta_n)$, $\mu_n(\beta_n)$, and $r_c$, respectively. Mathematically,

$$\rho_n(\theta_n) = \sqrt{(x - x_n)^2 + (y - y_n)^2} \tag{25}$$

$$\mu_n(\beta_n) = \sqrt{(x_c - x_n)^2 + (y_c - y_n)^2} \tag{26}$$

From Figure 2, we get that $\angle ECB = \beta_n$ and $\angle GBA = \theta_n$.

$$\frac{\partial^2 \mathbb{U}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})}{\partial {\theta_n}^2} = -\left[\frac{\alpha_n}{2r_c}\frac{\Lambda_n}{\upsilon_n}\right]\left[\frac{1}{[\rho_n(\theta_n) + \mu_n(\beta_n)\cos(\beta_n - \theta_n)]^2}\right]\left[\begin{array}{r} \rho_n(\theta_n)\mu_n(\beta_n)\cos(\beta_n - \theta_n) - [\mu_n(\beta_n)]^2\cos^2(\beta_n - \theta_n) \\ -\rho_n(\theta_n)[\mu_n(\beta_n)]^2\sin^2(\beta_n - \theta_n) \\ +\frac{[\mu_n(\beta_n)]^2}{2}\sin 2(\beta_n - \theta_n)\frac{\partial \rho_n(\theta_n)}{\partial \theta_n} \end{array}\right] \tag{67}$$

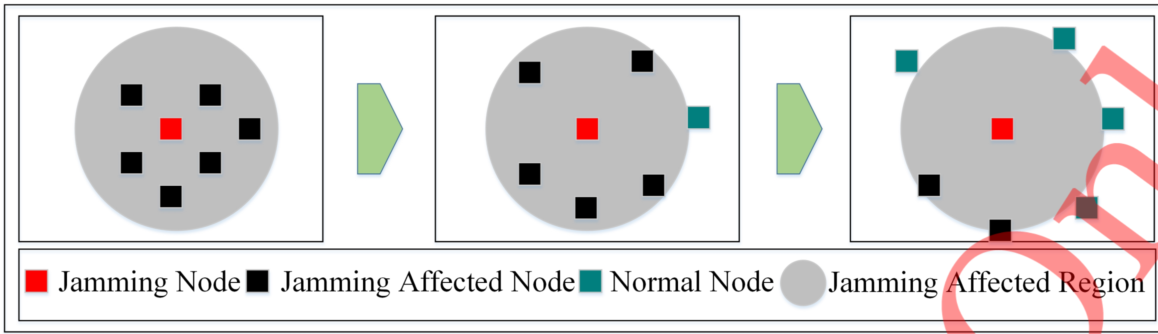



Fig. 3: Graphical snapshot of the proposed RMM



Therefore, $\angle GBC = (180^\circ - \beta_n)$, as $\overline{DE}$ and $\overline{FG}$ are parallel. Hence,

$$\angle ABC = \angle GBA + \angle GBC = \theta_n + (180^\circ - \beta_n) \tag{27}$$

We consider that $\angle BCA = \gamma$. Therefore, from $\triangle ABC$, we get:

$$\begin{aligned} \angle BAC &= 180^\circ - (\angle ABC + \angle BCA) \\ &= (\beta_n - \theta_n - \gamma) \end{aligned} \tag{28}$$

According to the *Law of Sines* [30], we observe that in a triangle, the ratio of the length of the sides and the sine of corresponding opposite angle is the same. Hence, from Figure 2, we get:

$$\begin{aligned} & \frac{\sin\angle BCA}{\rho_n} = \frac{\sin\angle ABC}{r_c} = \frac{\sin\angle BAC}{\mu_n} \\ \Rightarrow & \frac{\sin\gamma}{\rho_n} = \frac{\sin(\beta_n - \theta_n)}{r_c} = \frac{\sin(\beta_n - \theta_n - \gamma)}{\mu_n} \end{aligned} \tag{29}$$

From Equation (29), we get:

$$\left.\begin{aligned} \sin\gamma &= \frac{\rho_n(\theta_n)}{r_c}\sin(\beta_n - \theta_n) \\ \cos\gamma - \cot(\beta_n - \theta_n)\sin\gamma &= \frac{\mu_n(\beta_n)}{r_c} \end{aligned}\right\} \tag{30}$$

From Equation (30), we get:

$$\begin{aligned} & \sqrt{1 - \left[\frac{\rho_n(\theta_n)}{r_c}\sin(\beta_n - \theta_n)\right]^2} - \frac{\rho_n(\theta_n)}{r_c}\cot(\beta_n - \theta_n) \\ & \qquad \sin(\beta_n - \theta_n) = \frac{\mu_n(\beta_n)}{r_c} \\ \Rightarrow & \, {r_c}^2 - \rho_n(\theta_n)^2 \sin^2(\beta_n - \theta_n) \\ & \qquad = [\rho_n(\theta_n)\cos(\beta_n - \theta_n) + \mu_n(\beta_n)]^2 \end{aligned} \tag{31}$$

Therefore, taking the first order partial derivative of Equation (31) with respect to $\theta_n$, we get:

$$\frac{\partial\rho_n(\theta_n)}{\partial\theta_n} = -\frac{\rho_n(\theta_n)\mu_n(\beta_n)\sin(\beta_n - \theta_n)}{\rho_n(\theta_n) + \mu_n(\beta_n)\cos(\beta_n - \theta_n)} \tag{32}$$

On the other hand, taking the first order partial derivative of Equation (22) with respect to $\rho_n(\theta_n)$, we get:

$$\frac{\partial\mathbb{U}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})}{\partial\rho_n(\theta_n)} = -\left[\frac{\alpha_n}{2r_c} + \frac{\Lambda_n}{\upsilon_n}\right] \tag{33}$$

Hence, from Equations (32) and (33), we get:

$$\frac{\partial\mathbb{U}_n(\cdot)}{\partial\theta_n} = \left[\frac{\alpha_n}{2r_c} + \frac{\Lambda_n}{\upsilon_n}\right]\left[\frac{\rho_n(\theta_n)\mu_n(\beta_n)\sin(\beta_n - \theta_n)}{\rho_n(\theta_n) + \mu_n(\beta_n)\cos(\beta_n - \theta_n)}\right] \tag{34}$$

We compute the second order partial derivative of Equation (22) with respect to $\theta_n$, as shown in Equation (67). We argue that the second order partial derivative of $\mathbb{U}_n(\upsilon_n, \theta_n)$ with respect to $\theta_n$ has a negative value, as $\frac{\partial\rho_n(\theta_n)}{\partial\theta_n} < 0$. Therefore, we conclude that the generalized Stackelberg-Nash equilibrium (GSNE) exists for the proposed scheme, M-JAW. □

**Corollary 1.** *In order to get out of the jamming affected region, each jamming affected node $n \in \delta\mathcal{N}_n$ has to cover minimum distance $\rho_n^{min}$, and has to travel for minimum $t_n^{min}$ amount of time. Mathematically,*

$$\left.\begin{aligned} \rho_n^{min} &= r_c - \sqrt{(x_c - x_n)^2 + (y_c - y_n)^2} \\ t_n^{min} &= \frac{\rho_n^{min}}{\upsilon_n^{max}} \end{aligned}\right\} \tag{35}$$

*Proof.* From Theorem 2, we calculate the minimum distance to be covered by a node $n$, i.e., $\rho_n = \rho_n^{min}$, which is evaluated from:

$$\frac{\partial\mathbb{U}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})}{\partial\theta_n} = 0 \Rightarrow \theta_n = \beta_n, (180^\circ - \beta_n) \tag{36}$$

It may be noted that $(180^\circ - \beta_n)$ and $\beta_n$ belong to two different quadrants. We consider that $\theta_n$ has the only viable solution $\theta_n = \beta_n$, as by moving at an angle $(180^\circ - \beta_n)$, node $n$ has to cover the maximum distance, as depicted in Figure 2. Therefore, from Figure 2, we get $\rho_n^{min} = \overline{BH}$, where $\theta_n = \beta_n$. On the other hand, $\overline{BH}$ and $\overline{CB}$ form a single line $\overline{CH}$, where $\overline{CH} = r_c$. Therefore, we get:

$$\rho_n^{min} = r_c - \sqrt{(x_c - x_n)^2 + (y_c - y_n)^2} \tag{37}$$

As mentioned in Section IV-C, the maximum velocity of node $n$ is denoted by $\upsilon_n^{max}$. Therefore, the minimum time, $t_n^{min}$, node $n$ needs to travel is evaluated as — $t_n^{min} = \frac{\rho_n^{min}}{\upsilon_n^{max}}$ □

## VI. Proposed Algorithms

In M-JAW, after the deployment of nodes over a terrain, each node evaluates the neighborhood graph, and accordingly forms the RNG using Algorithm 1. Thereafter, to circumnavigate the jamming effect, the *jamming affected region* (JAR) needs to be identified using Algorithm 2. After identifying the jamming affected region, each node needs to choose its action *rationally*, based on the available strategies, i.e., the action needs to be taken based on the rational mobility model (RMM), as depicted in Figure 3. Hence, we propose three different algorithms, which are needed to be executed sequentially, to ensure QoS in the presence of a proactive or constant jamming node. These algorithms are as follows — (a )*RNG Formation*, (b) *JAR Identification*, and (c) *RMM Implementation* Algorithms, i.e., Algorithms 1, 2, and 3, respectively.

### A. RNG Formation Algorithm

Algorithm 1 is executed by each node $n \in \mathbb{N}$, distributively. Using this algorithm, each node $n \in \mathbb{N}$ optimizes the number of edges available over the terrain to ensure QoS in terms of packet loss and energy consumption for successful communication.

**Algorithm 1** RNG Formation Algorithm

**INPUTS:**
$G(\mathbb{N}, E)$ ▷ Neighborhood graph of network
**OUTPUT:**
$G_{rng}(\mathbb{N}, E_{rng})$ ▷ Updated RNG of network
**PROCEDURE:**
$E_{rng} \leftarrow \{\emptyset\}$
**for** each $n \in \mathbb{N}$ **do**
  $E^n_{rng} \leftarrow \{\emptyset\}$; ▷ Initialization of $E^n_{rng}$
  **for** (each $p \in \mathcal{N}_n$) && $(\{(p,n)\} \notin E_{rng})$ **do**
    **for** each $q \in \mathcal{N}_p$ **do**
      **if** $(q \notin \mathcal{N}_n)$ && $(\max(d_{pq}, d_{qn}) \geq d_{pn})$ **then**
        $E^n_{rng} \leftarrow E^n_{rng} \cup \{(p,n)\}$;
      **end if**
    **end for**
  **end for**
  $E_{rng} \leftarrow E_{rng} \cup E^n_{rng}$;
**end for**
**return** $G_{rng}(\mathbb{N}, E_{rng})$;

### B. JAR Identification Algorithm

The proposed *JAR Identification Algorithm*, i.e., Algorithm 2, is executed by the *CU*. If the CU gets any ERROR message from any node $n \in \mathbb{N}$ deployed over a terrain, it initiates Algorithm 2. Considering that at time instant $t_0$, the CU receives an ERROR message, at time instant $t_1$, where $t_1 > t_0$, the CU requests each node to explore its neighbor nodes. Hence, at time instant $t_2$, where $t_2 > t_1$, if any node finds mismatch in its neighbor node table from its earlier neighbor node table, i.e, neighbor node table at time instant $t_2^- < t_2$.

At node $n$, the set of neighbor nodes in the neighbor node table at time instants $t_2^-$ and $t_2$ are defined as $\mathcal{N}_n|_{t_2^-}$ and $\mathcal{N}_n|_{t_2}$, respectively. Hence, node $n$ calculates $\Delta\mathcal{N}_n$. For any node $n \in \mathbb{N}$, if $\Delta\mathcal{N}_n$ is an empty set, the node $n$ sends an UPDATE message to the CU with null value. Otherwise, node $n \in \mathbb{N}$ sends an UPDATE message to the CU having information of sets $\Delta\mathcal{N}_n$. After receiving responses from each node $n \in \mathbb{N}$, the CU calculates the change $\Delta\mathcal{N}_n, \forall n \in \mathbb{N}$ in the neighbor list, i.e., the elements of $\Delta\mathcal{N}|^-_{\delta t=(t_2^- - t_2)}$, and $\Delta\mathcal{N}_n|^+_{\delta t=(t_2^- - t_2)}$, which are defined as follows:

**Algorithm 2** JAR Identification Algorithm

**INPUTS:**
$\mathcal{N}_n|_{t_2^-}, \forall n \in \mathbb{N}$
$\mathcal{N}_n|_{t_2}, \forall n \in \mathbb{N}$
**OUTPUT:**
$\Delta\mathcal{N}$
**PROCEDURE:**
$\Delta\mathcal{N} \leftarrow \{\emptyset\}$
**for** each $n \in \Delta\mathcal{N}$ **do**
  Calculate $\Delta\mathcal{N}|^-_{\delta t=(t_2^- - t_2)}$; ▷ Set of change in neighbor nodes within time instants $t_2^-$ and $t_2$
  Calculate $\delta\mathcal{N}|^+_{\delta t=(t_2^- - t_2)}$; ▷ Set of newly discovered neighbor nodes at time instant $t_2$
  Calculate $\Delta\mathcal{N}_n$;
  $\Delta\mathcal{N} \leftarrow \Delta\mathcal{N} \cup \Delta\mathcal{N}_n$ ▷ Set of jamming affected nodes at time instant $t_2$
**end for**
**return** $\Delta\mathcal{N}$;

**Algorithm 3** RMM Implementation Algorithm

**INPUTS:**
$\theta_{min}$, $\theta_{max}$, $(x_c, y_c)$, $r_c$, $\alpha$, $E^{res}_n$
**OUTPUTS:**
$\upsilon^*_n, \theta^*_n$
**PROCEDURE:**
Choose a value for $\theta_n$, where $\theta_{min} \leq \theta_n \leq \theta_{max}$;
Calculate $\mathbb{U}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ using Equation (22);
**do**
  Choose an optimum value for $\theta^\dagger_n$;
  Calculate $\mathbb{U}^\dagger_n(\upsilon^\dagger_n, \theta^\dagger_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}})$ using Equation (22);
**while** $(\mathbb{U}^\dagger_n(\upsilon^\dagger_n, \theta^\dagger_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}}) \geq \mathbb{U}_n(\upsilon_n, \theta_n, \upsilon_{-\boldsymbol{n}}, \theta_{-\boldsymbol{n}}))$;
$\theta^*_n \leftarrow \theta^\dagger_n$;
$\upsilon^*_n \leftarrow \upsilon^\dagger_n$;
**return** $\upsilon^*_n, \theta^*_n$;

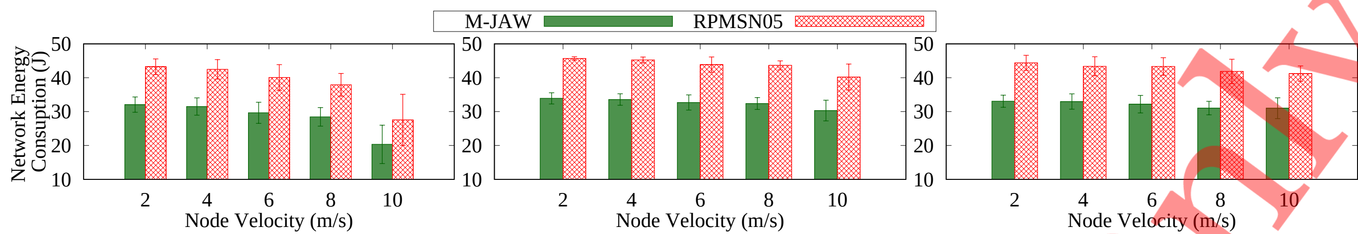
$$\Delta\mathcal{N}_n|^-_{\delta t=(t_2^- - t_2)} = \left[\left(\mathcal{N}_n|_{t_2^-}\right) - \left(\mathcal{N}_n|_{t_2}\right)\right] \quad (76)$$

$$\Delta\mathcal{N}_n|^+_{\delta t=(t_2^- - t_2)} = \left[\left(\mathcal{N}_n|_{t_2}\right) - \left(\mathcal{N}_n|_{t_2^-}\right)\right] \quad (77)$$

where $\Delta\mathcal{N}_n|^-_{\delta t=(t_2^- - t_2)} \neq \Delta\mathcal{N}_n|^+_{\delta t=(t_2^- - t_2)}$. Hence, we evaluate the set of jamming affected nodes in the terrain, i.e., $\Delta\mathcal{N}$, as follows:

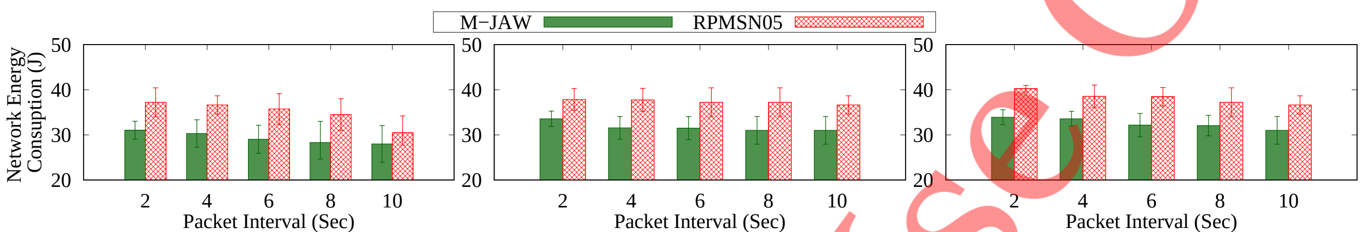
$$\Delta\mathcal{N}_n = (\Delta\mathcal{N}_n|^-_{\delta t=(t_2^- - t_2)})/(\Delta\mathcal{N}_n|^+_{\delta t=(t_2^- - t_2)}) \quad (78)$$

Thereafter, the CU finds the location of each jamming affected node $n \in \Delta\mathcal{N} \subseteq \mathbb{N}$, i.e., $(x_n, y_n)$ at time instant $t_2^-$, where $\Delta\mathcal{N} = \bigcup_{n \in \Delta\mathcal{N}} \Delta\mathcal{N}_n = \bigcup_{n \in \Delta\mathcal{N}} (\Delta\mathcal{N}_n|^-_{\delta t=(t_2^- - t_2)} \cup \Delta\mathcal{N}_n|^+_{\delta t=(t_2^- - t_2)})$. Thereafter, the CU evaluates the center and radius of the circle covering the jamming affected region using Equation 13, respectively.



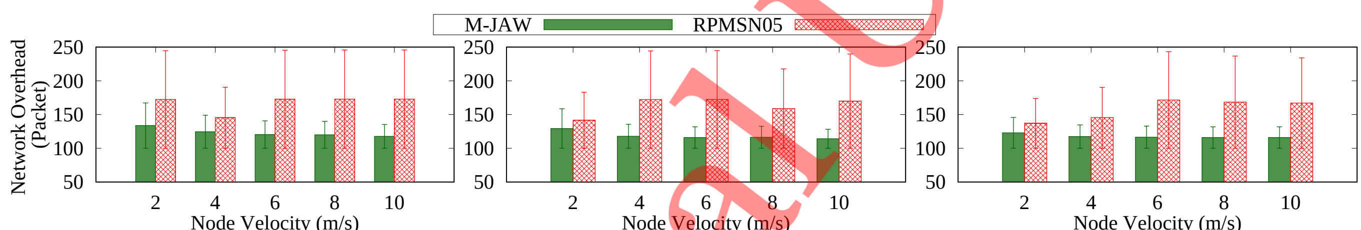

(a) Packet Interval: 4 Sec (b) Packet Interval: 8 Sec (c) Packet Interval: 10 Sec

Fig. 4: Overall Energy Consumption of Network with 200 Nodes




(a) Node Velocity: 2 m/s (b) Node Velocity: 6 m/s (c) Node Velocity: 10 m/s

Fig. 5: Overall Energy Consumption of Network with 200 Nodes




(a) Packet Interval: 4 Sec (b) Packet Interval: 8 Sec (c) Packet Interval: 10 Sec

Fig. 6: Network Overhead with 200 Nodes

### C. RMM Implementation Algorithm

This algorithm takes the outcome of the rule-based approach performed by the CU. Thereafter, Algorithm 3 is executed by each node $n \in \Delta\mathbb{N}$, distributively. Using this algorithm, each node $n$ decides its strategy, rationally, while choosing an optimum strategy, i.e., direction, to avoid the jamming affected region. Hence, considering the strategy of the CU, each node $n$ aims to maximize the payoff of $\mathbb{U}_n(\theta_n, \upsilon_n)$.

## VII. Performance Evaluation

### A. Simulation Parameters

For evaluating the performance of M-JAW, we deployed the nodes and jammers, randomly, over the region specified in Table I. We performed the simulation in MATLAB platform. Additionally, we chose the source-destination pair, randomly. We assumed that each sender node has packets to transmit, and initial 10 packets are successfully delivered to the destination node.

### B. Benchmark

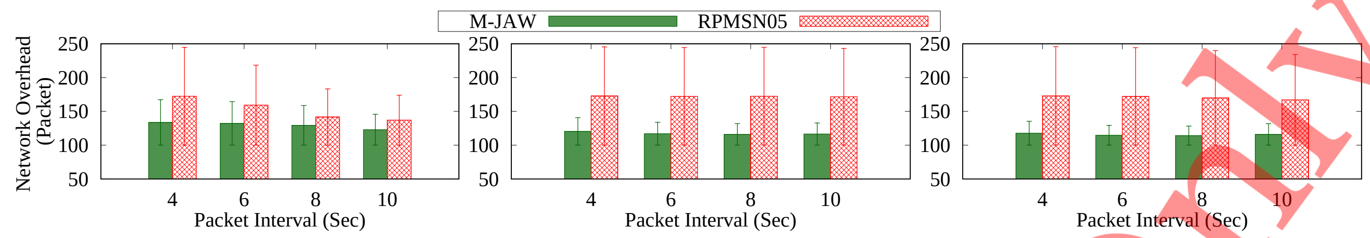
The performance of the proposed scheme, M-JAW, is evaluated by comparing it with a state-of-the-art mobility-based jamming avoidance approach — the RPMSN05 [11]. In RPMSN05, Ma *et al.* [11] considered a network with mobile nodes in the presence of single jammer. The authors proposed a random mobility model for the jamming to affected nodes. However, they did come up with a novel mobility model for avoiding jamming in the WSN environment. Thus, we can improve the energy consumption of each node and network overload using the proposed scheme, M-JAW over RPMSN05.

TABLE I: Simulation Parameters

| **Parameter** | **Value** |
|---|---|
| Simulation area | $1000\ m \times 1000\ m$ |
| Number of jammers | 4 |
| Number of normal nodes | 200-800 |
| Initial energy of each node | 20 $J$ [23] |
| Communication range | 100 $m$ |
| Node velocity | 2-10 $m/s$ |
| Packet interval | 4-10 $sec$ |
| Packet size | 2034 $bytes$ |
| Energy consumption at Tx and Rx | 50 $nJ/bit$ [27] |
| Energy consumption at amplifier | 100 $pJ/bit\text{-}m^2$ [27] |
| Energy consumption due to mobility | $0.1v\ mW\text{-}meter/s$ |

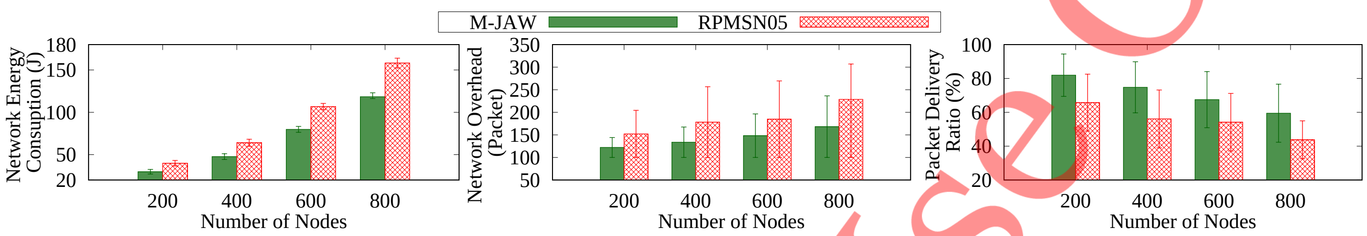
### C. Performance Metrics

The performance of M-JAW is evaluated using the following metrics.




(a) Node Velocity: 2 m/s (b) Node Velocity: 6 m/s (c) Node Velocity: 10 m/s

Fig. 7: Network Overhead with 200 Nodes




(a) Network Energy Consumption (b) Network Overhead (c) Packet Delivery Ratio

Fig. 8: $\upsilon$ = 4 m/s, Packet Interval = 6 Second

*Energy Consumption of Network:* Each time a packet is sent or received by a node, the residual energy of that node gets depleted. If the residual energy of a node becomes very small, the node is considered as 'dead' node. Additionally, when the first node dies in the network, is considered as the network lifetime. As an energy-constrained network, the energy consumption of a WSN is one of the important performance metrics.

*Network Overhead:* The number of packets sent by the nodes over the network is defined as network overhead. With an increase in network overhead, the network gets more congested. Additionally, packet delivery probability gets reduced.

*Packet Delivery Ratio:* It is calculated as a quantified value of packets delivered to the total number of packets sent.

### D. Results and Discussions

In simulation, we consider that the maximum packet rate of each node is 15 packets/min. We considered a topology with 200 normal nodes and 4 jammers. Using M-JAW, the network energy consumption is improved by 11.42–20.36%, than using RPMSN05. From Figure 4, we observe that with varying packet interval, M-JAW performs better than RPMDN05. Similarly, from Figure 5, we observe that with varying node velocity, M-JAW consumes a reduced amount of energy than RPMSN05. Therefore, we conclude that M-JAW performs better than RPMSN05 in terms of energy consumption. On the other hand, we observe that with the increase in node velocity and packet interval, respectively, the network energy consumption reduces, because of the reduction in packet retransmission path length covered during mobility.

On the other hand, the proposed scheme, M-JAW, reduces the network overhead by 44.13 – 50.12% than RPMSN05. Figure 6 illustrates that the network overhead is less using M-JAW than using RPMSN05. Similarly, from Figure 7, we observe that the network overhead is at least 44.13% less using M-JAW than using RPMSN05. Hence, we can conclude that the network overhead reduces significantly using M-JAW. Additionally, it reflects that network lifetime increases using M-JAW than using RPMSN05. Additionally, we see that with the increase in node velocity and packet interval, respectively, the network overhead gets reduced as a result of a reduction in the number of packets transmitted in a jammer affected area during a certain period.

We varied the number of nodes placed over the terrain while considering that the velocity of each node is 4 $m/s$ and the packet interval is 6 seconds. In Figure 8(a), we observe that the network energy consumption reduces by 23.7–26.0% using M-JAW than using RPMSN05. On the other hand, Figure 8(b) reflects that the network overhead reduces by 24.64 – 35.88% using M-JAW than using RPMSN05. On the contrary, Figure 8(c) depicts that the packet delivery ratio improves by 41.07% using M-JAW than using RPMSN05. Additionally, we see that with the increase in the number of available nodes, the network energy consumption and overhead increases, because of the energy consumption and control (hello) packet transmission by each node during the neighbor finding phase. Additionally, the network energy consumption decreases using M-JAW due to the optimized mobility of nodes than using RPMSN05. On the other hand, with the increase in the number of nodes, the packet delivery ratio gets reduced, because of an increase in the available paths between the sender and the destination nodes.

## VIII. Conclusion

In this paper, we formulated a game-theoretic approach to ensure QoS in the presence of jammer in mobile WSN. We used single leader multiple follower Stackelberg game. Based on the proposed approach, M-JAW, we show how using the proposed mobility model, i.e., RMM, each node ensures QoS, while consuming less energy and less network overhead. The simulation results show that the proposed scheme outperforms the existing scheme.

Future extension of this work includes understanding how QoS can be improved while considering the channel fading and predicting jamming phenomena in advance in mobile WSN for increasing in network lifetime by reducing energy consumption and network overhead. This work also can be extended to understand how QoS of the network will be ensured while considering the mobile jammers instead of considering static jammers. Additionally, we can investigate the effect of mobile jammers, while ensuring QoS of the network.

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