OPTIMUM NEIGHBORS FOR RESOURCE-CONSTRAINED MOBILE AD HOC NETWORKS

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ABSTRACT

This paper presents an investigation on the optimum number of neighbors for mobile ad hoc networks (MANETs). The MANETs are self-configuring and self-organizing networks. In such a network, energy-constrained mobile nodes share limited bandwidth to send their packets to the destinations. The mobile nodes have a limited transmission range and they rely on their neighbors to deliver their packets. Hence, the mobile nodes must be associated with the required (i.e., optimum) number of neighbors. As the number of neighbors is varied, a trade-off exists between the network connectivity and available bandwidth per mobile node. To investigate this issue, we consider Dynamic Source Routing (DSR) as the routing protocol and IEEE 802.11 as the MAC layer protocol in this work. We consider both static and dynamic scenarios in this work. We simulated the ad hoc networks via network simulator (NS-2) and the simulation results show that there exists an optimum number of neighbors for the static case. We also show that mobility has a grave impact on the performance of the MANETs in terms of network throughput, end-to-end delay, energy consumption, and packet loss. Hence, we need to increase the number of neighbors under mobility conditions. However, there is no global optimum number of neighbors for the mobility case.

KEYWORDS

MANETs, Wireless, MAC, Protocol, End-to-end Delay, Energy Consumption, Routing Overhead, Throughput

1. INTRODUCTION

Wireless networking has been an active research focus since the early days of the packet radio network introduced by the Defense Advanced Research Project Agency (DARPA) [1]. Recent developments in wireless devices have made laptop computers, personal digital assistants (PDA), pagers, and cellular telephones portable. Now, users can carry these devices to any place at any time. Hence, there is a need for a network that can be deployed at any place at any time without any infrastructure support. In some cases, an infrastructure-based network is hard to build. Networks used by the soldiers on the battlefield are worthwhile to mention here. In some cases, infrastructures may not exist due to natural calamities such as cyclones, tsunami, and tornados. Hence, there is always a need for setting up a temporary network among a group of users without any pre-existing infrastructure and centralized administration. Mobile Ad hoc Networks (MANETs) are considered suitable solutions for these kinds of temporary networks. MANETs consist of a group of mobile nodes, which have limited battery and limited processing power. MANETs are self-organizing and self-configuring networks and they can be deployed without any infrastructure support. Numerous groundbreaking applications have been proposed based on MANETs. These applications include disaster management, search and recovery, remote

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healthcare, tele-geoprocessing, education, traffic management, process control, and security [2]. These applications impose diversified design and performance constraints on the MANETs.

However, MANETs have many limitations too. They have many unique characteristics that are not present in wired networks. Dynamic topology is one of them. Mobile nodes can join and leave the network at any time. Hence, route 'breakage' is a very frequent phenomenon in the MANETs. The wireless is the communication medium for the MANETs. The wireless medium is always unreliable and random due to high interference and noise. The channel randomness can cause a mobile node to receive a packet at a signal level that is below a minimum threshold level. Hence, a mobile node may fail to detect a packet that it receives from other mobile nodes. In MANETs, mobile nodes share wireless channel among themselves. Hence, each mobile node can enjoy only a very limited bandwidth. Another major limitation of the MANETs is that the mobile nodes have a very limited transmission range. Hence, they communicate with each other in a multi-hop fashion. It means that they deliver packets to their destinations through other mobile nodes. Hence, network connectivity is a very challenging issue in MANETs. The mobile nodes must be associated with a required number of neighbors. However, the random movement of the neighbors worsens the network-partitioning problem.

Routing protocol is the most important element of MANETs that provides them with self-organizing and self-configuring capabilities [3]. Researchers have proposed many routing protocols for the MANETs. Broadly, these routing protocols can be classified as proactive and reactive. In proactive routing protocols, like Destination Sequence Distance Vector (DSDV) [3], mobile nodes periodically exchange routing information among themselves. This kind of periodic routing information exchange among nodes generates a huge number of overhead packets in the network. Hence, the proactive routing protocols are not considered suitable for the MANETs. Reactive routing protocols like Ad hoc On-demand Distance Vector (AODV) [4] and Dynamic Source Routing (DSR) [5] work on-demand. It means that a route is discovered when it is required. Hence, reactive routing protocols generate fewer overhead packets compared to proactive routing protocols. However, the proactive routing protocols use a global search procedure called 'flooding' to discover routes to the destinations and the neighbors of a mobile node helps them to find these routes. This 'flooding' procedure also generates a huge number of overhead packets in the network, especially when the network size is large.

To ensure efficient routing operation, mobile nodes must be associated with enough neighbors. In a lightly populated network, a mobile node may not find the required neighbors to assist in the route discovery process. Hence, network partitioning will occur. On the other hand, in a densely populated network, a mobile node finds enough neighbors to assist them during the route discovery operation. However, as the number of neighbors increases, per-node throughput decreases because more nodes contend with each other to access the medium. Hence, each node will be associated with an optimum number of neighbors. We investigate this issue in this paper. We choose DSR protocol as the routing protocol and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) (i.e., IEEE 802.11) [6] as the underlying medium access protocol.

The rest of the paper is organized as follows. Some related works are presented in section 2. A brief description of the DSR protocol has been presented in section 3 to provide the readers with enough background to understand the importance of the optimum number of neighbors. The need for optimum node density is explained in section 4. The simulation results are presented in section 5. The paper is concluded with section 6.

2. RELATED WORKS

Optimum node density has been an active research area for a long time. One of the initial well-known works on this topic can be found in [7]. The paper presents an analytical model that shows that there is a trade-off between the transmission range and available bandwidth per node in the packet radio network. The work shows that the optimum number of neighbors for a given node must be six. The major limitation of the work is that it considers only static networks. One of the earliest works that investigate the optimum number of neighbors under mobility conditions is presented in [8]. The authors introduce the critical transmission range in ad hoc networks. The authors define the critical transmission range as the transmission range that is good enough to maintain the connectivity in ad hoc networks.

Transmission power adjustment, to maintain connectivity and to conserve energy, has been addressed in [9]. The authors suggest that mobile nodes should adjust transmission power depending on the network topology and hence transmission power adjustment must be adaptive. A cluster-based power management technique for ad hoc networks has been presented in [10]. In this work, mobile nodes form a group called a cluster and they adjust transmission power dynamically so that they can reach other mobile nodes located at the farthest distance in the cluster. The authors show that this type of power adjustment saves energy of the mobile nodes and increases network throughput.

In [11], the optimal transmission range of a mobile node is determined by the progress of a packet in a desired direction. The authors choose slotted ALOHA [12] as the multiple access technique. They conclude that mobile nodes should be associated with eight neighbors to maximize network throughput. However, they did not consider other important performance factors including energy consumption, end-to-end delay, and routing overhead in their work.

In a similar work [13], the mobile nodes are allowed to adjust their transmission range independently. The authors conclude that mobile nodes should use the lowest possible transmission power to maximize the network throughput. Another similar work, presented in [14], shows appropriate transmission range can conserve energy in ad hoc networks. The authors present a position-based technique to determine the transmission range of the mobile node.

The optimum transmission range, for a low mobility and high node density network, has been presented in [15]. The authors argue that optimum transmission range must be considered as a system design issue. The authors suggest that the optimum transmission range should depend on the propagation environment as well as the type of radio transceiver. In the work, it is assumed that mobile nodes are associated with a large number of neighbors that are readily available to forward the packet in a given direction.

To minimize energy consumption, a bit-meter-per-joule metric has been used in [16]. It is shown in the work that the energy consumption in a network depends on several factors including transceiver characteristics, node density, and traffic distribution. A relay architecture has been presented in the work. According to this architecture, a source chooses a relay neighbor based on the lowest bit-meter-per-joule metric. In a recent work [17], the authors present a comparative analysis of three different routing protocols namely DSR, Zone Routing Protocol (ZRP) [18], and Optimized Link State Routing (OLSR) [19]. In the work, the authors investigate the effects of transmission range, mobility, and node density on these three routing protocols. They conclude that the DSR protocol outperforms ZRP and OLSR in terms of delay and packet delivery ratio.

The effects of signal fading and shadowing have been investigated in [20]. The authors have shown that signal fading and shadowing affect the network performances. Hence, the authors determine the optimal transmission range in the presence of fading and shadowing.

In [21], the authors present a position-based algorithm that minimizes the energy consumption in ad hoc networks. The authors argue that the optimum transmission range needs to be fixed in a way so that the energy consumption in the network becomes minimum.

In our work, we also consider the DSR protocol. We consider three network conditions namely (a) without mobility (i.e., static network), (b) with low mobility (i.e., maximum node velocity of 10 m/sec), and (c) with high mobility (i.e., maximum node velocity of 30 m/sec) to find the optimum number of neighbors. We also consider the two-ray ground reflection model [22] as the propagation model and the random waypoint [23] as the mobility model. In contrast to other related works, we consider four performance parameters namely end-to-end delay, throughput, energy consumption, and routing overhead to find the optimum number of neighbors, instead of the throughput.

3. THE DSR PROTOCOL

The DSR protocol consists of two basic mechanisms: (1) route discovery and (2) route maintenance. By route discovery, a mobile node discovers a route to a destination, and by route maintenance; a mobile node detects a route 'breakage'.

A source node initiates the route discovery process when it wants to send some data packets to a destination. It first searches its route cache to find a route to that destination. If a source cannot find a route in the route cache, it initiates a route discovery mechanism by broadcasting a request packet to its neighbors. When the neighbors of a source receive the request packet, they first check whether the request packet is intended for it or not. If a neighbor discovers that it is the destination, it sends a reply back to the source after copying the accumulated routing information contained in the route request packet into a route reply packet. Otherwise, it forwards the request to its neighbors. When a destination receives a route request, it replies to the source through unicast transmission.

When a source node receives a route reply packet, it starts sending data packets using the route indicated in the reply packet. If multiple paths are discovered, it chooses a path that is the shortest one. It continues using this path until the path 'breaks'. When the shortest path breaks, a source uses the available alternative paths.

A route discovery mechanism is illustrated in Figure 1. Here, the source 'S' discovers two routes to the destination 'D' and it uses the shortest route 'S-E-F-J-D' to send the data packet. One of the major limitations of the DSR protocol is that it uses a source routing technique. It means a data packet carries complete routing information with it. Hence, the packet size is large in the DSR protocol compared to other protocols. A mobile node needs to spend higher energy for transmitting this kind of longer packet.

Route maintenance is the mechanism by which a node can detect any change in the network topology. When a node detects a broken link by using the underlying MAC layer acknowledgment [24], it removes the link from its route cache. It also creates a special packet called route error message and sends this route error message to each node that has previously sent the packets over that broken link. The route maintenance of the DSR protocol is illustrated in Figure 2. In this figure, the node "F" detects that the link between the node itself and node 'J' is broken. The node 'F' generates a route error message and sends it to the source. The source marks this route 'invalid' in the route cache and starts using the alternative path (for example 'S-C-G-K-W-D') to send the packet.

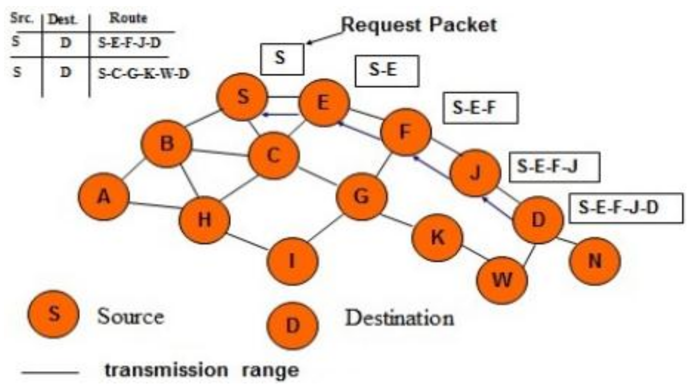

Figure 1. The route discovery mechanism of DSR protocol.

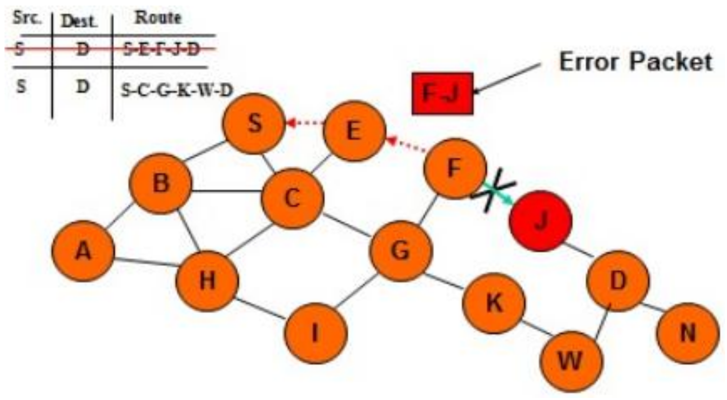

Figure 2. The route maintenance of DSR protocol

4. NEED FOR OPTIMUM NEIGHBORS

To ensure the correct operation of the routing protocol (like DSR), the mobile nodes must be associated with the optimum number of neighbors. We will consider the following two cases in this work namely (i) lightly populated network: where mobile nodes are associated with a very few number of neighbors, and (ii) densely populated network: where mobile nodes are associated with a large number of neighbors.

4.1. Low Populated Network

When the mobile nodes are not associated with enough neighbors, the following problems will occur: (a) node isolation, (b) inefficient path discovery, (c) unsuccessful route maintenance, and (d) multipath routing problems.

A. Node Isolation

To ensure successful route discovery, a source node needs to find suitable neighbors to spread the request messages throughout the network and they must reach the destination. Let us consider the illustration shown in Figure 3. The scenario, shown in Figure 3, is similar to the scenario shown in Figure 1; however, nodes “B”, “C”, and “E” are outside the range of source “S” or these nodes are ‘dead’ due to battery exhaustion. In this case, source “S” is isolated from the network and hence it will not be able to discover a path to the destination node “D”. In this case, the source will initiate route discovery for a certain number of times and it will give up.

B. Inefficient path discovery

It is very essential in ad hoc networks that a source should discover an efficient path. Let us assume that the most efficient path is the one that has the fewest number of hops (i.e., the lowest cost path). Without enough number of neighbors, a source may discover a path that may not be the optimum one (i.e., the shortest path). For example, the shortest path discovered by source "S" is "S-E-F-J-D" as shown in Figure 1 and it has four hops. It is assumed that the neighbors "E" and "C" do not exist due to node movement or battery exhaustion. In this case, the source discovers the paths "S-B-H-I-G-K-W-D" or "S-B-H-I-G-F-J-D" as shown in Figure 4. These paths have seven hops. Since these paths have more hops, it is more likely that a packet travels along these paths will suffer from larger delay. Routing through these paths will also increase the interference level in the network.

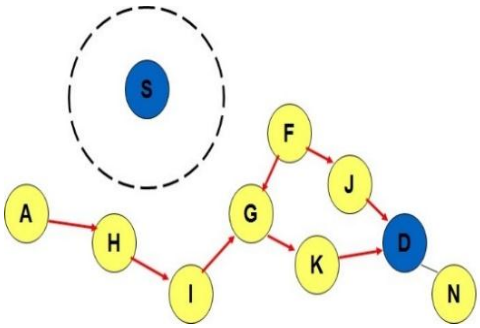

Figure 3. The node isolation problem.

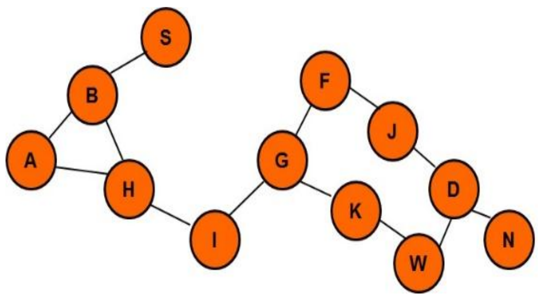

Figure 4. Inefficient route discovery

C. Unsuccessful Route Maintenance

To ensure correct operation of the route maintenance, a source must have more than one path to a destination. According to the route maintenance algorithm, a source uses alternative paths as soon as it detects a route breakage. Without enough number of neighbors, a source may fail to find alternative paths. In this case, the source needs to initiate another route discovery and the network will be flooded with new route request again. This type of route discovery generates a huge number of overhead packets in the network and increases the interference level in the network.

D. Multipath Routing Problem

In multipath routing protocols, the mobile nodes must discover multiple paths to a destination and they select the optimum path or a set of paths among these paths [25]. If mobile nodes are not associated with enough neighbors, a few paths will be discovered. Hence, multipath routing protocols may not work properly and the routing protocols may behave like a single path routing protocol.

4.2. Densely Populated Networks

When mobile nodes are associated with a large number of neighbors (more than that are required to maintain connectivity), the following problems will arise (a) broadcast storm, (b) high interference, and (c) larger delay.

A. Broadcast Storm

Routing protocols, like DSR, use broadcast techniques during the route discovery phase. In ad hoc networks, mobile nodes are obligated to forward request message that it receives for the first time. This forwarding process is done directly or indirectly. In the first case, a single-hop routing will occur. The packets, originated by a source, are delivered to the destination in a single-hop because the source and destination are within the range of each other. In the latter case, a multi-hop scenario will occur, where several intermediate nodes relay the request messages, originated by a source, before reaching the destination. This process is called "flooding". In a CSMA/CA based ad hoc network, "flooding" causes redundant rebroadcasting in the network because all mobile nodes receive multiple copies of a request [26]. The flooding may cause high 'contention' and packet collisions in the network when many neighbors try to rebroadcast the request messages at the same time.

B. High Interference

In a densely populated network, the number of mobile nodes participating in packet transmission increases. Although some underlying MAC protocol like CSMA/CA uses some techniques (i.e., exponential back-off) [24] to reduce interference level in the network, mobile nodes still generate high interference because they are obligated to transmit a packet that they receive from their neighbors.

C. Larger Delay

In a densely populated network, many mobile nodes exist in a given region and these mobile nodes contend with each other to get access to the medium. When a mobile node tries to get access to the medium, it may fail to do so because of the other mobile nodes. Hence, they often go for the back-off period for a long time, which consequently increases the delay in the network.

5. THE SIMULATION RESULTS

To investigate the optimum number of nodes we conduct simulations by using NS-2.35 network simulator [27]. In these simulations, we create an ad hoc network consisting of 63 mobile nodes and distribute them over an area of 3000m by 1000m. In the network, a mobile node's location is determined by (x, y) coordinates, where x and y are uniformly distributed random variables in the range of 0-3000m and 0-1000m respectively. The average number of neighbors is determined by

$$n = \frac{N}{A}\pi R^2 \tag{1}$$

, where n is the number of neighbors, A is the network area (in sq. m), N is the total mobile nodes in the network, and R is the transmission range. We set the transmission range to 250m in the simulations so that each node will be associated with four neighbors under the two-ray propagation model. Then, we increase the number of nodes to 73, 92, 107, 122, 137, 152, 162, and 182 without increasing the network area so that the number of neighbors will increase to 5, 6, 7, 8, 9, 10, 11, and 12 respectively. Ten Unigram Data Protocol (UDP) connections are set up during each simulation. These connections start randomly during the simulation time by using the Constant Bit Rate (CBR) agent. The source and destination for each connection are chosen randomly. Each simulation is run by using ten different topologies for a given number of neighbors. The total simulation time is 250 seconds. The transmission range of a mobile node, is determined based on the two-ray model [20], is expressed by

$$P_r = P_t G_t G_r \left(\frac{h_t h_r}{d^2}\right)^2 \quad (2)$$

, where P_t is the transmission power, G_t is the transmission antenna gain, G_r is the receiving antenna gain, d is the distance between the transmitter and receiver, and h_t is the transmission antenna height, h_r is the receiving antenna height. By using the simulation parameter mentioned in Table 1, the transmission range (i.e., d=250 m) is calculated.

Table 1: Simulation Parameters

Parameters	Value
No. of nodes	73,92,107,122, 137, 152, 162, and 182
Node distribution	Uniform
Network areas	1000m x 3000m
No. of connections	10
Antenna height (transmitter and receiver)	1.5 m
Transmission power	0.2818 watts
Received threshold power	3.631×10^{-10} watts
Application	Constant Bit Rate (CBR)
Transport layer protocol	Unigram Data Protocol (UDP)
Simulation time	250 sec
Propagation model	Two-ray ground reflection
Medium Access Control	IEEE 802.11
Number of simulations	10
Packet rate	1 packet/sec
Packet size	512 bytes.

The simulation results for the static network (i.e., without mobility) are shown in Figure 5-8. The network throughput is plotted in Figure 5. The staircase pattern plot shows that the network throughput is very low for a few neighbors. The reason is that not all sources could find a neighbor to discover paths because of the low number of neighbors. It is also shown that the throughput increases with the number of neighbors and it reaches maximum (i.e., 290 kbps) at 10 number of neighbors.

The end-to-end delay per packet is shown in Figure 6, which shows that the delay slightly increases with the number of neighbors. However, it increases abruptly when the number of neighbors exceeds 10. A similar conclusion can be drawn from Figure 7, which shows the packet loss in the network. This figure shows that the packet loss is low until 10 number of neighbors. Later, it increases to a very high level with the number of neighbors. Based on the simulation results for the static network, we can conclude 10 is the optimum number of neighbors for MANETs under static conditions.

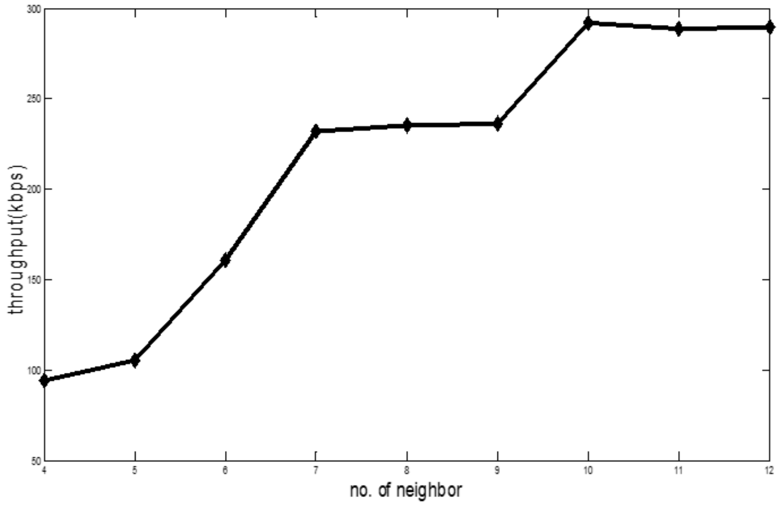

Figure 5. The network throughput

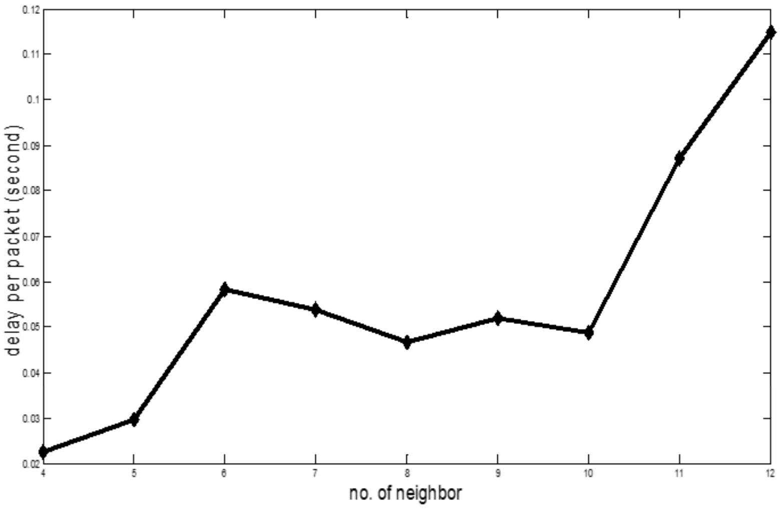

Figure 6. The end-to-end delay per packet

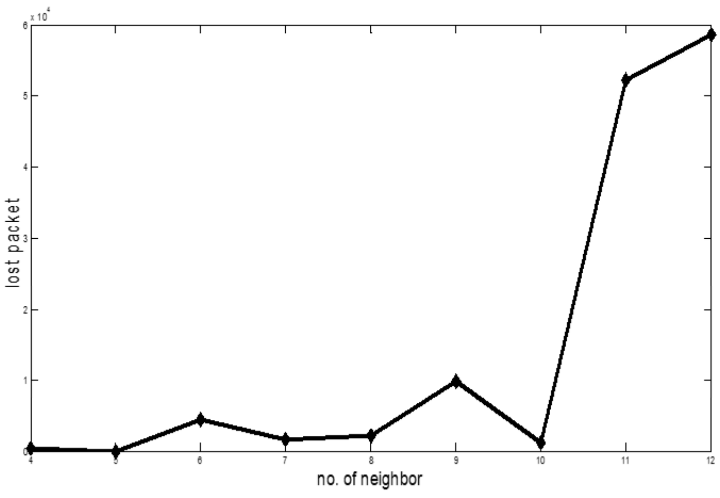

Figure 7. The lost packets

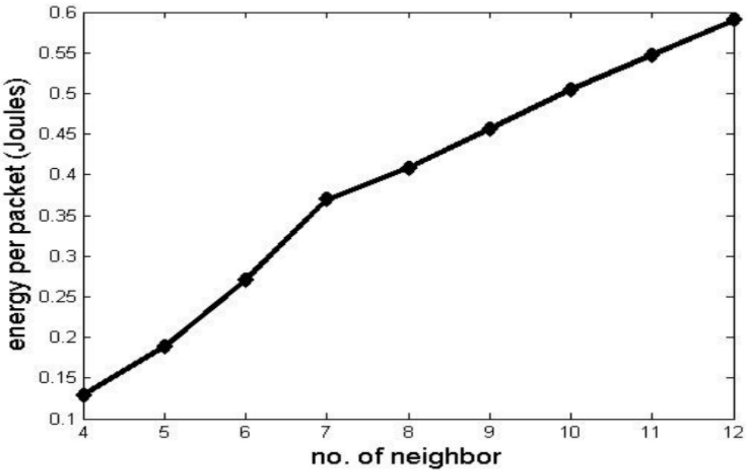

Figure 8. The energy consumption per packet

Energy consumption is an important issue in the energy-constrained MANETs. To find the optimum number of neighbors, we also consider energy consumption in the network. We measure the total energy consumed by all nodes and we divide the total consumed energy by the total packets delivered to the destination to find the energy consumption per packet, which is plotted in Figure 8. This figure shows that the energy consumption, expressed in Joules/packet increases linearly with the number of neighbors in the network. This conclusion is contrary to another claim [9] that the optimum transmission range minimizes energy consumption.

The simulation results for the mobility cases are shown in Figure 9-12. In this investigation, we consider two cases (a) low mobility (i.e., node velocity 10m/sec) and (b) high mobility (i.e., node velocity 30m/sec). We use a random waypoint model [18] to generate node movement in the network. The network throughput is plotted in Figure 9, which shows that the optimum node density is six for the low mobility case. However, the same is eight for the high mobility case. We can conclude that the optimum number of neighbors need to increase when mobility increases in the network. However, comparing Figure 5 and Figure 9, we also conclude that the network throughput is significantly low for mobility cases compared to the same as the static network.

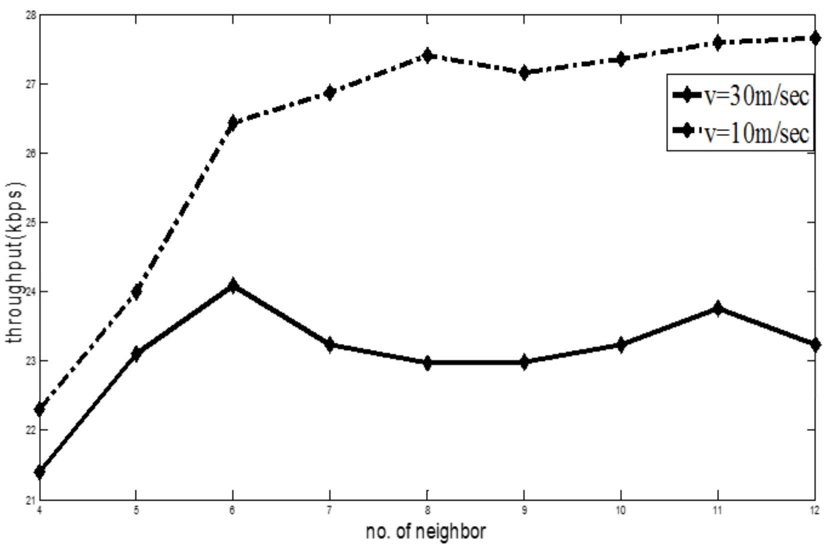

Figure 9. The network throughput for mobility case

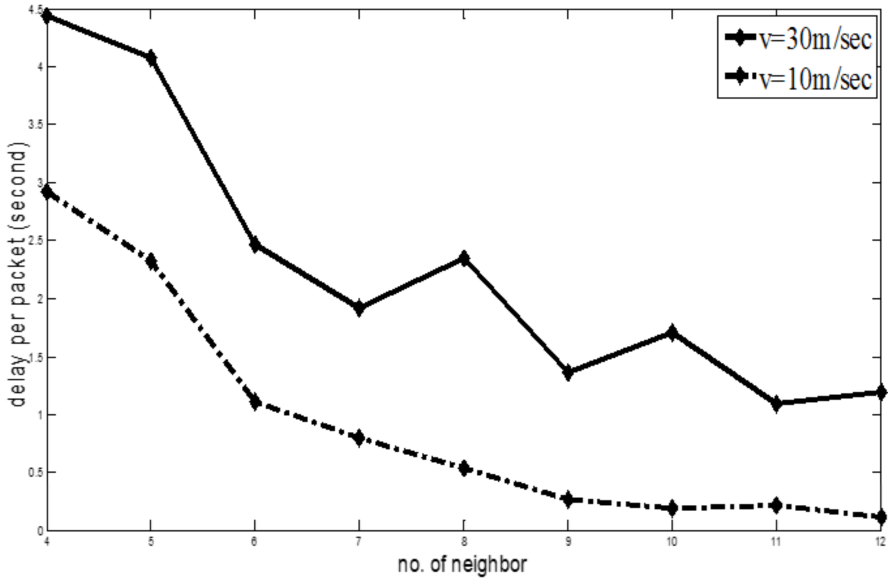

Figure 10. The end-to-end delay per packet for mobility cases

The end-to-end delay per packet for the mobility cases is presented in Figure 10. This figure shows that the end-to-end delay per packet decreases with the number of neighbors. This figure also shows that the delay-per-packet is always higher for high mobility case. The energy consumed by the data packet under the mobility case is shown in Figure 11, which depicts energy consumption per packet increases with the number of neighbors. However, the energy consumed under the high mobility case is much higher compared to the same in the low mobility case.

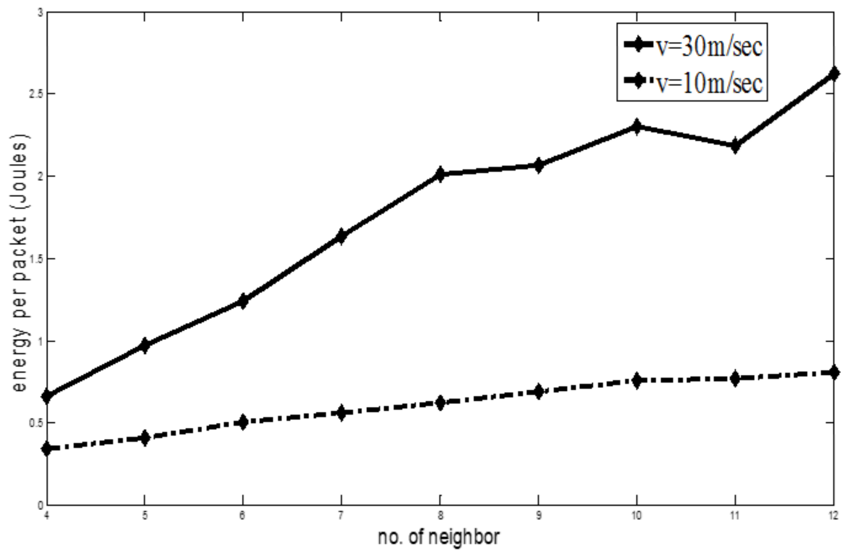

Figure 11. The energy consumption for mobility cases

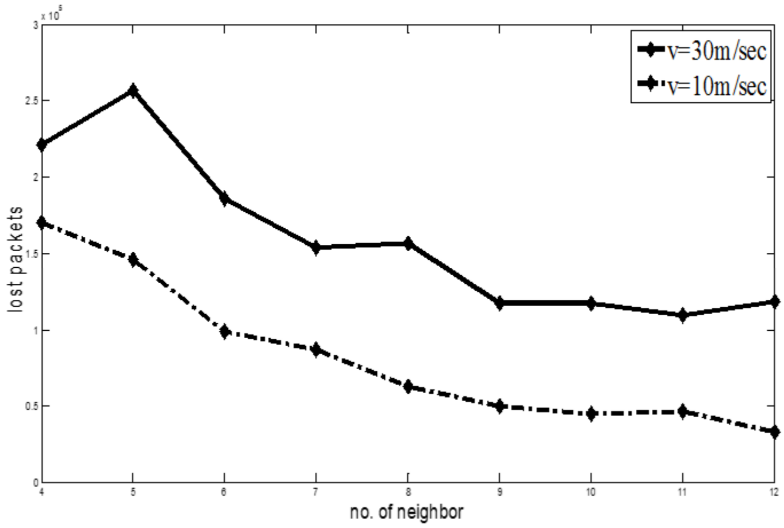

Figure 12. The lost packets for mobility cases

Finally, the lost packets are plotted in Figure 12. This figure shows that the lost packet decreases with the number of neighbors for both mobility cases. This is contrary to the static networks, where the packet loss increases sharply after the optimum number of neighbors. However, the lost packets are always higher for high mobility cases compared to its low mobility counterpart. The reason is that more route breakages occur as the mobility increases in the network.

6. CONCLUSION

In this paper, we investigate the optimum number of neighbors for MANETs. It is shown that the optimum node density depends on the network conditions. It is shown that the optimum number of neighbors is 10 for a static MANET. However, the same is very difficult to determine in dynamic networks. The simulation results show that the number of end-to-end delays is very high in dynamic networks and hence network throughput is less compared to static networks. The main reason for this is that there occur more unsuccessful route discovery, more breakages, and unsuccessful data transmission in dynamic networks compared to their static counterparts. All these ultimately affect network throughput. It is also shown that the maximum network throughput in mobility cases is much lower compared to the same in the static case. As the mobility increases, the maximum network throughput decreases. However, there is no global optimum number of neighbors for dynamic networks. It is also shown in the paper that increasing the number of neighbors can only improve the network throughput to some extent, but the network throughput cannot reach the same level as that in static networks.

In this work, we consider two-ray propagation model in our simulations. However, the two-ray model may not represent a realistic propagation model for the ad hoc networks that are deployed in hazardous areas. Hence, a more practical propagation models (like probabilistic models, shadowing models etc.) need to be considered in the simulations. Another limitation of this paper is that we consider only two values for the velocity of the mobile nodes. We arbitrarily select these two values. A further investigation is required to choose a realistic velocity for the mobile nodes. To find the energy consumption by the mobile nodes, we use the built in energy consumption model provided with the NS-2.35 network simulator. However, many practical energy consumption models have been presented in the literature. These models also need to be included in the simulations for accurately determining the energy consumption by the mobile nodes. These all are left for the future investigations.

REFERENCES

[1] Jubin, J. and Torrow, J. “The DARPA Packet Radio Network Protocol,” Proceedings of the IEEE, vol. 75, no. 1, January 1987, pp. 21-32

[2] Goldsmith A.J. and Wicker S.B., “Design Challenges for Energy-Constrained Ad hoc Wireless Networks”, IEEE Wireless Communication, vol. 9, no. 4, August 2002, pp. 8-27

[3] Perkins, C.E. and Bhagwat, P., “Highly dynamic destination-sequence distance-vector routing (DSDV) for mobile computers,” Proceedings of ACM SIGCOMM, London, UK, August 1994, pp. 234-244

[4] Perkins, C.E., “Ad Hoc On-Demand Distance Vector (AODV) Routing,” Internet-Draft, draft-ietf-manet-aodv-00.txt, November 1997

[5] Broch, J., Johnson, D.B., and Maltz, D.A., “The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks”, IETF Internet-Draft, draft-ietf-manet-dsr-00.txt March, 1998

[6] Crow, B. P., Widjaja, I., Kim, , J, G. and Sakai, P. T., “IEEE 802.11 Wireless Local Area Network,” IEEE Communication Magazine, vol. 35, no. 9, September 1997, pp.116-127

[7] Kleinrock, L. and Silvester, J. “Optimum Transmission Radii for Packet Radio Networks or Why six is a magic number”, Proceedings of the IEEE International Conference on Communication, New Orleans, LA, June 2000, pp. 4.3.1-4.3.5

[8] Chansez, M., Manzoni, P., and Haas, Z.J., “ Determination of Critical Transmission Range in Ad hoc networks”, Proceedings of Multi-access, Mobility, and Tele-traffic for Wireless Communications Conference, Venice, Italy, 2000

[9] Ramanathan, R. and Rosales, H. R., “Topology Control of Multihop Wireless Networks using Transmission Power Adjustment”, Proceedings of IEEE Conference on Computer Communication, Tel Aviv, Israel, March 2000

[10] ElBatt,T.A. , Krishnamurthy S.V., Conners, D., and Dao, S. “Power Management for Throughput Enhancement in Wireless Ad hoc Networks”, Proceedings of the IEEE Conference on Communication, New Orleans, LA, June 2000, pp. 1503-1513

[11] Takagi, H., and Kleinrock, L. “Optimal transmission ranges for randomly distributed packet radio terminals,” IEEE Transaction on Communication, vol. COM-32, no. 3, March 1984, pp. 246–257

[12] Farouzan, B.A. “Data Communications and Networking”, Fourth Edition, McGraw-Hill, NY, pp. 364-370

[13] Hou, T.A. and Li, V. O. K. “Transmission range control in multihop packet radio networks,” IEEE Transaction on Communication, vol. COM-34, no. 1, January 1986, pp. 38–44

[14] Rodoplu, V. and Meng, T.H., “Minimum energy mobile wireless networks,” IEEE Journals on Selected Areas of Communications, vol. 17, August 1999, pp. 1333–1344

[15] Chen, P., O’Dea, B., and Callaway, E. “Energy-efficient system design with optimum transmission range for wireless ad hoc networks,” Proceedings of the IEEE ICC, 2002, pp. 945–952.

[16] Gao,J.L., “Analysis of energy consumption for ad hoc wireless sensor networks using a bit- meter-per-joule metric,” IPN Progress Report 42-150, August 2002, pp. 189–198.

[17] Kumar, D. and Gupta, S.C., “Transmission Range, Density & Speed based Performance Analysis of Ad Hoc Networks”, African Journal of Computing and ICT, vol. 8, no. 1, March 2015, pp. 173-178

[18] Zygmunt, J. H., Marc, R. P., and Samar, P. "The Zone Routing Protocol for Adhoc networks," IETF Draft available at draft-ietf-manet-zone-zrp-04 - The Zone Routing Protocol (ZRP) for Ad Hoc Networks

[19] Jacque, P. et.al., "Optimized Link State Routing Protocol for ad hoc network," Proceedings of the IEEE International Multi-Topic Conference: Technology for the 21st Century, December 30, Lahore, Pakistan, pp. 62-68

[20] Zorzi, M. and Pupolin, S., "Optimum transmission ranges in multihop packet radio networks in the presence of fading," IEEE Transaction on Communication, vol. COM-43, no. 7, July 1995, pp. 2201–2205

[21] Rodoplu, V., and Meng, T.H., "Minimum energy mobile wireless networks," IEEE Journals on Selected Areas of Communications, vol. 17, August 1999, pp. 1333–1344

[22] Rappaport, T.S., "Wireless Communication: Principles and Practices," Second Edition, Prentice-Hall, NJ, USA, pp. 120-124

[23] Broch, J., Maltz, D.A, and Johnson, D. Y.-C. Hu, and Jetcheva, J. "A Performance Comparison of multi-hop Wireless Ad Hoc Network Routing Protocols," Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom), Dallas, Texas, October 1998, pp. 85-97

[24] EEE Standards Department, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications", IEEE Standard 802.11-1997, 1994

[25] Tarique, M., Tepe, K., Abadi,S., and Erfani, S. "Survey of multipath routing protocol for Mobile Ad hoc Network," International Journal of Networks and Computer Applications, vol. 32, no. 6, pp. 1125-1143

[26] Tseng, YC., Ni, S,Y., Chen, Y,S. et al., "The Broadcast Storm Problem in a Mobile Ad Hoc Network." Wireless Networks, vol. 8, March 2002, pp. 151–162

[27] The Network Simulator (NS-2) available at https://www.isi.edu/nsnam/ns/