Adaptive Optimizing of Hello Messages in Wireless Ad-Hoc Networks

Essam Natsheh, Adznan Jantan, Sabira Khatun, and Shamala Subramaniam
Department of Computer and Communication Systems, University Putra Malaysia, Malaysia

Abstract: *Routing is an important functional aspect in wireless ad-hoc networks that handles discovering and maintaining the paths between nodes within a network. Due to nodes mobility, the efficiency of a dynamic ad-hoc routing protocol depends highly on updating speed of network topology changes. To achieve continuous updated routing tables, the nodes periodically broadcast short hello messages to their neighbors. Although benefits of these messages have been proven, many studies show some drawbacks for these messages. In this paper, we adaptively optimize the frequent needs of those messages using a fuzzy logic system. The proposed fuzzy algorithm used to model the uncertainty measurements for updating local connectivity successfully in time. Extensive performance analysis via simulation proves the effectiveness of the proposed method to improve the accuracy of neighborhood information and hence the overall network performance.*

Keywords: *Ad-hoc networks, AODV, beacon messages, fuzzy systems, intelligent networks.*

Received August 24, 2005; accepted April 8, 2006

1. Introduction

Mobile ad-hoc network is a network without infrastructure, where every node works as a router. In this network, every node must discover its local neighbors and through those neighbors it will communicate to nodes that are out of its transmission range (multi-hop). These networks suffer from nodes mobility causes continual link breaks. This causes the routing protocol to use different techniques to update its knowledge about local neighbors, which is known as Local Connectivity Management (LCM). One of those techniques is periodically broadcasting short beacon messages (called hello messages).

Although continual broadcasting the hello messages helped to get clearer view of the local network topology, it also produced some drawbacks for the whole network in general. Increased number of these messages consumes the network resources and bandwidth, increases collisions and interferences with data and control messages, and consumes the limited nodes battery life during sending and receiving operations. On the other hand, the decreased number of hello messages results in time gap between link failure event and its detection. In essence, it means that, the protocol designer has to trade-off sending these messages carefully to represent the real needs for connectivity updating.

In this study, we attempt to adaptively optimize the maximum time period that can transpire before the node broadcast the next hello message. Optimization of this time directly affects the number of sent hello messages during a fixed period of time. Optimization is based on the correlation between the topology reconstruction and the periodical interval for the hello message transmission. The highly changeable topology, due to nodes movements, should increase the number of sent hello messages to get fast and accurate update of link breaks. In contrast, slow changeable topology should decrease the needed hello messages to update connectivity information.

The decision of increasing or decreasing the frequency of hello messages is made during a fixed period of time through a fuzzy logic system. Fuzzy set theory allows high flexibility to imply information and to model complex systems or ill-defined. Uncertainty associated with node mobility estimation and drawbacks of mathematical model for local connectivity management makes the fuzzy system the best choice.

To implement the proposed method, the Ad-hoc On-Demand Distance Vector (AODV) routing protocol [15, 16, 17] is utilized as the underlying routing platform. AODV is a reactive routing protocol where the routes are determined as per needed only. It manages local connectivity using two parameters: Hello_Interval (HI) and allowed_hello_loss. The HI specifies the time between two hello messages; generally set to 1-second. If a neighbor does not receive any packets (hello messages or otherwise) for more than allowed_hello_loss × hello_interval seconds, the node should assume the link to this neighbor is broken. The recommended value for allowed_hello_loss is 2 [17].

There are several ad-hoc routing protocols in literature that uses the hello messages for neighborhood discovery such as Wireless Routing Protocol (WRP) and Optimized Link State Routing protocol (OLSR) besides AODV [1, 2, 19]. Although our proposed method is evaluated with AODV, we believe it can be employed by other ad-hoc routing protocols as well.

The rest of this paper is organized as follows. Section 2 summarizes related work on optimum LCM. Section 3 presents the implementation of the proposed fuzzy HI method. Section 4 presents performance analyzes of the proposed method. Section 5 includes simulation results and evaluation. Finally, the paper is concluded in section 6.

2. Related Work

Many studies have evaluated ad-hoc routing protocols efficiency via utilization of hello messages in LCM as a metric for those comparisons [1, 2, 19]. Research has also focused on the usage of mathematical methods to estimate the stability of the links in ad-hoc networks [6, 10, 20, 23]. These studies focus on the choice of links depending on its expected lifetime. This research focuses on frequency of checking link existence. This work draws importance due to unexpected nodes mobility or sudden nodes terminations (i. e., due to turning off or finishing battery life).

Perkins *et al.* [15], creators of AODV protocol, discussed the reasons for applying hello messages with AODV and presented some drawbacks for using these messages. They mentioned that they will investigate other ways to eliminate drawbacks of these messages. Hello messages frequency optimization can allow us to get its benefits and at the same time remove its drawbacks, which will be shown during this study. This idea endorsed by Hanemann *et al.* [7] where a mechanism to adapt the announcement messages presented. The proposed mechanism depends on using a history table to record the topology changes and according to the frequency of these changes the announcement rate is calculated.

Lundgren *et al.* [11] have provided evidence that the unreliable implementation of hello messages can lead to a systematic mismatch between the route state and the actual connectivity status. This area of mismatch is defined as "*communication gray zones*". In such zones, data messages cannot be exchanged although the hello messages indicate neighbor reachability. Chakeres *et al.* [3] have examined the effectiveness of hello messages for monitoring link status and found some influencing factors on the utility of these messages. Tauchi *et al.* [22] used the frequent sending hello messages to detect a link breaks and upon that they directed the nodes to reestablish new routes. Singh *et al.* [21] used Signal to Noise Ratio (SNR) for the same purpose.

McGlynn *et al.* [12] and Galluccio *et al.* [5] introduced analytical frameworks for modeling the neighborhood discovery process. These performance analysis frameworks allow evaluating the energy cost because of the hunting process and the probability that a timely discovery may occur.

In position-based routing protocols, each node periodically broadcasts a short hello message to announce its presence and position. Some studies introduced strategies to optimize these messages like [4, 8, 9]. Even our proposed method can easily be extended for these types of routing protocol by using GPS information (position, speed, and direction), in this study, topology-based routing protocols are our focus only.

3. AODV with Fuzzy Hello Interval

In this section, the proposed concept and rules for fuzzy HI that is used with AODV are introduced. In the following two subsections, we study the effect of some node parameters on HI. These parameters will be used in subsection 3.3 to create the rules of the fuzzy system and a method to design their membership functions is presented in the later subsection. Overall system design is presented in the last subsection.

3.1. Effect of Node Transmission Power on HI

Transmission power is a main parameter that determines the number of neighbors for nodes in our ad-hoc network. Transmission power (*TrPower*) is the strength by which the signal is sent.

In the proposed system, signal power degradation is modeled by the *free space propagation model* [18], where the received signal strength is:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{1}$$

Where P_r and P_t are the receive and transmit powers (in watts), G_t and G_r are the transmit and receive antenna gains, d is the transmitter-receiver separation distance, L is a system loss factor (L = 1 in our simulations which indicates no loss in the system hardware), and λ is the carrier wavelength (in meters) which is related to the carrier frequency (f_c) as:

$$\lambda = \frac{c}{f_c} \tag{2}$$

Where c is the speed of light (3×10^8 m/s). Assuming a unity gain antenna with a 900 MHz carrier frequency, Figure 1 shows the relation between the transmission range and the transmission power of a node for different values of the receive power. From the figure, there is a direct relation between the increased transmission power and the increased transmission range.

Definition: Suppose there are two nodes A and B in a specified area. At time t, node B will be a neighbor to node A if and only if the euclidean distance d_{AB} (t)

between the two nodes is less than the transmission range of node *A*.

If the TrPower of a node is too low, then the signal will reach to a few neighbors only and its links with those neighbors may be weak and easy to break. Consequently, the Hello_Interval (HI) must be small enough to get fast update for neighborhood changes. In contrast, high TrPower of a node will lead to high average number of its neighbors and hence increase the lifetime of its links, consequently the HI must be long due to fewer changes in node's neighborhood. Hence, the following rules are proposed:

- R1: If TrPower is high then HI must be high.
- R2: If TrPower is medium then HI must be medium.
- R3: If TrPower is low then HI must be low.

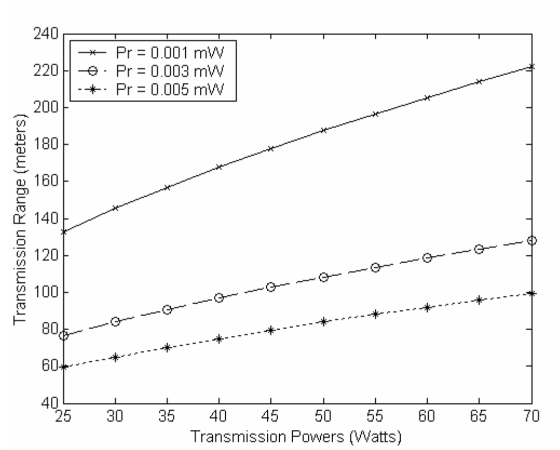


Figure 1. Transmission range versus transmission power.

3.2. Effect of Node Speed on HI

Ad-hoc networks experience dynamic changes in network topology because of unrestricted mobility of the nodes. If a node had fast movement, this leads an increase in probability of links breaks with its neighborhood. The node movement can be measured by its speed. High-speed of a node results a high probability of losing some of the current neighbors and acquiring new ones.

Galluccio *et al.* [5] calculated the neighborhood time, T_n, between two node n_1 and n_2 as:

$$T_n = \frac{2 \times \sqrt{R^2 - P_{n1}^2}}{v'_{n1}} \tag{3}$$

Where R is the transmission range, P_{n1} is the position of n_1 according to n_2, and v'_{n1} is the relative velocity and can be calculated as:

$$v'_{n1} = \sqrt{v_{n1}^2 + v_{n2}^2 - 2v_{n1}v_{n2}\cos(\Phi)} \tag{4}$$

Where v_{n1} is the magnitude of the vector $\vec{v}_{n1}$, v_{n2} is the magnitude of the vector $\vec{v}_{n2}$, and Φ is the angle between them. Even though this assumption of T_n is accurate only with constant relative velocity, it can show the effect of nodes' velocity on neighborhood time as shown in Figure 2. From this figure, it's clear that in fast nodes, their links' lifetime with their neighbors will be small. Therefore, the HI time of those nodes also must be small to send more hello messages to check the expected links breaks.

In general, a rule can be defined as: When speed is high, the HI must be low or vice versa. Consequently, the following rules are proposed:

- R4: If speed is high then HI must be low.
- R5: If speed is medium then HI must be medium.
- R6: If speed is low then HI must be high.

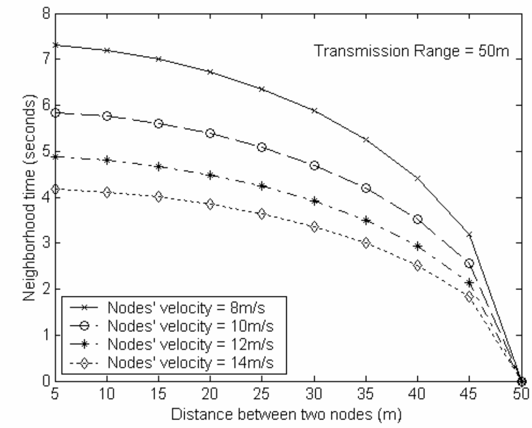


Figure 2. The effect of velocity on neighbourhood time.

3.3. Rule-Base for Fuzzy Hello Interval

To fulfill the fuzzy sets theory, the previous six rules (R1 to R6) can be combined within a 2-dimensional rule-base to control the HI adaptively as presented in Table 1. For example, according to Table 1 the first rule is:

If TrPower is *low* and speed is *low*
then HI is *medium*

Table 1. Rule-base for fuzzy HI.

TrPower	**Speed**		
	Low	**Medium**	**High**
Low	Medium	Low	Low
Medium	High	Medium	Low
High	High	High	Medium

3.4. Membership Functions for Fuzzy Variables

After defining the fuzzy linguistic ‘if-then’ rules, the membership functions corresponding to each element in the linguistic set must be defined. For example, if the TrPower equal to 7 mw, using conventional concept, it implies TrPower is either ‘low’ or ‘medium’ but not both. In fuzzy logic, however, the concept of membership functions allows us to say the TrPower is ‘low’ with 80% membership degree and ‘medium’ with 20% membership degree.

The membership functions we propose to use are shown in Figure 3 due to their economic nature of the parametric and functional descriptions. In these membership functions, the designer needs only to define two parameters; *midpoint* and *maxpoint*. These membership functions mainly contain the *triangular* shaped membership function [14]. This function is specified by three parameters (a, b, c) as follows:

$$triangle\left(x;a,b,c\right)=\begin{cases}\left(x-a\right)/\left(b-a\right) & for\ a\le x\le b\\ \left(c-x\right)/\left(c-b\right) & for\ b\le x\le c\\ 0 & elsewhere\end{cases} \quad (5)$$

Where $a = midpoint / 2$, $b = midpoint$, $c = 3 \times midpoint / 2$ and x is the input to the fuzzy system. The remaining membership functions are as follows: Z-shaped membership to represent the whole set of low values and S-shaped membership to represent the whole set of high values. *Midpoint* is the value of the fuzzy variable, which can be chosen from the real network measurements, simulation and analysis or from the default values of protocol specification as follows.

Normally, the transmission power of a node can be read from the properties of the network adapter. So, it's easy to expect the minimum and the maximum transmission power for the nodes sharing the network. Also, every node had its own speed range [s_{min}, s_{max}]. Hence, *midpoint* for those two variables is the average of their ranges. For example, if the transmission powers of a node are between 8 mw and 14 mw then *midpoint* for its TrPower membership function is 11 mw.

AODV protocol specification [17] states the static value of HI is 1-second. Hence, for the HI membership function, *midpoint* should be equivalent to 1-second.

Since the values of input variables (TrPower and speed) occur during the simulation run, exact knowledge of their values cannot be determined. The range of values (*maxpoint*) for these variables must be quite large. Hence, *maxpoint* can be defined as follows:

For input variables: $Maxpoint = 3 \times midpoint$.
For output variable: $Maxpoint = 2 \times midpoint$.

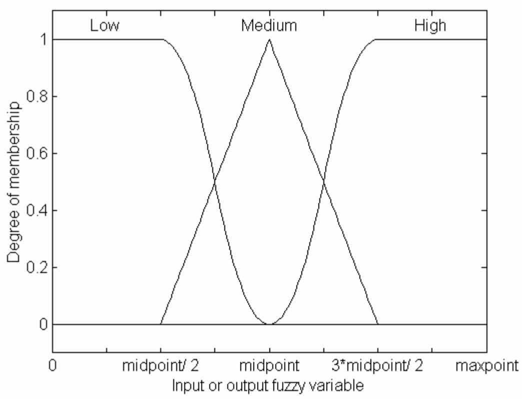


Figure 3. Membership functions used for the fuzzy variables.

3.5. Fuzzification, Inference and Defuzzification

The fundamental diagram of the fuzzy system is presented in Figure 4. Fuzzification is a process where crisp input values are transformed into membership values of the fuzzy sets (as described in the previous section). After the process of fuzzification, the inference engine calculates the fuzzy output using the fuzzy rules described in Table 1. Defuzzification is a mathematical process used to convert the fuzzy output to a crisp value; that is, HI value in this case.

There are various choices in the fuzzy inference engine and the defuzzification method. Based on these choices, several fuzzy systems can be constructed. In this study, the most commonly used fuzzy system, *mamdani* method, is selected; for further details on this system see [24].

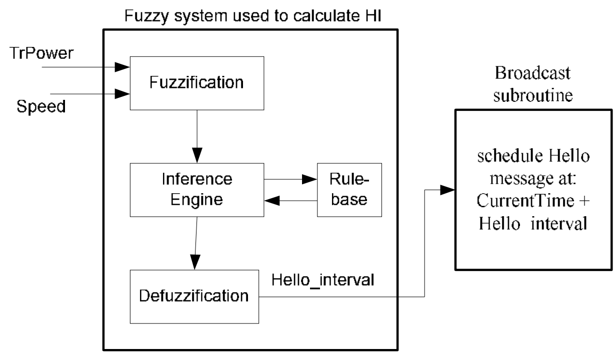


Figure 4. Block-diagram for the basic elements of the fuzzy system.

4. Performance Analysis of the Proposed Hello Interval

4.1. Simulation Environment

Simulation of the proposed AODV design was done using *OMNeT++* version 2.3 with *ad-hoc simulator* 1.0 [3]. *OMNeT++* is a powerful object-oriented modular discrete event simulator tool. Each mobile host is a compound module which encapsulates the following simple modules: An application layer, a routing layer, a MAC layer, a physical layer, and a mobility layer.

- *Application Layer:* This module produces the data traffic that triggers all the routing operations. In all scenarios, 5 nodes are enabled to transmit. The traffic is modeled by generating a packet burst of 64 packets sent to a randomly chosen destination that stays the same for all the burst length. The rate of each burst sending packets is 3 packets/s. The time elapsed between two application bursts is normally distributed in [0.1, 3] s. The packet size is 512 bytes.
- *Routing Layer:* The routing model is the heart of the simulator. This model depicts the AODV routing protocol, all of its functions, parameters and their implementation [17].

- *MAC Layer*: The simple implementation for this layer has been used. The outgoing messages are let pass through. The incoming one instead is delivered to the higher levels with an *MM1 queue* policy. When an incoming message arrives, the module checks a flag that advises if the higher level is busy. If so, the message will be saved in the buffer. If the buffer is full, it will be dropped. When the higher level is not busy, the MAC module picks the first message from the buffer and sends it upward.
- *Physical Layer*: It cares about the on-the-fly creation of links that allow the exchange of messages among the nodes. Every time a node moves from its position, an interdistance check on each node is performed. If a node gets close enough (depending on the TrPower of the moving nodes) to a new neighbor, a link is created between the two nodes with the following properties: Channel bandwidth is 11 Mb/s (IEEE 802.11a) and delay is 10 μ s. Each node has a defined transmission range chosen from an uniformly distributed number between [90, 120] m.
- *Mobility Layer*: The *random waypoint* model was adopted for the mobility layer. It is one of the most used mobility pattern in ad-hoc network simulations. This is because of its simplicity and its quite realistic mobility pattern. In this mobility model, a node randomly selects a destination. On reaching the destination, another random destination is targeted after 3 seconds *pause time*. The speed of movement of individual nodes range between [2, 12] m/s. The direction and magnitude of movement was chosen from an uniformly distributed random number.

Two different network sizes are modeled: 700m×700m map size with 25 nodes and 800m×800m map size with 35 nodes. Each simulation run takes 300 simulated seconds. Multiple runs were conducted for each scenario and collected data was averaged over those runs.

4.2. Performance Metrics

The following metrics were used for measuring performance:

- Routing Overhead:

$$Overhead = \frac{\sum_{i=1}^{n} Number\ of\ SentCtrlPkt\ by\ source}{\sum_{i=1}^{n} Number\ of\ received\ data\ by\ destination}$$

Where n is number of nodes in the network and *SentCtrlPkt* is control packets used by AODV and described in Table 2. This metric can be employed to estimate how many transmitted control packets are used for one successful data packet delivery to determine the efficiency and scalability of the protocol.

- *Average End-to-End Delay*: Average packet delivery time from a source to a destination. First, for each source-destination pair, average delay for packet delivery is calculated. Then the whole average delay is calculated from average delay of each pair. End-to-end delay includes the delay in the send buffer, the delay in the interface queue, the bandwidth contention delay at the MAC, and the propagation delay.
- *Invalid Route Ratio*:

$$Invalid\ Route\ Ratio = \frac{\sum_{i=1}^{n} Number\ of\ invalid\ routes}{\sum_{i=1}^{n} Number\ of\ valid\ routes}$$

Each time a route is used to forward a data packet, it is considered as a valid route. If that route is unknown or expired, it's considered as invalid route.

Table 2. Control packets used by AODV.

Message	Description
RREQ	A Route Request Message
RREP	A Route Reply Message
RERR	A Route Error Containing a List of the Invalid Destinations
RREP_ACK	A *RREP* Acknowledgment Message

5. Simulation Results and Evaluations

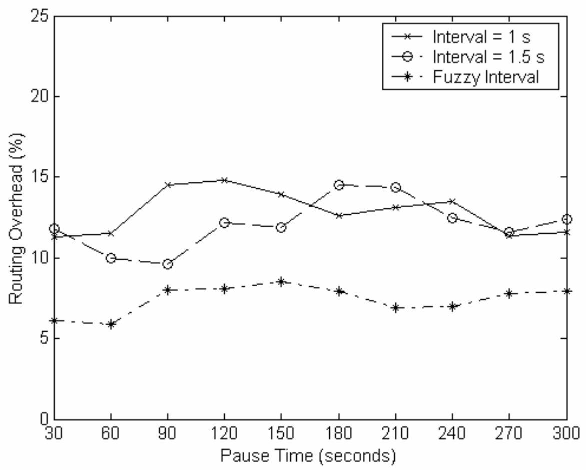
5.1. Routing Overhead Details

Comparison of routing overhead for AODV routing protocol using 2 static values for HI and the proposed fuzzy-HI are shown in Figure 5. Using original AODV as a base system, the results show that the proposed fuzzy methods decrease routing overhead around 42.2% and 38.7% compared to 1 s and 1.5 s intervals, respectively for 25 nodes network. Meanwhile, the decrement is about 35.5% and 38.6% compared to 1 s and 1.5 s intervals, respectively for 35 nodes network.

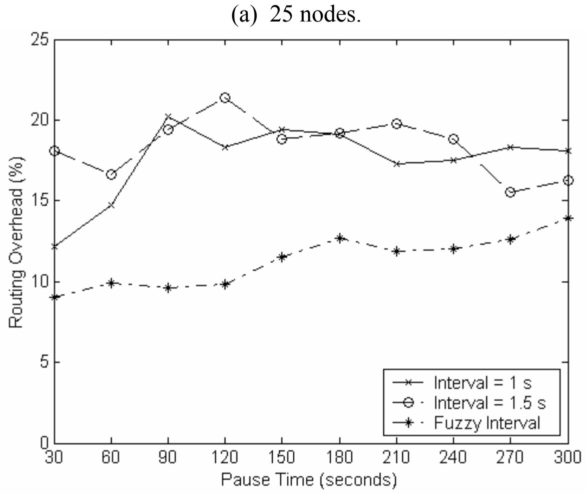
To complement further, Figure 6 presents the number of received data and SentCtrlPkt for 25 nodes network. The efficiency of fuzzy-HI method to decrease data loss through broken paths, hence increasing the number of received data by destinations is obvious here. This improvement is due to adaptive frequency to send hello messages according to network's need, described as follows.

In fuzzy-HI method, many links are given a very short HI because of the inability to keep them. Suppose the fuzzy system select HI equal to 0.5 second for one specific node. At time t unit this node sent hello message to its neighbor. Now we have three scenarios of second time to send hello message according to HI value (1 s or 1.5 or 0.5 using fuzzy-HI). Suppose one link with one of the neighbors is broken at t + 0.4. At time t + 0.5, the fuzzy method will discover broken link and will remark it as expired while the other methods will still keep it as active. Now suppose at time t + 0.8 the node wish to send data for specific destination across that neighbor. The fuzzy method will start by initiating a path discovery process, while using the other nonadaptive methods the nodes will send the data directly using the old broken link. They will soon discover the link is broken, after that they will start initiating the path discovery process.

From Figures 5 and 6, significant improvements of 1.5-second HI than 1-second HI can be observed, especially between 60 and 180 seconds pause time. This is due to the larger number of SentCtrlPkt used by 1.5 HI method. This increment in SentCtrlPkt is used to recover form higher invalid routes in this method as it will be discussed later.



(a) 25 nodes.

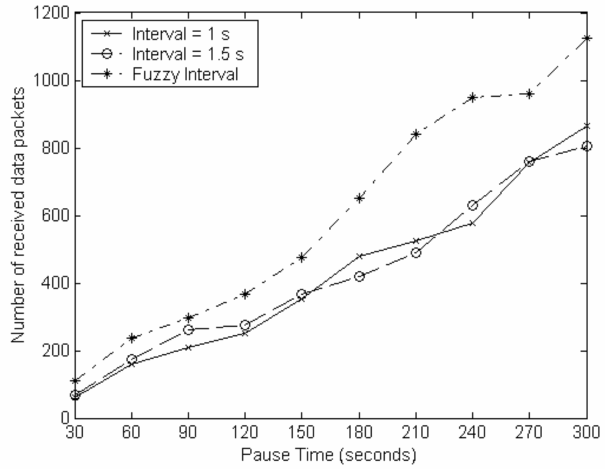


(b) 35 nodes.

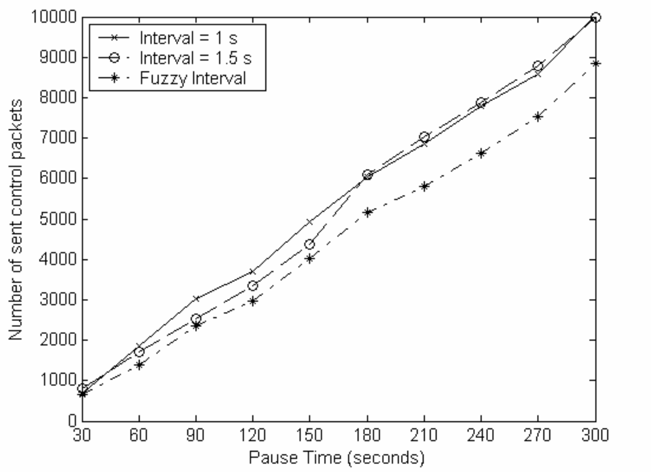
Figure 5. Routing overhead comparison.

5.2. Average End-to-End Delay Details

Figure 7 indicates that the proposed adaptive fuzzy-HI method has lower average end-to-end delay compared with static HI methods. This decrement is approximately 23.5% and 13.7% compared to 1 s and 1.5 s intervals, respectively for 25 nodes network. Meanwhile, the decrement is 29.6% and 15.6% compared to 1 s and 1.5 s intervals for 35 nodes network, respectively.



(a) Received data packets.



(b) Sent control packets.

Figure 6. Data and control packets used in 25 nodes network.

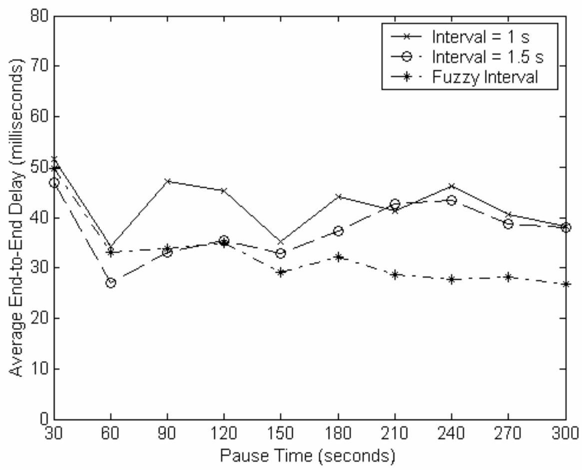
The static HI methods need more routing delay to recover from broken paths and discover new ones. To recover a broken path, an RERR message must first be launched from the intermediate nodes to tell the source node about the link break. The source node deletes the corresponding entry from its routing table. The RREQ must then be broadcast from the source to the destination, and an RREP consequently has to be transmitted back to the source. Data packets are buffered at the source node during this process and the duration of their buffering adds more time delay to the end-to-end delay. Fuzzy-HI method, on the other hands, has reliable routes that minimize the need to this recovery process.

Besides the mentioned reason, the number of hello messages sent during one period of time has a significant effect on this measurement. Increased number of sent hello messages increases buffer utilization and bandwidth consumption. That's the reason of improvement of 1.5- second HI method than 1-second HI method, where it sent fewer hello messages. In the other hand, fuzzy method optimizes this parameter intelligently.

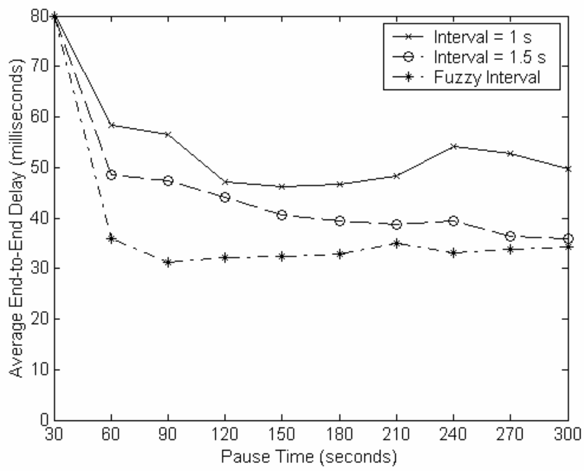
5.3. Invalid Route Ratio Details

As expected, the average invalid route ratio for fuzzy-HI method is less than other static methods as shown in Figure 8. The percentage of fuzzy-HI method improvement is about 4.9% and 31.6% compared to 1 s and 1.5 s intervals for 25 nodes network, whereas it is 33.2% and 56.8% compared to 1 s and 1.5 s intervals for 35 nodes network, respectively.

This improvement of the fuzzy methods is a result of choosing the reliable adaptive links status monitoring to update the paths in the routing table. The worse result of static methods is due to its specification stating that a route lifetime for a path has to be shifted in future each time a hello message is received using that path. This is a very bad role-played by the AODV as it makes the paths request more frequently than they actually needed. Work toward developing techniques for quickly reestablishing valid routes is likely to be of the highest importance for improving the AODV protocol.



(a) 25 nodes.



(b) 35 nodes.

Figure 7. End-to-end delay comparison.

5.4. Frequent Sending of Hello Messages Details

Here the effect of fast topology changes due to frequent sending hello messages especially with the proposed fuzzy method is investigated. This measurement is done by giving the nodes a fast movement to represent fast topology changes or a slow movement to represent slow topology changes. As mentioned earlier, all the previous study done with nodes speed range between [2, 12] m/s, those nodes can be considered as fast speed nodes. To simulate slow speed nodes, the simulation is done with nodes given speed between [0, 2] m/s. The results of the simulation using 25 nodes network are shown in Figure 9.

It must be clear the fuzzy method tries to optimize between the bandwidth consumption and the neighbors information update accuracy. For that reason, at some period of time the fuzzy method has the highest value of sending hello messages to get fast updating of topology changes. On the other hand, at the other period of time it has too low value for sending hello messages as a result of few changes in the topology. From Figure 9, it's clear that while the static HI methods keeps frequent sending of hello messages regardless of nodes speed, the fuzzy method decrease these messages by half using slow speed nodes.

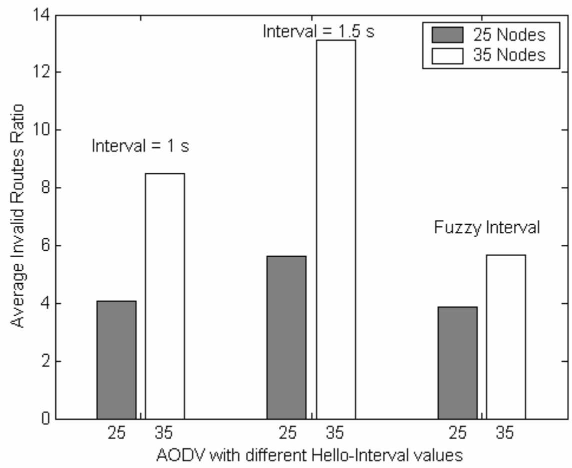


Figure 8. Invalid route ratio comparison.

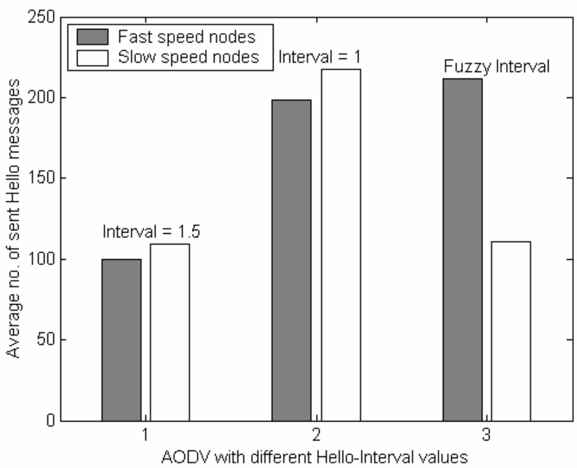


Figure 9. Frequent sending of hello messages comparison.

5.5. Hello Interval Values

In the AODV parameters [17], HI always take a static value of 1 seconds, Figure 10 shows the values used for proposed fuzzy method for randomly chosen node in the 25 nodes simulated network. It is shown the fuzzy HI uses a variety of values between 0.4 seconds and 2.2 seconds. Every node in the network has its own values of HI. It can be noticed from the figure that the starting values of HI is small, and this phenomena is expected to handle new network setup. It is also clear that the most used value for HI is 1-second and this is also the recommended value for AODV. Here the HIs are divided into three regions, as: [0.4, 1], [1, 2.2] and the overlap [0.4, 2.2]. This division is done according to the node speed to represent fast speed, slow speed, and moderate speed respectively.

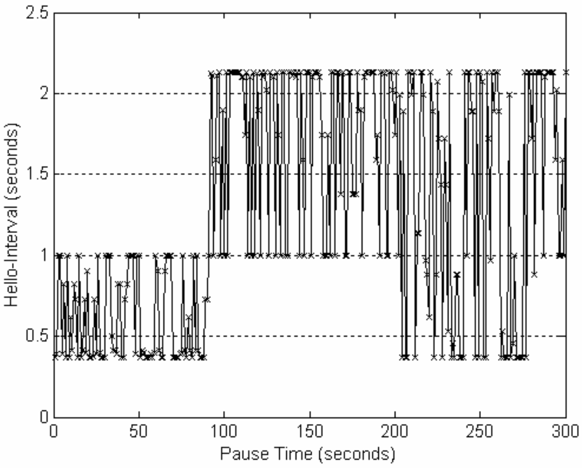


Figure 10. Fuzzy HI values used by a node.

The comparison between the average HI used by every node in the 25 nodes network using slow and fast movement is shown in Figure 11. Due to few topology changes, slow speed nodes have long HIs and these values are quite stable and similar while the reverse behavior is observed for fast moving nodes.

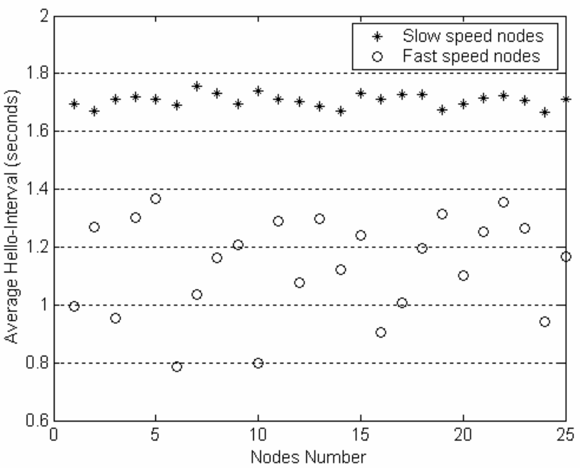


Figure 11. Average fuzzy HI values used by 25 nodes.

6. Conclusions

In this research, a novel approach for local connectivity management in ad-hoc routing protocols has been presented. We have used fuzzy logic system to optimize the frequency of sending hello messages. A fuzzy comparison criterion is developed depending on the nodes transmission range and speed and used to decide the hello messages interval. The routing procedure that has been developed has been simulated in the context of the AODV routing protocol. From the simulation results, the efficiency of the proposed fuzzy method in terms of routing overhead, average end-to-end delay and average percentage of invalid routes are apparent than the original static method. Overall, the work presented here has given us an insight that the ad-hoc routing protocols configuration parameters might be determined more accurately and dynamically by fuzzy logic system, instead of static values.

References

[1] Abolhasan M., Wysocki T., and Dutkiewicz E., "A Review of Routing Protocols for Mobile Ad Hoc Networks," *Elsevier's Ad Hoc Networks*, vol. 2, no. 1, pp.1-22, 2004.

[2] Boukerche A., "Performance Evaluation of Routing Protocols for Ad Hoc Wireless Networks," *Mobile Networks and Applications*, vol. 9, no. 1, pp. 333-342, 2004.

[3] Broch J., Maltz D. A., Johnson D. B., Hu Y., and Jetcheva J., "A Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols," *in Proceedings of the 4th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM'98)*, USA, pp. 85-97, October 1998.

[4] Chakeres I. D. and Royer E. M., "The Utility of Hello Messages for Determining Link Connectivity," *in Proceedings of the 5th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, Honolulu, Hawaii, pp. 504-508, October 2002.

[5] Fussler H., Widmer J., Kasemann M., Mauve M., and Hartenstein H., "Contention-Based Forwarding for Mobile Ad-Hoc Networks," *Elsevier's Ad Hoc Networks*, vol. 1, no. 4, pp. 351-369, 2003.

[6] Galluccio L., Leonardi A., Morabito G., and Palazzo S., "Tradeoff Between Energy-Efficiency and Timeliness of Neighbor Discovery in Self-Organizing Ad Hoc and Sensor Networks," *in Proceedings of the 38th Annual Hawaii International Conference on System Sciences (HICSS'05)*, USA, vol. 9, no. 9, pp. 286.1-286.10, 2005.

[7] Gerharz M., De Waal C., Frank M., and Martini P., "Link Stability in Mobile Wireless Ad Hoc

Networks," *in Proceedings of the 27th Annual IEEE Conference on Local Computer Networks*, USA, pp. 30-42, November 2002.

[8] Hanemann S., Jansen R., and Freisleben B., "Reducing Packet Transmissions in Ad Hoc Routing Protocols by Adaptive Neighbor Discovery," *in Proceedings of the International Conference on Wireless Networks (ICWN'2003)*, Las Vegas, USA, pp. 369-375, 2003.

[9] Heissenbüttel M. and Braun T., "Optimizing Neighbor Table Accuracy of Position-Based Routing Algorithms," *in Proceedings of IEEE INFOCOM'2005*, Miami, USA, March 2005.

[10] Heissenbüttel M., Braun T., Bernoulli T., and Wächli M., "BLR: Beacon-Less Routing Algorithm for Mobile Ad-Hoc Networks," *Elsevier's Computer Communications Journal*, vol. 27, no. 11, pp. 1076-1086, 2004.

[11] Jiang S., He D. and Rao J., "A Prediction-Based Link Availability Estimation for Mobile Ad Hoc Networks," *in Proceedings of IEEE INFOCOM' 2001*, Alaska, USA, vol. 3, pp. 1745-1782, April 2001.

[12] Lundgren H., Nordström E., and Tschudin C., "Coping with Communication Gray Zones in IEEE 802.11b Based Ad Hoc Networks," *in Proceedings of the 5th ACM International Workshop on Wireless Mobile Multimedia (WoWMoM'2002)*, Atlanta, Georgia, USA, pp. 49-55, 2002.

[13] McGlynn M. J. and Borbash S. A., "Birthday Protocols for Low Energy Deployment and Flexible Neighbor Discovery in Ad Hoc Wireless Networks," *in Proceedings of MobiHoc'2001*, Long Beach, , USA, pp. 137-145, October 2001.

[14] Omnetpp, "Discreet Event Simulation System," available at: http://www.omnetpp.org/, 2005.

[15] Perkins C. E. and Royer E. M., "Ad-Hoc On-Demand Distance Vector Routing," *in Proceedings of the 2nd IEEE Workshop on Mobile Computing Systems and Applications*, New Orleans, USA, pp. 90-100, February 1999.

[16] Perkins C. E. and Royer E. M., "The Ad-Hoc On-Demand Distance Vector Protocol," in Perkins C. E. (Ed), *Ad Hoc Networking*, Addison-Wesley, pp. 173-220, 2001.

[17] Perkins C. E., Royer E. M., and Das S. R., "*Ad-Hoc On-Demand Distance Vector (AODV) Routing*," available at: http://draft-ietf-manet-aodv-13.txt (work in progress), February 2003.

[18] Tauchi M., Ideguchi T., and Okuda T., "Ad-Hoc Routing Protocol Avoiding Route Breaks Based on AODV," *in Proceedings of the 38th Annual Hawaii International Conference on System Sciences (HICSS'05)*, USA, vol. 9, no. 9, pp. 322.1-322.7, 2005.

[19] Turgut D., Das S. K., and Chatterjee M., "Longevity of Routes in Mobile Ad Hoc Networks," *in Proceedings of the IEEE VTC*, Rhodes, Greece, vol. 4, pp. 2833-2837, May 2001.

[20] Pedrycz W., "Why Triangular Membership Functions?," *Fuzzy Sets Systems*, vol. 64, no. 1, pp. 21-30, 1994.

[21] Rappaport T. S., *Wireless Communications: Principles & Practice*, Prentice Hall, pp. 70-74, 1996.

[22] Royer E. M. and Toh C. K., "A Review of Current Routing Protocols for Ad-Hoc Mobile Wireless Networks," *IEEE Personal Communications Magazine*, vol. 6, no. 2, pp. 46-55, April 1999.

[23] Samar P. and Wicker S. B., "On the Behavior of Communication Links of a Node in a Multi-Hop Mobile Environment," *in Proceedings of the 5th ACM International Symposium On Mobile Ad Hoc Networking And Computing*, Tokyo, Japan, pp. 145-156, 2004.

[24] Singh J. P., Bambos N., Srinivasan B. and Clawin D., "Proposal and Demonstration of Link Connectivity Assessment Based Applications to Routing in Mobile Ad-Hoc Networks," *in Proceedings of the IEEE 58th Vehicular Technology Conference*, Orlando, Florida, vol. 5, pp. 2834-2838, 2003.

[25] Yager R. R. and Filev D. P., *Essentials of Fuzzy Modeling and Control*, John Wiley and Sons, 1994.

Essam Natsheh obtained the MSc in computer engineering from the Arab Academy for Science and Technology in Egypt in 1999. He subsequently worked as a lecturer at Al-Alamiah Institute for Computer and Technology, Saudi Arabia, from 1999 to 2002. He worked as a lecturer also at the Information Systems Department, King Faisal University, Saudi Arabia, from 2002 to 2003. Since 2003, he has been a member of a research group headed by Dr. Jantan A. at the University Putra Malaysia, which investigates issues related to the design and analysis of ad-hoc wireless networks.

Adznan Jantan is an associate professor at the Department of Computer and Communication Systems at the University Putra Malaysia, where he has been conducting research in computer networking, pattern recognition, and digital systems design since 2002. He obtained his MSc in digital systems from Cranfield Institute of Technology, UK, in 1982 and PhD in speech recognition systems from the University College of Swansea, UK, in 1988.

Sabira Khatun received her BSc (Hons), MSc in applied mathematics and PhD in hydromagnetic stability from the University of Rajshahi, Bangladesh in 1988, 1990 and 1994, respectively. She received her second PhD in communications and networking from University Putra Malaysia in 2003. She became a lecturer at the Discipline of Computer Science and Engineering, University Khulna, Bangladesh in 1991, assistant professor in 1994. She joined as a senior lecturer the Department of Computer & Communication Systems Engineering, University Putra Malaysia in 1998. She is an active researcher of Teman project and MyREN research community. She is a member of IEEE and her research interest spans broadband and wireless communications, and network management, including software defined radio and IPv6.

Shamala Subramaniam completed her PhD from University Putra Malaysia in 2002. Currently, she is a lecturer at the Department of Communication Technology and Networks, Faculty of Computer Science and Information Technology, University Putra Malaysia. Her research interest includes scheduling algorithms, congestion control, real-time systems, modeling and simulation.