Dynamic Reverse Route for On-Demand Routing Protocol in MANET

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Abstract

Route establishment in Mobile Ad Hoc Network (MANET) is the key mechanism to a successful connection between a pair of source and destination nodes. An efficient routing protocol constructs routing path with minimal time, less routing overhead and capable of utilizing all possible link connectivity. In general, most on-demand MANET routing protocols operates over symmetrical and bidirectional routing path, which is infeasible due to the inherent heterogeneous properties of wireless devices. Simulation results show that the presence of unidirectional links on a network severely affect the performance of a routing protocol. In this paper, a robust protocol independent scheme is proposed, which enable immediate rediscovery of alternative route for a path blocked by a unidirectional link. The proposed scheme is efficient; route rediscovery is locally computed, which results in significant minimization of multiple route packets flooding. Nodes may exploit route information of immediate neighbors using the local reply broadcast technique, which then redirect the control packets around the unidirectional links, therefore maintaining the end-to-end bidirectional connection. The proposed scheme along with Ad Hoc On-demand Distance Vector (AODV) and AODV-Blacklist routing protocol is investigated over three types of mobility models. Simulation results show that the proposed scheme is extremely reliable under poor network conditions and the route connectivity can be improved by as much as 75%.

Keywords: AODV, connectivity, MANET, mobility model, on-demand, routing, unidirectional link

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1. Introduction

Routing protocols that are particularly prominent for Mobile Ad Hoc Network (MANET) can be classified into proactive, reactive and hybrid techniques [1]. Proactive method is most commonly associated with table driven routing, which depends on frequent exchange of control packet, e.g. HELLO packet, between nodes to discover the complete network topology. On the contrary, reactive routing protocols are on-demand. Consequently, routing tables are less complex, where nodes record the information of only the network segment to which they are connected. In addition, on-demand routing protocol avoids constant periodic routing updates exchange with other mobile nodes, leading to less resource consumption and fewer transmission of route management packet. Another form of routing technique is the hybrid routing protocol. It is a complex approach, which combines the best attributes of both proactive and reactive technique.

Research works [2][3], have shown that on-demand routing protocols may suffer from high routing overhead. Excessive routing overhead is generally caused by multiple round of broadcast, i.e. route discovery packets, which lead to a broadcast storm problem [4]. As a result, a large amount of network resources may be consumed. To reduce the number of redundant routing packets, Ad hoc On-demand Distance Vector (AODV) [5] routing protocol employs a controlled flooding technique called the expansion-ring. By using hop count as a metric, the technique begins to search the destination node by flooding the network with control packets assigned with a lower metric value. For every unsuccessful route discovery, the source node subsequently expands the search area by increasing the value of hop count. The process terminates if the destination is found or the expand limit, i.e. maximum hop count, is reached.

Naturally, packet flooding is essential in on-demand routing, where it facilitates route discovery, resource discovery, route management and data distribution. Nevertheless, flooding technique alone is insufficient to discover bidirectional routing paths. This is due to the fact that MANET links can be unidirectional, unfeasible to many routing protocols operation. As a result, symmetrical and bidirectional routes may fail to be formed and packet could be routed via a path that is inferior to the system performance. In addition, link connectivity is also severely influenced by the external noise source, affecting the node's signal strength. Consequently, links become asymmetric in nature and communication between source and destination pairs may follow paths which are in fact unidirectional [6].

Many existing routing protocols are indeed restricted in that equal bidirectional links and symmetrical paths are implicit in their operation. Routing operation over unidirectional link increases end-to-end delay and the resulting performance advantage may be nearly non-existence [7][8]. There exist two main approaches to handle routing operation with unidirectional link. The first theory explicitly avoids and eliminates routing packet through such link, where all packets must be routed solely using bidirectional link. The benefit of this approach is that it supports link-layer protocol operation, where medium access reservation particularly depends on the bidirectional links availability between nodes. For instance, in order for IEEE 802.11 of Media Access Control (MAC) [9] to alleviate the classical hidden node problem, a request-to-send/clear-to-send (RTS/CTS) exchange between sender and receiver nodes is essential. This mechanism will fail to function if the path constructed by the routing layer passes through unidirectional links. Nevertheless, the RTS/CTS mechanism has also been shown to be less effective in a network that profoundly relies on the message relaying technique [10] such as MANET. For that reason, in the later approach, which utilizes unidirectional link to improve routing performance, the effect of RTS/CTS is simply not considered. In such approach, nodes are able to exploit full network connectivity and build the shortest route from the source to destination node. Previous researchers [2][7][11] have shown that, by using unidirectional links in addition to the existing bidirectional links can significantly improve MANET's routing performance.

The paper introduces a comprehensive analysis of routing protocol with several mobility models. Indeed, many simulations works commonly employ the Random Waypoint (RWP) [12] mobility model for nodes movement. However, several studies [13][14] have shown the harmful impact of random stochastic mobility pattern on simulation process. As a result, the simulation output of a routing protocol using such model may be inaccurate and insufficient for the analysis of routing performance. In this elementary model, each node moves unnaturally under a wide range of mobility patterns. In addition, the nodal movement is independent of the previous speed and direction, i.e. memory-less. As such, a node travelling in a straight line may instantaneously switch direction during its course, i.e. sharp turns and sudden stops. The model is considered unrealistic and may generate an extremely hostile topology condition. Nodes can move in a zigzag fashion at constant speed, causing severe performance degradation of the routing protocol.

Generally, every mobility model possesses four intrinsic properties, resulting in the variation of network topology generated. First, the speed and space distribution of nodes in the network can directly influences the path availability among nodes. The research studies [13][14] have indicated that the speed and spatial distribution of RWP mobility model is not uniform. Second, a mobility model is strongly characterized by the path duration between nodes. Nodes in proximity of each other, e.g. in a group mobility model, produce a higher number of available paths with fewer chances of disconnection over a short period of time. Such attributes significantly affect the network protocol performance, which must be taken into consideration when performing the simulation. Third is the neighbor node density, which is an extremely important parameter for the measurement of the proposed scheme in this work. Finally, a mobility model is also characterized by the number of neighbor nodes, which affects the degree distribution of the node in a particular area. Motivated by such points, the performances of routing protocols are thoroughly investigated against three mobility models, Gauss Markov (GM) [15], Reference Point Group Mobility (RPGM) [16] and Manhattan [17]. Each model possesses unique characteristics, which is essentially beneficial for the simulation analysis as it can provide valuable insights into the robustness of a routing protocol.

2. Related Work

A wide variety of routing schemes [18][19][20][21][22] have been proposed for MANET. However, many of the schemes simply disregard the presence of unidirectional links, which can severely affect the routing path construction. Consequently, the routing implementation often exhibits connectivity issues, leading to a sub-optimal network performance. Nevertheless, some schemes have been proposed [23][24][25][2][7] to counter the inherently unreliable effects of unidirectional links. **Table 1** presents the comparison of schemes that include various methods to deal with unidirectional link on the network as previously mentioned.

Table 1. Summary of routing schemes

	EUDA [23]	Flooding [24]	LBSR [25]	SRL [2]	RPS [7]
Base protocol	AODV	AODV	DSR	AODV	AODV
Multicast support	No	No	No	No	No
Routing path selection	Source	Source	Source	Destination	Source
Unidirectional link handling	Avoidance	Avoidance	Utilizing	Utilizing	Avoida nce
Routing Metric	Hop count	Hop count	Hop count	Hop count	Hop count
Multipath routes	No	No	Yes	No	Yes
Route discoveries	Single	Two-way	Single (back to source)	Single	Single
Asymmetrical route	No	No	Yes	Yes	No
Detection phase	Forward path	Reverse path	Forward and reverse path	Forward path	Reverse path
Protocol independent technique	No	No	No	Yes	No
Power routing control	No	No	No	No	No
Motivation and the impact on routing performance	Immediate detection of unidirectional link during route discovery	Increases routing overhead compared to base protocol	Multiple routes detection. Improves reliability	Discovers route using the reverse of Bellman Ford algorithm	Rely on multipat h for reverse route constru ction

The presence of unidirectional links in MANET has been shown [26] to severely affect the link connectivity between nodes. As a result, the process to construct a routing path is inefficient, causing data packets to be transmitted via a path that has a higher routing overhead and lower packet delivery ratio. An experimental study [27] has indicated that the occurrences of unidirectional link are quite common. In the study, a large number of nodes are uniformly distributed in a grid-like fashion with each node is set with identical radio parameters. The study shows that even in such organized node settings, the number of unidirectional link can constitutes up to 15% of the total link in the network. Therefore, in a sparsely connected network, i.e. low node density, the number of such link may be substantially increased, which can severely affect the routing protocol's performance.

In light of this, the proposed scheme is designed with the main purposes are to minimize the communication overhead and to increase the chances of creating routing path in a network with low node density. The scheme is also protocol independent, which is feasible to be implemented on other on-demand routing protocols that share similar properties with the AODV routing protocol. The proposed scheme is called Dynamic Reverse Route (DRR) and it offers a simple approach to protect the propagation of routing packets, i.e. control packets. Ideally, the DRR scheme does not incur additional overhead when all links on the network are bidirectional.

3. On-Demand Routing Protocol Operation

Most on-demand routing protocol depends on the bidirectional link availability between nodes.

The two-way communication over symmetrical link ensures that the routing protocols are able to correctly exchange control packets to establish and maintain the routing path. In the following section, the AODV routing protocol operation is presented, followed by the discussion of DRR.

3.1 Route Discovery and Bidirectional Link

To form a communication path, the source node first seeks to find the destination node address from its routing table. If the address can be determined, data is then immediately sent; otherwise the source node initiates a new route discovery by flooding the route request (RREQ) packet. A maximum of two additional route discovery attempts is allowed upon the failure of the first, after which the source node remains silent for a time set by the MAX_REQ_TIMEOUT as shown in **Table 2**. The process is then repeated until the route is finally established.

Table 2. Configuration Parameters

Parameter Name	Value
RCAST_WAIT_TIME	1.5 sec
HELLO interval	1 sec
NODE_TRAVERSAL_TIME	0.03 sec
RREQ_RETRIES	3
MAX_RREQ_TIMEOUT	10 sec
RREP_WAIT_TIME	1 sec
NETWORK_DIAMETER	30
ACK_WAIT_TIME	0.5 sec

Each node in AODV scheme constantly seeks to find for the fresh route advertised by the neighbor nodes. To differentiate between the current and previous route discovery phase, the RREQ packet includes the sequence number along with the source node ID, hop-count towards the source node, packet lifetime and packet time-stamp. A fresh route is defined as a RREQ packet containing the highest sequence number, followed by the lowest hop count. To identify a fresh route, a node compares the sequence number included in the RREQ packet with the sequence number recorded in the routing table. If the current value within the RREQ packet is higher, the route is considered new and the current entry in the routing table is replaced by the information from the RREQ packet. However, if the RREQ's sequence number is lower, the packet is immediately discarded. A packet with equivalent sequence number with the routing table entry is subsequently compared for the lowest hop count, which is then recorded in the routing table. Packets with higher hop count are ignored for routing path selection. Based on such process, each node is able to remove duplicates and identify a fresh packet to be recorded in the routing table. Therefore, irrespective of the order of packet received, a route with the lowest hop count can be guaranteed to be established. The algorithm shown by **Fig. 1** is the summary of the route freshness inspection in the system.

The algorithm ensures the AODV routing protocol to compute the shortest routing path with using only bidirectional links. Nevertheless, constructing routes exclusively through bidirectional links may not always be possible, since link condition frequently varies. As such, if the system is unable to find at least a single bidirectional link between the source and destination node pair, the routing protocol may fail to function.

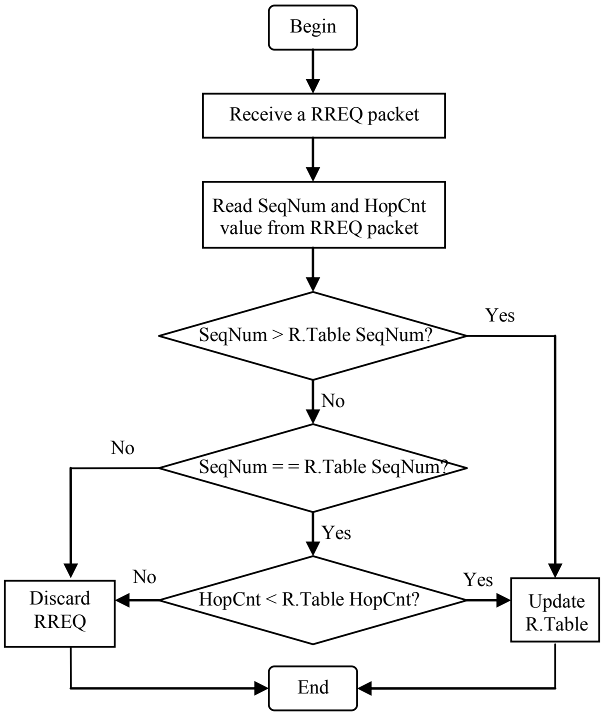


Fig. 1. AODV RREQ packet freshness inspection procedure

3.2 Routing with Unidirectional Link

On a network with high presence of unidirectional links, AODV routing path selection may be detrimental to the network performance. For example, a network with low node density and a high node separation distance may increase the chances of forming routes through unidirectional links. Consequently, RREP packet is prevented from reaching the source node using the reverse of the forward route created by RREQ packet. Refer to **Fig. 2**, where node A is the source and node G is the destination. The RREQ packet from A is assumed to reach G through the path A-B-E-G. The link (B-E) is unidirectional, pointing to node E. Assuming that nodes are moving at a relatively low speed, route discovery will fail to constructs a reverse route from G to A. Node E is able to receive packets from node B, but not vice versa, even though E has established a reverse route with B as the next hop candidate to reach A. Further attempts of RREQ broadcast by the source node produces a similar result, hence increasing the overall routing overhead. On the contrary, the AODV with blacklist mechanism can rapidly detect and avoid such link. The scheme reads every RREP received, i.e. originated or forwarded by a node, and responded by returning a network layer acknowledgement (ACK) packet. As shown in **Fig. 2**, as soon as node E transmits a RREP packet to the next hop node B, it expects an immediate reply of ACK packet. In the event that node E fails to receive the ACK packet, it identifies the link pointing to B as unidirectional and set node B in the blacklist database. All current routing entries to node B are then removed and the system waits for another round of RREQ discovery. Subsequently, node E discards every RREQ packet forwarded by node B. As a result, a new forward route can be constructed via a different path, e.g. A-C-F-G.

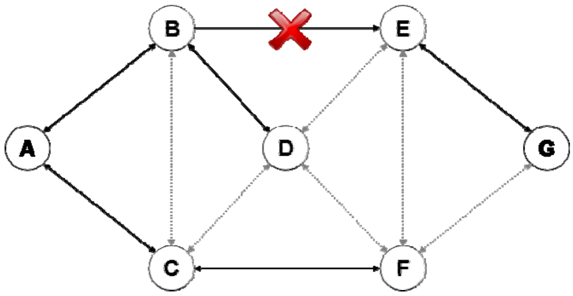


Fig. 2. Unidirectional link facing to node E from B.

4. The Proposed Scheme

The proposed scheme is based on AODV but the core mechanism is protocol independent and as such, it may be employed by other routing protocol that shares similar properties with AODV. The proposed scheme is called Dynamic Reverse Route (DRR).

4.1 Dynamic Reverse Route (DRR)

As previously discussed, the current AODV specification of AODV uses a technique known by 'blacklist', where links detected as unidirectional are avoided in the routing path. The DRR scheme employs a different approach. Instead of avoiding, the scheme utilizes such links to advantage in route construction. In the event of a failure to receive an ACK packet, the identified unidirectional link is not blacklisted. However, alternative paths are immediately computed, which may have access path to the source node. In order to find the potential routes, nodes that are affected by the unidirectional link store the information of the current RREP packet, and promptly invoked a one-hop local reply broadcast packet. The mechanism takes advantage from the unused route entries recorded by intermediate nodes after the route discovery phase. **Table 3** represent the summary of routing entries for the network shown in **Fig. 2**, recorded just after the first RREQ discovery. Note that the duplicate routes are shown as the dotted line, where RREQ packet is subsequently dropped after being cached. For example, node D receives two copies of RREQ from node B and C respectively. Both packets are identical in sequence number and hop count and as such, only the first copy received is stored in the routing table, i.e. packet received from node B.

Table 3. Nodes Routing Entry after Route Discovery

Node	Destination	Next Hop	Hop Count
A	-	-	-
B	A	A	1
C	A	A	1
D	A	B	2
E	A	B	2
F	A	C	2
G	A	E	3

Assume the broadcast RREQ packets have established a forward route through link A-B-E-G. This is, perhaps, because the destination node G has received the first copy of RREQ through such link via node E. In addition to the active nodes along the routing path, other nodes such as C, D and F also record the RREQ entries pointing to the source node. Later, the nodes may be able to provide alternative routes to the RREP packet blocked by a unidirectional links. After receiving the RREQ packet, node G responds to node E by unicasts a RREP packet with RREP_NO_FLAG bit set. Additionally, prior to every RREP unicast transmission, each node stores a copy of the packet along with its contents. The information can be used by the local reply broadcast transmission if the preceding RREP forwarding fails. Node E then compares the content of RREP packet against the routing table shown by **Table 3**, where node B is identified as the potential next-hop node towards node A. Subsequently, node E forwards the RREP packet to node B and in return expects to receive an ACK packet. Node E waits for a duration of time set by ACK_WAIT_TIME, which is reset after the receipt of ACK packet. On the other hand, if node E fails to receive the ACK packet, it results in B being cached as an unreachable node. As such, node E immediately invokes the one-hop local reply broadcast mechanism and a copy of the previously stored RREP packet is broadcast to the adjacent neighbors with TTL = 1.

Node D, F, and G receives the broadcast RREP because they are within node's E radio transmitting power (P_t). Node G drops the packet because it is the originator, whereas both node D and F forward them to their next hop node. To indicate that the RREP packet has been salvaged by the local reply mechanism, each node along the RREP propagation path includes in its cache a unique combination list of the source address, destination address and sequence number <*Src ID, Dest ID, seq_num*>. Therefore, any RREP packet received by the node that matches the combination is dropped and prevented from being propagated further to reduce congestion.

Based on the DRR approach, the routing path is guaranteed to be constructed on the first route discovery attempt only if there are sufficient alternative routes available in the network. Nevertheless, a node in MANET may moves away from each other after forming the routing path. Such situation often causes link breakages, which are typically handled by the AODV route recovery mechanism. As such, if a link breakage occurs during an active data packet transmission, the recovery mechanism chooses either to repair the routing path locally or to propagate the error message upstream to the source node. The scheme specifies that if the broken link is closer to destination, a local repair is invoked. Otherwise, the breakage is notified to the source node, which then rebroadcast the RREQ packet. In a worst case scenario, where a forward route could not be established by the first route discovery, multiple RREQ broadcast will need to be made by the source node until the maximum RREQ_RETRIES shown in **Table 2** is reached. In addition, the RREP packet from destination node must reversely follow, as much as possible, the forward route created, and diverted to the alternative route only when the primary forward path is blocked.

4.2 Network Layer Feedback (Acknowledgement)

The introduction of ACK packet in the DRR scheme causes a slight increase in terms of the overall routing overhead. Therefore, a countermeasure has been implemented in the scheme, which is necessary to minimize such effect. The ACK packet exchange can be significantly reduced if nodes are correctly set to respond to different type of RREP packet. First, the ACK packet can only be returned by the node for a RREP packet with the flag bit set to RREP_NO_FLAG. Secondly, nodes will not return an ACK packet when the flag bit is set to one-hop-broadcast (OHR). As a result, control packet exchange can be reduced, leading to a more efficient use of the bandwidth.

In addition to the ACK message exchange reduction, the DRR scheme can also substantially reduce the number of RREQ in the system. The analysis in [28] shows that the number of RREQ generated by source node account for the majority of control packet in on-demand based routing protocol. For example, the AODV-Blacklist method requires a multiple RREQ flooding in order to re-establish a broken routing path due to unidirectional links. By using the DRR scheme that locally restores the routing path, such problem can be effectively avoided. Therefore, a failure of ACK reception by intermediate node will not cause subsequent RREQ flooding by the source node.

4.3 Reverse Path and Local Reply Broadcast

As previously mentioned, when the propagation of RREP packet is blocked by a unidirectional link, DRR allows a node to rediscover alternative reverse paths. As a result, multiple copies of RREP packet may be received by the source node on several different paths. Such problem can be efficiently avoided by comparing the current and previous RREP broadcast packet. For instance, after the local broadcast reply by node E, the recovered RREP packet will propagates via two reverse paths towards node A, e.g. E-D-B-A and E-F-C-A. Assuming the first RREP packet arrives from path E-D-B-A, node A then immediately records the packet information, i.e. <*node A, Node G, seq_num*>. Later, when the second RREP packet arrives from path E-F-C-A, the packet is discarded because the content of the packet matches to the stored information. In addition, the recorded RREP packet is cached for only a short period of time set by RCAST_WAIT_TIME shown in **Table 2**. The value must not exceed the roundtrip time of RREQ-RREP packet, which is the time difference between sending the RREQ and receiving the RREP at the source node. An estimation of the roundtrip can be computed by Equation (1).

$$3 * \textit{Network Diameter} * \textit{Node Traversal Time} \tag{1}$$

The *Network Diameter* is set to 30, in accordance to the maximum hop allowed in AODV. On the other hand, the *Node Traversal Time* is set to 0.03 seconds, based on the estimated time for a packet to traverse one-hop, which includes the queue, transmission, propagation and all other delays.

The reverse link created by the local reply broadcast enables the source node to reach the destination node via an alternative reverse path. However, using such path, data packet can be transmitted only from the source node to the destination node, but not vice versa. This may not be an issue for some applications, which typically rely on fast data transfer and best effort delivery with using user datagram protocol (UDP). There is typically a trade-off between reliability (two-way handshake) and speed. For instance, sending updates on stock markets, news, and bulletins to customers requires fast data dissemination but may compensate for unreliable communication.

Nonetheless, a two-way communication may be enabled with the proposed scheme. Upon unidirectional link detection, an additional flag i.e. ALT, is included to the RREP packet advertised by the local broadcast mechanism. The ALT is set to indicate that the current RREP packet has been recovered by the node along the reverse path. Therefore, when the source node receives a RREP packet with the flag set to ALT, it reconstructs the forward path by propagating a REPAIR packet. To reduce the routing overhead, the packet is unicast to downstream nodes towards the destination along the reverse path, where details such as hop count and sequence number at each node's routing table are updated. Note that as soon as the REPAIR packet is unicast, the source node can start sending the data packets.

5. Simulation Setup

The DRR scheme is compared to the AODV and AODV-Blacklist routing protocol, which employs unidirectional link avoidance technique using a blacklist database. The performance of each routing protocol is investigated in terms of several performances metric. Every network scenarios is simulated using NS-2.33 [29], a discrete event simulation tool that allows for experiment to be replicated using controlled parameters. Most of the simulation settings are similar to the study [28], where nodes' P_t is randomly varied with two levels. The first P_t value is set to 13dBm that typically provide an outdoor radio transmitting range of approximately 250m. The second P_t is reduced to 50%, which correspond to a radio range of 125m. As a result of different level of P_t assignment, most adjacent nodes on the network are expected to produce a significant number a unidirectional link throughout the simulation.

Table 4 and **Table 5** shows the parameters used in the simulation experiment. The number of source-destination pair is set to 6, to simulate a moderately congested network. P_t values are fixed to 13dBm and 7dBm in the first part of the experiment, which then is varied between from 0dBm on up to 20dBm in the second part of the experiment. Also, the signal propagation model is set to two-ray ground model, without considering the effect of shadowing and fading. The MAC parameters are based on Cisco Aironet 350 Client Series Data Sheet [30], where the bit rate is set to 11Mb/s operating at 2.4GHz frequency. Although nodes are set to transmit at low data rate, i.e. 4 packets/s, such a rate is sufficient to monitor the impact of packet loss as a result of unidirectional link on the network. Indeed, increasing the frequency of packet transmission can substantially increases the traffic load, which may cause the routing performance to deteriorate. This is true if other parameters, e.g. source-destination pair and seed numbers, remain identical. Nonetheless, changing the packet ratio to a higher value, e.g. 20 m/s, leads to the increase in terms of simulation output time. However, the effect of such changes to the result analysis is minimal and may not provide any significant benefits to performance evaluation.

Table 4. Simulation Parameters

Parameter	VALUE
Simulation network area	1000 x 1000 m^2
Number of nodes	50 and 150
Simulation time	250 s
Source-destination pair	6
Pause time	0 s
Maximum node speed	10 m/s
Transmission power, (P_t)	Between 0dBm and 20dBm
Radio frequency	2.422 GHz
Transmission speed (*bit rate*)	11 Mb/s
Receive threshold (*RXThresh*)	-91 dBm
Carrier sense threshold (*CSThresh*)	-104 dBm
Capture threshold (*CPThresh*)	10dB
Routing protocol	AODV, AODV-Blacklist, DRR
Data traffic	Constant Bit Rate, UDP
Data packet size	512 bytes
Data packet rate	4 packets/s

Table 5. Mobility Models Configuration Parameters

Parameter	GAUSS MARKOV[15]	RPGM[16]	MANHATTAN[17]
Number of nodes	50	50	50
Speed update frequency	2.5 s	n.a.	n.a.
Angle std deviation	45^o	n.a.	n.a.
Speed std deviation	1.5 m/s	n.a.	n.a.
Group deviation	n.a	2	n.a
Number of blocks (x,y)	n.a	n.a	(5, 5)
Pause time	0 s	0 s	0 s
Number of groups	n.a.	10 groups	n.a
Max. node distance from group leader	n.a.	100 m	n.a
Cut off time	0-1000 s	0-1000 s	0-1000 s

Network topologies are generated using BonnMotion [31] tool. The first part of the experiment is simulated using 50 scenarios, which corresponds to the result of packet delivery ratio (PDR), normalized routing load (NRL), average route length (ARL), and average delay (AD). On the second part of the experiment, which compute the probability of route connectivity (P_{rc}), a total of 500 unique scenarios are generated. The same set of scenarios is then repeated for every scheme in each mobility model. In other words, each point plotted on the graph corresponds to an average of 500 experiment repetition. Due to the extensive processing time, we limit the number of results generated from the experiment. The nodes are restricted to a maximum speed of only 10 m/s, tested with different ratio of unidirectional links identical to the research study [28].

6. Routing Performance Analysis

The DRR scheme is compared against AODV and AODV-Blacklist in terms four performance metrics, which is packet delivery ratio [4], normalized routing load [4], average route length [4], average delay [4] and probability of route connectivity [28].

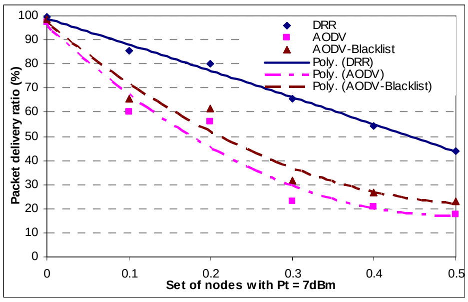
6.1 Packet Delivery Ratio

First, the routing protocol’s PDR is quantified based on the average ratio of accumulated data packets delivered to destinations compared to those generated by the data sources.

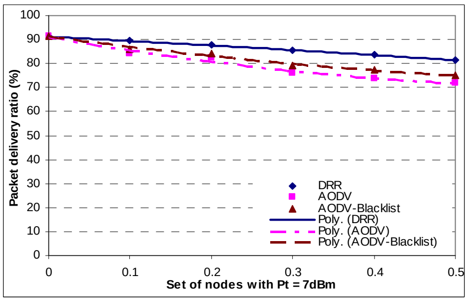
Routing protocols analyzed with GM and Manhattan mobility model show a significant PDR deterioration with respect to the increased number of unidirectional link. This is consistent with the analysis presented in the research work [28], which shows that the radio settings in the simulation setup has correctly produce the appropriate number of unidirectional links in the network. As the ratio of nodes with low power setting, i.e. radio power of 7dBm, increases, the average number of RREQ packet sent by the source node substantially increases. Such an effect is a result of unidirectional link presence, which causes the RREP packet propagation to fail via the reverse path. Consequently, the source node may have to frequently rebroadcast the RREQ to find a new routing path. A higher routing overhead is incurred, which severely affect the system’s PDR. As shown is the subsequent simulation results, the routing protocol’s PDR performance is generally the reverse of the NRL.

Based on the results for set 0.5, AODV's PDR drops as much as 82% when set to GM model and 88% with the Manhattan model. On the contrary, the DRR scheme achieves a much better performance compared to the AODV and AODV-Blacklist scheme. **Fig. 3(a)** shows that the AODV-Blacklist improves PDR by only 40% compared to 200% with using the DRR scheme. In general, the DRR scheme has shown high level of resilience to unidirectional links presence, where it constantly outperform other competing protocols analyzed with each mobility model.

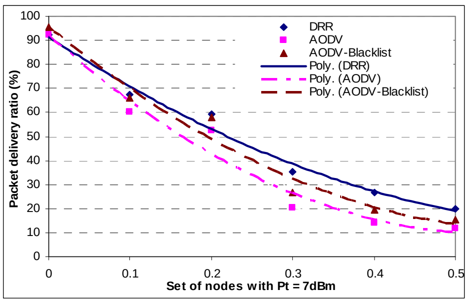
As expected, the resultant PDR of RPGM mobility model in **Fig. 3(b)** shows a significant dissimilarity compared to the GM and Manhattan mobility model. Nodes in RPGM mobility model are substantially affected by the group leader assignment, where nodes' movements are restricted to a distance of only 100m away from the group leader, as shown in **Table 4**. Consequently, the proximity of nodes leads to a network with fewer number of unidirectional link, increasing the PDR. On the other hand, the distribution of nodes and their movement in the Manhattan mobility model produces the highest number of unidirectional links compared to other mobility models. As such, the PDR are severely affected and this is shown by **Fig. 3(c)**.



(a) GM



(b) RPGM



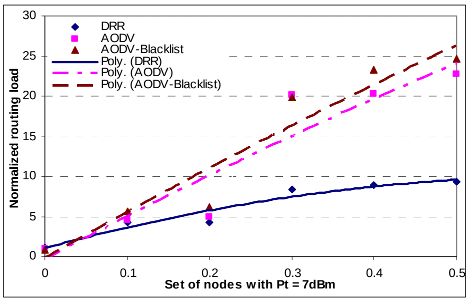
(c) Manhattan

Fig. 3. Packet Delivery Ratio

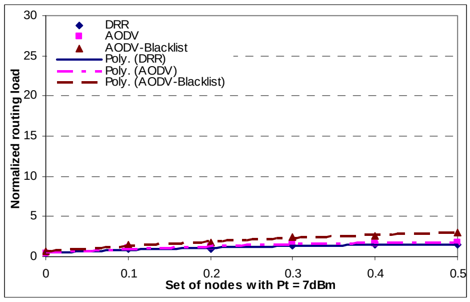
6.2 Normalized Routing Load

The NRL performance metric is computed based on the number of routing packets sent and forwarded by each node over the entire simulation time to the number of data packets received by the destination nodes. Essentially, a NRL of less than 1 indicates an efficient network, where the number of data packets received is higher than the number of routing packets generated for that particular connection. Nevertheless, the NRL value can be affected by many factors such as the frequency of data packet sent and the number of nodes participating in the routing packet exchange. Since the computation of NRL in this experiment is based on a large number of nodes, i.e., 50 nodes, this explains the reason for the extremely high value of NRL in every simulation outputs.

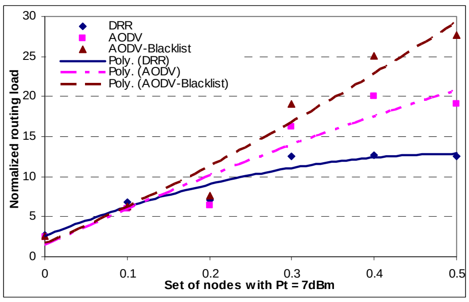
Fig. 4(a), Fig. 4(b) and Fig. 4(c) respectively show the NRL for GM, RPGM and Manhattan mobility model. Nevertheless, the NRL incur by AODV and AODV-Blacklist is comparable to the DRR scheme, shown by **Fig. 4(b)**. A significant difference is observed in the NRL performance is when the routing protocols are evaluated using GM and Manhattan mobility model. Although the AODV-Blacklist scheme is able to detect and avoids unidirectional links, route construction may not be as efficient as the DRR scheme. Further analysis on AODV-Blacklist simulation output indicates that the system generates an excessive number of routing packets, a consequence of multiple RREQ flooding by the source node. For example, **Fig. 4(c)** shows that the number of data packets received by the AODV-Blacklist is similar to the DRR scheme, i.e. for set ≤ 0.2. However, when more links become unidirectional, i.e. set > 0.2, the AODV-Blacklist's routing overhead significantly increases, resulting in a higher value of NRL.



(a) GM



(b) RPGM



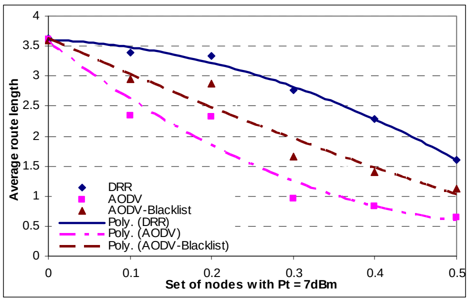
(c) Manhattan

Fig. 4. Normalized Routing Load

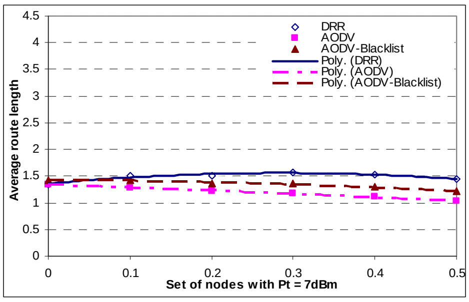
6.3 Average Route Length

Fig. 5 shows the ARL computed by each routing protocol. The ARL is quantified by the total number of hops along each routing path, averaged over the total number of routing path established throughout the simulation. In every simulation output, shown by **Fig. 5(a)**, **Fig. 5(b)** and **Fig. 5(c)**, the AODV routing protocol consistently computes the shortest path between source and destination pair compared to the DRR and AODV-Blacklist scheme. This is due to the fact that AODV uses hop count as the metric and therefore, does not allow the path to be constructed over a longer alternative link, resulting in a shorter routing path.

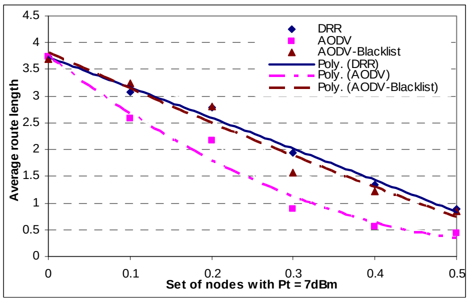
The DRR incurs the highest ARL compared to the other competing protocols. For example, in **Fig. 5(c)**, the ARL respectively increases by as much as 1.7 and 1.1 hops against the AODV and AODV-Blacklist scheme. The increase is a due to the local reply broadcast technique, which rediscovers a longer alternative path around the unidirectional links. Nevertheless, at set 0, the DRR scheme is comparable to AODV, and AODV-Blacklist. At this point, the number of unidirectional link on the network is at the lowest and therefore, the DRR scheme performs relatively similar to the other competing protocols.



(a). GM



(b). RPGM



(c). Manhattan

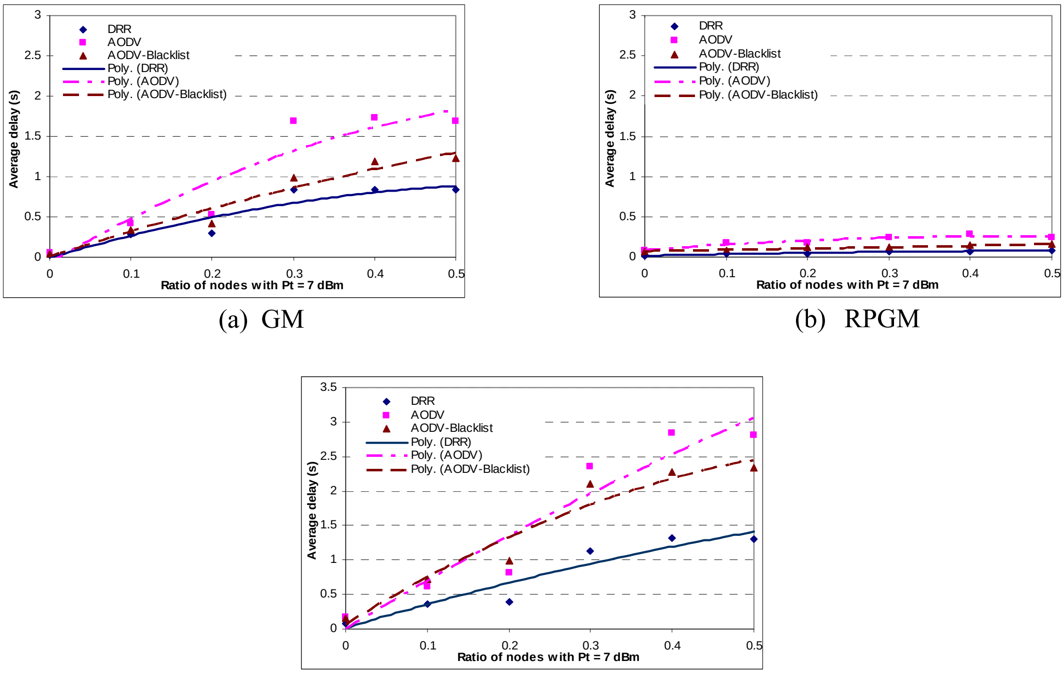
Fig. 5. Average Route Length

6.4 Average Delay

Fig. 6 shows the effect of unidirectional link on the average end-to-end delay. Such performance metric is quantified as the total time for every packet to propagate from source to destination averaged over the total number of packets. The computed value includes the delay at each node such as packet queuing, propagation and transmission.

The DRR and AODV-Blacklist show significant decrease in the average delay compared to AODV in GM mobility model, as shown in **Fig. 6(a)**. The basic AODV scheme is not able to identify links that are unidirectional. As a consequence, the system waits for RREP packet timeout and the RREQ packet is rebroadcast by the source node. Subsequently, the RREQ packet may travel through the similar route as previously detected, i.e. unidirectional. In contrast, both DRR and AODV-Blacklist prevents such link from being used for packet forwarding. Based on the network layer ACK, a forward route can be rapidly detected as unidirectional and temporarily avoided for future routing path computation. **Fig. 6(b)** shows the average delay performance of all competing protocols in GM mobility model. The result is expected since nodes are in proximity, causing fewer link breaks and unidirectional link formation. As a result, schemes in such mobility model relatively have higher PDR and lower delay.

Although the DRR scheme may potentially finds alternative route through a longer path, the delay incurred in the routing path construction is significantly reduced. The amount of time for a particular node to successfully complete a data transmission is substantially lower compared to when using the AODV and AODV-Blacklist routing protocols. In such schemes, delay caused by route rediscovery by way of RREQ broadcast may significantly dominate the total delay. If a link fails as a result of unidirectional link or nodes movement, the AODV and AODV-Blacklist scheme need to reconstruct the routing path. As such, the average delay of AODV and the Blacklist scheme may remain at a level consistently higher than the proposed scheme throughout the entire experiment. This is expected since both schemes constrain routing by using only bidirectional links. In contrast, the proposed scheme takes a different approach; it utilizes the unidirectional links for route computation by compromising a slightly higher hop count; therefore, an improved overall routing performance can be achieved. The average delay incurred in Manhattan mobility model is slightly higher compared to GM, shown in **Fig. 6(c)**. For instance, at the ratio of nodes of 0.5, the DRR scheme incurs a delay of 1.4 sec. That is an increase of 55% compared to the GM mobility model at the same nodes ratio.



(a) GM

(b) RPGM

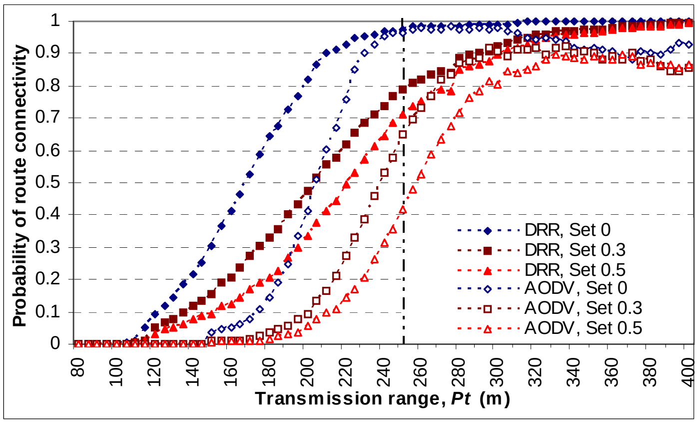
(c) Manhattan

Fig. 6. Average Delay

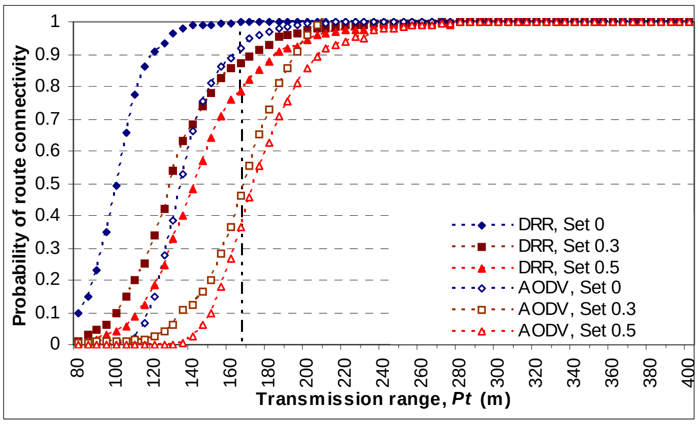
6.5 Probability of Route Connectivity

Fig. 7(a) and **Fig. 7(b)** shows the simulation output of P_{rc} performances metric. In this analysis, the DRR scheme is compared against only the AODV routing protocol with using the GM mobility model. The two schemes is selected to demonstrate two extreme cases of routing protocol operation with unidirectional link; first, a routing operation that avoids unidirectional link and solely depends on bidirectional link availability, i.e. AODV, and secondly, a routing operation that is able to detect unidirectional link and partly used the link for route construction, i.e. DRR. The number of nodes is increased from 50 to 150 to observe the impact of nodes density on the P_{rc}. As shown by **Fig. 7**, the DRR scheme is able to offer a higher success rate of routing path construction compared to the AODV routing protocol. Additionally, when the node density is increased from 0.00005 to 0.00015 (nodes/m^2), both schemes show an improved performance. This is expected since nodes now have more adjacent neighbors, resulting in higher link connectivity. This is shown by the significant shift of P_{rc} towards a lower P_t value, indicating improved connectivity.

Based on the results, the DRR scheme shows a substantial advantage over AODV routing protocol at every P_t range. This indicates that the scheme's mechanism is able to efficiently detect and recover the lost RREP packet during route construction. For example, as shown by the reference line in **Fig. 7(a)** intersecting set 0.5, which denotes a high presence of unidirectional link, the DRR scheme is able to achieve as much as 70% success in route construction compared to only 40% by AODV. In a network with a higher node density shown by **Fig. 7(b)**, the DRR scheme offers 100% improvement over the AODV routing protocol that relies only on bidirectional link.



(a) Node density - (50 nodes/1000 m^2)



(b) Node density - (150 nodes/1000 m^2)

Fig. 7. P_{rc} of the proposed scheme is compared to AODV in two different node density using GM mobility model

7. Conclusion

The paper presented a scheme to improve the performance of on-demand routing protocols with unidirectional links. The overall routing performance is analyzed with respect to three different mobility models to vary the effect of nodes movement pattern on the routing protocol's performance. In general, the simulation results have shown that in whichever choice of mobility model, the DRR scheme significantly outperforms the competing protocols. Another important aspect of the paper is the investigation of DRR scheme using the P_{rc} performance metric. It shows that the DRR scheme is able to offer a higher success rate of route construction even at lower P_t, an important attributes that can significantly reduce the system's energy consumption.

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