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Research Article

A Novel Dynamic Link Connectivity Strategy Using Hello Messaging for Maintaining Link Stability in MANETs

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Maintaining link stability among randomly deployed network nodes is one of the key challenges for effective communication in mobile ad hoc networks (MANETs). Under uniform speed and random trajectory of mobile nodes, there must be a unified model to determine an adequate strategy that addresses the issue of link stability in MANETs. We present a novel dynamic link connectivity (DLC) strategy that maintains link stability through efficient link connectivity among the neighboring nodes using Hello messaging. We also perform stochastic analysis of the proposed strategy, which predicts the future link status among the neighboring nodes at different time steps of a Markov process. We find that the link stability is affected by the received signal strength, signal-to-noise ratio, transition rates between the connection and disconnection states, and probabilities of link connectivity and disconnectivity at steady state. Analytical and simulation results indicate efficacy of the proposed strategy in terms of reduced communication overhead, lower propagation delay, and better energy efficiency of the network. The results also demonstrate that the proposed strategy minimizes the average response time, increases the throughput, and reduces the packet loss ratio, thereby, maintaining efficient link stability among the neighboring nodes.

1. Introduction

A mobile ad hoc network (MANET) is a collection of wireless mobile nodes that do not rely on centralized administration or established infrastructure and, thus, form a temporary network [1]. Maintaining link stability [2] is an important performance metric in MANETs, since nodes tend to be disconnected in a randomly deployed network scenario [3]. In the jargon of MANETs, link stability represents the robustness and the longevity of the link. Several factors can influence the link stability in MANETs, such as the mobility of network nodes, communication overhead, and energy efficiency in the network.

A volume of literature is available, which addresses link stability among the randomly deployed network nodes for effective communication in MANETs [4–16]. However, there are a number of shortcomings in the existing literature, in terms of calculating the optimum transmission rate of Hello message(s), transition rate estimation between connection and disconnection states, probabilities of connectivity and disconnectivity, and stability of neighboring nodes in terms of received signal strength (RSS) and signal-to-noise ratio (SNR) at different time steps of the Markov process. To address these shortcomings, there is a need for an adaptive network strategy that predicts link connectivity for future communication among the neighboring nodes.

In this paper, we propose a novel dynamic link connectivity (DLC) routing strategy that analyzes status of the link for future communications among the neighboring nodes and, thus, determines stability of a link for efficient connectivity among these neighbor nodes. For designing an adaptive routing algorithm, the movement pattern of mobile nodes is taken into account. The movement pattern has a tremendous impact on many network aspects, such as RSS, stability of a neighboring node in terms of SNR, efficient link connectivity, and effective transition rate estimation between the connection and disconnection states [6, 8]. For example, a node's spatial distribution has a great impact on the connectivity property of the network, i.e., specifying the necessary condition for average minimum power (AMP) required for a node to remain connected to its neighbors.

In order to achieve the DLC strategy, first we analyze multiple parameters of interest for the proposed model, as presented in Section 4 of the paper. This consequently provides effective measures for predicting the link movement and status, thereby maintaining link stability for the proposed DLC strategy as a continuous function of time, as presented in Section 5 of the paper. In the proposed strategy, a link between neighboring nodes is active if the RSS is above a certain threshold value. The RSS has a close relation with the transmission range of a cluster, distance between the source and other ordinary nodes, speed with which the nodes are moving inside the cluster, and transmission rate of Hello messages. The transmission rate of Hello messages evaluates the condition for the stability of a neighboring node, which is helpful in analyzing the transition rates estimation for the connection and disconnection states among neighboring nodes inside the cluster. Hence, stability of a neighboring node ultimately calculates link connectivity as a continuous function of time. In addition, probabilities of link connectivity and disconnectivity at steady state are derived by incorporating the concept of stationary probability distribution for link connectivity.

The main contributions of this paper are summarized as follows.

(i) We present a novel DLC strategy using Hello messaging in MANETs, which addresses the issue of maintaining link stability through efficient link connectivity among neighboring nodes.

(ii) We perform stochastic analysis of the proposed DLC strategy by deriving expressions to predict the future link status among the network nodes at different time steps of the Markov process in Section 4 of the paper.

(iii) Additionally, we derive expression for the optimum RSS among the neighboring nodes inside a cluster, as presented in Section 5.1. Through RSS, we obtain link longevity, lower propagation delay, and better efficiency of the network under the proposed DLC strategy in Section 6.1.

(iv) Moreover, we derive expression for the stability of a neighboring node in terms of SNR, as presented in Section 5.2. Through SNR, we show that lower communication overhead and node interference are achieved by the proposed DLC strategy in Section 6.2.

(v) We also derive expressions for the transition rate estimation between connection and disconnection states, and probabilities of link connectivity and disconnectivity at steady state in Sections 5.3 and 5.4, respectivley. Through these expressions, we show that the proposed DLC strategy reduces the average response time, increases throughput, and reduces packet loss ratio in Section 6.3.

(vi) Finally, through analytical and simulation results, we find that RSS among the neighboring nodes is affected by the transmission rate of Hello messages, AMP, and link probability. Furthermore, stability of a network node is affected by the transmission range of cluster and transmission and reception rates of Hello messages. We also find that probabilities of link connectivity and disconnectivity are affected by the transition rates between connection and disconnection states.

The rest of the paper is organized as follows. In Section 2, we present the related work. In Section 3, we present the network scenario and basic assumptions for the proposed strategy. In Section 4, we formulate the problem by modelling it as a Markov process. In Section 5, we analyze the proposed DLC strategy. In Section 6, we present performance evaluation of the proposed strategy. The paper is concluded in Section 7.

2. Related Work

This section reviews eminent MANET routing strategies, which address the problem of link stability among the randomly deployed network nodes for effective communication in MANETs. In [4], the authors employ Hello messaging to determine local connectivity. The authors investigate multiple factors that can affect the utility of Hello messages in the network. However, estimation of the probabilities of link connectivity and disconnectivity between the neighboring nodes is not considered in their study. In [5], the authors study the link property in MANETs for dynamic connectivity by considering the effective transmission range and node pair distance parameters. The authors find that these parameters have a great impact over the network lifetime. However, the authors do not consider the optimum power levels required by a neighboring node for link connectivity. In [6], the authors consider a Markov model for link connectivity in MANETs by deriving the link connectivity as a continuous function of time. This approach provides a generic framework for estimating the settling time for non-steady state mobility model. The major drawback of this work is the lack of transition rates estimation for calculating the probability of link connectivity at steady state for future communication among the neighboring nodes. In [7], the authors determine a novel turnover adaptive Hello protocol (TAP) for MANETs by dynamically adjusting the Hello messaging frequency depending upon speed of the network nodes. However, the authors do not consider the optimal transmission rate of Hello messages.

In [8], the authors present a routing strategy by adopting a variable sized sampling window to calculate link transition rates and, thus, estimate the link stability on the basis of link connectivity changes. However, the authors do not consider the stability of a neighboring node. In [9], the authors study an adaptive Hello messaging scheme for suppressing unnecessary Hello messages in the network. However, the authors do not consider the continuous time analysis of link connectivity and stationary probability to achieve controlled Hello messages for the network load management. In [10], the authors investigate a novel energy aware link stability routing algorithm for ad hoc on-demand distance vector (AODV) routing protocol for predicting link failure in route maintenance. However, this study lacks the analysis of prior estimation for determining link connectivity among the neighboring nodes. In [11], the authors deploy a reliable neighbor node selection scheme by establishing stable links among the nodes on the basis of energy level of nodes involved in communication, mobility of the nodes, and distance between the nodes. For achieving stable links among the nodes in [11], the authors propose a quality of service (QoS) based multicast routing protocol using reliable neighbor node selection scheme (QMPRNS). However, the authors do not consider the effect of SNR on the stability of a link for a reliable neighbor node selection. In [12], the authors determine a QoS aware routing metric for reliable forwarding node based link stability cost function (LSF). The authors in [12] achieve the optimum contention count for LSF with the help of RSS. However, the authors do not consider the effect of transmission rate of Hello messages on the obtained RSS.

In [13], the authors propose a novel smooth mobility and link reliability (LR) based optimized link state routing (OLSR) scheme for analyzing link reliability metrics in MANETs. However, LR metric presented by the authors does not consider the effect of varying a node's speed on mobility metric. In [14], the authors introduce various approaches for clustering the network region on the basis of different performance metrics. The selection of cluster head (CH) in [14] is based on the lowest network identity (ID) clustering algorithm, wherein the node with the lowest ID gets the status of a CH. However, this study does not consider the effect of residual and maximum energies of a neighboring node on the CH selection criteria. In [15], the authors propose a system that attains better performance in terms of network lifetime, average delay, and throughput. The authors in [15] present a fuzzy enhanced secure multicast routing (FSMR) strategy for determining stable links by identifying unstable nodes in the network. However, this study lacks the calculations for maintaining link stability among the neighboring nodes. In [16], the authors propose a multiconstraint quality of expression-centric routing (MCQR) technique for effective transmission of video streaming over a MANET link in terms of link stability and link delay. The authors in [16] determine that high SINR (signal-to-interference and noise ratio) affect the stable links for data transmission and, thus, increase in the probability of disconnectivity due to random trajectory of mobile nodes is observed. However, this study lacks the analysis for the expected change in the critical transmission range of a network node due to interference.

To fill the aforementioned gaps identified in the existing literature, the reminder of this paper will present and evaluate a DLC strategy using Hello messaging to address link stability among randomly deployed nodes. In the next section, we will present the network scenario and assumptions for the proposed DLC strategy.

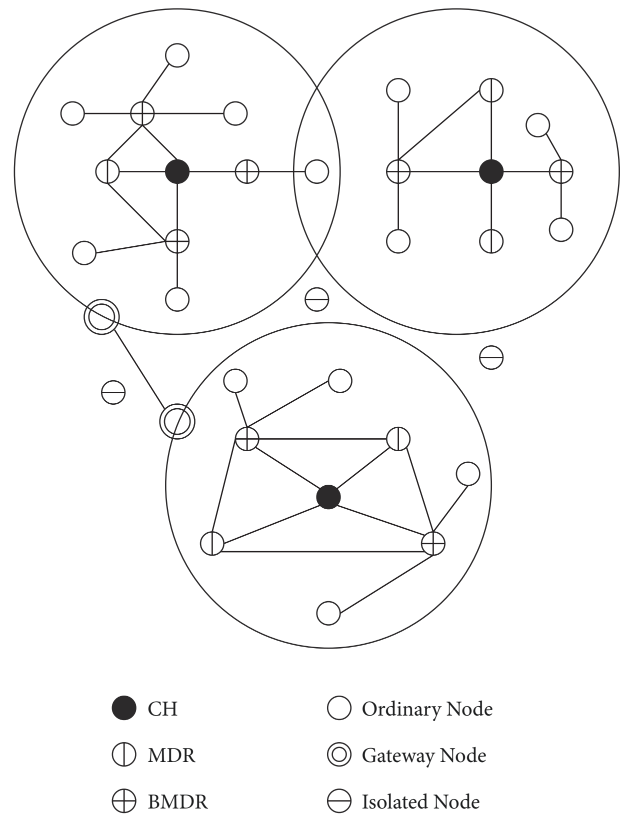


Figure 1: Network scenario.

3. Network Scenario and Assumptions

The network scenario for the proposed strategy is shown in Figure 1. The larger circles in this figure represent clusters, not a communication range, whereas the solid lines among the nodes denote connections between corresponding nodes. The nodes located physically closer to the cluster boundary are the ordinary nodes. In the considered scenario, there are a variable number of ordinary nodes in each cluster. The MANET designated routers (MDRs), which form a backbone scheme, are directly connected with the backup MANET designated routers (BMDRs). All the ordinary nodes are directly connected with the BMDRs only. In each cluster, MDRs are directly connected with the BMDRs and, thus, are indirectly linked with ordinary nodes. There can be multiple BMDRs for each cluster, depending upon the nodes deployment scheme. Nodes that are immediate neighbors of CH and are directly connected with other network nodes to form connecting and bi-connecting dominating sets can be selected as MDRs and BMDRs, respectivley [18]. Assigning such roles to network nodes in MANETs is realistic because, in highly dynamic topologies, MDRs/BMDRs can actively communicate with CH from at most adjacency value equal to two (Hop count) [19]. Thus, under random trajectory of network nodes MDR/BMDR nodes can be easily reached by CH. Furthermore, this scheme offers an added advantage of achieving optimal adjacency and reduced congestion between the neighboring node pairs inside a cluster. Furthermore, the nodes lying on the boundary of the cluster are gateway nodes, responsible for the intercluster communication. It is important to mention here that ordinary nodes, isolated nodes, and gateway nodes have identical hardware configuration, contrary to the cluster CH, MDR, and BMDR nodes, which have identical hardware configuration. In addition, the hop count between the CH and MDR and between the MDR and BMDR is one, between the CH and an ordinary node is two, and between the CH and the gateway node is three.

A CH is one of the MDR nodes selected on the basis of maximum residual energy, maximum cardinality with the neighboring nodes, and high cluster head selection probability [20, 21]. It is pertinent to mention here that, in the proposed strategy, there is exactly one CH residing inside the considered cluster and the nodes residing outside this cluster are the isolated nodes. CHs are special in terms of hardware configuration, as higher storage and memory is required for an MDR node selected on the basis of CH selection probability, as presented in Section 4.5 of the paper.

We assume that the Hello messages arrive at the neighboring nodes according to a Poisson point process (PPP) [22]. This is a suitable assumption as PPP is a natural arrival process [23], the moment of arrival of a Hello message at a particular node is random, and the probability of receiving two consecutive Hello messages simultaneously at the same instant can be practically considered negligible. Two CHs can be linked together either directly or through gateway nodes. A CH and the rest of the nodes within its own cluster move with uniform speed and in random directions. Due to random trajectories at each time step of a Markov process, nodes frequently join or leave the cluster. Therefore, at each time step of the process, new position of the CH must be determined with reference to an ordinary node. Initially, we assume that the mobile nodes inside the cluster are uniformly distributed over the range $[0, 2\pi]$. Furthermore, we assume that two nodes are successfully connected if the required RSS for link connectivity between neighboring nodes is greater than or equal to a predefined RSS threshold, η. A neighboring node is said to be stable if the received SNR by this node is greater than or equal to a fixed SNR threshold, justifying the former assumption. We further assume that initially $P_L = 0.5$ represents the minimum probability, according to the Bernoulli distribution [17], that the transmission of Hello message is successful at first time step of the Markov process. After the first step, the probability will be controlled by the environmental factors, like RSS and SNR.

In order to achieve the proposed DLC strategy, we need to determine the transmission rate of Hello messages, AMP, link probability, condition for link connectivity, condition for the stability of a neighboring node, probabilities of disconnectivity and connectivity at steady state, and transition rate estimation for the connection and disconnection states. To calculate these parameters of interest, we formulate the problem in the next section for establishing a relationship between the multiple parameters of interest under random behavior of the network nodes.

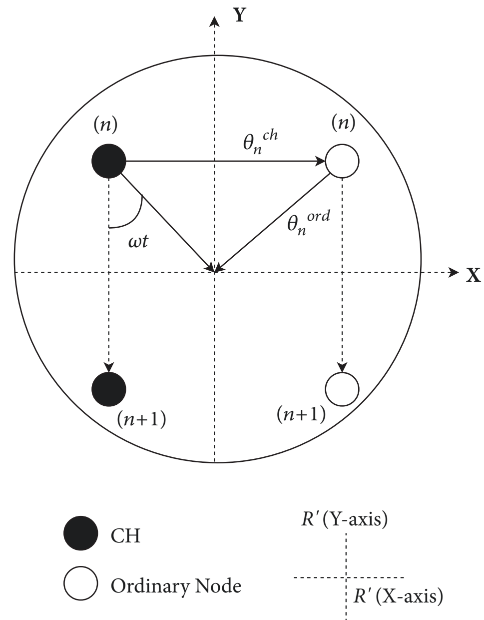


Figure 2: Position of CH and an ordinary node at different time steps of the process.

4. Problem Formulation, Modelling, and Analysis

First, we determine the initial position of a CH and the neighboring nodes within a cluster at time step (n) of the Markov process in order to calculate the logical distances between each pair of the neighboring nodes [24]. Next, the position of the CH at time step $(n+1)$, with reference to an ordinary node, is determined. This allows us to calculate the probability of a connected link, which consequently provides transmission rate λ of the Hello messages. The transmission rate of Hello messages is helpful in calculating the AMP levels required by a node to reach the CH. The probability of a connected link is useful in calculating the probability of successful reception of Hello messages by a neighboring node. This enables us to calculate the probability that the transmission of Hello message is successful. The notations used in this paper are given in Table 5.

4.1. Position of CH at Different Time Steps of the Markov Process. In the proposed strategy, there is exactly one CH for every cluster within the network region. The position of an ordinary node at time step (n) is determined from the position of the CH, as depicted in Figure 2. In this figure, as an example, moving with a uniform speed the CH moves from second to third quadrant, whereas the ordinary node moves from first to fourth quadrant inside the considered cluster. In Figure 2, single hop analysis is carried out in which multiple ordinary nodes are connected with the nearest BMDR, whereas BMDR(s) are connected to the CH through the nearest MDR, as previously discussed for Figure 1. Let, the distance, D, between the CH and an ordinary node is less than the transmission range, R', of the cluster, i.e., $(D < R')$, which means an ordinary node is inside the cluster. Hence, from the current position of the CH, we can estimate the distance between the ordinary node and the CH at future time steps of the process, by incorporating the prior knowledge of interarrival time, T_n, of Hello messages transmitted between the CH and the ordinary node.

Let t_n denote the time instance when the Hello message was received. At the time of reception of nth Hello message, the positions of the CH and an ordinary node are $C_{ch} = (x_{ch}, y_{ch})$ and $C_{ord} = (x_{ord}, y_{ord})$, respectively. Now in the time interval $(t_n, t_n + \Delta t)$, either a Hello message arrives at a node with probability $P(Hello\_arrival)_{(t_n, t_n+\Delta t)} = \lambda \Delta t$, or it does not arrive with probability $P(No\ Hello\_arrival)_{(t_n, t_n+\Delta t)} = 1 - \lambda \Delta t$, where Δt is the time gap between transmission of periodic Hello messages. Hence, new positions of the CH and the ordinary node are $C_{ch}^{(n+1)}$ and $C_{ord}^{(n+1)}$, respectively. In the considered case, Δt is sufficiently small such that CH can receive multiple requests for link connectivity from the neighboring nodes per second. Hence, the time delay between the consecutive requests for link connectivity through Hello messages is very small and the average arrival rate of Hello messages is greater than zero; thus, $\lambda > 0$. The time delay between $C_{ch}^{(n)}$ and $C_{ch}^{(n+1)}$, and between $C_{ord}^{(n)}$ and $C_{ord}^{(n+1)}$, is independent and identically distributed (i.i.d), which ultimately results in a lower propagation delay. At next time step of the Markov process, the position of CH with reference to the ordinary node depends only on the position when nth Hello message was arrived and not on any other previous positions. Therefore, the proposed process $\{C_{ch}^{(n)}$ with reference to $C_{ord}^{(n)}\}$ is modeled as a Markov process with discrete time and continuous state space.

Now, let $S^{ch} > 0$ be the speed of the CH with reference to an ordinary node (with speed $S^{ord} > 0$) by making an angle θ_n^{ch} with respect to θ_n^{ord}, respectivley. We can determine the location of the CH with reference to an ordinary node using $D = St$, where D is the distance and S is the speed of the CH.

At X-axis in Figure 2, the current position of the CH is the previous position (i.e., $C_{ch}^{(n)}$) plus the distance D covered while reaching the new position on X-axis, i.e., $x_{ch(new)}$, at time step $(n+1)$. The new X-axis position at time step $(n+1)$ is determined by

$$x_{ch(new)} = S^{ch} T_n \cos \theta_n^{ch}, \tag{1}$$

where T_n is the interarrival time between transmission of consecutive Hello messages and $\cos \theta_n^{ch}$ represents angle of the CH with an ordinary node on X-axis.

Thus, at time step $(n+1)$, the new X-axis location becomes

$$x_{ch}^{(n+1)} = x_{ch}^{(n)} + S^{ch} T_n \cos \theta_n^{ch}. \tag{2}$$

For the ordinary node, the new X-axis location becomes

$$x_{ord}^{(n+1)} = x_{ord}^{(n)} + S^{ord} T_n \cos \theta_n^{ord}. \tag{3}$$

Similarly, we can find the new Y-axis location for the CH and an ordinary node, respectively, as $y_{ch}^{(n+1)} = y_{ch}^{(n)} + S^{ch} T_n \sin \theta_n^{ch}$, and $y_{ord}^{(n+1)} = y_{ord}^{(n)} + S^{ord} T_n \sin \theta_n^{ord}$, where $\sin \theta_n^{ch}$ and $\sin \theta_n^{ord}$ represent angle of the CH with an ordinary node and angle of an ordinary node with the origin of cluster, respectivley.

4.2. Probability of a Connected Link. Let R' represent the transmission range of a CH; the probability that a link is no longer connected at time step $(n+1)$ is denoted as $P[(D(C_{ch}^{(n+1)}, C_{ord}^{(n+1)}) > R')]$, where $D(C_{ch}^{(n+1)}, C_{ord}^{(n+1)})$ represents the distance between the CH and an ordinary node. We consider two cases of node movement for calculating the probability of a connected link.

Case 1. If both the nodes (i.e., the CH and an ordinary node) are moving in the same direction, as depicted in Figure 3(a), where the circle in this subfigure represents a cluster, then the distance, D_1, between these nodes is given by

$$D_1 = D\left(C_{ch}^{(n+1)}, C_{ord}^{(n+1)}\right) = S^{ch} T_n + S^{ord} T_n. \tag{4}$$

This means

$$D_1 \leq (cluster\ head\ range) + (ordinary\ node\ range). \tag{5}$$

Case 2. If both the CH and an ordinary node are moving in the opposite direction, as shown in Figure 3(b), where the circle in this subfigure represents a cluster, then the distance, D_2, between these nodes is given by

$$D_2 = D\left(C_{ch}^{(n+1)}, C_{ord}^{(n+1)}\right) = D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right) + D_1. \tag{6}$$

Substituting (4) into (6), we get

$$D_2 = D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right) + S^{ch} T_n + S^{ord} T_n. \tag{7}$$

Hence

$$P\left(D_2 > R'\right) \geq P\left(T_n > \alpha\right), \tag{8}$$

where α can be obtained from (9) after algebraic manipulation in (7) and by using the assumption of uniform speed (i.e., $S^{ch} + S^{ord} = 2S$). Therefore

$$\alpha = \frac{R' - D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)}{2S}, \tag{9}$$

where D_2 is replaced by R'.

Rearranging (7), we can write

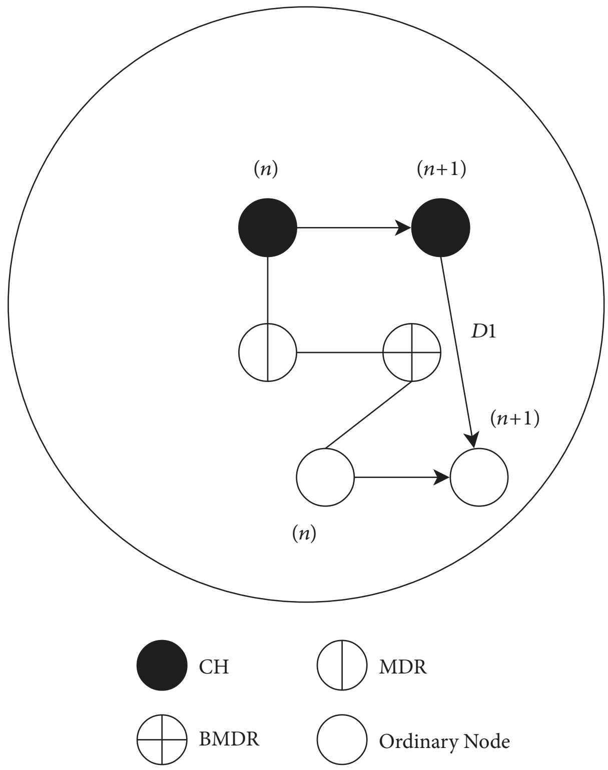
$$T_n\left(S^{ch} + S^{ord}\right) = D_2 - D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right), \tag{10}$$

$$T_n = \frac{D_2 - D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)}{S^{ch} + S^{ord}}, \tag{11}$$

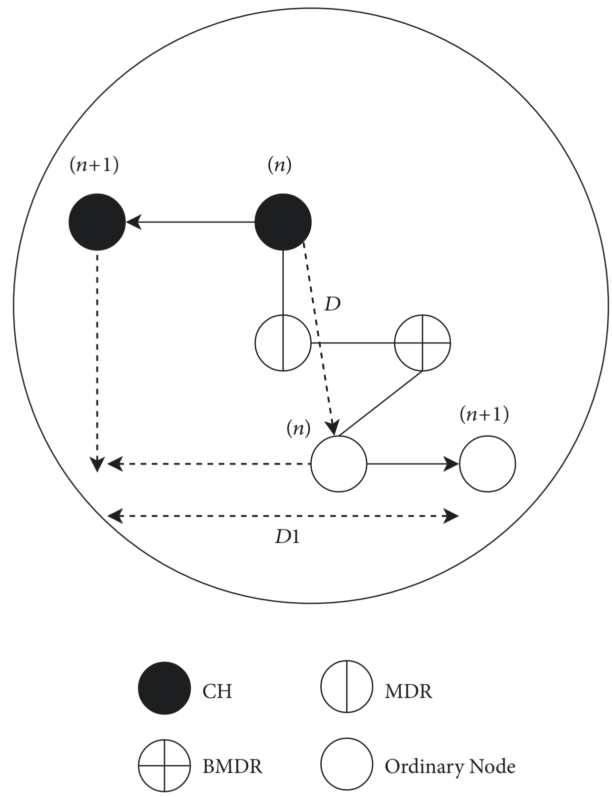
which ultimately gives us the interarrival time T_n as

$$T_n = \frac{R' - D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)}{S^{ch} + S^{ord}}. \tag{12}$$

Since the interarrival time between the Hello messages is exponentially distributed, as the Hello messages arrival



(a) Case 1



(b) Case 2

Figure 3: (a) CH and an ordinary node are moving in the same direction. (b) Cluster head and an ordinary node are moving in the opposite direction.

is assumed to follow the Poisson process, the probability of disconnectivity introduced in (8) can be written as

$$P\left(D_2 > R'\right) = \exp\left(-\alpha\lambda\right). \tag{13}$$

Now, if the probability of disconnectivity is less than a threshold value, η, then, $P(D_2 > R') \leq \eta$. Here, η can be defined on the basis of RSS. Therefore, (13) becomes

$$\eta \geq \exp\left(-\lambda\alpha\right). \tag{14}$$

This consequently gives the transmission rate of Hello messages as

$$\lambda = \frac{\ln\left(\eta\right)}{-\alpha}. \tag{15}$$

Substituting (9) into (15), we obtain expression for transmission rate of Hello messages inside a cluster, i.e.,

$$\lambda = \frac{\ln\left(\eta\right)2S}{D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right) - R'}. \tag{16}$$

In the presence of k number of mobile nodes in the network region, the value for the critical transmission range, R, of a node inside the cluster can be determined as [25]

$$R = C\sqrt{\frac{\ln\left(k\right)}{\pi k}}. \tag{17}$$

where C is a constant, $\forall C \geq 1$.

Assuming $C = 1$, we obtain expression for transmission range by a single neighboring node inside the cluster at current time step of the Markov process, i.e.,

$$R = \sqrt{\frac{\ln\left(k\right)}{\pi k}}. \tag{18}$$

Incorporating the critical transmission range, R, of a node inside the cluster, (16) can be written as

$$\lambda = \frac{\ln\left(\eta\right)2S}{D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right) - \sqrt{\ln\left(p_c\right)/\pi p_c}}, \tag{19}$$

where p_c denotes the number of nodes inside the cluster.

Hence, we obtain the expression to calculate the transmission rate of Hello messages for single hop analysis.

As shall be demonstrated in Section 6.1, the transmission rate of Hello messages can be affected by the power levels required by an ordinary node to reach the CH. Therefore, it is paramount to have an idea about the AMP levels for effective communication among the neighboring nodes inside the cluster.

4.3. Average Minimum Power. The AMP levels required by the number of nodes within the cluster, p_c, to reach the CH are given by

$$\text{AMP} = \frac{\sum_{g=1}^{p_c} p_{r,min}\left(g\right)}{p_c}, \tag{20}$$

where $p_{r,min}(g)$ is the minimum RSS required by node g for link connectivity with its neighbor node, as given by (14). Substituting (9) and (19) into (14), then substituting the result into (20), (20) can be reduced to

$$\text{AMP} = \frac{\sum_{g=1}^{p_c} \exp\left(-\lambda\left(\left(R' - D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)\right)/2S\right)\right)(g)}{p_c}. \quad (21)$$

Hence, the AMP required by all the ordinary neighboring nodes inside the cluster to reach the CH varies directly with R' and inversely with the number of nodes inside the cluster. In addition, AMP is an important parameter of interest to achieve successful transmission of Hello messages between the neighboring nodes to obtain a set of desirable RSS ($\eta \geq \Upsilon$) and SNR ($\text{SNR}_{\text{dB}} \geq \Gamma$) thresholds over the corresponding links, where Υ and Γ represent the RSS and SNR thresholds, respectivley, for AMP.

4.4. Probability of Successful Reception of a Hello Message. In order to determine that a Hello message was successfully received by the neighboring node, an expression is derived on the basis of Binomial distribution for the probability of successful reception of the Hello message(s). This is because at most N Bernoulli trials are required for link connectivity with a neighboring node once link failure is observed between these nodes at some previous instance of time. For a maximum number of Hello messages transmission retries, t_{tot}, which a node attempts for link connectivity before it is dropped by a neighboring node within the Hello interval of the transmitted Hello message, the link probability is given as

$$\begin{aligned} P(L) &= \frac{\left(N\left(1-(0.5)^{1/t_{tot}}\right)\right)^{N-t_{tot}}}{(N-t_{tot})!} \\ &\quad \cdot \exp\left(-N\left(1-(0.5)^{1/t_{tot}}\right)\right), \\ &\Longrightarrow \frac{\left(N\left(1-(0.5)^{1/t_{tot}}\right)\right)^{N-t_{tot}}}{(N-t_{tot})!} \\ &\quad \cdot \exp\left(-N\left(1-(0.5)^{1/t_{tot}}\right)\right) = 1-(1-P(L))^{1/t_{tot}}, \end{aligned} \quad (22)$$

where N represents number of trials in the current experiment for link connectivity and P_L is the link probability. Proof of (22) is given in the Appendix.

Once we have determined that a Hello message is successfully received by a neighboring node inside cluster, the criteria for the selection of CH must be evaluated to determine the possible node(s) inside the cluster to be selected as a CH at current time step of the Markov process.

4.5. CH Selection Criteria. In this subsection, we derive the criteria for the CH selection in the proposed DLC strategy. A source node is selected as a CH on the basis of maximum residual energy possessed by this node, maximum cardinality with its neighboring nodes, and the initial probability of CHs among all the nodes present inside the cluster. The CH selection probability, CH_{prob}, on the basis of RSS and AMP, is given by

$$\text{CH}_{prob} = C_{prob}^{(n)} \frac{E_{RES}}{E_{max}}. \quad (23)$$

In the above equation, $C_{prob}^{(n)}$ represents the initial probability of CHs among all the nodes present inside the cluster at time step (n) of the Markov process, E_{RES} indicates the current residual energy of the node, and E_{max} represents the maximum energy of a node. In the proposed strategy, $C_{prob}^{(n)}$ is defined as

$$C_{prob}^{(n)} = \frac{\sum_{p_c'} \text{CH}_{p_c'}^{(n)}}{p_c}, \quad (24)$$

where p_c' represents the number of CHs present at time step (n) of the Markov process.

If E is the initial energy assigned to a node [26], then E_{RES} at time step (n+1) of the process is given by

$$E_{RES} = E - E(T_n), \quad (25)$$

where $E(T_n)$ is the energy utilized by a node after time T_n and is given by

$$E(T_n) = (n\text{Hello}_t)\,\alpha_1 + (n\text{Hello}_r)\,\alpha_2. \quad (26)$$

In (27), $n\text{Hello}_t$ and $n\text{Hello}_r$ represent the number of Hello messages transmitted and received after time T_n, respectively. The traffic distribution ($0 \leq \lambda \leq 0.5$) of the transmitted Hello messages is determined for the neighboring nodes inside the cluster. The interarrival time constants α_1 and α_2 at current time step of the Markov process can be obtained from (9).

By substituting (25) and (26) into (24), we obtain

$$\text{CH}_{prob} = \frac{\sum_{p_c'} \text{CH}_{p_c'}^{(n)}}{p_c} \frac{E - E(T_n)}{E_{max}}. \quad (27)$$

Let C' denote the maximum cardinality of a node with MDR or BMDR inside the cluster; the CH selection probability can be written as

$$\text{CH}_{prob} = C'\left(\frac{\sum_{p_c'} \text{CH}_{p_c'}^{(n)}}{p_c} \frac{E - E(T_n)}{E_{max}}\right). \quad (28)$$

Hence, the CH selection probability is higher whenever we have larger ratio of residual energy to the maximum energy of a node with fewer nodes inside the cluster.

In this section we have modeled multiple parameters of interest as part of the problem formulation for predicting the future link status among the neighboring nodes in proposed DLC strategy, which is presented in the next section.

5. Analysis of Dynamic Link Connectivity

In this section, first, we determine the necessary condition that affects link connectivity between neighboring nodes

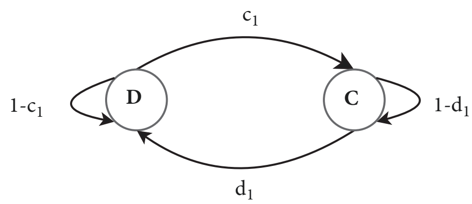


Figure 4: A Markov chain involving two states for the current process.

inside the cluster. Next, we determine the sufficient conditions for stability of a neighboring node. In the next subsection, transition rates for the connection and the disconnection states are estimated by taking into consideration the interarrival time between the consecutive Hello messages in the case of uniform speed of the network nodes. This allows continuous time analysis of link connectivity for the proposed DLC strategy by incorporating the stationary probability distribution and, thus, enables us to calculate the probabilities of connectivity and disconnectivity in the final subsection.

5.1. Condition for the Link Connectivity. A Hello message transmitted by a CH, at time instant, t, can be successfully received by its neighbor if

$$\eta \geq \exp\left(-\lambda\left(\frac{R' - D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)}{S^{ch} + S^{ord}}\right)\right). \tag{29}$$

It is important to mention here that the probability of disconnectivity for this particular condition needs to be less than η, where η represents the minimum RSS required to establish connectivity between the neighboring nodes, thereby maintaining the network connectivity [27].

5.2. Condition for the Stability of a Neighboring Node. It is important to check the stability of a mobile node during link connectivity through transmission of the Hello messages, which would follow the most stable route [28, 29]. In the proposed strategy, stability of a node [30] on the basis of SNR is given by [17]

$$\mathrm{SNR}_{\mathrm{dB}} = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right). \tag{30}$$

The noise level may be calculated from the RSS and SNR as [17]

$$P_{noise} = P_n = \frac{p_r}{10^{(\Gamma/10)}}, \tag{31}$$

where p_r represents the AMP given by (21) and Γ represents the SNR threshold. Now P_{signal} is given by

$$P_{signal} = \exp\left(-\lambda\left(\frac{R' - D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)}{S^{ch} + S^{ord}}\right)\right). \tag{32}$$

By substituting (21) and (33) into (31), we obtain the SNR for the proposed strategy as

$$\begin{aligned}\mathrm{SNR}_{\mathrm{dB}} &= 10\log_{10}\left(\exp\left(-\lambda 1\left(\frac{R' - D1\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)}{S^{ch} + S^{ord}}\right)\right)\right) - 10 \\ &\cdot \log_{10}\left(\frac{\sum_{g=1}^{p_c}\exp\left(-\lambda 1'\left(\left(R1' - D1'\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)\right)/\left(S^{ch} + S^{ord}\right)\right)\right)(g)}{p_c 10^{(\Gamma/10)}}\right),\end{aligned} \tag{33}$$

where R', D, and λ in (21) are replaced with $R1'$, $D1'$, and $\lambda 1'$, respectivley, in (34).

Hence, we obtain the expression to calculate the SNR for the proposed strategy.

In order to determine the status of a link, which could be either connected or disconnected in the long run, we need to have an idea about the steady state probability distribution of link connectivity for the proposed strategy.

5.3. Stationary Probability Distribution for the Proposed Strategy. In the proposed strategy, the connectivity between the CH and its neighbor, at next time step of the Markov process, depends only on its current state. In Figure 4, a scenario describing the connectivity between two nodes is shown as a discrete time markov chain (DTMC), where state C indicates that two nodes are connected, whereas state D represents disconnection. The transition probability from the disconnection to the connection state is represented by c_1, whereas the transition probability from the connection to disconnection state is given by d_1. Therefore, the transition probability matrix (TPM) [22] for the proposed DLC strategy, by taking into account (13), is given as

$$P = \begin{bmatrix} P\left(D_2 > R'\right) & P\left(D_2 > R'\right) \\ 1 - P\left(D_2 > R'\right) & 1 - P\left(D_2 > R'\right) \end{bmatrix}, \tag{34}$$

where $c_1 = 1 - P(D_2 > R')$ and $d_1 = P(D_2 > R')$ represent transition to the connection and disconnection states, respectively.

To describe the steady state behavior of the connection [31], the distribution vector for this process converges to a unique value. Hence, we instantly recognize that the TPM has an eigenvalue $\lambda = 1$ [22]. Therefore, at the steady state, the TPM for DLC is given as

$$\lim_{n \longrightarrow \infty} P^n = \begin{bmatrix} \exp(-\alpha\lambda) & \exp(-\alpha\lambda) \\ 1 - \exp(-\alpha\lambda) & 1 - \exp(-\alpha\lambda) \end{bmatrix}. \quad (35)$$

From (36), it is evident that the link remains in the disconnection state with probability $\exp(-\alpha\lambda)$, and in the connection state with probability $1 - \exp(-\alpha\lambda)$.

In order to calculate the probabilities of disconnectivity and connectivity, as presented in Section 5.5, it is required to estimate transition rates for the connection and disconnection states. Hence, the estimation of transition rates for the DLC strategy is given in Section 5.4.

5.4. Estimating the Transition Rates for Link Connectivity. It is important to mention here that a CH transmits periodic Hello messages to its neighbors after every Δt interval to indicate its presence in the neighborhood [32]. This small Δt interval is mapped to the interarrival time between the consecutive Hello messages, given by (11). Hence, the transition rates can be estimated on the basis of link state samples at a particular time step of the Markov process.

We know that $P(\mathit{Connectivity}) + P(\mathit{Disconnectivity}) = 1$, which implies that in a two-state Markov chain the probability of link connectivity is distributed between the connection and the disconnection states. Hence, from (36), we can write $P(\mathit{Disconnectivity}) = P(D_2 > R') = \exp(-\alpha\lambda)$ and $P(\mathit{Connectivity}) = 1 - \exp(-\alpha\lambda)$. Therefore, the probabilities of link connectivity at the next time step of the Markov process can be written, respectively, as [8]

$$P\left\{Y_{t+T_n} = C \mid Y_t = D\right\} = \lambda_2 T_n = 1 - \exp(-\alpha\lambda_2), \quad (36)$$

and

$$P\left\{Y_{t+T_n} = C \mid Y_t = C\right\} = \mu_2 T_n = 1 - \exp(-\alpha\mu_2). \quad (37)$$

Now by taking into account (23) with some algebraic manipulations, we can write the expression for a link that makes transition from the disconnection to the connection state as

$$(1 - P_{L1})^{1/t_{tot}} = \exp(-\alpha\mu_2); \quad \forall P_{L1} < 0.5, \quad (38)$$

where P_{L1} represents the link probability of a link that remains in a disconnection state at previous time step of the Markov process.

Similarly, the expression for a link that remains in the connection state is given by

$$(1 - P_{L2})^{1/t_{tot}} = \exp(-\alpha\lambda_2); \quad \forall P_{L2} \geq 0.5, \quad (39)$$

where P_{L2} represents the link probability of a link that remains in a connection state at previous time step of the Markov process. Hence, we compute the transition rates for the disconnection and the connection states at current time step of the process, by taking into account (15) and (12), respectively, as

$$\mu_2 = \frac{\left(S^{ch} + S^{ord}\right) . \ln\left((1 - P_{L1})^{1/t_{tot}}\right)}{D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right) - R'}, \quad (40)$$

and

$$\lambda_2 = \frac{\left(S^{ch} + S^{ord}\right) . \ln\left((1 - P_{L2})^{1/t_{tot}}\right)}{D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right) - R'}. \quad (41)$$

The threshold values for P_{L1} and P_{L2} are decided on the basis of transmission rate of Hello messages and total transmission retries for link connectivity at different time steps of the Markov process.

In order to study the behavior of link connectivity as a continuous function of time, we incorporate the concept of continuous time markov chain (CTMC) for achieving QoS routing [33, 34] by analyzing the link stability for the proposed DLC strategy.

5.5. Continuous Time Analysis of Dynamic Link Connectivity. Let us consider λ_2 and μ_2 as the transition rates of the process from the disconnection to the connection state, i.e., $D \longrightarrow C$, and from the connection to the connection state, i.e., $C \longrightarrow C$, respectively. A CTMC with λ_2 and μ_2 is a stochastic process, Y_t. Now, by taking into account T_n, as given by (11), the next Hello message(s) arrival instance at a neighboring node, i.e., $(t + T_n)$ for the process Y_t [5], at next time step of the Markov process, satisfies

$$\begin{aligned} P&\left\{Y_{t+T_n} = \mathrm{C} \mid Y_t = \mathrm{C}\right\} \\ &= 1 - \left(\mu_2\left(\frac{D_2 - D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)}{S^{ch} + S^{ord}}\right)\right), \end{aligned} \quad (42)$$

and

$$\begin{aligned} P&\left\{Y_{t+T_n} = \mathrm{C} \mid Y_t = \mathrm{D}\right\} \\ &= \lambda_2\left(\frac{D_2 - D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)}{S^{ch} + S^{ord}}\right). \end{aligned} \quad (43)$$

In the proposed DLC strategy, probability of disconnectivity is introduced in (8). In order to analyze the influence of λ_2 and μ_2 on the probabilities of link connectivity and disconnectivity, by considering the concept of conditional probability [5, 22], we obtain

$$\begin{aligned} P_C(t + T_n) &= P_C(t) P\left\{Y_{t+T_n} = C \mid Y_t = C\right\} \\ &\quad + P_D(t) P\left\{Y_{t+T_n} = C \mid Y_t = D\right\}. \end{aligned} \quad (44)$$

Now, by considering the probability law of Poisson process [5] and after algebraic manipulations, we obtain

$$\begin{aligned} &P_C(t + T_n) \\ &\quad = P_C(t)\left(1 - \left(\mu_2\left(\frac{D_2 - D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)}{S^{ch} + S^{ord}}\right)\right)\right) \\ &\qquad + P_{\mathrm{D}}(t)\lambda_2\left(\frac{D_2 - D\left(C_{ch}^{(n)}, C_{ord}^{(n)}\right)}{S^{ch} + S^{ord}}\right) P_C'(t) \\ &\quad = \lambda_2 P_D(t) - \mu_2 P_C(t). \end{aligned} \quad (45)$$

where $P_C'(t)$ indicates the first-order derivative of the probability of link connectivity at the current time step of the Markov process.

Similarly, the first-order derivative of the probability of link disconnectivity can be calculated by taking into account (41) and (42) as

$$P_D'(t) = \left(\frac{\left(S^{ch}+S^{ord}\right)\ln\left(\left(1-P_{L1}\right)^{1/t_{tot}}\right)}{D\left(C_{ch}^{(n)},C_{ord}^{(n)}\right)-R'}\right)P_C(t) - \left(\frac{\left(S^{ch}+S^{ord}\right)\ln\left(\left(1-P_{L2}\right)^{1/t_{tot}}\right)}{D\left(C_{ch}^{(n)},C_{ord}^{(n)}\right)-R'}\right)P_D(t). \quad (46)$$

Now, let the transition matrix x, which is the infinitesimal generator [22] of a Markov chain, and the column stochastic matrix $A(t)$ be represented for the proposed strategy as [22]

$$\mathbf{A}'(t) = \mathrm{x}A(t), \quad (47)$$

where x=$\begin{bmatrix} -\lambda_2 & \mu_2 \\ \lambda_2 & -\mu_2 \end{bmatrix}$ and $\mathbf{A}(t) = [P_D(t), P_C(t)]^T$.

By solving the differential equation and considering the inverse Laplace transform, (48) can be written as [8]

$$\mathbf{A}'(t) = \begin{bmatrix} \dfrac{\mu_2}{\lambda_2+\mu_2} + \dfrac{\lambda_2}{\lambda_2+\mu_2}e^{-(\lambda_2+\mu_2)t} & \dfrac{\mu_2}{\lambda_2+\mu_2} - \dfrac{\mu_2}{\lambda_2+\mu_2}e^{-(\lambda_2+\mu_2)t} \\ \dfrac{\lambda_2}{\lambda_2+\mu_2} - \dfrac{\lambda_2}{\lambda_2+\mu_2}e^{-(\lambda_2+\mu_2)t} & \dfrac{\lambda_2}{\lambda_2+\mu_2} + \dfrac{\mu_2}{\lambda_2+\mu_2}e^{-(\lambda_2+\mu_2)t} \end{bmatrix}, \quad (48)$$

where t represents the current instance of time.

At steady state [22], (49), for the proposed DLC strategy, reduces to (50).

$$\mathbf{A}'(t) = \begin{bmatrix} \dfrac{\ln\left(\left(1-P_{L1}\right)^{1/t_{tot}}\right)}{\ln\left(\left(1-P_{L1}\right)^{1/t_{tot}}\right)+\ln\left(\left(1-P_{L2}\right)^{1/t_{tot}}\right)} & \dfrac{\ln\left(\left(1-P_{L1}\right)^{1/t_{tot}}\right)}{\ln\left(\left(1-P_{L1}\right)^{1/t_{tot}}\right)+\ln\left(\left(1-P_{L2}\right)^{1/t_{tot}}\right)} \\ \dfrac{\ln\left(\left(1-P_{L2}\right)^{1/t_{tot}}\right)}{\ln\left(\left(1-P_{L2}\right)^{1/t_{tot}}\right)+\ln\left(\left(1-P_{L1}\right)^{1/t_{tot}}\right)} & \dfrac{\ln\left(\left(1-P_{L2}\right)^{1/t_{tot}}\right)}{\ln\left(\left(1-P_{L2}\right)^{1/t_{tot}}\right)+\ln\left(\left(1-P_{L1}\right)^{1/t_{tot}}\right)} \end{bmatrix}. \quad (49)$$

Hence, from (50), it is evident that probabilities of disconnectivity and connectivity, at current time step of the process, at steady state are given, respectively, by

$$\lim_{t\longrightarrow\infty} P_D(t) = \frac{\ln\left(\left(1-P_{L1}\right)^{1/t_{tot}}\right)}{\ln\left(\left(1-P_{L1}\right)^{1/t_{tot}}\right)+\ln\left(\left(1-P_{L2}\right)^{1/t_{tot}}\right)}, \quad (50)$$

and

$$\lim_{t\longrightarrow\infty} P_C(t) = \frac{\ln\left(\left(1-P_{L2}\right)^{1/t_{tot}}\right)}{\ln\left(\left(1-P_{L2}\right)^{1/t_{tot}}\right)+\ln\left(\left(1-P_{L1}\right)^{1/t_{tot}}\right)}. \quad (51)$$

Transmission rate of Hello messages is an important parameter of interest, which can be affected by the AMP levels required between neighboring nodes for effective communication inside the cluster. This is helpful in determining the necessary conditions for link connectivity and stability of a neighboring node in terms of RSS and SNR, respectivley. In addition, link probability and CH selection criteria play a pivotal role in estimating the transition rates for the connection and disconnection states and, thus, they are helpful in calculating the stationary probability distribution for the link connectivity and disconnectivity, as presented in Algorithm 1.

Algorithm 1, being part of the proposed DLC strategy, obtains efficient link connectivity among the neighboring nodes inside a cluster. In the Top phase, a CH is selected on the basis of the derived CH selection criteria, as presented in Section 4.5 of the paper. In the Middle phase, the necessary conditions for the link connectivity and stability of a neighboring node, as presented in Sections 5.1 and 5.2 of the paper, are determined for each pair of neighboring nodes inside the cluster. In the Final phase, the steady state probabilities of connectivity and disconnectivity, as presented in Section 5.5 of the paper, are calculated based on the prior transition rate estimation for the connection and disconnection states, as presented in Section 5.4 of the paper. These probabilities are helpful in determining the transition rates for the connection and disconnection states at the next time steps of the Markov process, respectively. In addition, the purpose of Algorithm 1 in the DLC strategy is to check the connectivity of a link among all neighboring nodes inside the cluster at each time step of the Markov process. Hence, link stability for all mobile nodes inside the cluster is analyzed, which is the role of Algorithm 1 in the proposed DLC strategy.

6. Performance Evaluation

This section presents performance evaluation of our proposed DLC strategy in comparison with the AODV routing protocol [35], utility of Hello messages (UHM) [4], link stability estimation (LSE) [8], and Markov model for link connectivity (MLC) [6]. The simulation of proposed DLC strategy is performed using the

Input: $p_c, p_n, p_r, T_n, R', S^{ch}, S^{ord}, \mathrm{c}_1, \mathrm{d}_1, \lambda, \lambda_2, \mu_2, \alpha, P_{L1}, P_{L2}, t_{tot}, \Delta t, D\,(C_{ch}^{(n)}, C_{ord}^{(n)}), E_{RES}, E_{max}, \eta$
1: **Top:**
2: Solve $CH_{prob}(p_c, E_{RES}, E_{max})$ to obtain the CH selection Probability.
3: **for** each CH-Other node pair **do**
4: **if** $D\,(C_{ch}^{(n)}, C_{ord}^{(n)}) \le R'$ **then**
5: Calculate $\eta\,(R', D(C_{ch}^{(n)}, C_{ord}^{(n)}), S^{ch}, S^{ord})$ to determine the necessary condition for link connectivity.
6: **end if**
7: **Middle:**
8: **if** $\eta \ge \left(\dfrac{R' - D(C_{ch}^{(n)}, C_{ord}^{(n)})}{S^{ch} + S^{ord}}\right)$ **then**
9: Solve $\mathrm{SNR_{dB}}(\lambda 1, \lambda 1', R', R1', S^{ch}, S^{ord}, D1(C_{ch}^{(n)}, C_{ord}^{(n)}), D1'(C_{ch}^{(n)}, C_{ord}^{(n)}), p_c, \mathrm{SNR})$ to check the stability of a neighboring node.
10: **for** each CH-Other node pair **do**
11: **if** $\mathrm{SNR_{dB}} \ge \Gamma$ **then**
12: goto step 5
13: **else**
14: Calculate $P\,(\mathrm{SNR_{dB}} < \Gamma \wedge \eta < \Upsilon)$ to determine probability of disconnectivity at current time step of the Markov process.
15: **end if**
16: **end if**
17: **Final:**
18: **for** each CH-Other node pair inside the cluster **do**
19: Calculate $\lim_{t\longrightarrow\infty} P_C(t)(\lambda_2, \mu_2)$ and $\lim_{t\longrightarrow\infty} P_D(t)(\lambda_2, \mu_2)$ to determine the probabilities of connectivity and disconnectivity at steady state of the Markov process.
21: Calculate $\lambda_2(S^{ch}, S^{ord}, P_{L2}, R', D(C_{ch}^{(n)}, C_{ord}^{(n)}), t_{tot})$ and $\mu_2(S^{ch}, S^{ord}, P_{L1}, R', D(C_{ch}^{(n)}, C_{ord}^{(n)}), t_{tot})$ to determine the transition rates for the connection and disconnection states, respectively for next time step of the Markov process.
21: goto step 18
22: **end**

Algorithm 1: Efficient Link Connectivity Inside Cluster.

Iuriivoitenko-simplemanet simulator (http://www.mathworks.com/matlabcentral/fileexchange/59007-Iuriivoitenko-simplemanet). The simulation results presented are averaged over 30 replicated simulation runs. The simulations are carried out for the network scenario depicted in Figure 1 and for the simulation parameters presented in Table 1. Total number of nodes inside the network is 160. The number of nodes assumed inside each cluster before the start of simulation is 50. The random way point (RWP) mobility model [31] is used in the simulations. The transmission range of a cluster is assumed to be 50 meters, unless otherwise stated. The transmission retries of Hello messages and probability of link connectivity are 1 and 0.5, respectively, unless otherwise stated. In addition, the SNR threshold between the CH and its neighbor, before the start of simulations, is assumed to be 30 dB. Simulation results of the proposed DLC strategy are validated through analytical results obtained on MATLAB (R2017a). The performance evaluation metrics include optimum received signal strength, stability of a neighboring node in terms of SNR value, transition rates from disconnection to connection state and vice versa, and probabilities of disconnectivity and connectivity at steady state of the Markov process.

6.1. Optimum Received Signal Strength. In this subsection, we evaluate the RSS required between the neighboring nodes for link connectivity under random trajectory of mobile nodes, uniform speed of CH and an ordinary node, and variable sized critical transmission range of a cluster. Figure 5 shows the RSS required for link connectivity by varying the transmission range of the considered cluster from 10 to 50 meters. From this result, it is clear that, by increasing the transmission range of the cluster, the RSS required to maintain link connectivity between the neighboring nodes decreases. This is due to the fact that if the required RSS

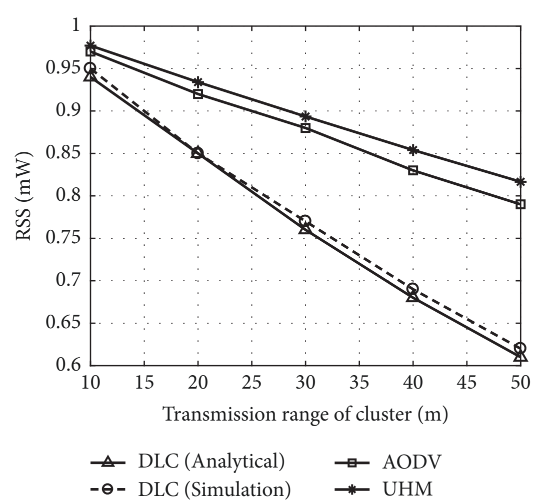


Figure 5: Obtained RSS for the given transmission range of the cluster.

Table 1: Simulation Parameters.

Parameter	Configuration
Area (m × m)	500×500
Simulation time (s)	500
Pause time (s)	0
Traffic type	CBR
Packet size	512 bytes
MAC layer protocol	MAC 802.11
Antenna type	Omni directional
Radio-propagation model	**Two—ray ground—reflection**
Fading model	**Log—distance path loss**
Random jitter[4]	10 ms
R'(m)	$[10, 20, 30, 40, 50]$
S^{ch}(m/s)	$[5, 10, 15, 20, 25]$
S^{ord}(m/s)	$[5, 10, 15, 20, 25]$
$D(C_{ch}^{(n)}, C_{ord}^{(n)})(m)$	5.0
Γ	30 dB
Additive background noise [8]	0.5 dB
λ	0.213
$\lambda 1$	$[0.1, 0.2, 0.3, 0.4, 0.5]$
$\lambda 1'$	$[0.1, 0.15, 0.2, 0.4, 0.5]$
$R1'$(m)	$[10, 15, 20, 40, 50]$
$D1(C_{ch}^{(n)}, C_{ord}^{(n)})(m)$	$[5, 10, 15, 20, 30]$
$D1'(C_{ch}^{(n)}, C_{ord}^{(n)})(m)$	$[5, 7.5, 10, 25, 30]$
p_c	50
P_L	**0.5 [17]**
t_{tot}	$[1, 2, 3, 4, 5]$

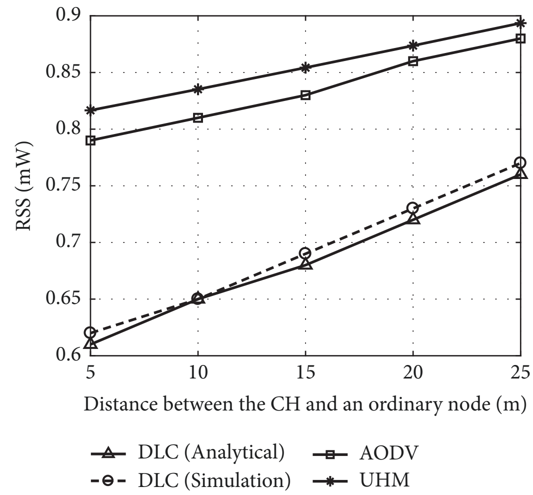


Figure 6: Obtained RSS for the given distance between the CH and an ordinary node.

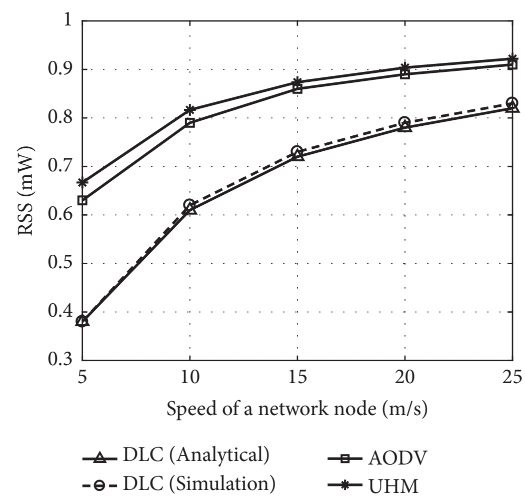


Figure 7: Obtained RSS for the given speed of a network node.

increases from the threshold η, there is a possibility that a neighboring node will be linked to one of its other possible neighbors for which the required RSS is less than or equal to η. Therefore, with the higher transmission range of a cluster, the optimum RSS level needs to be maintained for link connectivity between the neighboring nodes. Thus, with increase in distance between the neighboring nodes, as a result of higher transmission range for a cluster, the required RSS decreases. This result also holds true for AODV and UHM but higher AMP is required for link connectivity, contrary to the proposed DLC strategy that requires lower AMP for its link establishment with a neighboring node. Hence, the proposed DLC strategy improves energy efficiency of the network.

In Figure 6, the RSS is obtained by varying the distance between neighboring nodes inside the cluster from 5 to 25 meters. From the result it is clear that, by increasing the distance between the neighboring nodes, the RSS required to maintain the link connectivity between the neighboring nodes also increases. Therefore, the higher the distance between the neighboring nodes, the higher the delay between transmission and reception of the consecutive Hello messages. This is due to the fact that, with high speed and random motion of network nodes inside the cluster, there are greater chances of link disconnectivity among the neighboring nodes at particular time step of the Markov process. Thus, for network nodes moving with high speed and in random trajectories, the RSS required for link connectivity among the neighboring nodes increases. Hence, for an optimum RSS level in the case of the proposed DLC strategy, propagation delay between transmission and reception of the consecutive Hello messages can be minimized. Therefore, the DLC strategy yields better results compared with AODV and UHM.

In Figure 7, the RSS is obtained by varying the speed at which the neighboring nodes are moving inside the cluster from 5 to 25 m/s. From the figure it is clear that, by increasing the speed of neighboring nodes, the RSS required to maintain link connectivity between the neighboring nodes increases. This is due to the fact that, with higher speeds of the neighboring nodes, the chances of transition from the disconnection to the connection state at current time step of the Markov process are lower. Thus, the probability of disconnectivity increases. Hence, the RSS required for link connectivity in this particular case is higher. Therefore, for

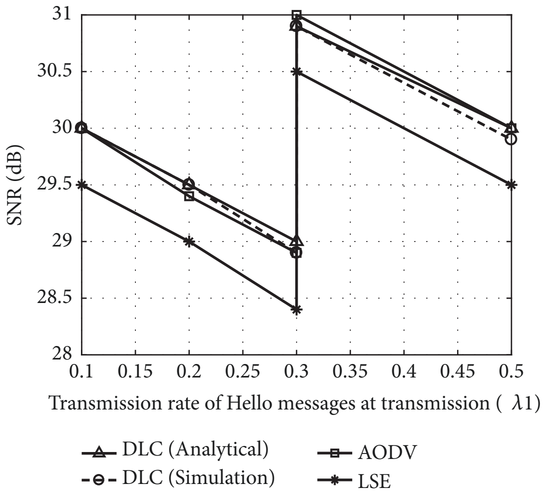


Figure 8: Stability of a network node by varying the transmission rate of Hello messages.

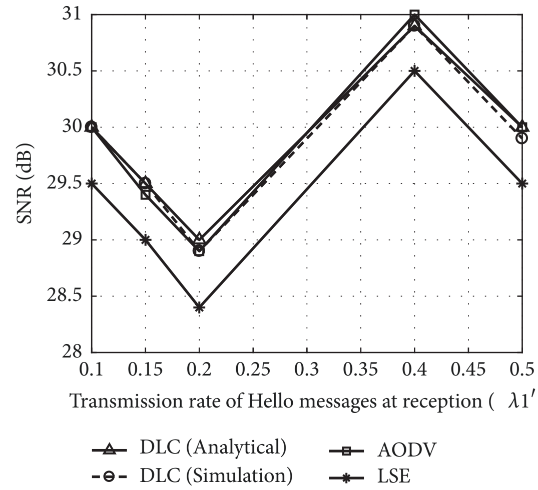


Figure 9: Stability of a network node by varying the reception rate of Hello messages.

an optimum RSS level in the case of the proposed DLC strategy, the robustness and longevity of a link among the neighboring nodes can be ensured. Thus, better link stability can be obtained for the DLC strategy compared with AODV and UHM.

6.2. Stability of a Neighboring Node in terms of Signal-to-Noise Ratio. In this subsection, we analyze the stability of a network node with reference to its neighbor in terms of SNR by varying the transmission rate of Hello messages at transmitter and receiver, transmission range of the variable sized cluster, and distances between the neighboring nodes at transmitter and receiver. Importantly, for Figure 8 through Figure 13, it is evident that, by keeping the fixed value for the transmission rate, the SNR remains fixed. In Figure 8, stability of a neighboring node, in terms of SNR ratio, is obtained by varying the transmission rate of Hello messages from 0.1 to 0.5 between the neighboring nodes for link connectivity inside the cluster. Furthermore, by increasing the transmission rate of Hello messages, the SNR decreases. This is due to the fact that, with higher transmission rate of Hello messages between the neighboring nodes, the probability of link disconnectivity at next time step of the Markov process decreases due to higher stability of a neighboring node. Hence, the higher the transmission rate of Hello messages, the lower the propagation delay between transmission and reception of the consecutive Hello messages due to reduced congestion. Therefore, the proposed DLC strategy also contributes to the reduction of end-to-end delay by means of reducing the propagation delay. Importantly, at $\lambda 1 = 0.3$, there is a sharp transition in the stability of a neighboring node. Hence, for this particular value of $\lambda 1$, the chances of link disconnection are higher. The proposed strategy yields better results for $(0.1 \le \lambda 1 \le 0.3)$, due to high probability of link transition to the connection state compared with AODV. However, in the range $(0.3 \le \lambda 1 \le 0.5)$, AODV yields better results due to smaller transmission rate of Hello messages compared with DLC and LSE. For $\lambda 1 = 0.3$, we obtain the same result for the proposed DLC strategy as in the case of AODV. In addition, we take multiple SNR values at $\lambda 1 = 0.3$ because $\mathrm{SNR}_{\mathrm{dB}} \ge \Gamma$ does not hold true for current neighbors at present time step of the Markov process. Hence, we take multiple values of SNR at two different time steps of the process.

In Figure 9, stability of a node is obtained in terms of SNR by varying the reception rate of Hello messages from 0.1 to 0.5 between the neighboring nodes inside the cluster. From the result, it is clear that, by increasing the reception rate of Hello messages compared with the transmission rate, the SNR increases, whereas by increasing the transmission rate of Hello messages, the SNR decreases. This is due to the fact that, with the higher reception rate of Hello messages by the neighboring node, the link connectivity at next time step of the Markov process is higher due to less congestion. Hence, stability of a neighboring node is greater. Hence, for an optimum SNR threshold over the corresponding link in the proposed DLC strategy, lower communication overhead can be achieved due to less congestion among the neighboring nodes. Importantly, in the range $(0.2 \le \lambda 1' \le 0.4)$, their is a uniform increase in the stability of a neighboring node. Hence, we obtain the maximum stability at $\lambda 1' = 0.4$. Thus, for this value of $\lambda 1'$, we achieve maximum probability of link connectivity. The proposed strategy yields better results in the range $(0.1 \le \lambda 1' \le 0.3)$ compared with AODV and LSE due to high probability of link connectivity. However, in the range $(0.3 \le \lambda 1' \le 0.5)$, AODV yields better results due to less congestion among the neighboring nodes.

In Figure 10, stability of a node is obtained in terms of SNR by varying the transmission range of cluster from 10 to 50 meters at transmitter. From the result it is evident that, by increasing the transmission range of the cluster, the SNR first increases and then decreases to reach a minimum peak value for transmission range of 30 meters. This is due to the fact that a small transmission range of cluster at transmission

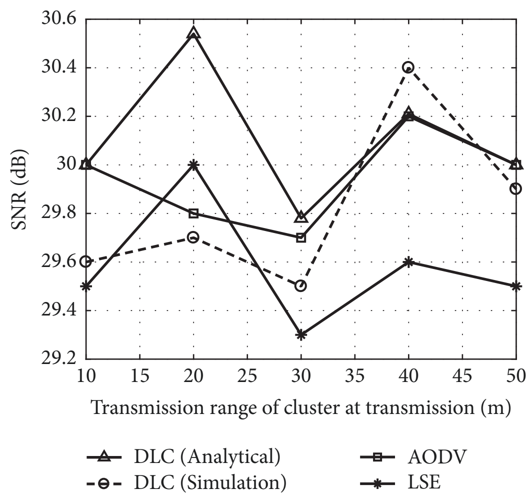


Figure 10: Stability of a network node by varying the transmission range of the cluster.

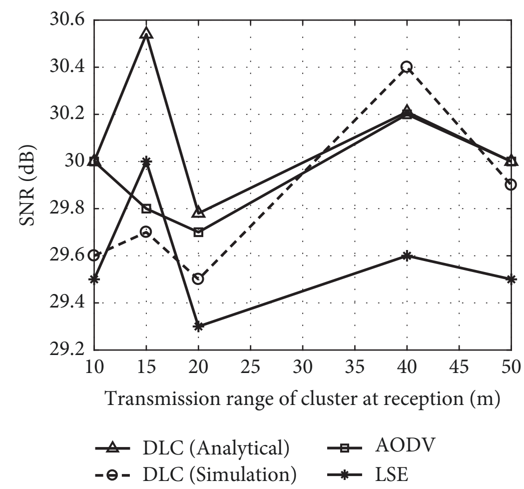


Figure 11: Stability of a network node by varying the reception range of the cluster.

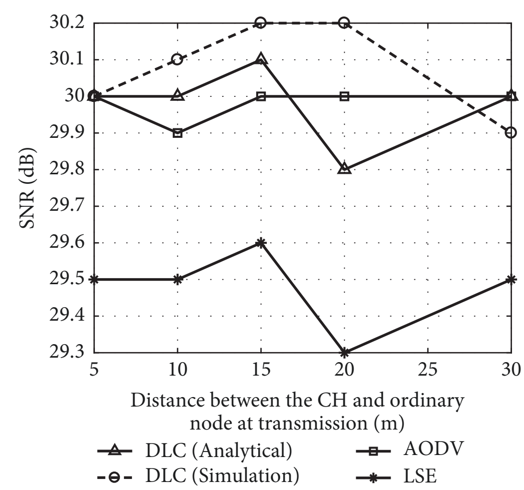


Figure 12: Stability of a network node by varying the distance between the neighboring nodes at transmission.

indicates that λ between neighboring nodes is high. Therefore, probability of link connectivity at next time step of the Markov process increases. Hence, stability of a neighboring node is greater. In addition, increasing the transmission range of cluster beyond this point, where the average distance between the CH and its neighbor is less than the average distance between the neighbor and the cluster boundary, the SNR decreases due to increase in the link disconnection rate as a result of lower transmission rate of Hello messages. This does not hold true for AODV because, for the fixed transmission range of cluster in AODV, the rate at which the Hello messages are transmitted remains fixed. In addition, for the transmission range of 35 meters, the simulation result matches with AODV, which indicates that λ is independent of this value of R' in the case of both AODV and the proposed strategy. The analytical results deviate from the simulation results because there is an expected increase in the critical transmission range of an individual neighboring node as a result of possible overlapping with other neighboring node(s) inside the cluster after transmission of the first Hello message retry. Hence, for an optimum R', the proposed DLC strategy can minimize the node interference among the neighboring nodes by reducing possible overlapping among them. For this result, DLC and AODV perform better in the particular ranges compared with LSE. Similar results are also observed in Figure 11.

In Figure 11, stability of a node is obtained in terms of SNR by varying the transmission range of cluster from 10 to 50 meters at reception. From the result it is clear that, by increasing the transmission range of the cluster, the SNR first increases and then decreases to reach a minimum peak value for transmission range of 20 meters. This difference of 10 meters between the minimum peak values at transmission and reception is due to the fact that the probability of disconnectivity between the CH and its neighbor is higher at reception compared with the transmission. Hence, the probability of link connectivity at next time step of the Markov process is lower. Therefore, stability of network node is degraded in this particular case. In addition, increasing the transmission range of cluster beyond this point, stability of a neighboring node increases uniformly. This result indicates that, on average, with decrease in the transmission rate of Hello messages, the chances for the link connection and disconnection are identically distributed. Hence, the probability of link connectivity exhibits uniform distribution in the range ($20 \le R' \le 40$) where LSE performs better compared with AODV and DLC. Furthermore, for transmission range of 30 meters, the simulation result matches with the AODV indicating that λ is independent of this particular value for R', in both the case of AODV and the proposed strategy. Importantly, the 10-meter difference in the transmission range of the cluster at transmission and reception accounts for the 5-meter difference in the converging point where the DLC (simulation) and AODV results meet with each other.

In Figure 12, stability of a neighboring node is obtained in terms of SNR by varying the distance between the CH and its neighbor from 5 to 30 meters at transmission inside

Table 2: Maintaining link stability under DLC strategy.

Input	(+) SNR deviation	(-) SNR deviation
λ	0.9 dB	1.1 dB
R'	0.4 dB	0.5 dB
$D(C_{ch}^{(n+1)}, C_{ord}^{(n+1)})$	0.2 dB	0.1 dB
Mean	+0.5 dB	-0.56 dB

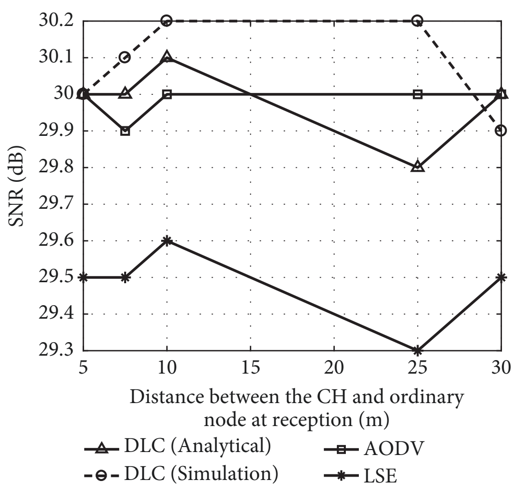


Figure 13: Stability of a network node by varying the distance between the neighboring nodes at reception.

the cluster. From the result it is evident that, by increasing the distance between CH and its neighbor, the SNR first increases and then remains constant in the range of 15 to 20 meters for the simulation results. The analytical results remain fixed for the distance in the range of 5 to 10 meters, due to lower chances of link disconnection for such small distance between the neighboring nodes inside the cluster. Furthermore, by increasing the distance between the neighboring nodes, the SNR for the simulation result decreases. This is due to the fact that the higher the distance between the neighboring nodes, the smaller the transmission rate of Hello messages at the next time step of the Markov process. Therefore, the chances of link connectivity decreases. Hence, stability of the neighboring node decreases in this particular case. In addition, in the case of AODV, the SNR initially exhibits the dip-down triangular behavior and then remains constant for the rest of the values. This is due to the fact that, for smaller values of distance, the chances of link connection and disconnection are identically distributed, whereas for higher values of distance, the AODV is independent of λ. The analytical results deviate from the simulation results because the probability of successful reception of expected Hello messages by a neighboring node varies in the case of simulation. Thus, the probability of successful reception of Hello messages in any t_{tot} transmission retries varies at next time step of the Markov process. Thus, the number of nodes inside a cluster varies, which consequently affects the distance between the CH and its neighbor. For Figures 12 and 13, DLC and AODV perform better compared with LSE. Similar results are also observed in Figure 13.

In Figure 13, stability of a neighboring node is obtained in terms of SNR by varying the distance between the CH and its neighbor from 5 to 30 meters at reception inside the cluster. From the result, it is clear that, by increasing the distance between CH and its neighbor, the SNR first increases and then remains constant in the range of 10 to 25 meters for the simulation results. This difference of 5 meters for SNR between the maximum peak values at transmission and reception is due to the fact that the chances for the link connectivity, for the fixed transmission rate of Hello messages, increase between the neighboring nodes at reception. The analytical result remains fixed in the range of 5 to 7.5 meters due to very rare chances of link disconnection for such small distance between the neighboring nodes inside the cluster. Furthermore, by increasing the distance between the neighboring nodes, the SNR for the simulation results touches the minimum peak for transmission range of 25 meters compared with the 20 meters in the case of transmission. This clearly indicates that our proposed strategy exhibits better performance in terms of high SNR with increase in distance. Therefore, stability of the neighboring node increases. In addition, in the case of AODV, the SNR initially exhibits the dip-down triangular behavior and then remains constant for the rest of the values. This is due to the fact that for smaller values of distance the chances of link connection and disconnection are identically distributed, whereas for higher values of distance the AODV is independent of λ. Hence, at reception the AODV shows fluctuations in the connection and disconnection states for smaller values of λ.

Table 2 analyzes the link stability in terms of SNR presented in Figure 8 through Figure 13. The table shows that link stability is maintained under the proposed DLC strategy for multiple X-axis parameters (i.e., transmission rate of Hello messages, transmission range of the cluster, and distance between the CH and an ordinary node at next time step of the Markov process). Significantly, a mean SNR deviation of [-0.56—0.5] from the initial SNR threshold of 30 dB is observed for the DLC (Simulation) results.

6.3. Transition Rate Estimation between Connection and Disconnection States. In this subsection, we determine the rate at which transition takes place between the connection and disconnection states regarding the current status of the previously connected or disconnected link among the neighboring nodes at the current time step of the Markov process. This can be done by considering the transmission retries of Hello messages, speed of a network node, and

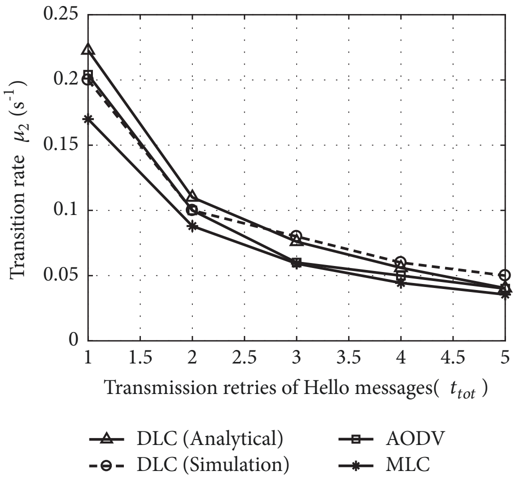


Figure 14: Transition rate for the disconnection state given the transmission retries of Hello messages.

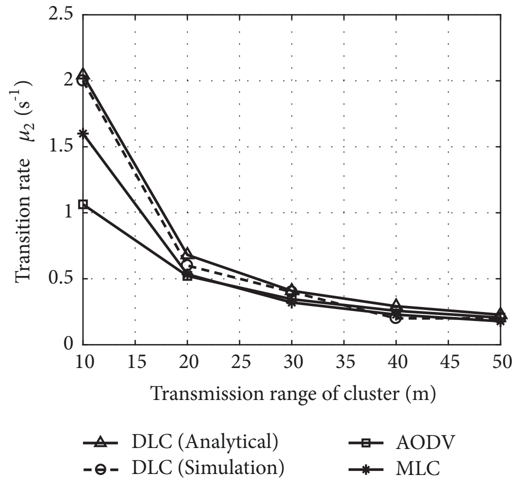


Figure 16: Transition rate from the disconnection state given the transmission range of a cluster.

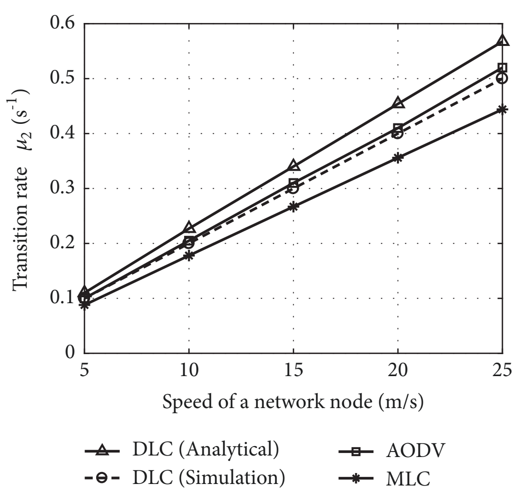


Figure 15: Transition rate from the disconnection state given the speed of a network node.

transmission range of the considered cluster. In Figure 14, transition rate from the disconnection to the connection state is obtained by varying the transmission retries of Hello messages from 1 to 5. From the figure it is evident that, by increasing the transmission retries of Hello messages between the neighboring nodes inside the cluster, the transition rate from the disconnection to the connection state decreases. This is due to the fact that, by increasing transmission retries for link reconnectivity after disconnection, the chances of link connectivity decrease. Therefore, the higher the transmission retries of Hello messages, the smaller the chances of link reconnectivity at the next time step of the Markov process.

In Figure 15, transition rate from disconnection to the connection state is obtained by varying the speed at which the nodes are moving inside the cluster from 5 to 25 m/s. From the figure it is evident that, by increasing the speed, the transition rate from the disconnection to the connection state increases. This is due to the fact that, with high speed after disconnection, the rate at which transition is made between the two states is higher. Therefore, with the higher speed of a network node, the chances of link reconnectivity increase at a uniform rate. Thus, the average response time for link establishment among the neighboring nodes after link failure(s) in the proposed DLC strategy minimizes. Hence, the DLC strategy yields better results compared with the AODV and MLC.

In Figure 16, the transition rate from the disconnection to the connection state is obtained by varying the transmission range of the considered clusters from 10 to 50 meters. It is evident from this result that, by increasing the transmission range, the transition rate from the disconnection to the connection state decreases. It is due to the fact that the higher the transmission range of a cluster, the greater the distance between the neighboring nodes. Therefore, the chances of making transition from the disconnection to the connection state are lower. Hence, with the higher transmission range of a cluster, there is a higher likelihood for a link to remain in a disconnection state. Thus, for an optimum R', the proposed DLC strategy can obtain higher throughput in terms of successful reception of Hello message(s) from the neighboring nodes due to robust transition from disconnection to connection state.

In Figure 17, transition rate to remain in the connection state is obtained by varying the transmission retries of Hello messages from 1 to 5. From the figure it is evident that, by increasing the transmission retries of Hello messages between neighboring nodes inside the cluster, the chances to remain in the connection state, at the next time step of the Markov process, decrease. It is due to the fact that, with increasing transmission retries after link connectivity, the chances of link disconnectivity increase due to increased congestion as a result of large number of Hello messages retries. Thus, the probability of link connectivity decreases. Therefore, the higher the transmission retries of Hello messages, the smaller the chances for a link to remain in the connection state at the

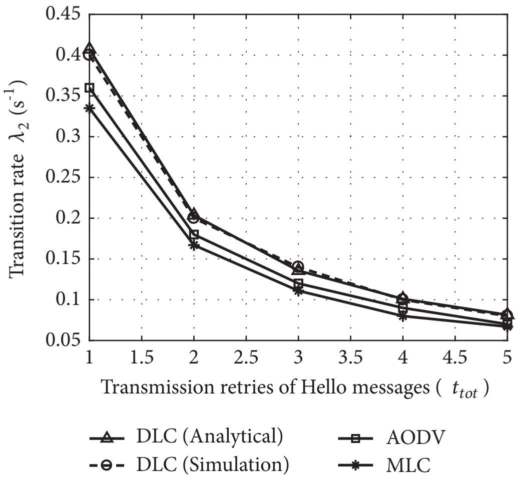


Figure 17: Transition rate to remain in the connection state given the transmission retries of Hello messages.

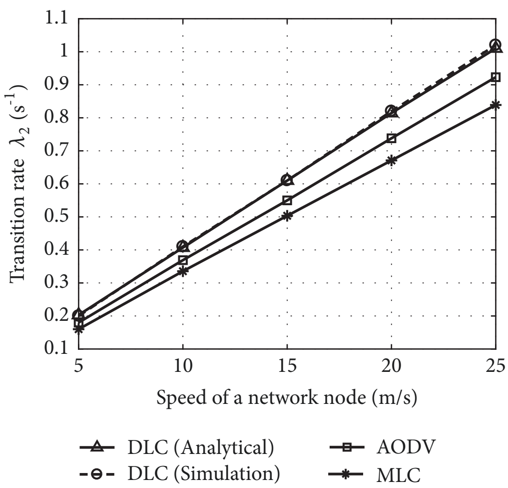


Figure 18: Transition rate to remain in the connection state given the speed of a network node.

next time step of the Markov process. Hence, for an optimum t_{tot}, lower Hello messaging packet loss ratio can be achieved due to lower congestion in the network.

In Figure 18, transition rate to remain in the connection state is obtained by varying the speed at which the nodes are moving inside the cluster from 5 to 25 m/s. From the figure it is evident that, by increasing the speed, the transition rate to remain in the connection state at the next time step of the Markov process increases. It is due to the fact that, with high speed after link connectivity, the rate at which transition is made from the connection state decreases for large (if the neighboring nodes are moving away from each other) distances among the neighboring nodes. Similarly, with high speed after link connectivity, the rate at which transition is made to the connection state increases for small (if the neighboring nodes are moving towards each other) distances among the neighboring nodes. Therefore, for high speed of network nodes, the chances to maintain link connectivity

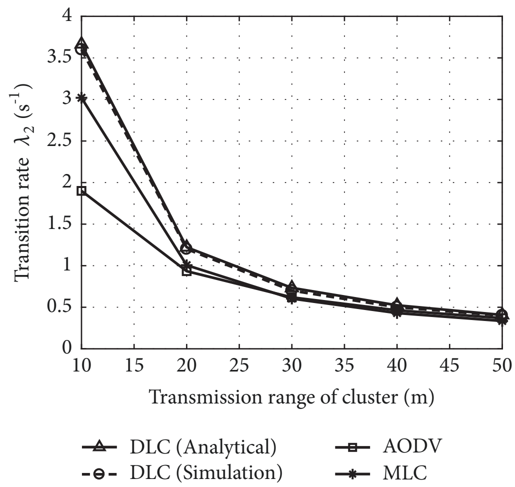


Figure 19: Transition rate to remain in the connection state given the transmission range of a cluster.

between the neighboring nodes decrease for large distance at the current time step of the Markov process. This result also holds true for AODV and MLC.

Figure 19 shows the transition rate to remain in the connection state by varying the transmission range of a cluster from 10 to 50 meters. It is clear from this result that, by increasing the transmission range, the transition rate to remain in the connection state at next time step of the Markov process decreases. This is due to the fact that the higher the transmission range of a cluster, the greater the distance between the neighboring nodes, as evident from (12). Hence, the chances of obtaining the minimum RSS and SNR threshold for a larger distance are low in the proposed DLC strategy. Therefore, with the higher transmission range of a cluster, there is a low likelihood for a link to remain in the connection state at next time step of the Markov process.

6.4. Impact of DLC Strategy on Application Layer Performance. In this section, we present the impact of DLC strategy on peer-to-peer (P2P) performance in terms of throughput, packet loss ratio, and communication overhead. In order to check the optimized applicability of DLC strategy for P2P application, we perform analysis on each independent type of X-axis parameters for results presented in Section 6. The obtained results are compared with AODV, as shown in Figure 20 through Figure 23. From these figures, it is evident that the proposed DLC strategy exhibits better performance compared with AODV by taking into account the optimum values for average response time, speed of a network node, distance between the CH and an ordinary node, probability of link connectivity, transmission retries for link reconnectivity, and the transmission range of cluster. Significantly, maintaining link stability and efficient link reconnectivity after link/node failure(s) are the two major metrics for performance evaluation of the DLC strategy at the application layer. Furthermore, for employment of the DLC strategy for P2P application, the possible changes that can be incorporated are highlighted, as shown in Tables 3 and 4.

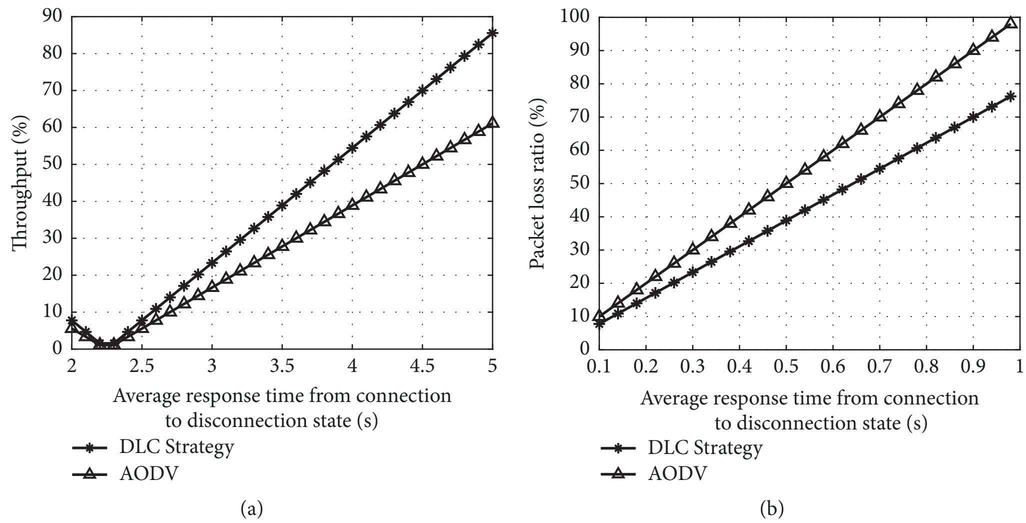


FIGURE 20: (a) Effect of average response time on throughput for the DLC strategy. (b) Effect of average response time on packet loss ratio for the DLC strategy.

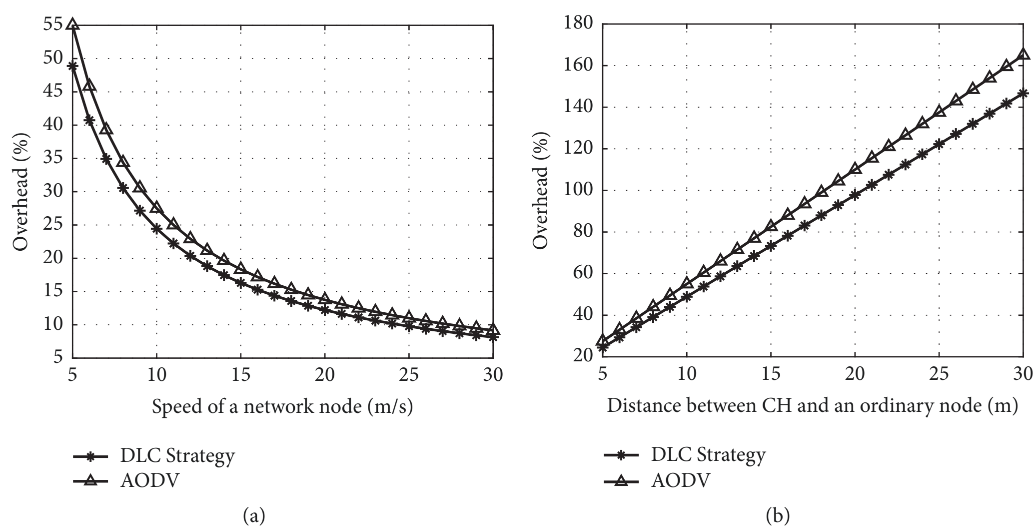


FIGURE 21: (a) Effect of speed of a network node on overhead for the DLC strategy. (b) Effect of distance between CH and an ordinary node on overhead for the DLC strategy.

6.5. Discussion. The results presented in the previous subsections indicate that the proposed DLC strategy effectively maintains link stability due to efficient link connectivity among neighboring nodes. Through analytical and simulation results, we find that optimum RSS among the neighboring nodes is affected by the transmission range of cluster, speed of a network node, distance between the CH and an ordinary node, transmission rate of Hello messages, AMP, and link probability. Furthermore, stability of a network node is affected by the transmission range of cluster, transmission and reception rates of Hello messages, and distance between the CH and an ordinary node. In addition, we find that transition rate between connection and disconnection states is affected by transmission retries of Hello messages, speed of a network node, transmission range of cluster, and probabilities of connectivity and disconnectivity at different time steps of the Markov process.

TABLE 3: Possible ranges in DLC link stability parameters for P2P applications.

Parameter for maintaining link stability	Possible Range
λ (s^{-1}) [Figures 5, 6, and 7]	[0—1]
Probability of link connectivity [Figures 16, 17, 18, and 19]	[0.6—1]
T_n (s) [Figures 8 and 9]	[0.1—0.5]

Due to optimum RSS level among the neighboring nodes, link longevity, lower propagation delay, and better energy

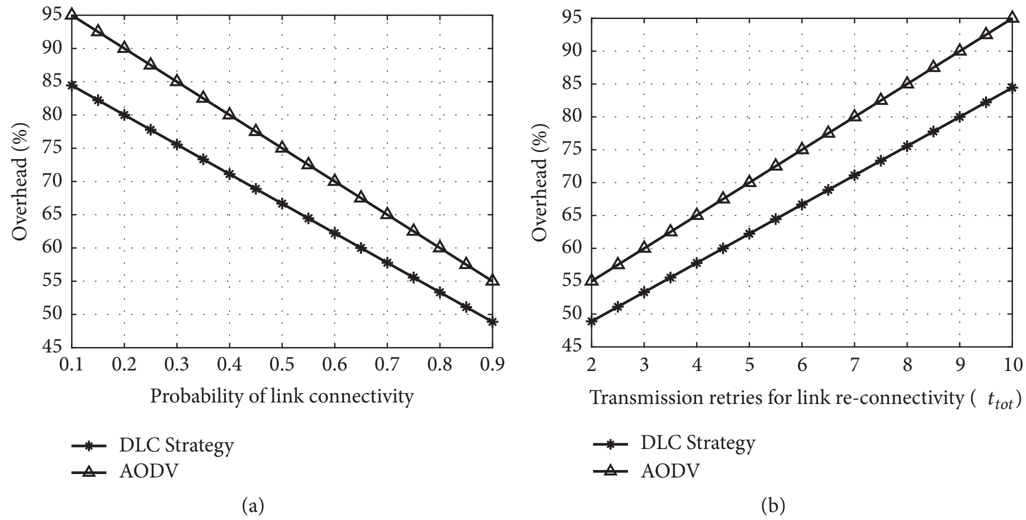


Figure 22: (a) Effect of probability of link connectivity on overhead for the DLC strategy. (b) Effect of transmission retries for link reconnectivity on overhead for the DLC strategy.

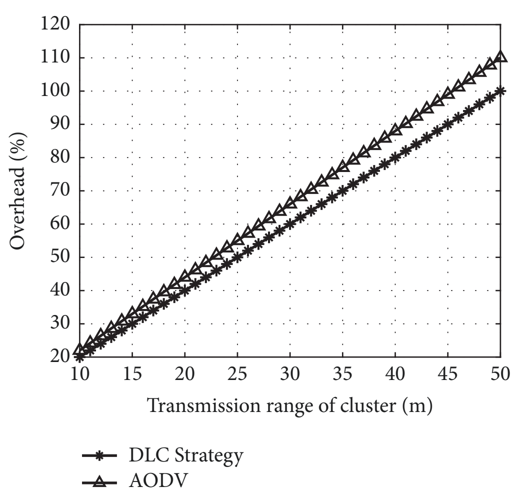


Figure 23: Effect of transmission range of cluster on overhead for the proposed DLC strategy.

Table 4: Possible ranges in DLC link reconnectivity parameters for P2P applications.

Parameter for link reconnectivity	**Possible Range**
Average path duration (s) [Figures 10, 11, 12, and 13]	[1—5]
t_{tot} [Figures 14 and 16]	[1—2]
Time to repair broken links (s) [Figures 14, 15, and 16]	[1—5]

efficiency are ensured by the proposed DLC strategy. Furthermore, higher stability of a network node, in terms of SNR, is obtained by achieving lower communication overhead and minimum node interference. Interestingly, in the case of DLC strategy, higher transition rates for a link to remain in the connection state, and transition from disconnection to the connection state, are obtained due to reduction in the average response time, increase in the throughput, and decrease in the packet loss ratio. Importantly, the lower the link probability of disconnection state, the higher the probability of connectivity at the steady state.

The proposed DLC strategy can be useful in numerous MANET applications that require link stability and efficient link connectivity, such as medical health-care, global positioning system (GPS), and video surveillance, to name a few. The proposed strategy can also bring advantages in routing by minimizing end-to-end delay. The end-to-end delay refers to the time taken for a packet to be transmitted across the network from source to destination and is the sum of transmission, propagation, processing, and queuing delays a packet experiences on its path. We have been referring to delay as the interarrival time between transmissions of consecutive Hello messages throughout the paper. As shown in Section 4.1, reducing this delay contributes to the reduction of propagation delay in the network. Therefore, the proposed DLC strategy also contributes to the reduction of end-to-end delay by means of reducing the propagation delay. In addition, as relevant for outdoor environments, the proposed DLC strategy may also be applicable for indoor environments. By carefully configuring the parameters of interest, as presented in Section 4 of the paper, better link connectivity and low propagation delay can be achieved for indoor environments. However, further study is needed to model and evaluate DLC strategy for indoor environments.

7. Conclusion

We have presented a novel DLC strategy using Hello messaging in MANETs, which addresses the issue of maintaining link stability through efficient link connectivity among neighboring nodes inside cluster. We have performed stochastic analysis of the proposed DLC strategy, which predicts the

Table 5: List of notations.

Parameter	Description
α	Inter-arrival time for uniform speed of the network nodes
α_1,α_2	Constant terms involved for calculating the energy utilized by a node
C'	Maximum cardinality of a node with MDRs and BMDRs
$C_{prob}^{(n)}$	Initial CH selection probability
CH_{prob}	CH selection probability
c_1	Transition probability from disconnection to the connection state
d_1	Transition probability from connection to the disconnection state
D	Distance between the CH and an ordinary node
D_1	Distance between the CH and an ordinary node at next time step of the Markov process
Δt	Time gap between transmissions of periodic Hello messages
E_{max}	Maximum energy of a node
E_{RES}	Current residual energy of a node
η	RSS threshold
g	Maximum number of nodes inside the cluster for calculating the average minimum power
k	Total number of nodes in the network region
λ	Transmission rate of Hello messages
$\lambda 1$	Transmission rate of Hello messages by the transmitting antenna
$\lambda 1'$	Reception rate of Hello messages by the receiving antenna
λ_2	Transition rate for the connection state
μ_2	Transition rate for the disconnection state
N	Number of trials or repetitions of the random experiment for link connectivity.
(n)	Current time step of the Markov process
$(n+1)$	Next time step of the Markov process
ωt	CH angle with reference to the origin
P^n	Transition probability matrix at steady state
P_L	Link probability
$P(D_2 > R')$	Probability of disconnectivity
$P\{Y_{t+\Delta t} = \mathrm{C} \mid Y_t = \mathrm{D}\}$	Probability that currently the process is in the connection state given it was in the disconnection state previously
$P(r/p_r)$	Probability of a successful Hello message reception by a neighboring node, given the minimum RSS
$p_{r,min}$	Minimum achieved RSS for AMP
p_c	Total number of nodes inside the cluster
P_n	Noise level involved in calculation of SNR
p_r	Received power by a node
p_t	Transmit power by CH
p_c'	Number of CHs at current time step of the Markov process
R	Critical transmission range of a network node
R'	Transmission range of the cluster
S^{ch}	Speed of CH
S^{ord}	Speed of ordinary node
T_n	Inter-arrival time between transmissions of the consecutive Hello messages
t_{tot}	Maximum number of Hello messages transmission retries for link connectivity
θ_n^{ch}	Angle of the CH with an ordinary node
θ_n^{ord}	Angle of an ordinary node with the origin of cluster
C_{ch}	Position of the CH
x_{ch}	X-axis position of the CH

Table 5: Continued.

Parameter	Description
x_{ord}	X-axis position of the ordinary node
x	Infinitesimal generator of the Markov chain
C_{ord}	Position of the ordinary node
y_{ch}	Y-axis position of the CH
y_{ord}	Y-axis position of the ordinary node

future link status among randomly deployed network nodes. Analytical and simulation results have enabled us to make a number of significant findings. We find that an optimum RSS level is required for maintaining link connectivity among the neighboring nodes. In addition, higher SNR is achieved among the neighboring nodes and, thus, network stability is obtained. Furthermore, transition rate between the connection and disconnection states is affected by the probability of link connectivity and disconnectivity at steady state. We demonstrate that the proposed DLC strategy obtains lower communication overhead, lower propagation delay, and minimum node interference. In addition, link longevity and energy efficiency of the network are also improved. Furthermore, it has been shown that our proposed strategy reduces the average response time, increases the throughput, and reduces the packet loss ratio in the network. The aforementioned results provide effective measures to ensure link stability by maintaining link connectivity among the neighboring nodes for future communications inside the cluster. In the future, we intend to develop an algorithm for path stability estimation under randomly deployed network nodes inside the cluster.

Appendix

Proof of (22)

Proof. For a discrete random variable L, which represents l successes in any experiment of N trials, the probability mass function (PMF) can be written as

$$P(L = l) = \binom{N}{l} a^l b^{N-l}; \quad 0 \leq l \geq N, \tag{A.1}$$

where a represents probability of successful reception of a Hello message by a neighboring node and $b = 1 - a$, which describes the unsuccessful reception of Hello messages.

Hence, (A.2) can be rewritten as

$$P(L = l) = \binom{N}{l} a^l (1-a)^{N-l}. \tag{A.2}$$

Now, for the maximum number of transmission retries by a Hello message, i.e., t_{tot}, that a node attempts before it drops a Hello message from the neighboring node, the link probability is given by

$$P(L) = 1 - \left(1 - P\left(\frac{r}{p_r}\right)\right)^{t_{tot}}. \tag{A.3}$$

Now rearranging (A.4), we get

$$\left(1 - P\left(\frac{r}{p_r}\right)\right)^{t_{tot}} = 1 - P(L). \tag{A.4}$$

By comparing (A.5) with (A.3), we obtain

$$P(L = l) = \binom{N}{N - t_{tot}} \left(P\left(\frac{r}{p_r}\right)\right)^{N-t_{tot}} \left(1 - P\left(\frac{r}{p_r}\right)\right)^{t_{tot}}. \tag{A.5}$$

The mean, μ_1, and variance, σ^2, of L are given, respectively, by

$$\mu_1 = N\left(P\left(\frac{r}{p_r}\right)\right), \tag{A.6}$$

and

$$\sigma^2 = N\left(P\left(\frac{r}{p_r}\right)\right)\left(1 - P\left(\frac{r}{p_r}\right)\right). \tag{A.7}$$

For the expected value of this distribution, i.e., $N(a) \cong 1$, then (A.6) is approximated to

$$P(L) = \frac{N(P(r/p_r))}{(N - t_{tot})!} \exp\left(-N\left(P\left(\frac{r}{p_r}\right)\right)\right). \tag{A.8}$$

Now substituting $P(r/p_r) = 1 - (1 - P_L)^{1/t_{tot}}$ for σ, we get

$$\sigma = \sqrt{2N\left(1 - (1 - P_L)^{1/t_{tot}}\right)\left(1 - \left(1 - (1 - P_L)^{1/t_{tot}}\right)\right)}. \tag{A.9}$$

$P_L = 0.5$ represents the minimum probability that transmission of Hello message is successful by the neighboring node. By substituting $P_L = 0.5$ in (A.10), we get

$$\sigma = \sqrt{2N\left(1 - (0.5)^{1/t_{tot}}\right)\left(1 - \left(1 - (0.5)^{1/t_{tot}}\right)\right)}. \tag{A.10}$$

Similarly, μ_1 becomes

$$\mu_1 = N\left(1 - (0.5)^{1/t_{tot}}\right). \tag{A.11}$$

Consequently, (A.9) becomes

$$P(L) = \frac{\left(N\left(1 - (0.5)^{1/t_{tot}}\right)\right)^{N-t_{tot}}}{(N - t_{tot})!} \cdot \exp\left(-N\left(1 - (0.5)^{1/t_{tot}}\right)\right). \tag{A.12}$$

This completes the proof of (22). □

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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