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A Stochastic Distribution Based Methodology to Estimate Control Phase Time for Software-Defined Radios in Tactical MANETs

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ABSTRACT Unlike commercial networks, the tactical networks drive in a critical environment and without a backbone infrastructure. These networks involve mission-critical operations that are dependent on the rapid and reliable transfer of delay-sensitive data to conduct command and control (C2). Owing to the decentralized and dynamic nature, tactical networks need to survive by maintaining seamless and simultaneous time-sensitive communication among software-defined radios (SDRs). Under mobility and dynamic network topology, link status continuously changes that cause substantial packet loss, and degrade network performance. It is challenging to maintain the connectivity between communicating nodes and find a suitable time for sending control messages (e.g., packet forwarding and route discovery), known as control phase time (CPT). Given a maximum transmission range for narrowband (NB) and wideband (WB) communication, the knowledge of link duration between communicating radios are of major concern, particularly for low latency and reliable communication requirements. Many existing techniques focus on topology control by exchanging mobility parameters in control transmissions, increasing the delay in data transmission. Therefore, it is a non-trivial task to calculate the expected time for the control transmissions due to the confrontation of speed and random movement of nodes. This paper presents a novel methodology to estimate a suitable time to execute the control phase based on the lifetime of communication links between SDRs in tactical MANETs. It uses stochastic distribution to make a network capable of effectively figuring out operative connectivity. The proposed methodology evaluates the maximum network connectivity based on the distances between communicating radios and radio transmission ranges for different quality-of-service (QoS) requirements. The simulation results validate that the proposed methodology's CPT estimations are more appropriate for the timely link-formations in tactical radio MANETs. The proposed technique is generic and can be applied to any MANET environment using different mobility models.

INDEX TERMS Mobile ad hoc networks, tactical network, time-critical data, software-defined radio.

I. INTRODUCTION

Tactical networks are mission-critical, congested, and delay-sensitive. These networks are usually distributed and operated in infrastructure-less terrains with self-forming and self-healing capabilities. It uses mobile ad hoc networks (MANETs) for instant and better communication of voice and data between software-defined radios (SDRs) in a dynamic environment.

In MANETs, the network topology incessantly fluctuates and faces unpredictable topology changes owning to mobility and thus, the network connectivity may not be preserved. As the moving speed increases, the network connectivity proportion decreases significantly and affects the transmission performance [1]. Many topology control algorithms are proposed to identify the network connectivity [2], [3]. The schemes involve an exchange of network or mobility

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parameters in topology update intervals. These recurrent updates lead to the insignificant use of bandwidth and add latency in the network [4], [5].

In a tactical network, SDRs need to have reliable non-intermittent connectivity in different mobility scenarios with less communication delays. Many proposed schemes focus on delay tolerance and quality-of-service (QoS) requirements in tactical networks [6]–[8]. However, these schemes do not handle the link connectivity problem in dynamic network conditions. Particularly in a tactical network, the radios are limited in number, which usually operates in the form of a group e.g., troops or platoons; therefore, the mobility patterns can be sparse or congested. This includes the node's position and velocity relative to other nodes. Whereas in some cases (e.g., disaster areas), the movement of radios is random, and their position is independent of each other [9]. These factors determine the stability of links and successful communication patterns since the communication is peer-to-peer [10], [11]. In this paper, we are interested in the connectivity of links concerning individual nodes at the mesoscopic level.

In conjunction with high mobility cases, we cannot assume that any two communicating nodes will be within the transmission range of each other for a longer duration and have few seconds of opportunity to set up and transfer data. In tactical configurations, it is a primary challenge to estimate suitable time for control transmissions based on the trade-off between link connectivity and reliability of the network. Depending on physical location, the nodes may disconnect if they go beyond the effective communication range, measured in terms of the distance between communicating radios [12]. Therefore, it is required to check radios' connectivity for non-intermittent communication in different mobility scenarios; otherwise, insistent packet losses degrade the network performance [13].

In mission-critical networks, the path of nodes can be completely random or their position at any point in time may be stated by its previous position and speed. It is superficial to say that during data transmissions, nodes are static. In tactical scenarios, nodes continue their movement though it is slow or static for a pause time. The primary factor that affects the changes in distance between radios is that the communication pattern is random.

This paper presents a methodology to estimate the lifetime of connectivity links between communicating radios in terms of distance. Based on the estimation, a network can run a control phase to keep the communication impeccable before losing the required connectivity ratio for a safe run of the control phase. In the tactical network perspective, the reference point group mobility model (RPGM) is used for methodology validation. The RPGM model provides relatively higher link duration and results in high throughput gain and low control overhead [14]. However, the radios are deployed in an area of hundreds of kilometers, therefore result in low link connectivity between communicating radios and make frequent update intervals. The normal distribution is used to analyze the distance between communicating nodes for the network's operation time. A threshold distance that is the maximum transmission range of radios (e.g., for narrowband (NB) and wideband (WB) communication) is employed to check the maximum network connectivity. To maintain QoS and reliability, the proposed methodology measures control phase time (CPT) intervals for required application based on the distance assessment with respect to the threshold value. The parameters of normal distribution; mean (μ) and standard deviation (σ) are effectually utilized for distance assessment, calculated over speed and time for the purpose.

Intuitively, the finding of the instant at which a topology change occurs in modeling can considerably improve the accuracy of network reliability estimation. Therefore, if we know the mobility parameters of two communicating radios, we can determine the link lifetime between the radios [15]. The proposed methodology is applicable for all MANETs, following any mobility model because no particular parameters exchange is involved. However, in those mobility cases (e.g., RWP, Random walk mobility, Random direction mobility, etc.), where nodes have independent mobility patterns, the network may face frequent control runs and consume larger bandwidth in connection or topology maintenance.

Considering mobility and the nature of delay-sensitive communications, finding appropriate control phase time and duration is a non-trivial task. The change in the surrounding, such as connectivity, triggers routing updates to maintain data sending paths. It requires appropriate network connectivity for the control phase run, which differs depending upon the speed of nodes. As the speed of nodes increases, more randomness is encountered and incites frequent control phase runs. The proposed methodology yields significant research contributions to the field. It provides:

1) A stochastic distribution based method to estimate reliable link connectivity between communicating nodes in different mobility scenarios.
2) Adjustment of control phase time to meet certain QoS levels required by the application in mobile environments.
3) Prediction on link lifetime, which can help determine the reliability of a route and the best possible time of control messaging based on the distance measurement concerning maximum transmission ranges.
4) Estimation of reliable network connectivity bounds computed using normal distribution parameters for different applications, e.g., voice and data including email, file transfers, critical telemetry, etc.

II. RELATED WORK

Few considerable researches have been carried out on link connectivity and reliability of nodes connections in a distributed wireless network environment. A Monte Carlo simulation-based method for MANETs is proposed in [16] to evaluate network reliability by using link disconnection and border time. The method determines the incremental time at which the change in topology may occur. A scheme to estimate link stability in MANETs is proposed by [17] based on link connectivity changes on the network layer. It focuses on a probabilistic model and proposes a routing protocol that operates on the estimated link stability. A strategy is proposed in [18], which uses hello messages to detect link failure in MANETs. It also presents algorithms to minimize delay incurred during link re-connectivity for better network performance. An approach for mobility prediction in MANET is proposed in [19] that precisely predicts the mobility pattern and link quality. The scheme allows for the establishment of stable connections and experiences occasional node disconnection. An efficient connectivity determination for IoT applications is proposed in [20]. The method provides testing algorithms for components connectivity created using node connectivity random graph. A closed-form analytical model for the connectivity and route lifetime for multihop mobile networks is presented in [21]. The model evaluates the effect of different network characteristics, include number of nodes, hops, transmission range, speed of nodes, and derive bounds of link and route lifetime. The graph-based methods for vehicular ad hoc networks (VANETs) connectivity analysis are discussed in [22]. The study shows the behavior of the graph-based method compared to the use of probabilistic models to estimate the connectivity probability. A study on connection duration in freeway VANETs is presented in [23], which considers connectivity probability and communication time between vehicles.

The performance of long-range connectivity scenarios for military applications is compared in [24]. The study highlights the accurate parameters prediction such as size of military units, network area size according to mission types. A methodology is proposed in [25], which uses a free space propagation model to determine node connectivity during network operation. A traffic-centric analysis on expected time delay and connectivity distance in VANETs is presented in [26]. The study adopted a mesoscopic vehicular mobility model in a multi-lane highway with steady-state traffic conditions. The prediction on link availability to optimize the link capacity for high mobility wireless ad hoc networks is proposed in [27]. The algorithm provides the prediction based on the characteristics of the link and transmission modes. Furthermore, a routing method is proposed based on the link availability analysis to reduce the routing overhead caused by mobility. An extended link duration prediction (ELDP) model to estimate the link connectivity between vehicles is proposed in [28]. The model estimates the relative velocity distribution and computes the expected link duration between vehicles based on relative speeds, inter-vehicle distance, the impact side road units, and vehicles movement patterns.

The MANETs encounter link failures and are required to have frequent topology updates or control messages transmissions to retain the network connectivity. This becomes perilous when the mobile nodes are involved in exchanging mission-critical data and have few seconds to hold the connectivity. In this situation, the prior knowledge on control messaging time can help to increase the reliability of the network and reduce the latency for better QoS requirements.

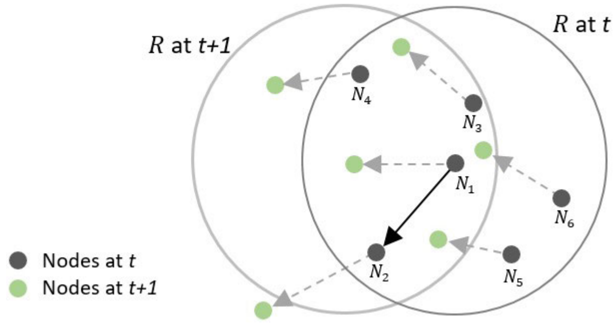

FIGURE 1. Position of paired nodes at time t and $t + 1$.

The schemes and studies mentioned above are focused on link stability estimation and quality of connections in mobile networks. Few methods involve exchanging messages to detect link failures, node's position, and speed to maintain the required connectivity, which increases the control messaging time. These approaches have overlooked the mission-critical nature of the tactical network and underestimated the reliability concern. However, our proposed CPT estimation methodology can estimate link connectivity and evaluate the expected control phase time in different mobility scenarios required for reliable and time-sensitive applications. The proposed model suggests different intervals for CPT based on the network requirement beforehand and uses these pre-computed intervals on the field. This drives the use of the adaptive control phase during network operation to sustain the frequent disconnection of data paths in dynamic network environments.

III. BACKGROUND

Mobility affects network performance on a larger scale due to connection and disconnection among communicating nodes. Depending on physical location, a node can communicate to its neighbors if they are in its effective transmission range, measured in terms of the distance between communicating nodes [29].

In mobile wireless network, suppose a node N_1 transmits data to node N_2, which is in its transmission range R at time t. When nodes move, the receiver N_2 goes out of the range R at time $t + 1$, as shown in Fig. 1. In multi-hop communication, if the node is connected to its 1-hop neighbor, providing a path to the destination, the disconnection provokes route error messages. The source node needs to send a route request to one of its direct neighbors to maintain the connectivity.

In corresponding to other communicating pairs in a network, the disconnection decreases the packet delivery ratio and severely affects network performance [30]. In a dynamic environment, the network topology changes rapidly and creates unpredictability on node movements, resulting in frequent link breaks. For tactical communication, the loss in connectivity disrupts exchanging mission-critical

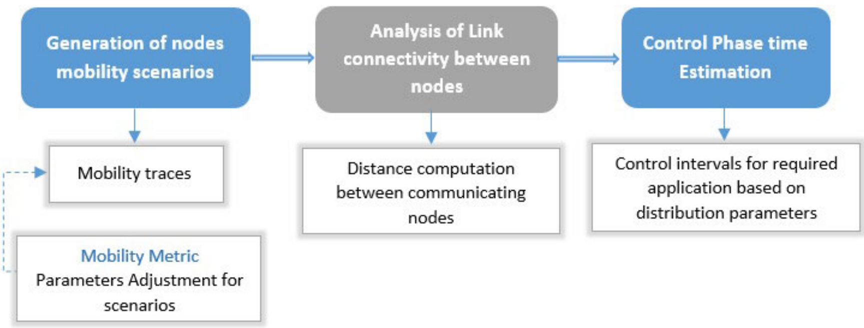

FIGURE 2. A methodology to estimate link connectivity and control phase intervals.

information. Therefore, it is important to find an innocuous time to run the control phase for incessant data transmission.

IV. PROPOSED METHODOLOGY

In a successful military operation, reliable communication is the key, and without non-intermittent connections, surveillance data may not be communicated properly. Therefore, there is a requirement to propose an efficient methodology for effective communication systems to increase command, control, communication, and intelligent surveillance efforts. The proposed methodology includes the generation of mobility scenarios for tactical communication based on radios' speed, the analysis on link connectivity between communicating nodes for the threshold distances that is the maximum transmission range of radios. Finally, it measures control phase time (CPT) intervals for required application based on the distance assessment for the threshold value, as shown in Fig. 2. The link connectivity estimation is performed for the network's operation time and probes the network for control messaging to keep the communication impeccable before losing the suitable connectivity ratio. The following is a brief description of the proposed methodology modules.

A. GENERATION OF NODES MOBILITY SCENARIOS

Mobility models emulate the nodes' movement pattern in targeted real-life applications includes their location, position, velocity, and acceleration which change over time. For realistic mobility patterns, trace-based mobility models are appropriate for accurate mobility traces [31], [32]. However, MANETs have not been instigated and deployed on a wider scale and obtaining real mobility traces is a major challenge. Therefore, various researchers use stochastic models representing mobility in a somewhat realistic fashion [33], [34].

In tactical network, the mobility pattern of radios may usually be influenced by specific reference radios in its neighborhood. The RPGM model is the better choice to imitate the movement of grouped nodes, e.g., platoons or troops, where the nodes' speed is correlated, as shown in Fig. 3. In the RPGM model, each group has a reference point, and its movement determines the mobility behavior of the whole group, including location, speed, and

FIGURE 3. Group mobility in tactical MANETs.

direction. In this model, a path is provided to the reference point determining the group trajectory, and nodes are uniformly distributed within the group's geographical scope. Each node of the group makes independent random movements being randomly placed around its logical center at each step.

The RPGM model involves a group motion vector $\overrightarrow{V_G}$ that provides a reference point to move from time t to $t+1$. At each time, new position is calculated by adding a random motion vector $\overrightarrow{RM}$ to the new selected reference point at time $t+1$. The $\overrightarrow{RM}$ is independent of the previous position of the node with a length that is uniformly distributed within a defined radius centered at the reference point along with its direction between 0 to 2π [35]. The motion vector of group member i at time t is defined in (1).

$$Vi^t = \overrightarrow{V_G} + \overrightarrow{RM_i^t} \tag{1}$$

In order to generate group mobility patterns for tactical communication, different speed values are considered. However, the movement pattern of each node is provided by an RPGM model itself.

B. ANALYSIS ON LINK CONNECTIVITY BETWEEN NODES

Link connectivity between nodes is the critical performance metric to be affected by mobility. Nodes' movement causes the link status changes, e.g. having the same transmission range when two nodes move far from each other and lost the connectivity. To analyze the connectivity between radios, we assume that all radios have global positioning system (GPS) and know their physical positions in the area. In the designed methodology, each node computes the distance for its receiver using the euclidean formula.

TABLE 1. Specification of narrowband and wideband waveform for their ranges.

Waveform	Range
Narrowband wavefrom	20-30 Km
Wideband waveform	10-20 Km

For communication between node i and node j, the distance between them must be smaller than the maximum transmission range i.e., $d_{i,j} \leq R$. The distance of communicating nodes changes depending on the speed of nodes and the mobility pattern.

The tactical SDRs communication requirements are achieved by using narrowband or wideband waveform. Usually, the NB waveform can provide long distance connectivity to the users, whereas the WB waveform works for smaller distances. The specification of NB and WB waveforms for ranges offered by typical VHF/UHF SDRs are listed in Table 1.

In the proposed methodology, we use a normal distribution to perform distance-based link connectivity estimation. The maximum transmission range of a node is identified in terms of distance denoted as threshold distance $TH\_distance$ and represents a one-hop distance. The methodology calculates mean μ_d to find average distances between nodes in communicating node pairs C_n at time t, as described in (2).

$$\mu_d = \frac{\sum_{t=1}^{C_n} d_{i,j}(t)}{C_n} \tag{2}$$

The parameter standard deviation σ_d calculates the deviation from the mean μ_d, as described in (3)

$$\sigma_d = \sqrt{\frac{\sum_{t=1}^{C_n}(d_{i,j}(t) - \mu_d)^2}{C_n}} \tag{3}$$

With the help of normal distribution, we can observe the link connectivity of communicating nodes using μ_d and σ_d compared to $TH\_distance$, as shown in Fig. 4. If the distance between communicating nodes falls under the area μ_d to $\mu_d + \sigma_d$, it is considered that 34.13% of communicating nodes have lost the connectivity. Similarly, the values under $\mu_d + \sigma_d$ to $\mu_d + 2\sigma_d$ and $\mu_d + 2\sigma_d$ to $\mu_d + 3\sigma_d$ identify 13.60% and 2.13% link connectivity lost respectively.

In group mobility, nodes follow reference point trajectory but move around it randomly within the group's scope. To maintain nodes connectivity, the source node needs to send a route request to one of its direct neighbors to preserve the communication.

C. ESTIMATION ON CONTROL PHASE TIME

In tactical networks, transmission reliability and latency are two major concerns. All the information exchange between radios is delay-sensitive and require to reach at receiving radio properly and in time. However, due to radios' mobility, the communication is disrupted, especially when the communicating pairs move randomly and are at large distances.

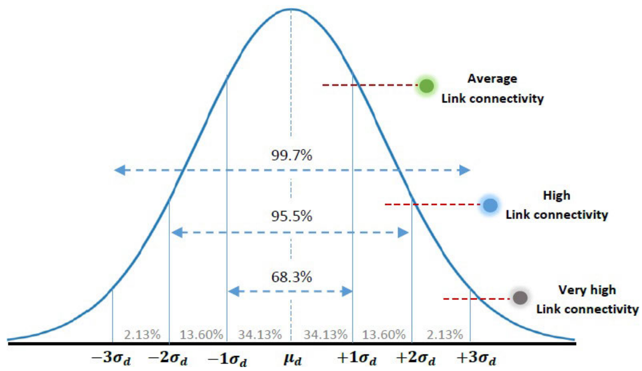

FIGURE 4. Normal distribution for link connectivity between communicating nodes.

In wireless communication, link duration measures the lifetime of a node-to-node link and tells the connection's stability. It is important to estimate the connectivity time between nodes otherwise, the link failures affect spectral efficiency. The connectivity of nodes is closely related to the speed of nodes and their transmission range. It is already established that when there is an increase in the range, more nodes get into connectivity and improve the network performance. Whereas, speed parameter affects the connectivity at large and adds instability in link connections. With an increase in time, slow speed nodes get effected little depending on the distance from their transmitter. In contrast, high-speed nodes change their positions fast and frequently disconnect, mainly when operating on smaller transmission ranges. Ordinarily, when nodes are moving in a group or independently, their movement is random and communicating nodes can depart at any time depending on their speed.

In the proposed methodology, distance is the important measurement on which the health of connectivity depends. A network must know the suitable time to run the control phase in a dynamic environment, which requires maximum connectivity of nodes. The network can find appropriate CPT for one and more than one hop communication settings based on designed steps, described in algorithm 1. The proposed methodology provides four distribution bounds or possibilities for CPTs based on the QoS requirement of the network.

V. SIMULATION AND ANALYSIS

To validate the designed methodology, random mobility scenarios are generated for the RPGM model on the BonnMotion-3.0.1 tool. It is a mobility trace generator that saves mobility traces in the ".movements file" and shows statistics related to nodes' positions at different times. The implementation parameters use to validate the methodology are listed in Table 2. In the simulation, the initial 100s are discarded to ensure that the network has reached a steady state.

In the RPGM model, the minimum reference distance of 4km is assigned to the group to keep the radios close to their reference points. The pause time T_p is considered at a minimum where nodes move continuously inside the

Algorithm 1 Control Phase Time Estimation

Notations:
1. $P(X, Y)$: the position of nodes through GPS
2. T: Time
3. N: Number of nodes
4. C_n: Number of communicating node pairs
5. $d_{i,j}$: the distance between TX and RX nodes

while $(t \leq T)$ **do**
- Generate positions $P(x, y)$ of nodes N_i using vector
$$Vi^t = \overrightarrow{V_G} + \overrightarrow{RM_i^t}$$
- Compute distance $d_{i,j}$ between nodes in C_n using euclidean formula
$$d_{i,j} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}$$
- Calculate distribution parameters mean μ_d and standard deviation σ_d for $d_{i,j}$
$$\mu_d = \frac{\sum_{t=1}^{C_n} d_{i,j}(t)}{C_n}, \sigma_d = \sqrt{\frac{\sum_{t=1}^{C_n} (d_{i,j}(t) - \mu_d)^2}{C_n}}$$
- Calculate $\mu_d + \sigma_d$ and $\mu_d + 2\sigma_d$ to find link connectivity between nodes
//for all C_n
if $(\mu_d == TH\_distance)$ **then**
Most of the C_n are disconnected
else if $(\mu_d + \sigma_d == TH\_distance)$ **then**
Few of the C_n are disconnected
end
else if $(\mu_d + 2\sigma_d == TH\_distance)$ **then**
Almost all nodes in C_n are connected
end
end
Control phase time (CPT) estimation using distribution parameters wit respect to time t.
end

TABLE 2. List of mobility scenarios and simulation parameters for designed methodology.

Parameters	Description
Mobility model generator	BonnMotion-3.0.1
Simulation area	100km x 100km
Mobility models	RPGM with group size=20
Number of nodes	20
Min. speed of nodes (V_{min})	1 m/s
Max. speed of nodes (V_{max})	5, 15, 25 m/s
Transmission range (R)	12km (WB), 23km (NB)

simulation region. Different speed values for SDRs movement is chosen, e.g. 5m/s, 15m/s, 25m/s.

VI. EXPERIMENTS, SIMULATION RESULTS AND ANALYSIS

For the analysis of the designed methodology, a network scenario of twenty nodes is considered where nodes are moving with constant speed V_{max}, following the group mobility pattern. Each node sets to a transmission range, referred to as $TH_{distance}$ of 12km for WB and 23km for NB communication. Any two communicating radios with a distance less than $TH_{distance}$ can receive the transmitted messages. The RX_node is located at a certain distance from the TX_node and successfully receives the transmitted packets (packet loss = 0%) if it is in the transmission range of the TX_node. For tactical communication, one and two-hop transmission is considered between radios.

TABLE 3. Distribution parameters for RPGM model with different nodes' speed.

Time (s)	V_{max}=5m/s		V_{max}=15m/s		V_{max}=25m/s	
	μ_d (m)	σ_d (m)	μ_d (m)	σ_d (m)	μ_d (m)	σ_d (m)
5	11,726.4	4,986.92	11,016.4	4,916.05	17,391.8	9,397.36
10	14,471.9	5,700.42	16,882.7	16,887.9	21,562.3	8,958.97
15	18,636.5	8,290.95	23,418.6	27,541.5	26,643.8	14,815.1
20	17,607.8	9,612.74	27,187.4	7,896.41	34,228.2	19,973.8

A. EFFECT OF MOBILITY ON DISTANCE BETWEEN COMMUNICATING NODES

For detailed analysis over distances and link connectivity between communicating nodes, the normal distribution parameters μ_d and σ_d are computed at each TX_node for RPGM mobility model. An assumption is made that all nodes start moving with constant speed having minimum distance between them with respect to the reference distance. As nodes keep moving, the distance between communicating pairs increases with time and sometimes decreases due to the random movement of nodes.

For the RPGM model, the values of distribution parameters for 5s to 20s of the simulation time are shown in Table 3. The nodes move with different speeds e.g., 5m/s, 15m/s, and 25m/s. For V_{max} = 5m/s, the mean distance μ_d between communicating nodes is increased from 11,726.4m to 17,607.8m with a standard deviation σ_d of 9,612.74m in a time period of 20s. The distances are clustered around the mean and change slowly due to the slow speed of nodes; therefore, the distribution is taller and will steadily become flatten with time, as shown in Fig. 5.

Since nodes' movement is not uniform, the distance between communicating nodes fluctuates and, most of the time, further apart for high-speed scenarios. Fig. 6 shows that the difference of μ_d between 10s and 15s simulation time is around 6,536m, which keeps increasing with time. In the next few seconds, μ_d increases with a notable difference because, with high speed, nodes change their positions rapidly and cause impulsive distance variations. The curves become shorter and exhibit a large spread. However, it is not necessary in every case due to the random mobility patterns. Distance values may increase fewer or more when the speed of the node is high.

In most cases, as the nodes' speed increases, the distance between communicating nodes also increases, and nodes cover large distances. For V_{max} = 25m/s, μ_d between communicating nodes is increased from 17,391.8m to 21,562.3m in the duration of 5s with σ_d of around 1,000m, as shown

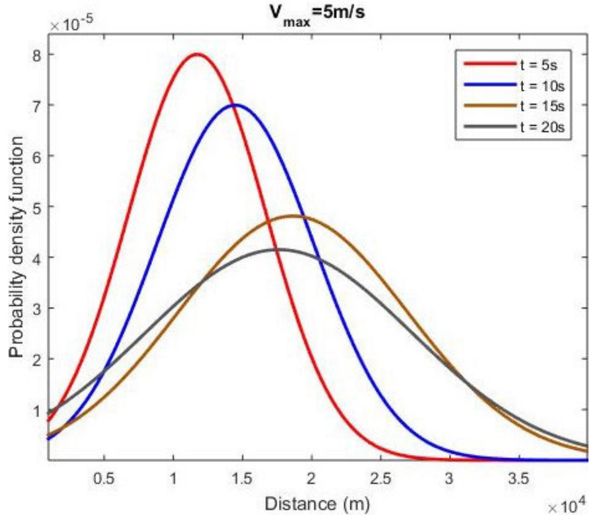

FIGURE 5. PDF of distances between communicating nodes moving with $V_{max} = 5m/s$.

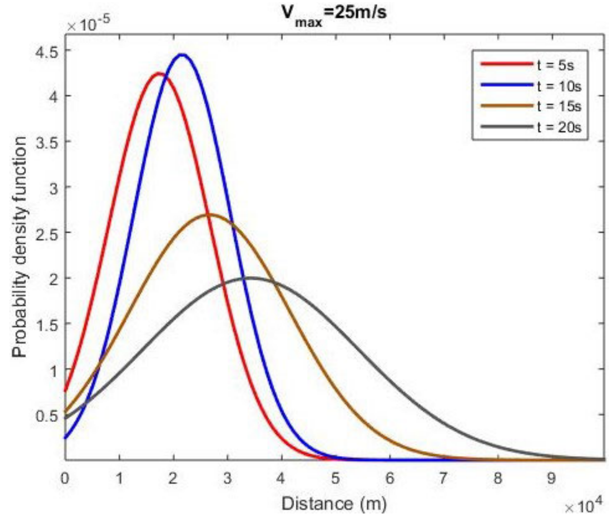

FIGURE 7. PDF of distances between communicating nodes moving with $V_{max} = 25m/s$.

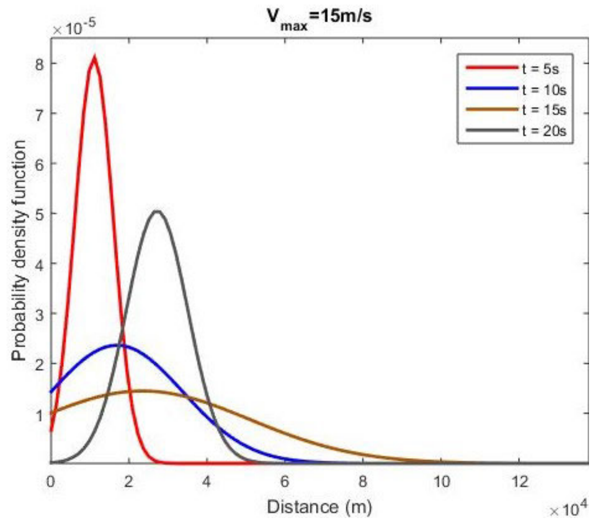

FIGURE 6. PDF of distances between communicating nodes moving with $V_{max} = 15m/s$.

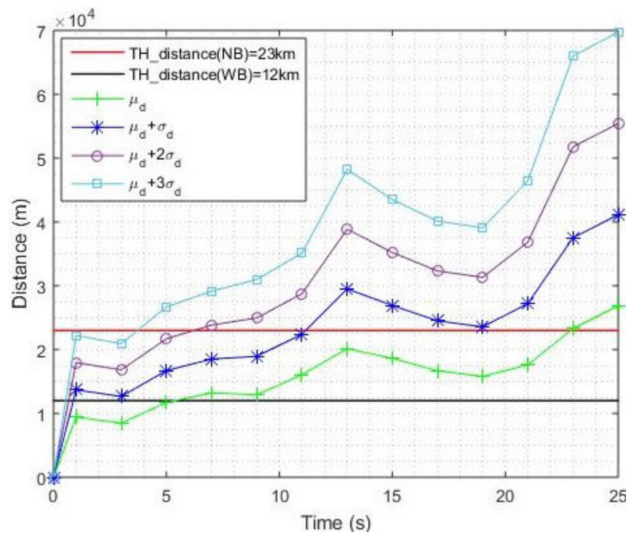

FIGURE 8. Link connectivity between communicating nodes in terms of distribution parameters, moving with $V_{max} = 5m/s$.

in Fig. 7. Due to the random movement of communicating nodes, the μ_d between communicating nodes increases with a small spread, e.g., at t = 5s $\mu_d = 17{,}391.8$m with $\sigma_d = 9{,}397.36$m that cut down to $\sigma_d = 8{,}958.97$m with $\mu_d = 21{,}562.3$m at t = 15s. Nevertheless, with an increase in time, σ_d increases, and distances between communicating pairs spread out around the mean, making the normal distribution flatter and wider.

B. EFFECT OF MOBILITY ON LINK CONNECTIVITY BETWEEN COMMUNICATING NODES

The impact of speed and time on radios connectivity is analyzed for the maximum transmission range of radios measured in terms of *TH_distance*, e.g., 23km and 12km for NB and WB communication, respectively. In slow speed movements, the communicating pairs maintain their connectivity for a longer time. As μ_d reaches *TH_distance*, most nodes have lost the connectivity with their paired nodes. With NB communication, μ_d reaches 12km at t = 5.2s, and at t = 22.8s, μ_d becomes equal to 23km when SDRs are tuned to WB communication, as shown in Fig. 8. However, $\mu_d + \sigma_d$, $\mu_d + 2\sigma_d$ and $\mu_d + 3\sigma_d$ reach *TH_distance* earlier and show few, very few and no disconnection of nodes, respectively. The normal distribution parameters concerning the connectivity between most communicating nodes are shown in Table 4.

For high-speed mobility scenarios, the movement of nodes results in sparse connectivity, which causes disconnection for many communicating nodes. Fig. 9 shows that at t = 14.5s, μ_d equals *TH_distance* of 23km and reaches to 12km in around 2.8s duration, which indicates several connectivity losses. As we increase speed, the disconnections occur

TABLE 4. Distribution parameters with respect to $\mu_d + 2\sigma_d \sim= TH\_distance$ for $V_{max} = 5$m/s.

Time (s)	μ_d (m)	σ_d (m)	$\mu_d + \sigma_d$ (m)	$\mu_d + 2\sigma_d$ (m)	$\mu_d + 3\sigma_d$ (m)
1	9,420.99	4,267.16	13,688.15	17,955.31	22,222.47
5	11,726.4	4,986.92	16,713.32	21,700.24	26,687.16
10	14,471.9	5,700.42	20,172.32	25,872.74	31,573.16
15	18,636.5	8,290.95	26,927.45	35,218.40	43,509.35
20	17,607.77	9,612.74	27,220.51	36,833.25	46,445.99
25	26,851.6	14,289.8	41,141.4	55,431.20	69,721

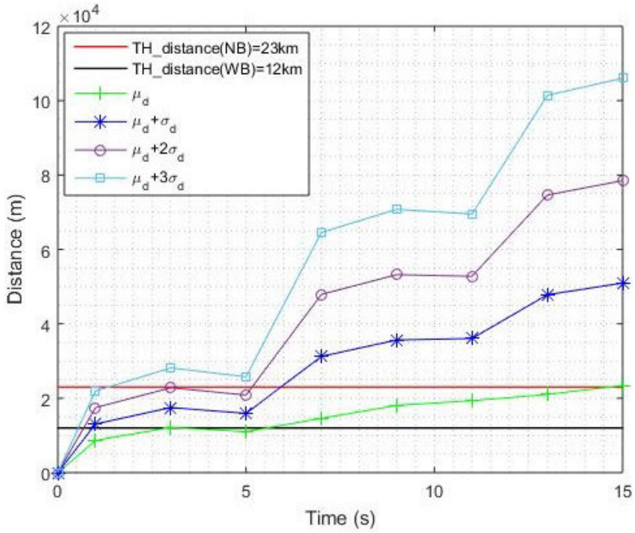

FIGURE 9. Link connectivity between communicating nodes in terms of distribution parameters, moving with $V_{max} = 15m/s$.

TABLE 5. Distribution parameters with respect to $\mu_d + 2\sigma_d \sim= TH\_distance$ for $V_{max} = 15$m/s.

Time (s)	μ_d (m)	σ_d (m)	$\mu_d + \sigma_d$ (m)	$\mu_d + 2\sigma_d$ (m)	$\mu_d + 3\sigma_d$ (m)
1	8,631.71	4,428.08	13,059.79	17,487.87	21,915.95
5	11,016.4	4,916.05	15,932.45	20,848.50	25,764.55
10	16,882.7	16,887.9	33,770.6	50,658.50	67,546.40
15	23,418.6	27,541.5	50,960.1	78,501.60	106,043.10

earlier than slow speed scenarios with recurrent fluctuations in distance values. With $V_{max} = 25$m/s, most of the nodes lost the connectivity at t = 0.91s and t = 6.8s for NB and WB communication, respectively, as shown in Fig. 10. Whereas, many nodes have the connection when $\mu_d+2\sigma_d$ and $\mu_d+3\sigma_d$ are less than $TH\_distance$ or greater than $\mu_d + \sigma_d$ for which calculations are shown in Tables 5 and 6.

The measurement and analysis over distribution parameters state the link connectivity where μ_d identifies the major connectivity loss, $\mu_d + \sigma_d$, $\mu_d + 2\sigma_d$ represent average and high link connectivity and reach to $TH\_distance$ earlier than μ_d.

The speed of SDRs and their operating time in the field has a substantial effect on network performance. When communication time increases, there is an insatiability in connectivity even with low-speed values because of the intrinsic characteristic of spatial dependency between nodes. Therefore it is essential to consider the impact of time on link connectivity, specifically in tactical networks for reliable and unremitting communication.

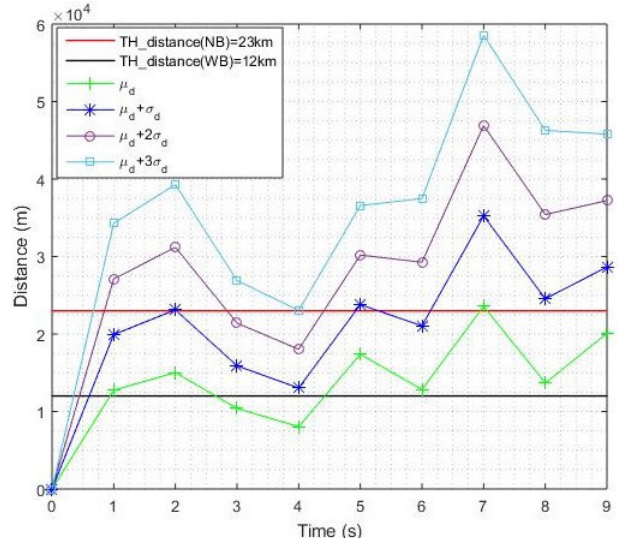

FIGURE 10. Link connectivity between communicating nodes in terms of distribution parameters, moving with $V_{max} = 25m/s$.

TABLE 6. Distribution parameters with respect to $\mu_d + 2\sigma_d \sim= TH\_distance$ for $V_{max} = 25$m/s.

Time (s)	μ_d (m)	σ_d (m)	$\mu_d + \sigma_d$ (m)	$\mu_d + 2\sigma_d$ (m)	$\mu_d + 3\sigma_d$ (m)
1	12,745.1	7,181.55	19,926.65	27,108.20	34,289.75
5	17,391.8	6,397.36	23,789.16	36,186.52	45,583.88
10	21,562.3	8,958.97	30,521.27	39,480.24	48,439.21

C. ESTIMATION ON CONTROL PHASE TIME

In tactical communication, latency is the primary concern as SDRs need to exchange mission-critical information; hence, the control phase's time must be short and reliable to keep the information intact and useful. During data transmission, nodes' connection becomes unstable due to node's mobility and the network needs to go into the control phase repeatedly. It has been observed that radios moving with moderate or fast speed i.e. 15m/s or 25m/s frequently change their positions. There is a fluctuation in packet reception if $d_{i,j} \sim= TH\_distance$. Therefore, it is important to find the time where the network has maximum link connectivity and can be identified through distribution parameters.

The designed methodology considers the CPT to run at four distribution bounds for all mobility scenarios. At these bounds, disconnected transmitters can send route error messages to their neighbors which are in their range R, and request a route for the disconnected RX. Following are the four possibilities for the control phase run concerning the application requirement.

1) CPT AT μ_d

In all mobility scenarios, μ_d tells that many of the communicating nodes have lost the connectivity. When μ_d reaches $TH\_distance$, most of the communicating nodes are disconnected, and transmission between nodes either control or data becomes inadequate. Therefore, it is worthless to run the control phase at this time which will only increase control overhead and waste radio bandwidth.

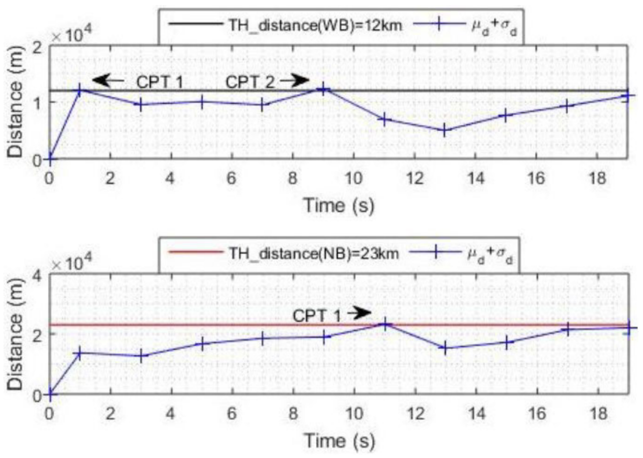

FIGURE 11. Control phase times using $\mu_d + \sigma_d$ when nodes are moving with $V_{max} = 5m/s$.

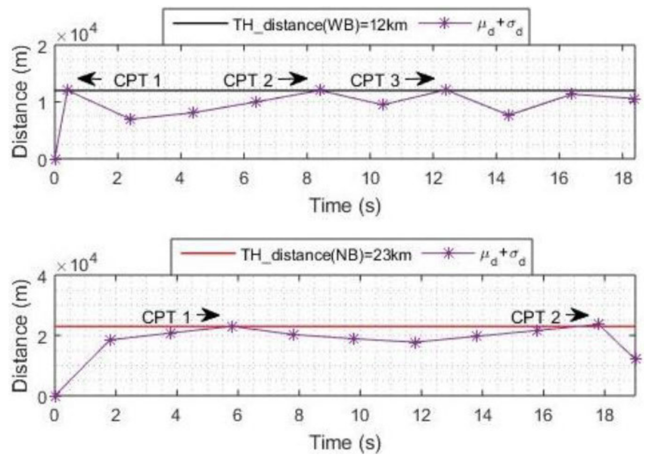

FIGURE 12. Control phase times using $\mu_d + \sigma_d$ when nodes are moving with $V_{max} = 15m/s$.

2) CPT AT $\mu_d + \sigma_d$

The time at which $\mu_d + \sigma_d$ reaches *TH_distance* is appropriate to run a control phase for applications that require moderate reliability. At this time, few communicating nodes are disconnected and need a routing protocol to build a new link between them.

For the RPGM model, when nodes are moving with V_{max} = 5m/s the nodes of the network encounter two control phases CPT1 and CPT2 (labeled using arrows) for $\mu_d + \sigma_d$ equals to *TH_distance* when set for WB communication, as shown in Fig. 11. Whereas for *TH_distance* of 23km, the network runs the control phase once. For both the cases, whenever $\mu_d + \sigma_d$ is reached to *TH_distance*, all nodes of the network get into the control phase, and transmitters of the communicating pairs look for the route to get back the connection with their receivers. At this point, routing protocol plays the role, and nodes send RREQ messages (use in AODV routing protocol) to all nodes which are in their transmission range R.

With the increase in speed, the number of control phases also increases due to the rapid changes in mobility patterns of nodes, i.e. for V_{max} = 15m/s, nodes go into the control phase thrice at t = 0.8s, 8.7s and 12.7s, as shown in Fig. 12. The duration between CPT1 and CPT2 is more due to the re-connection with the one-hop neighbors with μ_d equals to around 6km. With V_{max} = 25m/s, all node have CPTs at t = 0.8s, 8.48s, 12.5s and 18.5s for WB communication. The nodes restore the connection with their receivers by establishing a link connectivity with one of its direct neighbor (in R), as shown in Fig. 13. Similarly, with NB transceivers, radios go into the control phase thrice and show rapid changes in distance values.

3) CPT AT $\mu_d + 2\sigma_d$

The consideration of $\mu_d + 2\sigma_d$ for CPT is highly suitable for reliable communication where almost all communicating nodes are connected. It is time when nodes can safely run the control phase before losing the connection with many nodes

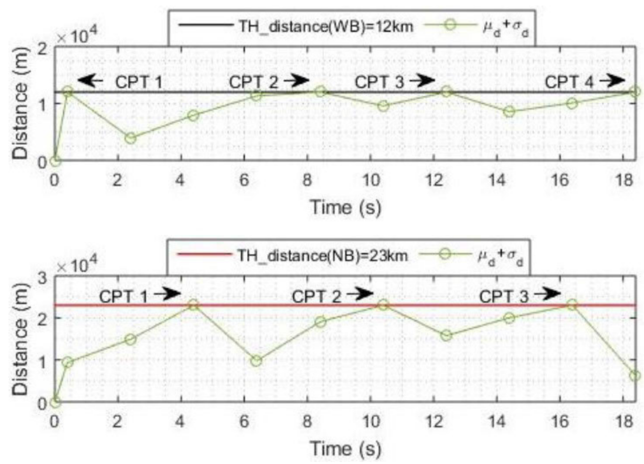

FIGURE 13. Control phase times using $\mu_d + \sigma_d$ when nodes are moving with $V_{max} = 25m/s$.

of the network. As shown in Fig. 14, the network goes into three control phases for both NB and WB communication ranges, when $\mu_d + 2\sigma_d$ equals to or greater than *TH_distance*.

For high-speed scenarios, the randomness in mobility pattern increases and demands frequent control phases, as shown in Fig. 15 and Fig. 16. By doing this, nodes send RREQ messages and maintain the possible routes for better network performance and in time delivery of mission-critical information.

4) CPT AT $\mu_d + 3\sigma_d$

The CPT can also run at $\mu_d + 3\sigma_d$, where all communicating nodes are connected and indicate high reliability. However, considering these nodes may remain in the control phase for a longer time or operate in consecutive control phases. This is because the value of $\mu_d + 3\sigma_d$ is higher than the other three distribution bounds and reaches *TH_distance* earlier, especially when the nodes' speed is high.

From the above analysis, a network can select suitable CPT for an application based on its QoS requirement, as shown in Fig. 17. In tactical communication, the cost of concern

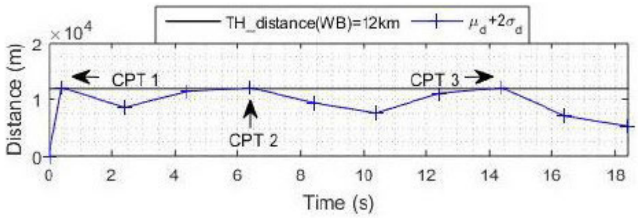

FIGURE 14. Control phase times using $\mu_d + 2\sigma_d$ for a network when nodes are moving with $V_{max} = 5m/s$.

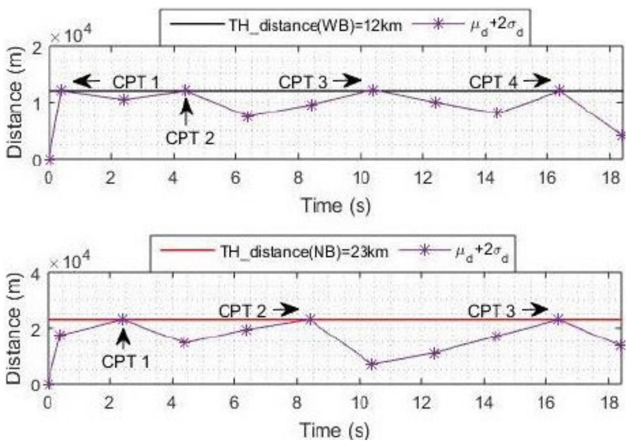

FIGURE 15. Control phase times using $\mu_d + 2\sigma_d$ for a network when nodes are moving with $V_{max} = 15m/s$.

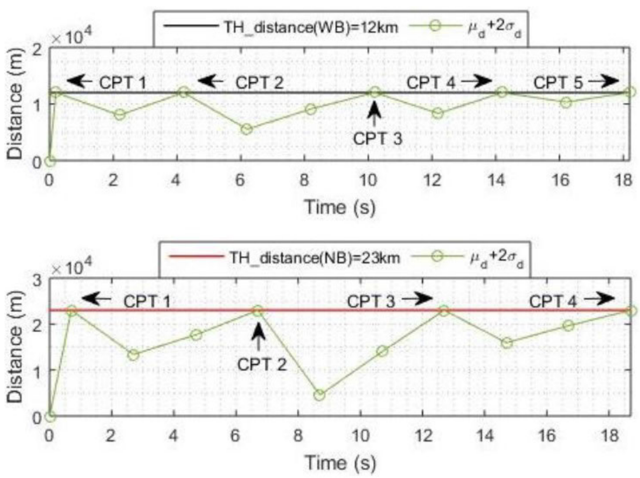

FIGURE 16. Control phase times using $\mu_d + 2\sigma_d$ for a network when nodes are moving with $V_{max} = 25m/s$.

is related to bandwidth, latency, jitter, and error rate. Consequently, it is a non-trivial task to estimate the suitable time for SDRs to go into the control phase due to the nodes' random movement. However, using the normal distribution, we can

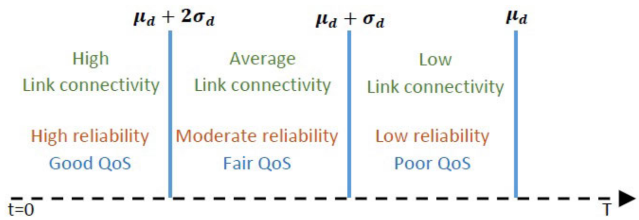

FIGURE 17. Time diagram with respect to link connectivity and reliability.

evaluate the link connectivity between communicating nodes with defined mobility parameters and estimate the suitable time for the control phase in different mobility scenarios.

D. OBSERVATIONS AND LIMITATIONS

Following important observations are made over the analysis of mobility effect on nodes connectivity.

1) The estimated control phase times are not fixed for all mobility scenarios, whether nodes are moving in groups or have sparse connectivity. However, stochastic-based modeling can estimate the control phase time by providing information on suitable network connectivity.
2) In random mobility models, nodes' pause time is also an important factor, but in group mobility, specifically in the RPGM model nodes do not pause on their own and follow the reference node's path. Therefore we do not consider this mobility metric in design validation.
3) All the analysis is done on mobility scenarios, which are based on unrealistic maps extracted through simulation tools. However, the analysis over distance measurements using speed and time parameter is substantial to evaluate the estimated control interval in dynamic network environment.

The analysis and simulation results show that the designed methodology can be implemented on real network scenarios irrespective of the particular mobility patterns. The evaluation of distances elucidates the link connectivity between communicating pairs for the network operating time and provides rationals on network connectivity to run control phases. Some parameters such as traffic flows, node density, and node deployment affect the performance of the routing protocols having different mobility patterns. The influence of these parameters may compromise reliability where delay and throughput are the primary concerns.

VII. CONCLUSION AND FUTURE WORK

In tactical networks, reliable transmission of time-sensitive and critical data is required among SDRs for seamless field operations. In these networks, radios move in the form of a group and disperse in the area by following random movement patterns. However, the mobility patterns can disrupt the connection when the communicating radio moves outside the range of its transmitter. This paper presented a methodology that shows the impact of mobility on link connectivity between communicating nodes in different mobility scenarios. The stochastic distribution provisions the beforehand estimate on link connectivity based on the distances between SDRs. It provides the possibilities of control messaging time to maintain the reliability of data transmission. The analysis on distribution parameters presented the estimated time for the application requirement. The designed methodology can opt for any MANET in which nodes operate on random mobility configurations.

The proposed methodology is further to be extended for adaptive control messaging in real network scenarios using different routing protocols and mobility models. In commercial networks, the requirement of control message transmission may differ depending on the number of nodes and transmission interference.

REFERENCES

[1] H. Nishiyama, T. Ngo, N. Ansari, and N. Kato, ''On minimizing the impact of mobility on topology control in mobile ad hoc networks,'' *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, pp. 1158–1166, Mar. 2012.

[2] P. Rahmani and H. H. S. Javadi, ''Topology control in MANETs using the Bayesian pursuit algorithm,'' *Wireless Pers. Commun.*, vol. 106, no. 3, pp. 1089–1116, Jun. 2019.

[3] S. Xiang and J. Yang, ''Performance reliability evaluation for mobile ad hoc networks,'' *Rel. Eng. Syst. Saf.*, vol. 169, pp. 32–39, Jan. 2018.

[4] H. Zhang and L. Dai, ''Mobility prediction: A survey on state-of-the-art schemes and future applications,'' *IEEE Access*, vol. 7, pp. 802–822, 2019.

[5] M. Anand and T. Sasikala, ''Efficient energy optimization in mobile ad hoc network (MANET) using better-quality AODV protocol,'' *Cluster Comput.*, vol. 22, no. S5, pp. 12681–12687, Sep. 2019.

[6] I. Zacarias, L. P. Gaspary, A. Kohl, R. Q. A. Fernandes, J. M. Stocchero, and E. P. de Freitas, ''Combining software-defined and delay-tolerant approaches in last-mile tactical edge networking,'' *IEEE Commun. Mag.*, vol. 55, no. 10, pp. 22–29, Oct. 2017.

[7] I. Zacarias, J. Schwarzrock, L. P. Gaspary, A. Kohl, R. Q. A. Fernandes, J. M. Stocchero, and E. P. de Freitas, ''Employing SDN to control video streaming applications in military mobile networks,'' in *Proc. IEEE 16th Int. Symp. Netw. Comput. Appl. (NCA)*, Oct. 2017, pp. 1–4.

[8] Z. Zhao, P. Cumino, A. Souza, D. Rosário, T. Braun, E. Cerqueira, and M. Gerla, ''Software-defined unmanned aerial vehicles networking for video dissemination services,'' *Ad Hoc Netw.*, vol. 83, pp. 68–77, Feb. 2019.

[9] Y. Jahir, M. Atiquzzaman, H. Refai, A. Paranjothi, and P. G. LoPresti, ''Routing protocols and architecture for disaster area network: A survey,'' *Ad Hoc Netw.*, vol. 82, pp. 1–14, Jan. 2019.

[10] M. U. Rahman, ''Investigating the effects of mobility metrics in mobile ad hoc networks,'' 2020, *arXiv:2006.16441*. [Online]. Available: http://arxiv.org/abs/2006.16441

[11] S. Hussain, D. Wu, S. Memon, and N. K. Bux, ''Vehicular ad hoc network (VANET) connectivity analysis of a highway toll plaza,'' *Data*, vol. 4, no. 1, p. 28, Feb. 2019.

[12] X. Zhong, F. Chen, Q. Guan, F. Ji, and H. Yu, ''On the distribution of nodal distances in random wireless ad hoc network with mobile node,'' *Ad Hoc Netw.*, vol. 97, Feb. 2020, Art. no. 102026.

[13] M. B. Talawar and D. Ashoka, ''Link failure detection in MANET: A survey,'' in *Modern Approaches in Machine Learning and Cognitive Science: A Walkthrough*. Cham, Switzerland: Springer, 2020, pp. 169–182.

[14] F. Bai, N. Sadagopan, and A. Helmy, ''IMPORTANT: A framework to systematically analyze the impact of mobility on performance of routing protocols for adhoc networks,'' in *Proc. 22nd Annu. Joint Conf. IEEE Comput. Commun. Soc. (INFOCOM)*, Mar. 2003, pp. 825–835.

[15] M. Zhao, Y. Li, and W. Wang, ''Modeling and analytical study of link properties in multihop wireless networks,'' *IEEE Trans. Commun.*, vol. 60, no. 2, pp. 445–455, Feb. 2012.

[16] G. Khanna, S. K. Chaturvedi, and S. Soh, ''Reliability evaluation of mobile ad hoc networks by considering link expiration time and border time,'' *Int. J. Syst. Assurance Eng. Manage.*, vol. 10, no. 3, pp. 399–415, Jun. 2019.

[17] Q. Song, Z. Ning, S. Wang, and A. Jamalipour, ''Link stability estimation based on link connectivity changes in mobile ad-hoc networks,'' *J. Netw. Comput. Appl.*, vol. 35, no. 6, pp. 2051–2058, Nov. 2012.

[18] A. Naushad, G. Abbas, Z. H. Abbas, and L. Jiao, ''A novel faster failure detection strategy for link connectivity using hello messaging in mobile ad hoc networks,'' *Int. J. Ad Hoc Ubiquitous Comput.*, vol. 32, no. 2, pp. 75–98, 2019.

[19] U. Palani, K. C. Suresh, and A. Nachiappan, ''Mobility prediction in mobile ad hoc networks using eye of coverage approach,'' *Cluster Comput.*, vol. 22, no. S6, pp. 14991–14998, Nov. 2019.

[20] X. He, Z. Peng, J. Wang, and G. Yang, ''Generic and efficient connectivity determination for IoT applications,'' *IEEE Internet Things J.*, vol. 7, no. 6, pp. 5291–5301, Jun. 2020.

[21] O. S. Younes and U. A. Albalawi, ''Analysis of route stability in mobile multihop networks under random waypoint mobility,'' *IEEE Access*, vol. 8, pp. 168121–168136, 2020.

[22] S. Elaraby and S. M. Abuelenin, ''Connectivity analysis of directed highway vehicular ad hoc networks using graph theory,'' *Int. J. Commun. Syst.*, vol. 34, no. 5, p. e4745, Mar. 2021.

[23] S. M. Abuelenin and A. Y. Abul-Magd, ''Studying connectivity probability and connection duration in freeway VANETs,'' in *Emerging Technologies for Connected Internet of Vehicles and Intelligent Transportation System Networks*. Cham, Switzerland: Springer, 2020, pp. 27–38.

[24] D. Alshammari and S. Al-Shehri, ''Manets in military communications design concepts and challenges,'' *Int. J. Innov. Eng. Sci. Res.*, vol. 3, no. 2, 2019.

[25] B. V. Sai Kumar and N. Padmavathy, ''A hybrid link reliability model for estimating path reliability of mobile ad hoc network,'' *Procedia Comput. Sci.*, vol. 171, pp. 2177–2185, Jan. 2020.

[26] M. Zarei, ''Traffic-centric mesoscopic analysis of connectivity in VANETs,'' *Comput. J.*, vol. 63, no. 2, pp. 203–219, Feb. 2020.

[27] C. Ran, S. Zhang, and S. Huai, ''Link availability prediction based on capacity optimization in MANET,'' Eur. PMC, London, U.K., 2021, doi: 10.21203/rs.3.rs-150048/v1.

[28] X. Wang, C. Wang, G. Cui, Q. Yang, and X. Zhang, ''ELDP: Extended link duration prediction model for vehicular networks,'' *Int. J. Distrib. Sensor Netw.*, vol. 12, no. 4, Apr. 2016, Art. no. 5767569.

[29] X. Zhong, F. Chen, Q. Guan, F. Ji, and H. Yu, ''On the distribution of nodal distances in random wireless ad hoc network with mobile node,'' *Ad Hoc Netw.*, vol. 97, Feb. 2020, Art. no. 102026.

[30] R. K. Gujral, J. Grover, Anjali, and S. Rana, ''Impact of transmission range and mobility on routing protocols over ad hoc networks,'' in *Proc. Int. Conf. Comput. Sci.*, Sep. 2012, pp. 201–206.

[31] C. Qu, A. E. Morel, D. Dahlquist, and P. Calyam, ''Design of trace-based NS-3 simulations for UAS video analytics with geospatial mobility,'' *Proc. SPIE*, vol. 11398, Apr. 2020, Art. no. 1139809.

[32] B. K. Panda, U. Bhanja, and P. K. Pattnaik, ''Some routing schemes and mobility models for real terrain MANET,'' in *Machine Learning and Information Processing*. Singapore: Springer, 2020, pp. 523–534.

[33] T. Alam, ''Fuzzy control based mobility framework for evaluating mobility models in manet of smart devices,'' Authorea Preprints, Hoboken, NJ, USA, 2020.

[34] S. P. Bodra, ''Performance analysis of hybrid routing in MANET with group mobility for search and rescue applications,'' in *Proc. Int. Conf. Wireless Commun.* Singapore: Springer, 2020, pp. 353–361.

[35] X. Hong, M. Gerla, G. Pei, and C.-C. Chiang, ''A group mobility model for ad hoc wireless networks,'' in *Proc. 2nd ACM Int. Workshop Modeling, Anal. Simulation Wireless Mobile Syst.*, 1999, pp. 53–60.

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