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Theory and Applications of Ad Hoc Networks

Takuo Nakashima
Tokai University
Japan

1. Introduction

In ad hoc mobile networks (MANET), the mobility of the modes is a complicated factor that significantly affects the effectiveness and performance of ad hoc routing protocols. In addition, MANET requires the quality of data transmission. Improvement of a routing protocol between communication links provide high quality data transmission. The routing protocol of wireless network exchanges the route information to establish the communication link.

The routing algorithms exchanging the path construction and maintenance messages generate a connectivity related dynamic graph representing the topology of the network by a series of messages passes. Using such a data structure, messages can be transmitted over a number of intermediate nodes that interconnect the source with the destination, also known as routing paths or routes. These routing protocols can be classified into reactive or on-demand protocols (1) such as Ad hoc on-demand distance vector (AODV) (8) and proactive or table-driven protocols (2), such as Dynamic source routing protocol (DSR) (9Proactive protocols always maintain a route to every possible destination, while reactive protocols are considered to discover and maintain a route to a destination only when a route is demanded. AODV routing protocol uses an on-demand approach for finding routes, that is, a route is established only when it is required by a source node for transmitting data packets. It employs destination sequence numbers to identify the most recent path. The major difference between AODV and DSR stems out from the fact that DSR uses source routing in which a data packet carries the complete path to be traversed. However, in AODV, the source node and the intermediate nodes store the next-hop information corresponding to each flow for data packet transmission. The major difference between AODV and other on-demand routing protocols is that it uses a destination sequence number to determine an up-to-date path to the destination.

In a mobile environment, reactive routing protocols have more advantages than proactive routing protocols since reactive routing protocols exchange routing information only when a path is required by a node to communicate with a destination. On the contrary, proactive routing protocol exchanges routing information in order to maintain the global topology information whenever one of path information is required to update triggered by the node movement.

The performance analysis for proactive and reactive routing protocols has been explored in the last decade. To realize the real environment, the selection of the mobile pattern and the size of nodes are key element of simulation. Marinoni et al. (3) discussed routing protocol performance in a realistic environment. New mobility model has introduced and installed in

ns-2 simulator. The discussion, however, is limited in DSR protocol, and no comparison to other protocols appeared. To investigate the truth, Zhang et al. (4) researched the performance of routing protocol in very large-scale mobile area allocating about 50,000 mobile nodes in GTNetS simulator. As the traffic patterns are constructed by randomly selected sources and destinations, it is hard to separate communication overload and routing overload. Mbarushimana et al. (5) explored comparative study of reactive and proactive routing protocol performances. The parameter of simulation, however, is not clearly described, and mobility is not precisely evaluated in this research.

Various routing protocols have been compared in different conditions. In the radio models, Yang et al. (13) analysed the performance of three Ad Hoc routing protocols: AODV, DSR and DSDV considering two radio models TwoRayGround and Shadowing. This research concluded that the shadowing phenomena reduce the mean distance among nodes and increase the latency of packet transmission. The Data link and Physical layers have the potential of the technology improvements. One of our aims is to find the optimal parameter sets of each routing protocols. We focus the performances of routing protocols and the transport layer. The researches for the performance evaluation (14), (15), (16), (17) between the proactive and reactive protocols have found the features for different type routing protocols. These results, however, are obvious for the original design and aim of each protocol.

One approach to enhance the AODV protocol introduces the probability to forward the messages. The researches (18), (19) have proposed the probability based messaging mechanism especially in which (19), each node communicates to its' surrounding nodes/routers with calculated probability, and reduces the overhead of the routing protocols. The routing tables are maintained based on this probability leading to select the most optimal path for transmitting the data packets by sensing the breaking of route. Therefore this approach is effective to avoid the broken route. This method has the more significant meaning than hop count about adjacency between two nodes. The probability, however, is not utilized by the RREQ flooding mechanism meaning that this method does not reduce the RREQ flooding packets. The main degradation of AODV routing depends on the RREQ flooding leading that this method does not improve the end-to-end performance significantly.

The other enhancing approach is to introduce the awareness of the accessibility of the neighbour nodes (20). Nodes acquire the accessibility information of the other nodes through routine routing operations and keep it in their routing table. Later, this information worked to enhance the routing operations. The mobility, however, will change dynamically and induce the huge consumption of memory resources holding the access state for the accessibility prediction. The experiments have been conducted over a small number of mobile nodes. The experiments over the huge number of mobile nodes should be executed to verify the performance improvement.

If mobile nodes are equipped with a digital compass, each mobile node recognizes the direction of messaging. El-azhari et al. (21) proposed the routing protocol based on the direction angle and hop count. This approach easily expands to other devices such as a GPS leading the position based routing protocol. We will focus our discussion on the normal mobile node without any special devices.

In this research, firstly, we focus on the performance of reactive routing protocols such as DSR and AODV, and the throughput of TCP for different routing protocols in the variable, the number of intermediate mobile nodes and the speed of mobile nodes. Secondly, the new

metric, the node density, will be introduced to evaluate the routing performance. Thirdly, we focus on the AODV control messages such as RREQ (Route Request) and RREP (Route Reply), and evaluate the messaging overhead between adjacent nodes. Fourthly, the RREQ flooding patterns generated from both the source node and intermediate nodes are analyzed. Finally, we control the communication power to change the communication distance, and discuss the flooding features of the AODV protocol.

The final goal of our research is to improve the TCP performance over the ad hoc wireless network. Before the discussion of TCP congestion and flow control mechanism, the performance features of the routing protocol should be extracted to evaluate accurate performance. Our previous research indicated the AODV routing protocol had shown the high performance for the mobile node with high speed and the over the dense condition of intermediate nodes. Motivation of this research explores accrete flooding performance of AODV under different mobility models. We will split the overload performance to distinguish the total communication performance depended on the routing performance or TCP performance.

This paper is organized as follows; first, mobile Ad Hoc Networks are explained in Section 2 followed by the comparison of different type of routing protocols in Section 3. The performance of the AODV protocol are discussed in Section 4 followed by the RREQ flooding features of the AODV protocol in Section5. Section 6 the propagation features of the AODV protocol under different mobility models followed by the flooding features of the AODV protocol under the different communication distances in Section 7. Section 8 gives the summary and discussion for future work.

2. Mobile ad hoc networks

2.1 Reactive type routing protocols

Proactive type routing protocols decide the route direction based on the routing table maintained constantly to communicate between adjacent routers. These protocols are activated after preparing the routing table, so proactive type is called table-driven routing protocols. On the other hand, reactive type routing protocols decide the path when IP packets demand transferring to the destination. These protocols prepare the routing table after demanding the path, so reactive type is called on-demand routing protocols. Unlike the table-driven routing protocols, on-demand routing protocols execute the path-finding process and exchange routing information only when a path is required by a node to communicate with a destination. This subsection briefly explores two reactive type routing protocols.

2.1.1 Dynamic Source Routing Protocol

Dynamic Source Routing Protocol (DSR) is an on-demand protocol designed to restrict the bandwidth consumed by control packets in ad hoc wireless networks by eliminating the periodic table-update messages required in the table-driven approach. The major difference between this and other on-demand routing protocols is that it is beacon-less and hence does not require periodic hello packet (beacon) transmission, which are used by a node to inform its neighbors of its presence. The basic approach of this protocol during the route construction phase is to establish a route by flooding Route Request packets in the network. The destination node, on receiving a Route Request packet, responds by sending a Route Reply packet back to the source, which carries the route traversed by the Route Request

packet received. In addition, the TTL field constrains the reachable distance, and the sequence number filed prevents double transmission and loops.

2.1.2 Ad hoc On-demand Distance Vector

Ad hoc on-demand distance vector (AODV) routing protocol uses an on-demand approach for finding routes, that is, a route is established only when it is required by a source node for transmitting data packets. It employs destination sequence numbers to identify the most recent path. The major difference between AODV and DSR stems out from the fact that DSR uses source routing in which a data packet carries the complete path to be traversed. However, in AODV, the source node and the intermediate nodes store the next-hop information corresponding to each flow for data packet transmission. The major difference between AODV and other on-demand routing protocols is that it uses a destination sequence number to determine an up-to-date path to the destination.

2.2 Mobility models

In this section, we shortly introduce three mobility models that have been proposed for the performance evaluation of an ad hoc network protocol. The detailed discussion of the mobility model is described by Camp et. al.(11).

2.2.1 Random walk

In Random Walk Mobility Model, an Mobile Node (MN) moves from its present location to a new one by randomly choosing a direction and speed in which to travel. The new speed and direction are both chosen from pre-defined range, [*min_speed*, *max_speed*] and [0, 2π] respectively. Each movement in the Random Walk Mobility Model occurs in either a constant time interval *t* or a *d* traveled in constant distance, at the end of which a new direction and speed are calculated. If an MN which moves according to this model reaches a simulation boundary, it bounces off the simulation border with an angle determined by the incoming direction. The Random Walk Mobility is a widely used mobility model. On the other hand, if the specified time (or specified distance) an MN moves in the Random Walk Mobility Model is short, then the movement pattern is a random roaming pattern restricted to a small portion of the simulation area.

2.2.2 Random waypoint

The Random Waypoint Mobility Model includes pause times between changes in direction and/or speed. An MNbegins by staying in one location for a certain period of time. Once this time expires, the MN chooses a random destination in the simulation area and a speed that is uniformly distributed between [*min_speed*, *max_speed*]. The MN then travels to the newly chosen destination at the selected speed.

2.2.3 Random Direction

The Random Direction Mobility Model (12) was created to overcome density waves in the average number of neighbors by the Random Waypoint Model. A density wave is the clustering of nodes in one part of the simulation area. In the case of the Random Waypoint Mobility Model, this clustering occurs near the center of the simulation area. In the Random Waypoint Mobility Model, the probability of an MN choosing a new direction located in the center of the simulation area, or a destination which requires travel through the middle of

the simulation area, is high. In the Random Direction Mobility Model developed by (12), MNs choose a random direction in which to travel similar to the Random Walk Mobility Model. An MN then travels to the border of the simulation area in that direction. Once the simulation boundary is reached, the MN pauses for a specified time, choose another angular direction (between 0 and 180 degrees) and continues the process.

2.3 Propagation model

The propagation signal power between adjacent nodes is defined using the following the equation of the Two-Ray-Ground propagation model.

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

where $P_r(d)$ be the receiving signal power on the distance d (meter), P_t be the sending signal power, G_t be the gain of sending antenna, G_r be the gain of receiving antenna, h_t be the height of the sending antenna, h_r be the height of the receiving antenna, d be the distance and L be the system loss.

2.4 Flooding feature of RREQ and performance features of RREP

We introduce the new metrics to characterize the routing performance based on the message communication. The average number of RREQ (Route Request) adjacent nodes to evaluate the degradation of RREQ flooding performance and the average propagation rate of RREP(Route Reply) should be defined as follows.

$$Average\ number\ of\ RREQ\ adjacent\ nodes\ = \frac{The\ total\ number\ of\ RREQ\ receiving\ packets}{The\ number\ of\ RREQ\ sending\ packets} \tag{2}$$

This metric indicates how many average nodes are reachable on each node. As the RREQ is the broadcast message, average number of RREQ adjacent nodes is induced by the number of RREQ receiving packets divided by the number of RREQ sending packets.

$$Average\ propagation\ rate\ of\ RREP\ = \frac{The\ total\ number\ of\ RREP\ receiving\ packets}{The\ number\ of\ RREP\ sending\ packets} \tag{3}$$

The other metric of the average propagation rate of RREP indicates the percentage that the RREP packets could reach from the source node to the destination node on unicast message without loss.

2.5 Simulation model

We adopted the LBNL network simulator (ns) (6) to evaluate the effects of performance of ad hoc routing protocols. The ns is a very popular software for simulating advanced TCP/IP algorithms and wireless ad hoc networks. Our experiments configure two stationary end nodes and intermediate mobile nodes in the ad hoc networks. The TCP connection will be limited between two stationary end nodes to generate one TCP traffic through an appropriate route controlled by ad hoc routing protocols. While mobile nodes are located randomly on the 500 (m) * 400 (m) square area, and move through this area with the same speed. In our simulations, the speed of mobile node will be changed at 5, 10, 15 and 20

(m/sec) to emulate a bicycle and a normal car speed. The direction of movement changes after elapsing 10 simulation seconds with in a random manner. The number of intermediate mobile nodes varies from 10 to 50 with 10 nodes interval. MAC and physical layer consist of 802.11 (7) with omniantenna model.

To discuss separately in terms of two communication nodes and intermediate nodes, we classify the mobility pattern into three types. Firstly, two communication nodes are still stationary and other intermediate nodes randomly move. Secondly, two communication nodes randomly move with stationary intermediate nodes. Finally, all nodes move randomly. To verify the efficiency of routing protocol, we focus on the first pattern in our simulation.

3. Comparison of different type of routing protocols

Firstly, we focus on the end-to-end performance varying the node speed for different routing protocols. The accurate evaluation for the sensitivity of the speed requires the uniform speed, and that for the end-to-end performance requires the stationary nodes for TCP communication. From these requirements, we adopted the random walk mobility model with uniform speed, and classify nodes into two types, two communication stationary nodes and intermediate mobile nodes under the random walk mobility model.

3.1 AODV control packets

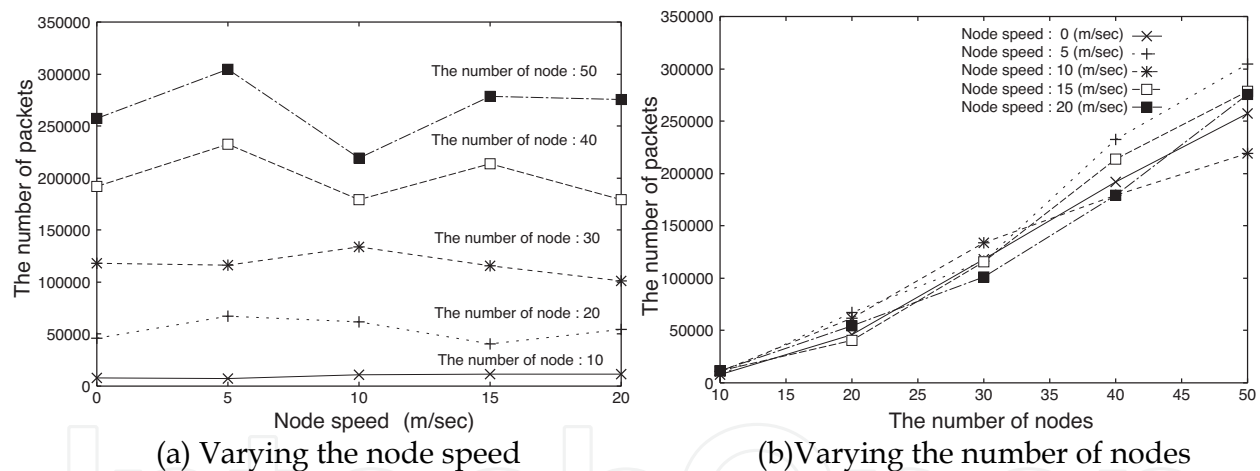(a) Varying the node speed   (b) Varying the number of nodes

Fig. 1. The number of Route Request (RREQ) packets.

Figure 1(a) shows the number of Route Request (RREQ) packets varying the node speed. Main significant result is that the number of RREQ packets does not depend on speed. The total number of RREQ packet does not change whether intermediate nodes stand still or move with 20 (m/sec). This simulation results is contrary to the prediction that if the node speed increases, then the connectivity is damaged, to be followed by the control packet to establish the connectivity increase. The unexpected result is caused by the following two reasons. Firstly, the reachable area of wireless MAC protocol covers the wide range. Secondly, the communication packet on the intermediate nodes is limited to the routing packet meaning that packets are smoothly transferred on the intermediate nodes and the path is decided faster than the moving speed. We can conclude that the constant change of moving direction does not follow the increase of the total number of RREQ packets since the reachable area covers the moving area.

To clarify the property between the number of node and the total number of RREQ packets, Figure 1(b) illustrates the number of RREQ packets varying the number of intermediate nodes. The number of RREQ linearly increases following the number of intermediate nodes, which means the number of RREQ linearly depends on the density of intermediate nodes. In addition, we confirm that the increase of the total number of RREQ is proportional to the increase of the number of reachable node for RREQ packets. This increase enhances the availability to communicate the destination node. In general, the enhancement of availability for path selection can improve the performance overload with path data saved in cache area in such a way that the relevant path is selected, while generating fluctuated path selection in this case.
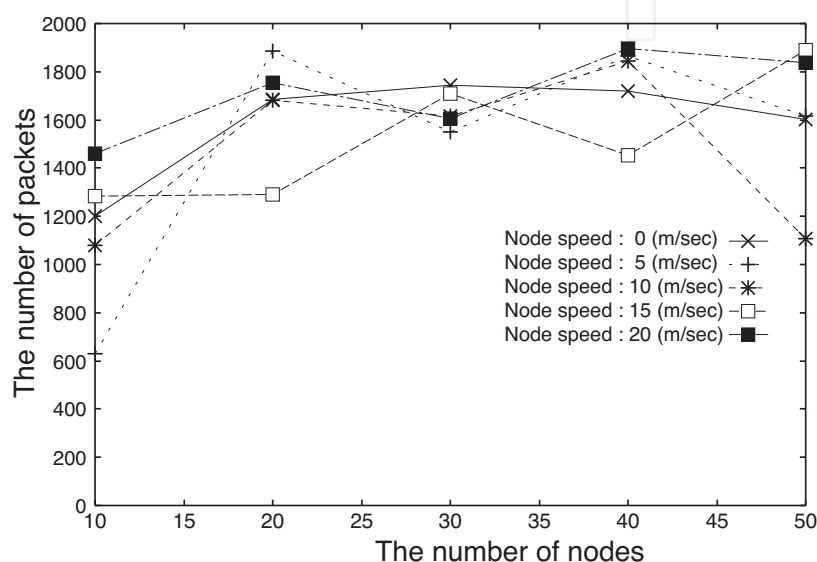
Fig. 2. The number of RREP packets varying the number of nodes.

So far, we discussed the performance of the RREQ packets transferred to the forwarding direction from source node so far, and then discuss the Route Reply (RREP) packets transferred to the backwarding direction. Figure 2 illustrates the number of RREP packets varying the number of nodes with different node speeds. In contrast to the number of RREQ packets, the number of RREP packets does not change apparently for each the number of node and each node speed. This indicates that the number of selection for paths does not change for the each number of nodes and each node speed, for one path selection generates the one RREP packet. As the AODV is a reactive type protocol, the path is decided when the request occurs. At that time, the RREP packet is generated on the destination node to notify the path information to the source node even if the intermediate node does not move. This property leads to generate some amount of RREP packets when the node speed is zero. The same amount of RREP packets in both cases - the node speed is zero and node moves with some speed – indicates that path selection is rarely rearranged during the communication, and the data is transferred on the first selected path regardless of the movement in intermediate nodes. Compared to the moving speed which are considered to be relevant to real environment, the data transmission time is very short. In addition, considering with the linear increase of RREQ packets, flooding based RREQ packets are affected by the number of intermediate nodes, but the number of RREP packets is stable after an appropriate path selection.

3.2 TCP performance

In this subsection, we evaluate the end-to-end performance on TCP, focusing on the throughput of TCP.

3.2.1 TCP performance on AODV

(a) Varying the number of nodes   (b)varying the number of nodes in wide area
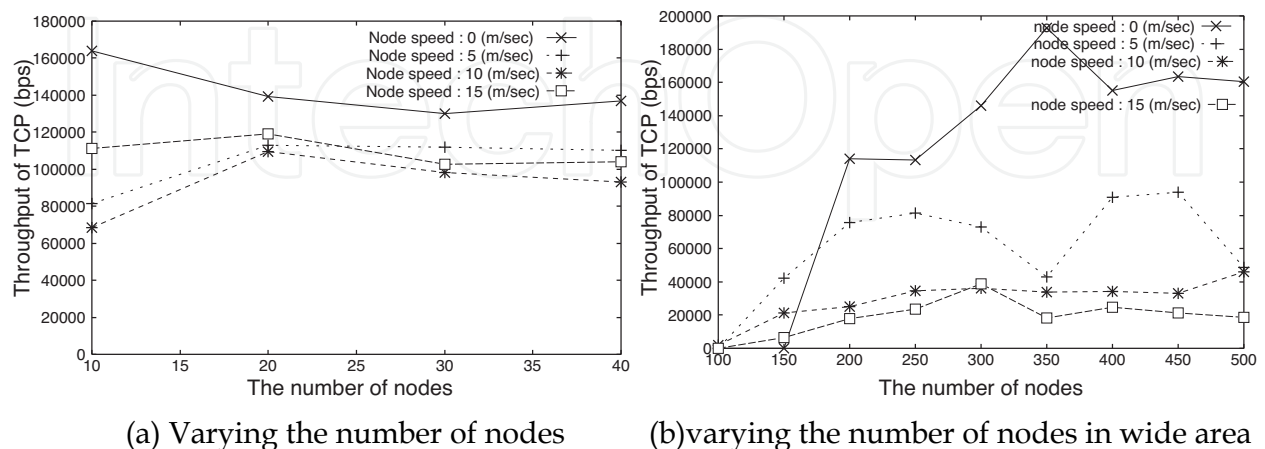
Fig. 3. The throughput of TCP.

Figure 3(a) shows the throughput of TCP varying the number of nodes in different node speeds. Each throughput has no significant difference except for the number of node being 10 meaning that throughput does not depend on the large number of nodes. In addition, the TCP throughput does not depend on the speed of mobile nodes. Compared to the stationary intermediate nodes, the performances of throughput of mobile nodes degrade about 20 % independently of the large number of nodes and node speeds. The coarse distribution of intermediate nodes such as ten nodes causing the loss of data transmission which results in performance deterioration. As the RREQ control packets equally flow in the case of ten nodes compared to other cases as previously mentioned, the frequency of route change can equally occur in this case. The coarse density, however, causes the performance deterioration. On the other hand, the performance gain for stationary ten intermediate nodes is influenced by the quick establishment of connection without wasted routing time.

To clarify the effect of coarse condition of intermediate nodes, we experimented in a wide area environment. Figure 3 (b) shows the fluctuations of TCP throughput, when the mobile area is enlarged to 3,000 (m) * 2,400 (m) with the number of intermediate nodes increased 500. If 40 intermediate nodes exist in 500 (m) * 400 (m) then the density is 20 nodes in 100 square meters. While intermediate nodes exist in this experiment, the density is 0.7 nodes in 100 square meters representing a very coarse condition. In a coarse condition, the throughput is significantly influenced by the node speed. When the node speed is zero, these nodes can not communicate with each other, i.e. the throughput value is zero under the condition of 150 intermediate nodes. However, if the number of intermediate nodes increases to greater than 200, the throughput indicates good performance for the stationary intermediate nodes. Then when the number of intermediate nodes exceeds 300, i.e. the density exceeds 0.4 nodes in 100 square meters, the stable performance of TCP is obtained.

On the other hand, when these intermediate nodes move with the speed such as 5, 10 and 15 (m/sec), the TCP performances enhance linearly for each speed until the number of nodes reaches 200. The throughput in dense nodes is stable and depends on the node speed. The

throughput performance drops drastically from zero to 10 (m/sec) node speeds meaning that the throughput performance does not linearly degrade in terms of the node speed, but exponentially degrades until 10 (m/sec) node speeds.
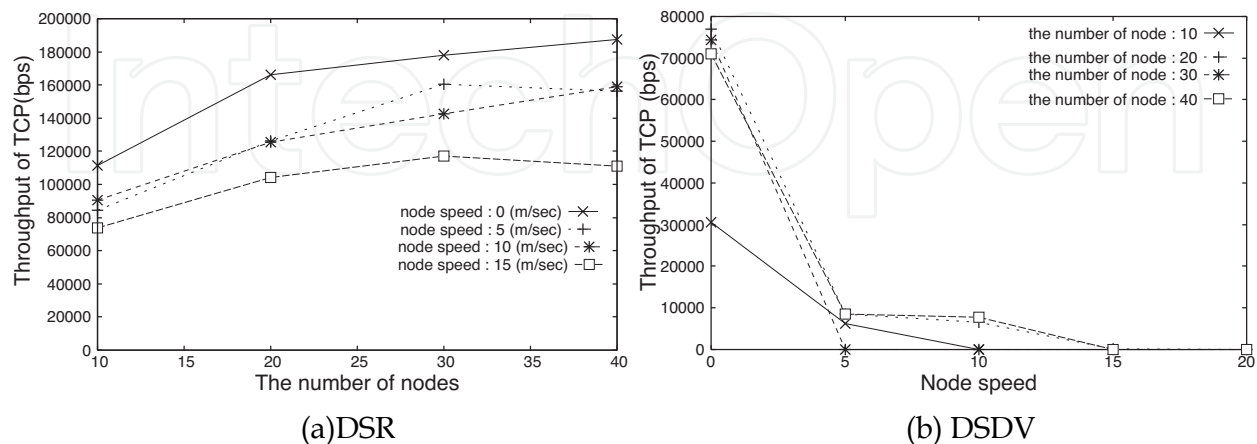
3.2.2 TCP performance on DSR and DSDV

Fig. 4. The throughput varying the number of nodes.

The throughput performance for DSR which is another typical reactive type routing protocol is shown in Figure 4 (a). Compared to AODV protocol, there are two distinct features. Firstly, the throughput increases in fine node condition representing that the communication path quickly connected both end nodes. Secondly, the throughput degrades for high-speed intermediate nodes indicating that the performance depends on the node speed, degrading to half the performance in the 15 (m/sec) node speed compared to the condition with zero speed. The dependency of the node speed is one of the disadvantages of DSR, which are caused by path changes and path management mechanism which hold total path information on only source and destination nodes in contrast to the fact that AODV can replay RREP packets on intermediate nodes.

We have previously discussed the performance of reactive type routing protocols. In this subsection, we focus on one typical proactive type routing protocol, DSDV (Destination Sequenced Distance-Vector Routing Protocol), and compare the throughput performances. Figure 4 (b) illustrates the throughput variation created by the node speed. All throughputs for each number of node drastically degrade when the node speed exceeds 5 (m/sec). In addition, the coarse node condition such as 10 intermediate nodes causes the poorer performance even if intermediate nodes are stationary. These results show that proactive type routing protocol is weak in terms of the node speed, and the coarse density node condition causes the performance degrade. The proactive type routing protocol is not a realistic selection in mobile communication.

3.3 Summary

Our simulation results explored two performance features for the AODV control packets as follows. Firstly, route stability is more sensitive to the number of intermediate nodes than the speed of intermediate nodes. Secondly, the number of RREQ packets linearly increases in terms of the number of node. In addition, we captured the following three features of TCP throughput performances for different protocols. Firstly, the TCP throughput on AODV

with mobile intermediate nodes degrades about 20 % compared to stationary intermediate nodes in dense node condition, and exponentially degrades until 10 (m/sec) node speeds in a coarse node condition. Secondly, the TCP throughput on DSR degrades in accordance with the increase of node speed meaning that it is sensitive to the node speed. Thirdly, the TCP throughput on DSDV drastically degrades in the mobile environment.

4. Performance of the AODV protocol

In this section, mobile nodes are located randomly on the 1,000 (m) * 1,000 (m) square area with four different density such as 0.1, 1, 5 and 10 nodes / 100 square meters, and move through this area with the same speed. The direction of movement changes after elapsing 10 simulation seconds with in a random manner.

4.1 AODV control packets
In this experiment, we separate the sending and receiving packets to clarify the differences between active (sending) nodes and non-active (receiving) nodes.

(a) Sending packets   (b) Receiving packets
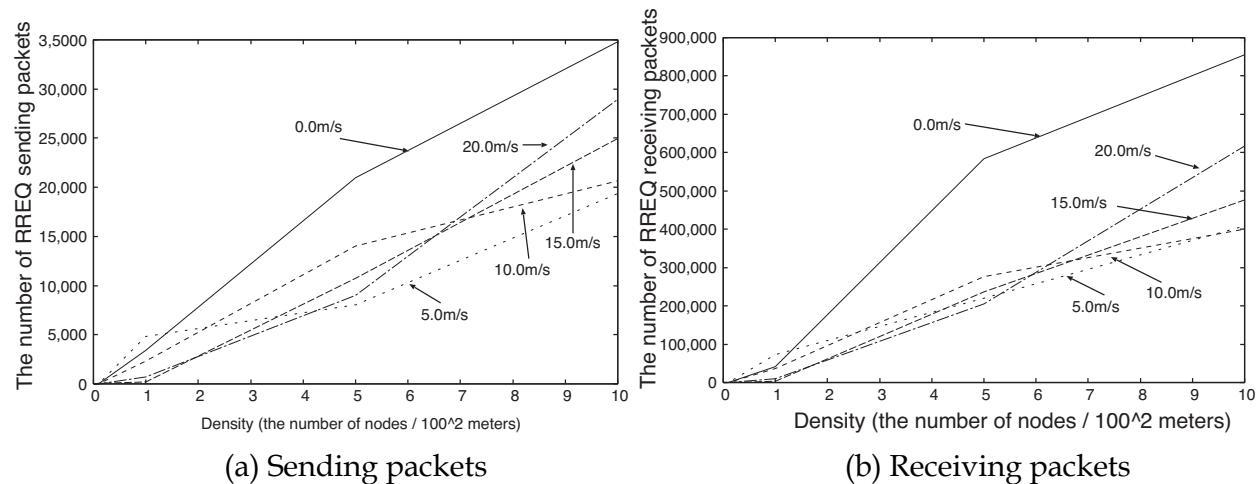
Fig. 5. The number of RREQ varying the node speed.

Figure 5 (a) shows the number of Route Request (RREQ) sending packets varying the node speed. As a standard property, when the density of node becomes denser, the number of sending packets increases in proportion to the node density. More wide-spread reachable areas of wireless network make the covering area wider in proportion to the node density. We captured two main properties; first, stationary condition such as the zero speed generates RREQ sending packets most frequently, and secondly, the condition with high speed mobility that creates RREQ sending packets more frequently than that with low speed mobility.

Node mobility makes it possible for a message to reach larger number of nodes in a wider area compared to a message in stationary condition. This leads to the conclusion that the number of sending nodes in mobile condition is smaller than in stationary condition. On the other hand, when a node density is as close to the density of 10 nodes in 100 square meters, high speed nodes can reestablish the route and can consume RREQ sending packets.

Compared to the sending packets in Figure 5 (a), the number of receiving packets is 20 times larger in the case of 2 nodes in 100 square meters as shown in Figure 5 (b). This figure illustrates two identical properties of sending packets; firstly, stationary condition generates

RREQ receiving packets most frequently, secondly, the condition with high speed mobility creates RREQ receiving packets more frequently than that with low speed mobility. The receiving node here does not mean the number of activated nodes, but mean the number of existing node of sending packets in reachable area.
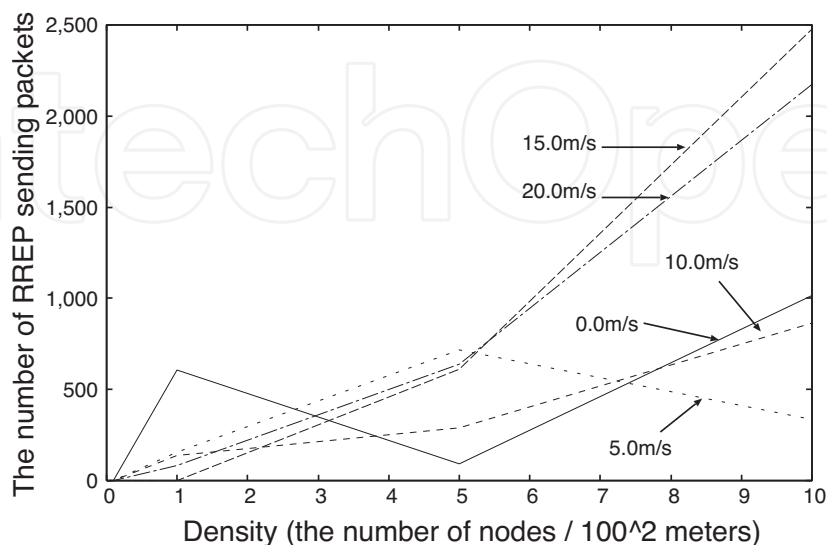

Fig. 6. The number of Route Reply (RREP) sending packets varying the node speed.

The number of RREQ packets indicates the extent of reachable area. On the other hand, the number of RREP packets indicates the stability of the path connection. The large number of RREP packets shows that the path is under the unstable condition and disconnected for the mobile activity of intermediate nodes.

Figure 6 shows the number of Route Reply (RREP) sending packets varying the node speed. We captured two properties; firstly, when the node speed is under 10 m/sec, then the number of RREP is restrained to small values over every density, secondly, when the node speed exceeds 15 m/sec, then the number of RREP suddenly increases, where the node density is as close to 10 nodes in 100 square meters. These results show that the stable and mobile nodes under 10 m/sec speed can communicate using the same path even if each node moves with 10 m/sec. When the speed, however, exceeds 15 m/sec, then the established paths are disconnected by the node mobility causing the increase of the number of RREP packets. The node density effects to increase of the number of RREP packets, since dense condition creates the path with long hops. The number of RREP sending packets and RREP receiving packets, which is not shown, vary with no significant differences.

4.2 DSR and DSDV control packets

Figure 7(a) illustrates the number of DSR RREQ packets varying the node speed. The number of RREQ increases in proportion to the node density, since that the reachable area spread widely in accordance with the increase of density. The number of DSR RREQ packets increases by 40 % compared to that of AODV meaning that AODV protocol behaves more effectively to establish the path than DSR protocol over every density.

As an example of Proactive type protocol, the number of control packets of DSDV is shown in Figure 7 (b). When the node density exceeds 1, control packets to maintain the routing table suddenly increase and reach the huge amount of packets for every speed. The DSDV protocol shows the inefficiency in terms of the node speed and the dense node condition.
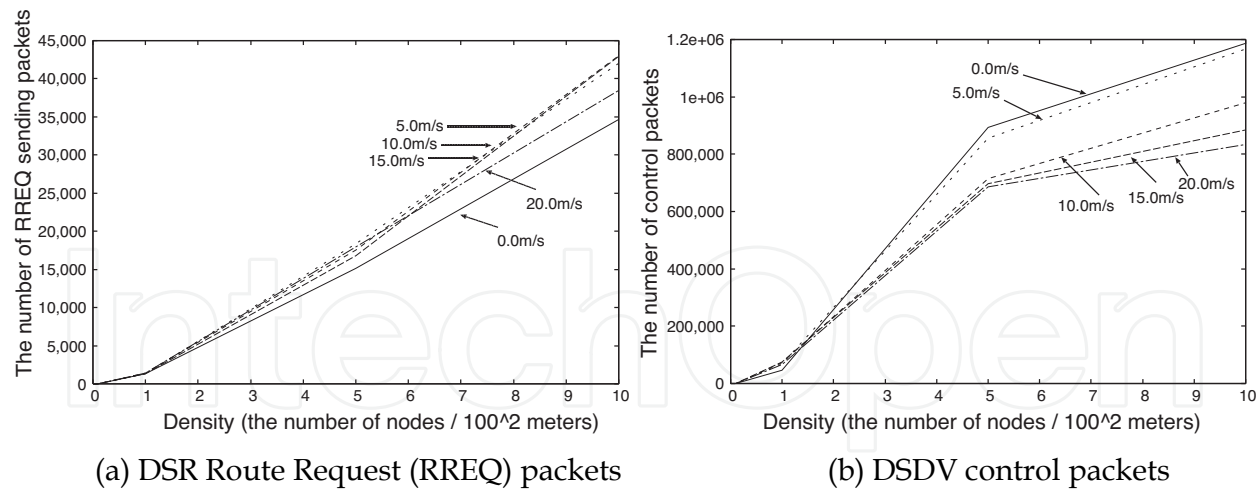
(a) DSR Route Request (RREQ) packets   (b) DSDV control packets

Fig. 7. The number of control packets varying the node speed.

4.3 Summary

Our simulation results explored following four performance features. Firstly, the high speed degrades in terms of AODV RREQ sending packets merely on the density of 10 nodes per 100 square meters. Secondly the high speed exceeding 15 m/s creates more RREP sending packets over dense node conditions. Thirdly, the number of DSR RREQ sending packets increases by 40 % compared to that of AODV. Finally, the DSDV protocol shows the inefficiency in terms of the node speed and the dense node condition.

5. RREQ flooding features of the AODV protocol

In this section, mobile nodes are located randomly on the 1000 (m) * 1000 (m) square area, and move around this area with the same speed. The direction of movement changes after elapsing 10 simulation seconds with in a random manner. The density of intermediate mobile nodes varies with 1, 5 and 10 (nodes / 100^2 meters).

5.1 Flooding feature of RREQ

Figure 8 (a) and (b) shows degradation features of RREQ, such as the average number of RREQ adjacent nodes and the frequency of DROP packets in different conditions respectively. "DROP" means the sign indicated by the ns simulator. In Figure 8 (a), the average number of RREQ adjacent nodes increases linearly at the density = 5. In a denser condition, the increase of RREQ sending packets leads to packet collisions and finally packet drops. These conditions maintain almost the same number of RREQ receiving packets, and keep or decrease the average number of RREQ adjacent nodes. Figure 8 (b) shows the frequency of DROP packets. If the node speed is 15 or 20 (m/s), the DROP packets on density = 10 is five times more frequent that on density = 5. On the other hand, at such slow node speed as 0, 5 or 10 (m/s), the frequency of DROP packets on density = 10 is around two times, meaning that packet DROP is dependable on the node speed.

In more detailed analysis for trace data, the cause of DROP packets is mostly collisions on the simultaneous broadcasting. Contrary to unicast packets such as the RREP packets, RREQ flooding causes the performance degradation.
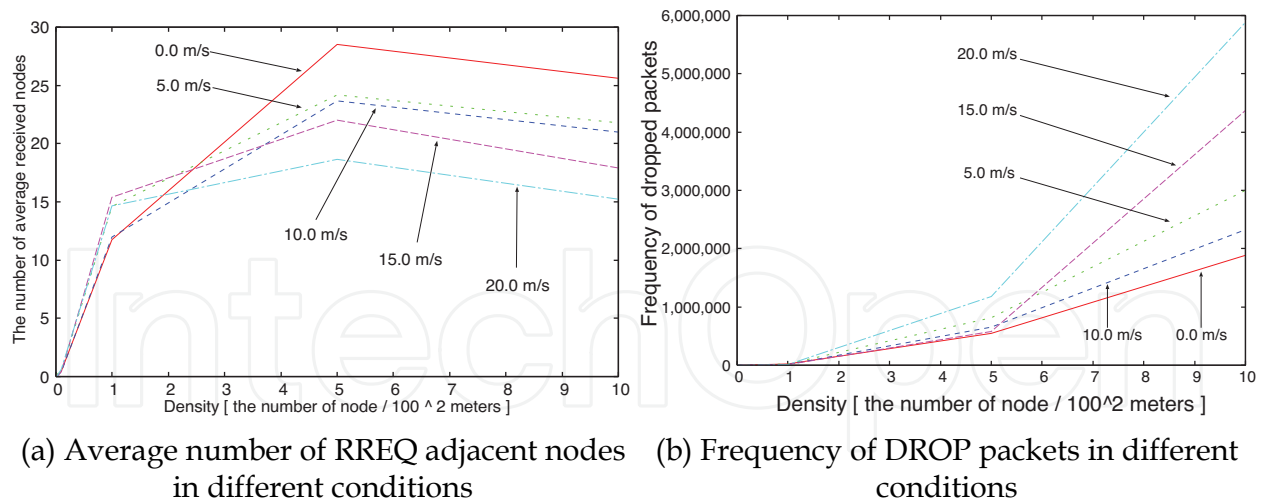
(a) Average number of RREQ adjacent nodes in different conditions

(b) Frequency of DROP packets in different conditions

Fig. 8. Degradation features of RREQ.

5.2 Time sequence features of RREQ flooding
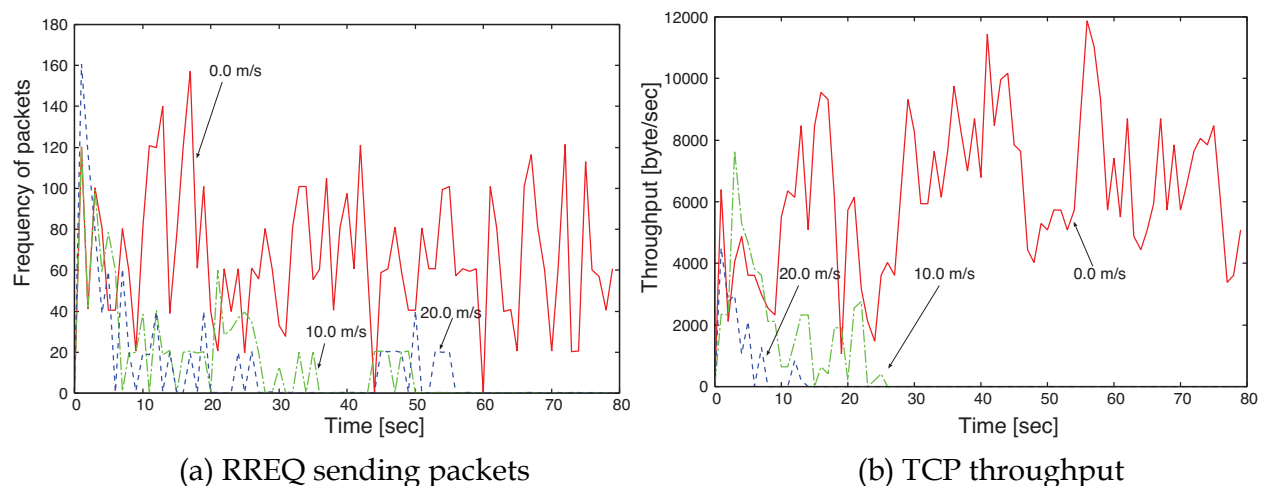

(a) RREQ sending packets

(b) TCP throughput

Fig. 9. Time sequence of frequency on the condition of density = 1.

Firstly, we examined the time sequence of frequency for RREQ sending packets and TCP throughput on the condition of density = 1 in Figure 2 (a) and (b) respectively varying the node speed on 0.0, 10.0 and 20.0 (m/s). Figure 9 (a) illustrates that the frequency of RREQ packets on the speed 0.0 keeps some amount of packets. On the other hand, when nodes have some speed such as 10.0 or 20.0 (m/s), the fluctuations of frequency gradually decrease and finally reach to zero traffic within 60 simulation seconds. These trends appear in the upper layer TCP as early as within 30 simulation seconds, and the TCP throughputs rapidly decrease to zero on 10.0 and 20.0 (m/s) case in Figure 9 (b). This performance degradation is caused by the unreachability between adjacent nodes on this course node condition.

On the dense condition such as the density = 10, Figure 10 (a) and (b) show the time sequence of frequency of RREQ sending packets and TCP throughput respectively. Each frequency of RREQ with different speeds spread over all simulation time, and the frequency with high speeds keep higher values than that with low speeds, meaning that the high speed movement requires more RREQ packet to maintain the route path. TCP throughput

time sequences in Figure 10 (b) illustrates that high speed movement such as 20.0 (m/s) creates more efficient TCP throughput than the case of 10.0 (m/s), even if RREQ packets for 20.0 (m/s) are sent more frequently meaning that the RREQ packets contribute to establish the path between two end nodes and the TCP throughput.
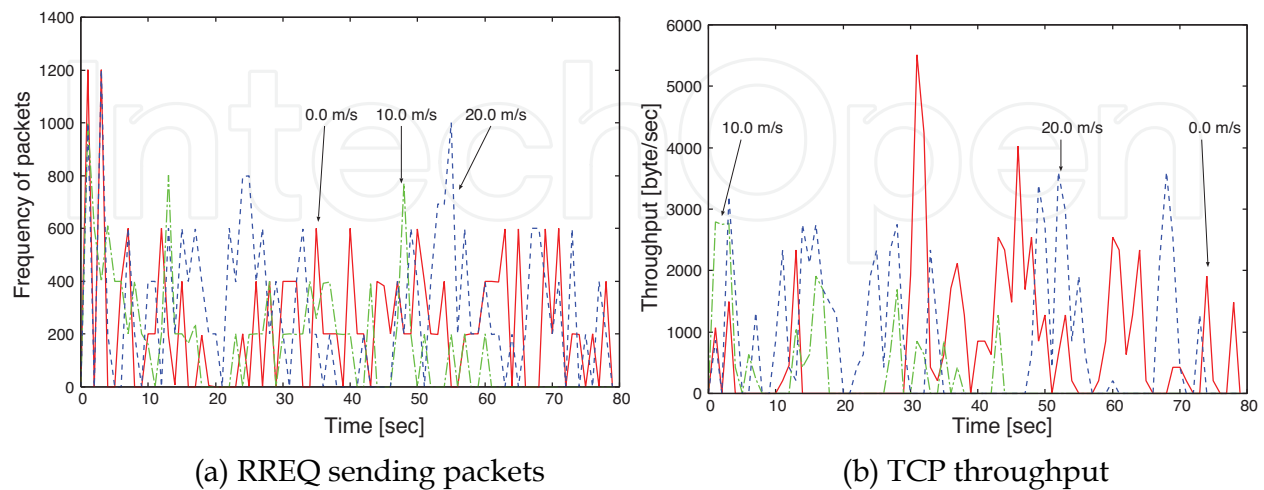

(a) RREQ sending packets   (b) TCP throughput

Fig. 10. Time sequence of frequency on the condition of density = 10.

5.3 RREQ flooding patterns

In this sub section, we examined the experiments and discussed flooding patterns showing the time sequences of flooding with the hop count. These experiments were carried out under the congested condition with density = 10 and node speed = 20.0 (m/s). As the result of experiments, we confirmed the flooding patterns visually using the nam, followed by classification into two patterns, "starting from the source node" and "starting from the intermediate node" Firstly, "starting from the source node" patterns are classified to two patterns depicted in Figure 11 (a) and 11 (b). The x-axis is the simulation time starting the first RREQ and first DROP, the y-axis is the hop count of RREQ and DROP packets. These properties are listed in Table 1 describing that main difference between the properties in Figure 11(a) and (b) is the average hop count.

In Table 1, "sending elapsed time" means the elapsed time from the start time of first RREQ packet to the last time of last RREQ packet over one RREQ flooding. "DROP elapsed time" also means the elapsed time from first DROP to last DROP.

We extracted the following features of RREQ flooding from Figure 11 (a). Firstly, delayed RREQ packets appear on hop count = 5 or 6 or 7. In general, flooding propagates sequentially from a node to an adjacent node. This propagation, however, is delayed causing the performance degradation. Secondly, long continuous DROPs appear after the

Properties	Pattern 1	Pattern 2
Maximum hop count	12	7
Average hop count	7.48	4.90
Sending elapsed time	0.079	0.029
DROP elapsed time	0.125	0.064

Table 1. Properties of the starting from source node pattern.

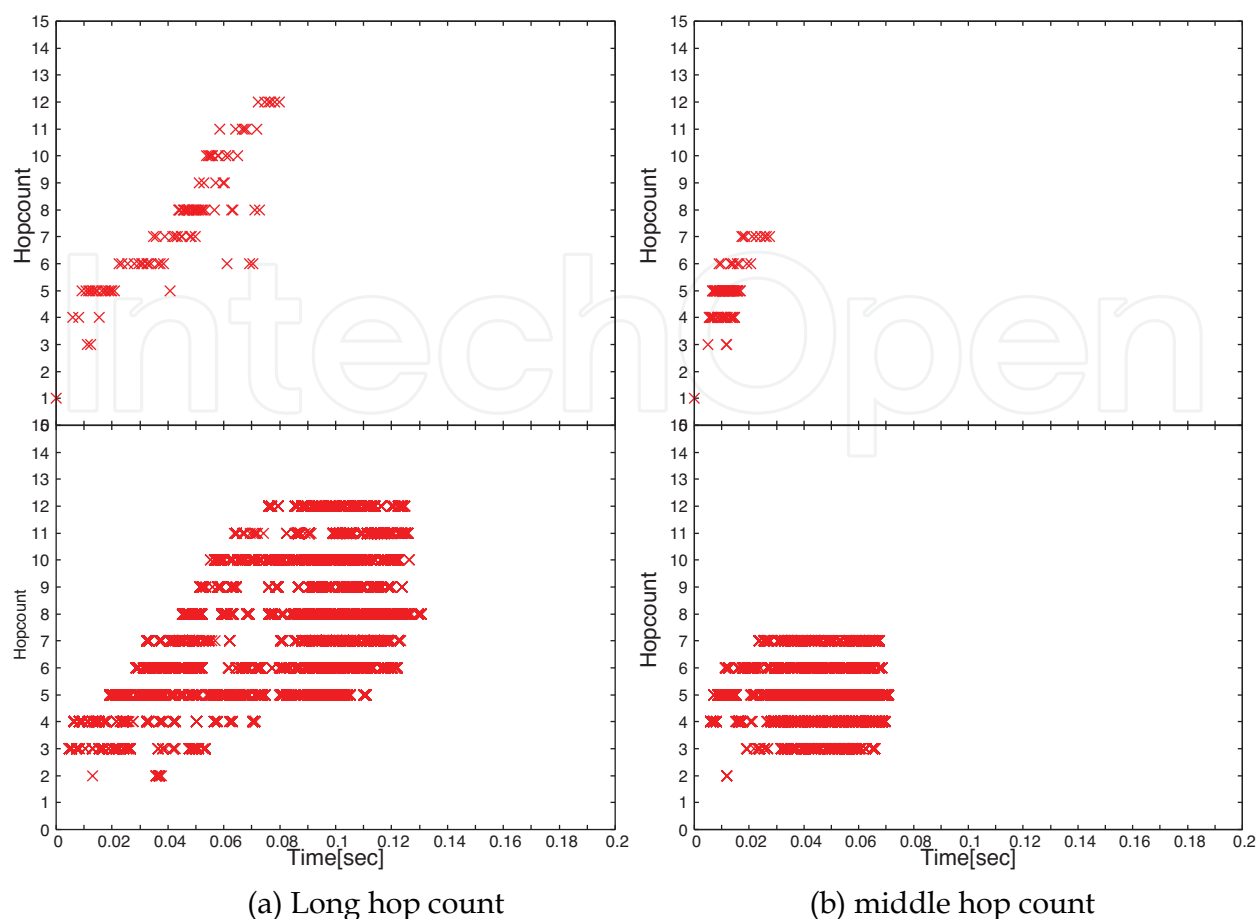(a) Long hop count   (b) middle hop count

Fig. 11. Starting from the source node.

hop count = 5. Considering the first feature, the reason of these DROPs seem to be generated by the delayed RREQ propagation.

The flooding features of RREQ in Figure 11 (b) show the different propagation pattern. In this case, the continuous time of RREQ flooding and DROP packets are very short, meaning that the shorter path seems to be selected in this flooding pattern.

The flooding patterns of the other category, "start from the intermediate node", are shown in Figure 12 (a)and (b) respectively. Both patterns (a) and (b) have the short and middle hop count respectively, since the start node is the intermediate node, and have the long propagation delay at the initial RREQ flooding. Table 2 shows that the case in Figure 12(b) has the long sending elapsed time. The reason of both long sending elapsed time and middle hop count is explained by the position of the starting intermediate node. The position of the intermediate node in Figure 12 (a) is in the middle of the moving area. On the other side, the position of the intermediate node in Figure 12 (b) is on the edge part of total communication area.

Properties	Pattern 1	Pattern 2
Maximum hop count	5	9
Average hop count	2.50	4.70
Sending elapsed time	0.053	0.133
DROP elapsed time	0.089	0.082

Table 2. Properties of the starting from intermediate node pattern.

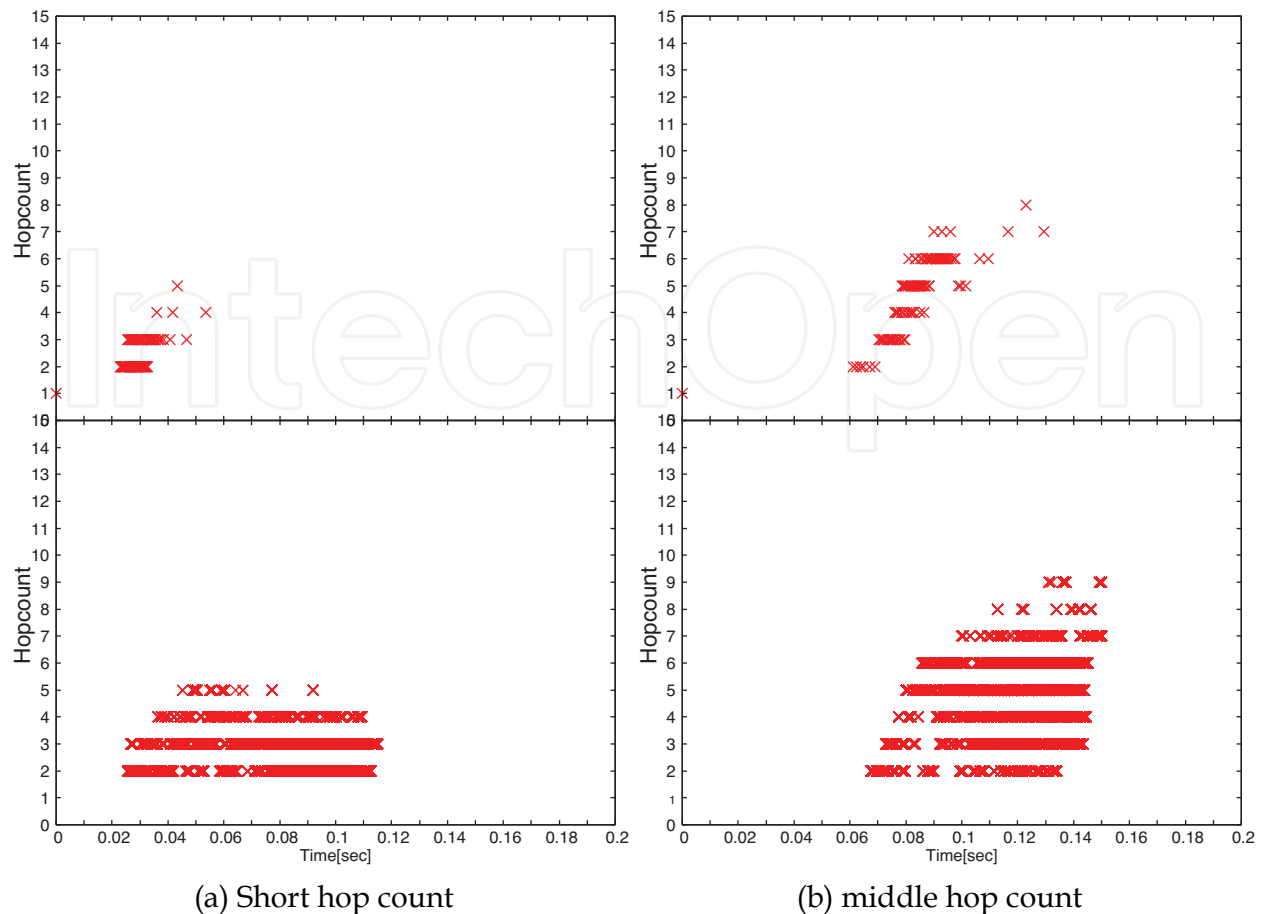(a) Short hop count   (b) middle hop count

Fig. 12. Starting from the intermediate node.

5.4 Summary

Our simulation results explored the following degradation features of RREQ flooding. Firstly, the main degradation of RREQ flooding is caused by the high density node condition and the high speed movement. Secondly, the reason of DROPs is generated by the delayed RREQ propagation on the case of RREQ flooding from the source node. Finally, the delayed start of RREQ flooding from the intermediate node generates the degradation of performance.

6. Propagation features of the AODV under different mobility models

In this section, mobile nodes are located randomly on the 1000 (m) * 1000 (m) square area to move around this area with the same speed. MNs start at 1.5 simulation seconds toward the selected direction. After the reach at the destination, MNs consume the pause time, and select the next direction. The pause time varies with 0 second, within 1 and 5 seconds, or within 1 and 10 seconds. The density of intermediate mobile nodes varies within 1, 5 and 10 (nodes / 100^2 meters).

6.1 Variation of each metric for different conditions

Figure 13 (a) and (b) respectively show the average propagation rate of RREP and the average number of RREQ adjacent nodes under the Random Direction Mobility Model with

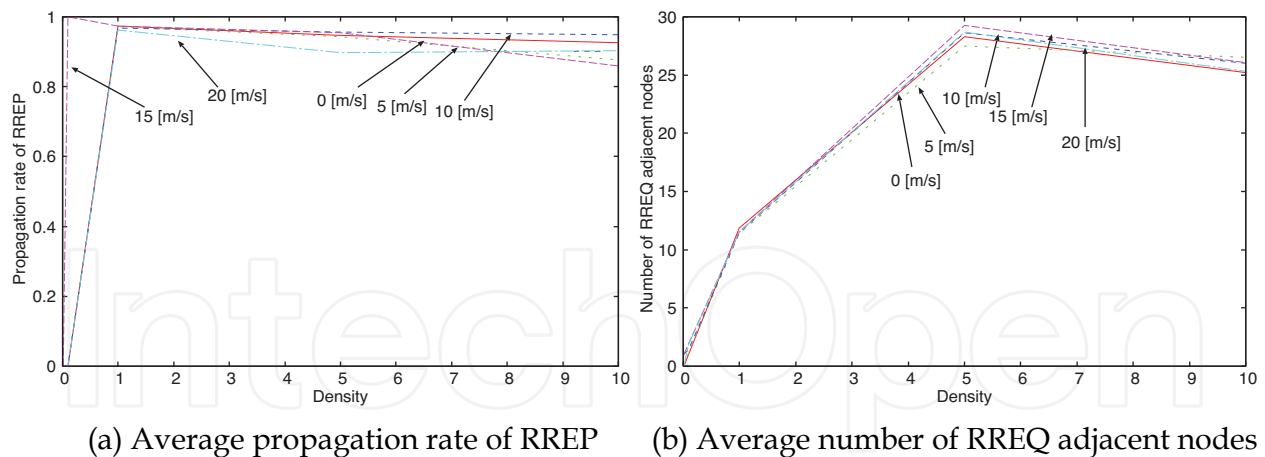(a) Average propagation rate of RREP   (b) Average number of RREQ adjacent nodes

Fig. 13. Variation of each metric under the Random Direction Mobility Model.

zero pause time. Both figures represent these plotting patterns which are independent on speed and density. Compared to Figure 14, the plotted lines of both Figure 13 (a) and (b) maintain higher values than that in Figure 14 meaning that the lossless traffics are generated and MNs have reachable adjacent MNs with high density. The Random Direction Mobility Model has an advantage to move widely in the simulation area.

(a) Average propagation rate of RREP   (b) Average number of RREQ adjacent nodes
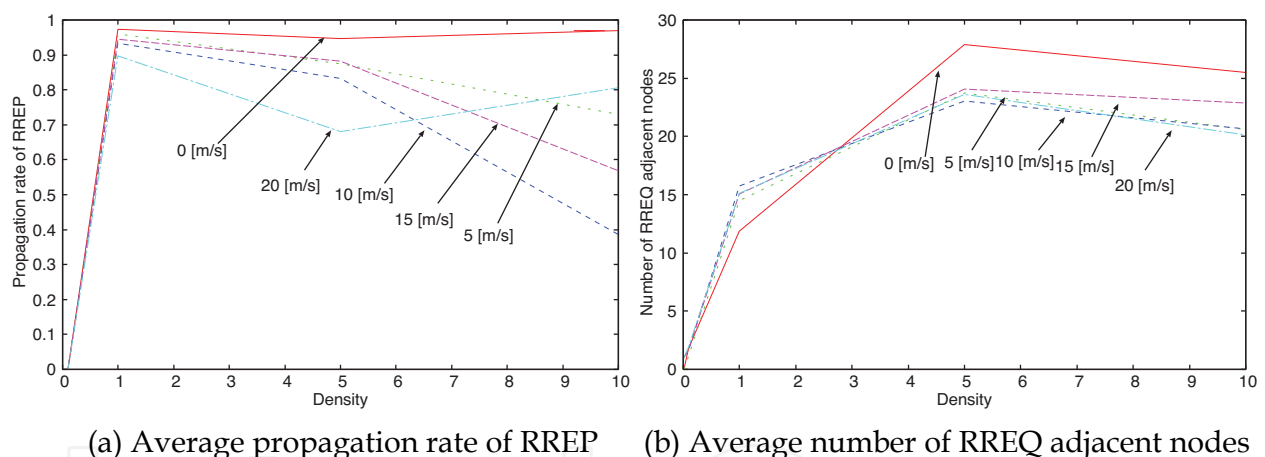
Fig. 14. Variation of each metric under the Random Waypoint Mobility Model.

Figure 14 (a) and (b) show the same metrics in Figure 13 (a) and (b) with the RandomWaypoint Mobility Model with zero pause time. This model with zero pause time causes the largest degradation of values for each speed, making the condition of the density waves fall quickly - typically in a condition where the density is greater than 5 (nodes / 100*100 meters).

6.2 Flooding features of RREQ

Figure 15 (a) and (b) respectively shows the average hop count and the elapsed time of propagation under the Random Direction Mobility Model. On the other hand, Figure 16 illustrates the same metrics under the Random Waypoint Mobility Model with zero pause time. Compared to respective hop counts in Figure 16 (a), those in Figure 15 (a) maintain higher values meaning that these MNs widely spread over the simulation area and require
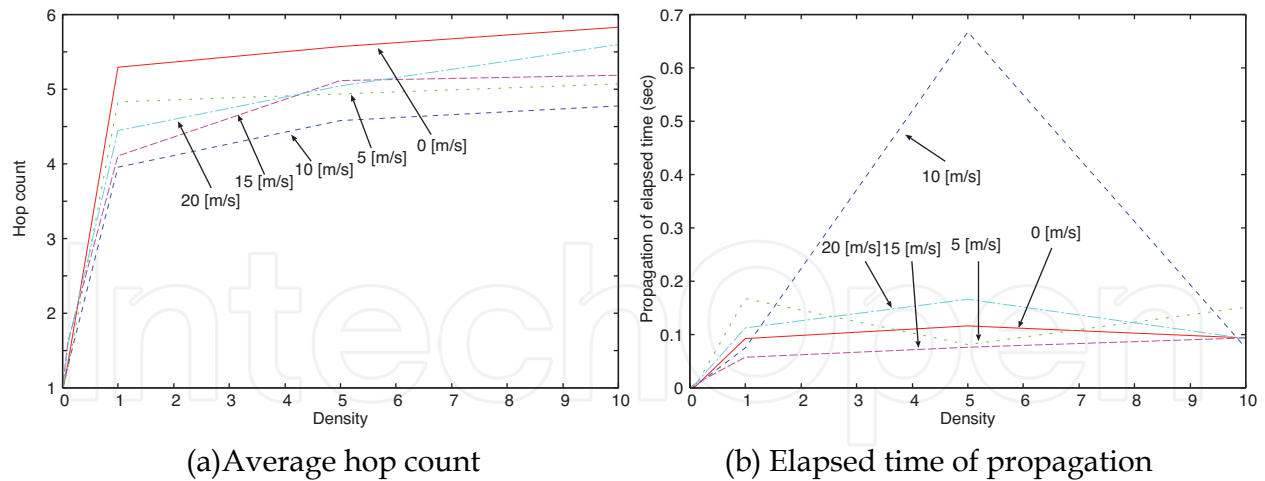
(a)Average hop count   (b) Elapsed time of propagation

Fig. 15. Flooding features under the Random Direction Mobility Model.

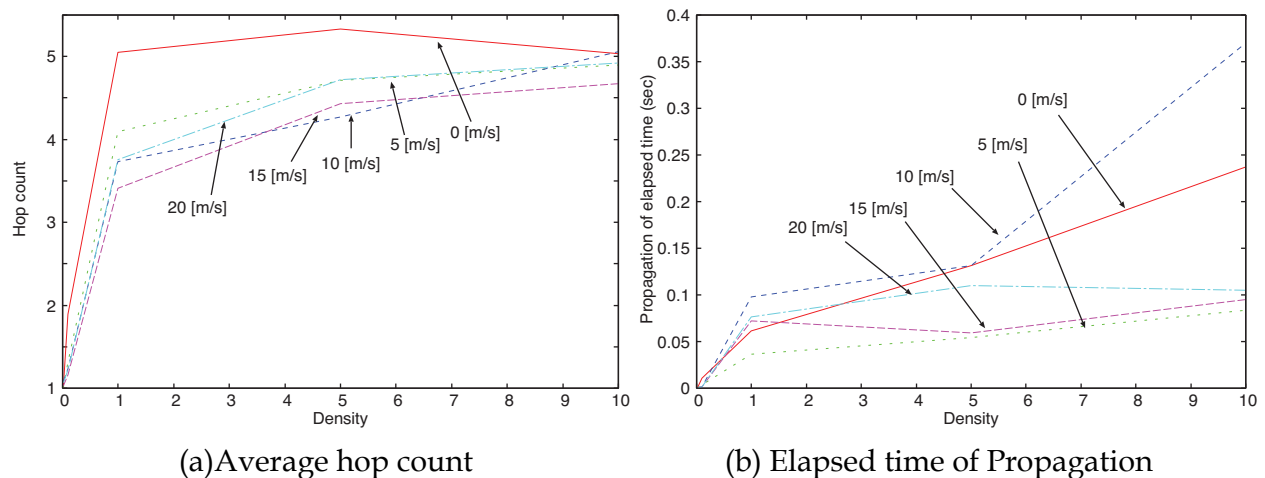(a)Average hop count   (b) Elapsed time of Propagation

Fig. 16. Flooding features under the Random Waypoint Mobility Model.

additional hops. The hop counts of MNs are smaller than those of stationary nodes indicating that the mobility efficiently causes the short hop transmission from source to destination node. The elapsed time of propagation under the specific speed with the density = 5 (nodes / 100*100 meters) takes the transmission time intensively under the Random Direction Mobility Model in Figure 15 (b). Other additional experiments confirmed that the elapsed time of propagation was sensitive and fluctuated over the middle density = 5 for some MNs with the speed = 5, 10, 15 (m/s). It means that the mobile condition with middle density is unstable for the middle speeds. Except for an irregular phenomenon like this, the elapsed times of propagation are restrained in small values meaning that the effective transmissions occur under the Random Direction Mobility Model. On the other hand, an ascending pattern appears in a dense condition under the Random Waypoint Mobility Model in Figure 16 (b). This degradation is likely to be caused by the density waves.

6.3 Summary
Our simulation results explored the following features. Firstly, the Random Direction Mobility Model provides the widely distributed position for MNs over the simulation area leading to the loss-less propagations of RREP and reachable transmissions of RREQ for both

speed and density. Secondly, flooding features of RREQ shows the degradation of the elapsed time of propagation caused by the density waves under the Random Waypoint Model.

7. Flooding features of the AODV under the different communication distances

In this section, mobile nodes are located randomly on the 1000 (m) * 1000 (m) square area to move through this area with the same speed. MNs start at 1.5 simulation seconds toward the selected direction. After reaching the destination, MNs consume the pause time to select the next direction. The pause time varies with 0 second, within 1 and 5 seconds, or within 1 and 10 seconds. The density of intermediate mobile nodes varies within 1, 5 and 10 (nodes / 100^2 meters). In addition, we examined the simulation varying the communication distance (radius) to 50, 100, 150, 200 and 250 meters.

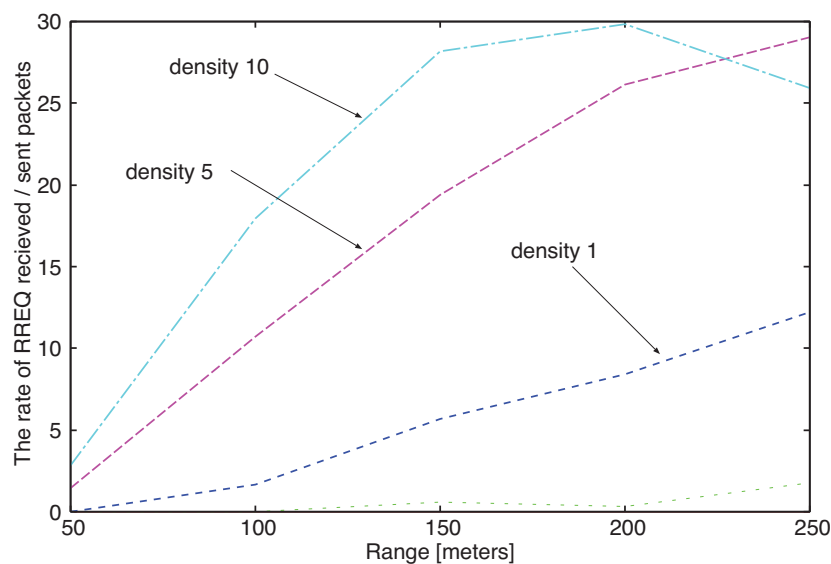### 7.1 RREQ adjacent nodes and propagation rate

Fig. 17. The average number of RREQ adjacent nodes.

Figure 17 shows the average number of RREQ adjacent node as the function of the communication distance (meter) with three different distances = 1, 5 and 10. The average number of RREQ adjacent node in the sparse condition less then density = 5 linearly increases in terms of the communication distance meaning that the communication area widely spreads with no much RREQ packets and the reachable adjacent node increases. On the other hand, the adjacent node in the dense condition over density = 10 has the peak point meaning that many RREQ packets frequently generate the packet collision causing the decrease of the adjacent node. These different ascending patterns in terms of the density value are caused by the spread of communication area. The long distance communication assists the establishment of end-to-end communication in the sparse mobile node condition, while degrading the communication performance caused by the packet collision.

The average propagation rate of RREP as the function of the communication distance is illustrated in Figure 18. Each line for different density shows the reachable area under the specific communication distance. In addition, the average propagation rate of the density =

10 decreases when the communication area exceeds 200 meters. These results indicate that the communication distance of each density has the effective range. If we control the communication distance of mobile node, the performance could be upgraded.
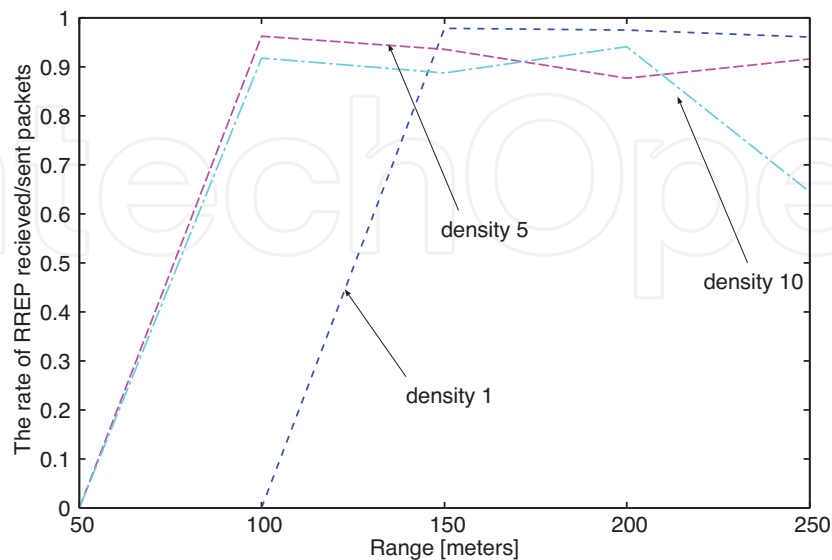

Fig. 18. The average propagation rate of RREP.

7.2 TCP throughput

Figure 19 (a) shows the TCP throughput as the function of the communication range (meter) with the three different density = 1, 5 and 10. In this stationary condition, the TCP performance with each density has the most effective value of the communication range for each other. For example, the TCP throughput with density = 5 shows the highest value under the communication range around 150 meters. The value of TCP performance could be kept highest in density under stationary condition, given the communication distances enabled to be tuned.

Figure 19 (b) shows the TCP throughput as the function of the communication range under the mobile node with the speed = 20 (m/s). Compared to the stationary condition in Figure 19 (a), Figure 19 (b) indicates that all TCP throughputs for the different density gradually
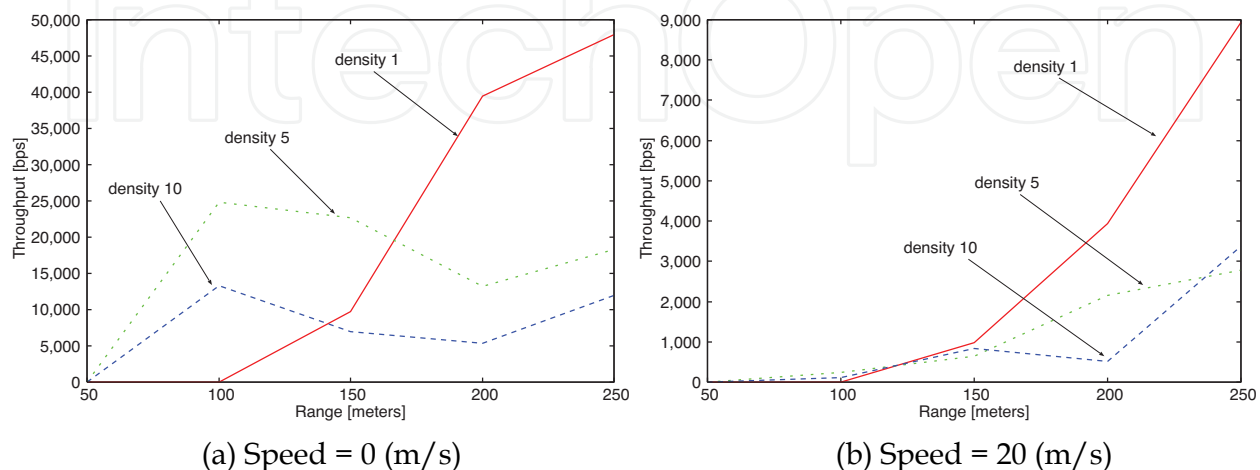
(a) Speed = 0 (m/s)   (b) Speed = 20 (m/s)

Fig. 19. TCP throughput.

increase in terms of the communication range. The results means if the communication range spread wider area leading to the expansion of the reachable area, the TCP throughput upgrades for every density. Controlling the communication range should enables us to tune maximum range to generate the high TCP performance regardless of the increase of RREQ packets and occurrence of packet collisions.

7.3 Summary

Our simulation results explored the following features. Firstly, the long distance communication assists the establishment of end-to-end communication in the sparse mobile node condition, while degrading the RREQ communication performance caused by the packet collision. Secondly, the communication distance of each density has the effective range in terms of the average propagation rate of RREP. Thirdly, tuning the communication distance keeps the TCP performance highest in the density under stationary condition. Finally, the maximum range to generate the high TCP performance should be tuned under mobile condition regardless of the increase of RREQ packets and occurrence of packet collisions.

8. Conclusion

In ad hoc mobile networks (MANET), the message exchange of the ad hoc routing protocol over the intermediate nodes is a significant factor that affects the effectiveness and performance. To focus on the performance of the routing protocols, mobility nodes are restricted to the intermediate nodes while communication nodes are restricted to two stationary end nodes in this section where the intermediate nodes operate merely as the routers for the application users. We especially focus on the AODV protocol and TCP throughput performance for stationary end nodes over the mobile intermediate nodes using the ns-2 network simulator. The Propagation properties of control packets, such as Route Request (RREQ) and Route Reply (RREP) as well as flooding properties of RREQ are extracted in our experiments.

In the comparison of different type of routing protocols, our simulation results explored two performance features. Firstly, route stability is more sensitive to the number of intermediate nodes than the speed of intermediate nodes for the AODV. Secondly, the number of RREQ packets of AODV linearly increases in terms of the number of node. In addition, we captured the following three features of TCP throughput performances for different protocols. Firstly, the TCP throughput on AODV with mobile intermediate nodes degrades about 20 % compared to stationary intermediate nodes in dense node condition, and exponentially degrades until 10 (m/sec) node speeds in a coarse node condition. Secondly, the TCP throughput on DSR degrades in accordance with the increase of node speed meaning that it is sensitive to the node speed. Thirdly, the TCP throughput on DSDV drastically degrades in the mobile environment.

In the performance of the AODV protocol, our simulation results explored following four performance features. Firstly, the high speed degrades in terms of AODV RREQ sending packets merely on the density of 10 nodes per 100 square meters. Secondly the high speed exceeding 15 m/s creates more RREP sending packets over dense node conditions. Thirdly, the number of DSR RREQ sending packets increases by 40 % compared to that of AODV.

Finally, the DSDV protocol shows the inefficiency in terms of the node speed and the dense node condition.

In the RREQ flooding features of the AODV protocol, our simulation results explored the following degradation features of RREQ flooding. Firstly, the main degradation of RREQ flooding is caused by the high density node condition and the high speed movement. Secondly, the reason of DROPs is generated by the delayed RREQ propagation on the case of RREQ flooding from the source node. Finally, the delayed start of RREQ flooding from the intermediate node generates the degradation of performance.

In the propagation features of the AODV under different mobility models, our simulation results explored the following features. Firstly, the Random Direction Mobility Model provides the widely distributed position for MNs over the simulation area leading to the loss-less propagations of RREP and reachable transmissions of RREQ for each speed and density. Secondly, flooding features of RREQ shows the degradation of the elapsed time of propagation caused by the density waves under the Random Waypoint Model.

In the flooding features of the AODV under the different communication distances, our simulation results explored the following features. Firstly, the long distance communication assists the establishment of end-to-end communication in the sparse mobile node condition, while degrading the RREQ communication performance caused by the packet collision. Secondly, the communication distance of each density has the effective range in terms of the average propagation rate of RREP. Thirdly, tuning the communication distance keeps the TCP performance highest in the density under stationary condition. Finally, the maximum range to generate the high TCP performance should be tuned under mobile condition regardless of the increase of RREQ packets and occurrence of packet collisions.

In the next step, we will propose the new mechanism to restrain the RREQ flooding in AODV protocol, and implement this mechanism in the ns-2 simulator to evaluate the effectiveness for the flooding performance.

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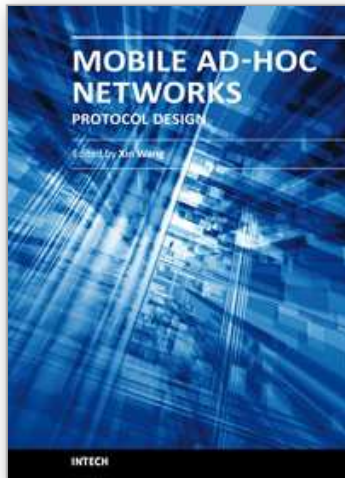
Mobile Ad-Hoc Networks: Protocol Design

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Being infrastructure-less and without central administration control, wireless ad-hoc networking is playing a more and more important role in extending the coverage of traditional wireless infrastructure (cellular networks, wireless LAN, etc). This book includes state-of-the-art techniques and solutions for wireless ad-hoc networks. It focuses on the following topics in ad-hoc networks: quality-of-service and video communication, routing protocol and cross-layer design. A few interesting problems about security and delay-tolerant networks are also discussed. This book is targeted to provide network engineers and researchers with design guidelines for large scale wireless ad hoc networks.

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