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Link Quality Aware Robust Routing for Mobile Multihop Ad Hoc Networks

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1. Introduction

A *mobile ad hoc network* (*MANET*) (Perkins, 2001; Siva Ram Murthy & Manoj, 2004; IETF, 2009) is a collection of mobile nodes without any fixed infrastructure or any form of centralized administration. In other words, it is a temporary network of mobile nodes without existing communication infrastructure such as access points or base stations. In such a network, each node plays a router for multihop routing as well. MANETs can be effectively applied to military battlefields, emergency disaster relief, and other application-specific areas including wireless sensor networks and vehicular ad hoc networks.

In mobile ad hoc networks, interference and noise are two major obstacles in realizing their full potential capability in delivering signals. In wireless links, the signal propagation is affected by path loss, shadowing and multi-path fading, and dynamic interferences generate additional noise from time to time degrading *link quality*. In this study, as an effective and practical metric of link quality, *signal-to-interference plus noise ratio* (*SINR*) is used because it takes interference and noise as well as signal strength into account. Note that SINR is measurable with no additional support at the receiver (Krco & Dupcinov, 2003; Zhao et al., 2005). Furthermore, as nodes are fast moving, poor links are unpredictably increased. Actually, it is shown that the communication quality of mobile ad hoc networks is low and users can experience strong fluctuation in link quality in practical operation environments (Gaertner & Cahill, 2004). In particular, sending real-time multimedia over mobile ad hoc networks is more challenging because it is very sensitive for packet loss and the networks are error prone due to node mobility and weak links (Karlsson et al., 2005). Accordingly, it is very important to include as many high-quality links as possible in a routing path. Also, the dynamic behavior of link quality should be taken into consideration in protocol design.

In the IEEE 802.11 MAC (IEEE, 1999), *broadcast packets* are transmitted at the base data rate of 1 Mbps. It is mainly due to the potential demand that a broadcast packet should cover as large area as possible in the wireless LAN environment. Note here that, given radio hardware and transmit power, the transmission range is affected by the transmit rate. In mobile ad hoc networks, the *route request* (*RREQ*) packet in routing protocols is a broadcast packet. Therefore, if a distant node receiving an RREQ rebroadcasts the RREQ, a long weak link with low data rate can be included in the discovered route. Intuitively, this helps the routing protocols to find out the *minimum hop-count route* from source to destination. Note here that the minimum hop-count route is a routing path with the minimum number of hops from source to destination and sometimes called the shortest path in the viewpoint of graph algorithm. However, such long links are relatively weak and unreliable and increase the possibility that they are broken. That is, the minimum hop-count route does not mean the best route as measured in (De Couto et. al., 2002; De Couto et. al., 2003). Furthermore, as an effort, SINR-based design of optimized link state routing was introduced for scenarios where VoIP (Voice over IP) traffic is carried over a static multihop networks (Kortebi et al., 2007). In our study, in order to find out a robust route for high delivery efficiency and network performance in MANETs, strong links are selected by examining link quality (or SINR) instead of the number of hops.

This paper proposes a *link quality aware routing protocol* for MANETs resulting in robust delivery and high throughput by finding out a robust route with strong links. During route discovery, the strong links are effectively exploited by forwarding the RREQ packet with the highest SINR among the multiple RREQ packets received. In case there are RREQ packets within δ dB ($\delta = 1$ in this study) from the highest SINR, the first-arrived one among them is chosen to cope with the dynamic behavior of SINR. Any node that has received an RREQ receives successive RREQ packets until the predetermined RREQ waiting time expires; afterwards, RREQ packets for the route discovery are ignored. Compared to the conventional protocols such as AODV, in which only the first-arrived RREQ is forwarded and the others are ignored, the proposed scheme may not have the minimum hop-count route but the one with more number of hops (links). However, the found route is a reliable path with high data rate because it consists of strong links, resulting in high performance as well as robust routing. For performance study, in this paper, the *link quality aware AODV* (*LA-AODV*) is implemented in ns-2 (NS-2, 2008; CMU, 2008). For practical system simulation, we introduce a realistic reception model that takes *BER* and *frame error rate* (*FER*) into account instead of the deterministic reception model in the ns-2 network simulator. Note that the deterministic reception model in ns-2 is based on three fixed thresholds such as carrier sense, receive and capture thresholds (NS-2, 2008; CMU, 2008). According to our performance study, it is shown that *packet delivery ratio* is improved by up to 70% and *per-route goodput* is dramatically increased by a factor of up to 12. It is also shown that the acceptable value of the *RREQ waiting time* (T_w) is 1 msec in the simulated environment, which is enough to achieve fairly good performance.

The rest of the paper is organized as follows: As preliminaries for this study, the basic AODV routing protocol and the rate adaptation mechanisms are summarized in the following section. Section 3 presents the proposed link quality aware routing; i.e., the RREQ forwarding algorithm and the robust routing protocol LA-AODV are described, and then the impact of link quality is analyzed. Performance study including reception model, simulation environment, and evaluation results is discussed in Section 4. Finally, conclusions are given in Section 5.

2. Preliminaries

In this section, the ad hoc on-demand distance vector (AODV) routing protocol (Perkins et al., 2003; Belding-Royer & Perkins, 2003), which is a representative routing protocol for MANETs, is briefly overviewed. Then, the rate adaptation mechanisms to exploit as high transmission rate as possible are summarized.

2.1 AODV routing

The AODV routing protocol (Perkins et al., 2003; Belding-Royer & Perkins, 2003) is an on-demand routing protocol based on the DSDV protocol (Perkins & Watson, 1994). The main characteristics of AODV are to use the periodic beaconing for neighbor sensing and sequence numbering procedure of DSDV and a flooding-based route discovery procedure.

In AODV, route discovery works as follows: Whenever a source needs a route to a destination, it first checks whether it has a route in its route cache (routing table). If it does not have a route, it initiates a route discovery by flooding a route request (RREQ) packet for the destination in the network and, then, waits for a route reply (RREP) packet. When an intermediate node receives the first copy of an RREQ, it sets up a reverse path to the source using the previous hop of RREQ as the next hop on the reverse path. In addition, if there is a valid route available for the destination, it unicasts an RREP back to the source via the reverse path; otherwise, it rebroadcasts RREQ. Duplicate copies of RREQ are immediately discarded upon reception at every node. The destination on receiving the first copy of an RREQ forms a reverse path in the same way as intermediate nodes, and it also unicasts an RREP back to the source along the reverse path. As RREP proceeds towards the source, it establishes a forward path to the destination at each hop. Note here that the destination generates RREPs only when its destination sequence number is grater than or equal to the destination sequence number of the RREQ received.

Route maintenance is done by means of route error (RERR) packets. When an intermediate node detects a link failure (*e.g.,* via a link-layer feedback), it generates an RERR. RERR propagates towards all sources having a route via the failed link, and erases all broken routes on the way. A source upon receiving RERR initiates a new route discovery if it still needs the route. Apart from this route maintenance mechanism, AODV also has a timer-based mechanism to purge stale routes.

2.2 Rate adaptation

As a wireless channel is time-varying and location-dependent due to path loss, shadowing and small-scale fading as well as interference, rate adaptation is a powerful way to overcome channel variations (Zhai et al., 2006). For example, IEEE 802.11b standard incorporates physical-layer multi-rate capability, the feasible data rate set of which is 1, 2, 5.5 and 11 Mbps. However, the IEEE 802.11 standards do not specify how to choose the data rate based on varying channel conditions and thus some schemes to select the rate adaptively have been proposed.

The auto rate fallback (ARF) protocol (Kamerman & Monteban, 1997) is the first commercial MAC that utilizes rate adaptation. Each sender attempts to use higher transmission rate after consecutive transmission successes at a given rate and revert to a lower rate after 1 or 2 consecutive failures. A timer is reset and started each time the rate is changed. When either the timer expires or the number of successfully received acknowledgements reaches the threshold of 10, the rate is increased. The first transmission after the rate increase must succeed or the rate is immediately decreased. When two consecutive transmissions fail in a row, the current rate is decreased. However, if the channel conditions change very quickly due to fast multipath fading, ARF cannot adapt effectively. The adaptive ARF (AARF) protocol (Lacage et al., 2004) continuously changes the threshold at runtime to better reflect the channel conditions. When the transmission of the probing frame fails, the data rate is switched back immediately and the threshold is doubled. The threshold is reset to its initial value of 10 when the rate is decreased due to two consecutive failed transmissions. However, AARF still cannot take the frame loss due to collisions over the wireless link into consideration. The loss-differentiating ARF (LD-ARF) protocol (Pang, 2005) effectively adapts to collision losses as well as link error losses. The data rate is reduced only when a loss of data frame is caused by link errors, not by collisions. Note that it is assumed that if the CTS frame is not received, most likely a collision has occurred because RTS and CTS are short and usually transmitted at a base rate of 1 Mbps.

In the receiver based auto rate (RBAR) protocol (Holland et al., 2001), each receiver measures the channel quality (SINR) of the received RTS frame and, then, selects the transmission rate to be used by the upcoming CTS, data, and acknowledgement frames according to the highest achievable value based on the SINR. The rate to use is then sent back to the sender in the CTS frame. Note that the sender chooses a data rate for RTS based on some heuristic or sets it at a base rate of 1 Mbps. To allow all the nodes within the transmission range to correctly update their network allocation vector (NAV), the RTS, CTS, and data frames have to contain information on the size and rate of the data transmission. If a node that heard the RTS frame hears the data frame, it should recalculate the reservation duration and update its NAV correctly. Since the channel quality is evaluated just before data packet transmission, RBAR yields significant throughput gain compared to ARF. In RBAR, only one packet is allowed to transmit each time, which is not efficient especially when the channel condition is good for a long time. To better exploit the duration of high-quality channel condition, the opportunistic auto rate (OSR) protocol (Sadeghi et al., 2002) opportunistically sends multiple back-to-back data packets whenever the channel quality is good. It achieves significant throughput gains compared to RBAR. In the opportunistic packet scheduling and auto rate (OSAR) protocol (Wang et al., 2004), a sender multicasts RTS to a group of candidate receivers simultaneously and, then, a receiver with channel quality better than a certain level replies CTS. If there are more than one candidate receivers with good channel condition, a coordinating rule is applied in a distributed fashion to avoid collision.

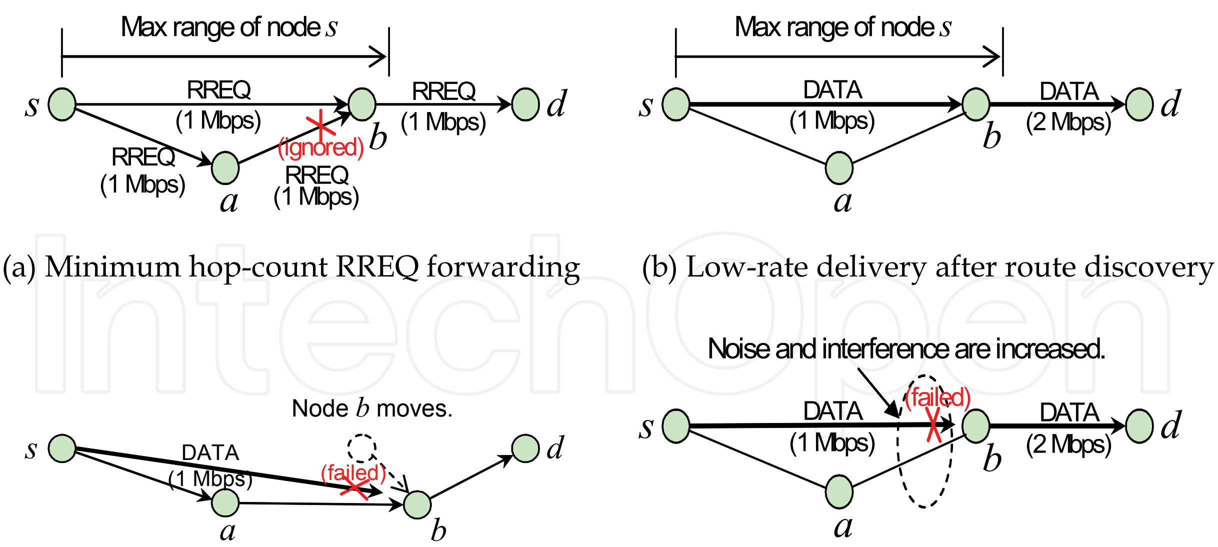
As in (Zhao et al., 2005), we implement a SINR-based rate adaptation scheme in ns-2 (NS-2, 2008; CMU, 2008). The scheme is based on RBAR (Holland et al., 2001), and the data rate of RTS is set at a base rate of 1 Mbps to safely cope with dynamically changing link quality in MANETs. Such a rate adaptation is effectively utilized in our link quality aware routing protocol which will be presented in Section 3.

3. Link quality aware routing

The proposed link quality aware routing protocol, which finds out a robust route with strong links during route discovery, is presented and discussed in this section. The key idea of finding out a robust route is to forward the *RREQ packet* with the *highest SINR* among multiple RREQ packets received. In case there are multiple RREQ packets within δ dB from the highest SINR, the first-arrived one among them is chosen to cope with the dynamic behavior of SINR. The RREQ forwarding algorithm is presented first and then the link quality aware AODV (LA-AODV) is followed. The route reliability and throughput are analyzed in terms of link quality or SINR.

3.1 RREQ forwarding algorithm

In the conventional routing protocols such as AODV, the intermediate nodes forward only the first-arrived RREQ during route discovery in order to find out the minimum hop-count route even though the route does not mean the best route as measured in (De Couto et. al., 2002; De Couto et. al., 2003). This results in a fragile route with long, weak and unreliable links. In this subsection, a new *RREQ forwarding algorithm* is presented to find out a robust and high-performance route.



(a) Minimum hop-count RREQ forwarding (b) Low-rate delivery after route discovery

(c) Delivery failure after node *b* moves (d) Delivery failure when noise increases

Fig. 1. Minimum hop-count RREQ forwarding and its possible problems.

Fig. 1 shows the minimum hop-count RREQ forwarding and its possible problems in the conventional routing protocols such as AODV. Since the first-arrived RREQ is forwarded and the others are ignored, node *b* receives the RREQ packet directly come from *s* and forwards it, resulting in a routing path <*s, b, d*> with two hops as shown in Fig. 1(a). The RREQ packet come from node *a* is ignored at node *b* because it arrives later. Once a route is discovered, subsequent data delivery is done through the route as shown in Fig. 1(b), but the throughput is 1 Mbps because the weak link <*s, b*> in the route limits the data rate to the base rate of 1 Mbps. On the other hand, if node *b* moves and exists out of the maximum range of node *s* as shown in Fig. 1(c), it does not receive data packets from node *s* any more, resulting in delivery failure and initiating a new route discovery. The effect of mobility changes the received signal power, which is exponentially decreased as the communication distance increases, and thus affects SINR. Fig. 1(d) shows another example of delivery failure. If interference and noise on the link <*s, b*> are increased due to unstable and dynamic network environment, SINR of the packet transmitted from node *s* becomes less than the threshold (*e.g.*, 10 dB) and, thus, node *b* does not receive the packet successfully even though it does not move. The interference and noise are influenced by unstable and dynamic network environment and unexpectedly changes from time to time, and thus affects SINR. As explained earlier, the weak point of the conventional routing protocols, which is got over in this paper, is the *RREQ forwarding algorithm* in which the intermediate nodes forward the first-arrived RREQ to find out the minimum hop-count route even though the route does not mean the best route as measured in (De Couto et. al., 2002; De Couto et. al., 2003).

In the proposed LA-AODV protocol, the route discovery and maintenance are necessary as in the basic AODV. The main difference between AODV and LA-AODV is RREQ forwarding during route discovery. Fig. 2 represents the proposed *RREQ forwarding algorithm*. The new RREQ forwarding algorithm helps find out a reliable route with strong links. When a node has a packet to send, it needs a route to the destination. If it has no route in its route cache or routing table, it issues route discovery by broadcasting an RREQ packet

```
// RREQ forwarding procedure at every node
/* This algorithm is carried out during route discovery at every node that receives an RREQ packet:
   i.e., if a node receives an RREQ packet, this routine is immediately called and run by the node.
*/
1:  S = {R1};  // keep track of received RREQs (including link quality or SINR).
2:             // subscript i in set element Ri represents the order of receipt
3:  set the timer as Tw;  // initialize the timer to Tw
4:  while the timer does not reach 0, do {   // repeat lines 4~7 until the timer reaches 0
5:        // receives successive RREQs until the predetermined RREQ waiting time expires
6:        if any successive RREQ arrives, append it into S;
7:  }
8:  k = |S|;  // number of elements in S
9:  if k = 1, forward R1;
10:  else{   // if there are two or more RREQs received
11:        sort S in decreasing (non-increasing) order of SINR;
12:        if there are one or more RREQs within δdB from the highest SINR in S { //δ =1 in this study
13:              // for coping with the dynamic behavior of SINR
14:              select the first-arrived one among them;
15:              forward the selected one;
16:        }
17:        else     forward the RREQ with the highest SINR;
18:  }
19:  return;  // afterwards, RREQ packets are ignored
```

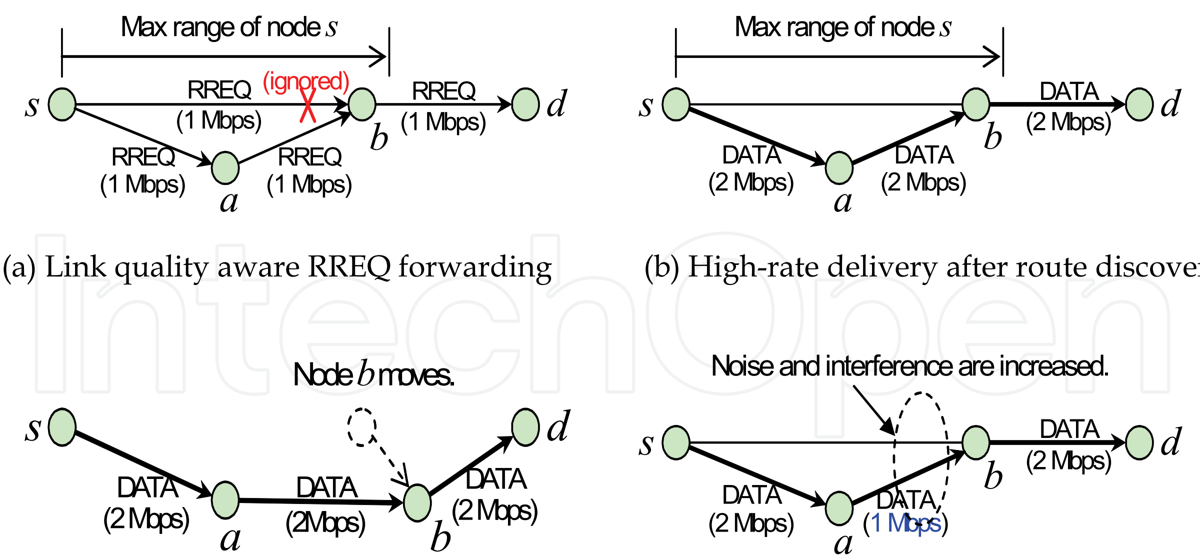
Fig. 2. Proposed RREQ forwarding algorithm.

for the destination. Intermediate nodes forward the RREQ packet with the highest SINR among multiple RREQ packets received for the predetermined *RREQ waiting time* (T_w) after the first RREQ is received. In case there are multiple RREQ packets within δ dB ($\delta = 1$ in this study) from the highest SINR, the first-arrived one among them is chosen to cope with the dynamic behavior of SINR. The other RREQ packets arrived later are ignored if any. Similarly, the destination takes the RREQ packet with the highest SINR for route reply.

3.2 Link quality aware end-to-end routing

Based on the RREQ forwarding algorithm, the *link quality aware AODV* (*LA-AODV*) routing protocol is presented and discussed in this subsection. Since the RREQ forwarding algorithm finds out a robust route with strong links, the proposed LA-AODV results in robust delivery and high performance. Note that the route discovery operation of LA-AODV differs from that of AODV but there is no noticeable difference in the route maintenance. Accordingly, LA-AODV can be easily implemented.

Fig. 3 shows the proposed link quality aware RREQ forwarding and its resulting effects for the same example as in Fig. 1. During route discovery, node *b* forwards the RREQ packet come from node *a* rather than that come from node *s* as shown in Fig. 3(a) because the former has the better link quality (*i.e.,* higher SINR) than the latter. Notice that, in the



(a) Link quality aware RREQ forwarding (b) High-rate delivery after route discovery

(c) Data delivery after node *b* moves (d) Data delivery when noise increases

Fig. 3. Link quality aware RREQ forwarding and its resulting effects for the same example as in Fig. 1.

proposed *RREQ forwarding algorithm*, the intermediate nodes forward the RREQ packet with the *highest SINR* among multiple RREQ packets received for the predetermined RREQ waiting time after the first RREQ is received. In case there are RREQ packets within δ dB ($\delta = 1$ in this study) from the highest SINR, the first-arrived one among them is chosen to cope with the dynamic behavior of SINR. Fig. 3(b) shows data delivery after route discovery, in which data is delivered at 2 Mbps along with 3 hops. That is, the throughput of the route is 2 Mbps, which is double of 1 Mbps in the conventional protocols as shown in Fig. 1(b), because strong links <*s, a*> and <*a, b*> instead of the weak link <*s, b*> are exploited in the proposed RREQ forwarding algorithm. Even when node *b* moves as in Fig. 3(c), the data delivery is successful with the same throughput of 2 Mbps without performance degradation. If node *b* moves further away from node *a* or node *d*, the throughput might be reduced but still the route may be alive. Fig. 3(d) shows another example of data delivery in case of unstable and dynamic network environment. If interference and noise are increased resulting in link quality fluctuation, SINR of the packet transmitted from node *a* is reduced but the link <*a, b*> is strong enough to receive the packet without error and, thus, node *b* can still receive the packet successfully at lower data rate (*e.g.*, 1 Mbps). Note here that the transmission data rate is decreased (*i.e.*, from 2 Mbps to 1 Mbps in the figure) because SINR is reduced due to the increased interference and noise on the link <*a, b*>. Conclusively, the proposed approach achieves high throughput as well as robust delivery by exploiting strong links during route discovery.

In the conventional protocols such as AODV, only the first-arrived RREQ is forwarded and the others are ignored. The rationale for such design is that it finds out the shortest path (*i.e.*, the minimum hop-count route) because the first arrival means the smaller number of hops from the source. That is, to discover the minimum hop-count route is the primary goal of the conventional protocols as in the most wired networks. As described in Introduction, however, the minimum hop-count route does not mean the best route as measured in (De Couto et. al., 2002; De Couto et. al., 2003). On the other hand, the proposed approach might

not have the minimum hop-count route but the one with more number of hops (links). However, the found route in the proposed LA-AODV is a reliable path with high data rate because it consists of strong links, resulting in high throughput as well as robust routing.
Obviously, a routing path with strong links is more reliable and has higher quality compared to that with weak links. It significantly extends the lifetime of a routing path, reducing *route discovery frequency*. Moreover, a high-quality link transmits packets at high data rate. Therefore, the proposed LA-AODV results in higher *packet delivery ratio* and higher *throughput* as well as more robust routing compared to AODV. In the proposed protocols, the *RREQ waiting time* is a critical design factor because it directly determines the amount of overhead affecting the route discovery time. Even though the overhead of the RREQ waiting time is a minor factor compared to the positive effects of finding out a robust routing path, it should be optimized to eliminate unnecessary operations. In Section 4, some different RREQ waiting time is applied to performance simulation in order to investigate the performance impact of the RREQ waiting time.
Note that LA-AODV is the same as AODV except for that the new RREQ forwarding algorithm presented earlier is used instead of the first-arrived RREQ forwarding used in AODV and DSR during route discovery. Therefore, LA-AODV protocol can be easily implemented by redesigning only the RREQ forwarding module in AODV and tuning some related modules appropriately. Note that the proposed RREQ forwarding algorithm is feasible since SINR is measurable with no additional support at the receiver (Krco & Dupcinov, 2003; Zhao et al., 2005). In this paper, the *link quality-aware AODV* (*LA-AODV*) routing protocol, which is the modified version of AODV (Perkins et al., 2003; Belding-Royer & Perkins, 2003), is implemented in *ns*-2 (NS-2, 2008; CMU, 2008) and its performance is evaluated and compared with the conventional routing protocols of AODV in Section 4.

3.3 Analysis on impact of link quality

For a multi-hop route, the impact of link quality is analyzed in this subsection. The route reliability and throughput are discussed in terms of link quality or SINR. In general, the link quality can be represented by signal strength, signal-to-noise ratio (SNR), or SINR. In our study, SINR is used as the metric of link quality because it takes all the signal strength, interference and noise into account. Note that SINR directly affects bit error rate (BER) which determines the probability that a packet is successfully transferred. Given a modulation method, BER is inversely proportional to SINR. How to calculate SINR and a typical example of SINR-BER curve will be given in Section 4.1.
Given a k-hop route R from source to destination in a mobile ad hoc network, the probability P_R that a packet is successfully delivered along with R can be represented by

$$P_R = \prod_{i=1}^{k} p_i \tag{1}$$

where p_i is the probability that a packet is successfully transferred via the i-th link in R. Note here that the data rate is fixed and the same for all the k links in R. When p_i is relatively low, P_R is quickly decreased as the number of hops in a route increases. Therefore, p_i needs to be as high as possible to provide scalability. In other words, a route with strong links is highly required to obtain a reliable route of high P_R. Note that P_R and p_i are *reliability* of R and the i-th link in R, respectively. P_R is often called *packet delivery ratio*.

On the other hand, the end-to-end throughput λ_R of a k-hop route R is calculated by using geometric mean. Note that geometric mean is used if the product of the observations is a quantity of interest. Therefore, λ_R can be simply given by

$$\lambda_R = (\prod_{i=1}^{k} \lambda_i)^{\frac{1}{k}} \tag{2}$$

where λ_i is the throughput or data rate of the i-th link in R. Note here that the data rate (λ_i) is directly correlated to the link quality (p_i). To attain high end-to-end throughput, every link of a route has to transmit frames at high data rate. To achieve high data rate for a link, the link need to be as strong as possible.

In summary, the reliability and throughput can be significantly improved by exploiting strong links during route discovery. The more strong links are taken, the better reliability and throughput are attained. In this paper, per-route goodput is evaluated via extensive simulation instead of throughput in the next section because goodput is more practical and application oriented than throughput.

4. Performance evaluation

In this section, the performance of the proposed link quality aware AODV (LA-AODV) is evaluated in comparison to the normal AODV using the *ns*-2 network simulator (NS-2, 2008; CMU, 2008). Section 4.1 introduces the realistic reception model we have used in this study and Section 4.2 explains the simulation environment including parameters. Simulation results are discussed in Section 4.3.

4.1 Reception model

The reception model implemented in the *ns*-2 network simulator (NS-2, 2008; CMU, 2008) is based on three fixed thresholds, *i.e., carrier sense threshold* (CSThresh), *receive threshold* (RxThresh) and *capture threshold* (CPThresh). When a frame is received, each node in the proximity calculates the received signal power based on radio propagation model and compares it against CSThresh and RxThresh. If it is smaller than CSThresh, the receiver ignores the signal. If it is in between the two thresholds, the receiver considers the medium busy but do not attempt to decode the signal. If it is higher than RXThresh, the receiver attempts to receive the frame. However, when the node receives another signal during receiving the first signal, their ratio is compared against CPThresh. If one of them is much stronger (*e.g.,* 10 dB higher), it captures the other; otherwise, both frames fail. However, real wireless links are characterized with random and probabilistic behavior.

Even though the abovementioned deterministic reception model is not realistic, it has been used in most simulation studies for simple comparison. For the realistic evaluation of wireless links with probabilistic behavior, however, it is important to simulate a realistic reception model. Our evaluation takes *bit error rate* (*BER*) into consideration in the context of *ns*-2 because BER is a function of SINR and modulation method (Pavon & Choi, 2003). In other words, given a modulation method, BER is inversely proportional to SINR.

Here, we describe how SINR is calculated in *ns*-2 (NS-2, 2008; CMU, 2008). While the receiver receives one signal, other signals may arrive at the receiver resulting in interference. As a result, SINR of the receiving signal, γ, is calculated by

$$\gamma = \frac{P_r}{\sum_{i \neq r} P_i + N} \tag{3}$$

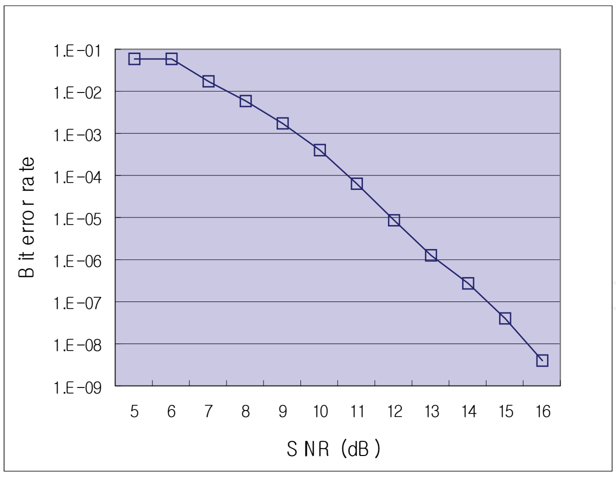
where P_r is the received power (signal strength) of the signal, P_i denotes the individual received power of other signals received by the receiver simultaneously, and N is the effective noise at the receiver. There are two components in the above equation – received power and interference plus noise.

First, the received power at the receiver (P_r) is calculated according to the radio propagation model at the receiver in *ns*-2. In our study, *Ricean fading* model (Punnoose et al., 2000; NS-2, 2009) is used as a radio propagation model. The Ricean fading is a radio propagation anomaly caused by partial cancellation of a radio signal by itself; *i.e.,* the signal arrives at the receiver by two or more different paths and at least one of the paths is changing. It occurs when one of the paths, typically a line of sight signal, is much stronger than others. The Ricean fading model is effectively applied to the environment that, in addition to scattering, there is a strongly dominant signal seen at the receiver usually caused by a line of sight.

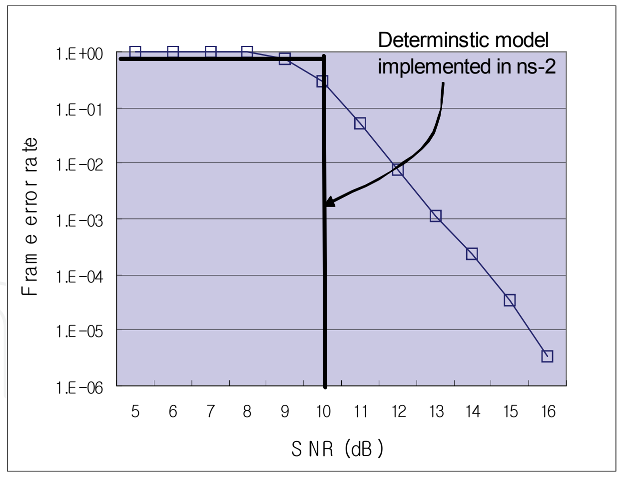
Second, noise contains the noise generated by the receiver and the one come from environment. The effective noise level generated by the receiver can be obtained by adding up the noise figure of a network interface card (NIC) onto the thermal noise (IEEE, 1994). We first compute the thermal noise level within the channel bandwidth of 22 MHz in the IEEE 802.11 standard (IEEE, 1999). This bandwidth is 73 dB above -174 dBm/Hz, or -101 dBm. Assuming a system noise figure of 6 dB as in (IEEE, 1994), the effective noise level generated by the receiver is -95 dBm. The environment noise or channel noise is the *additive white Gaussian noise* (*AWGN*) that is modeled as a Gaussian random variable. It is assumed that the environment noise is fixed throughout the whole medium access of a communication. For realistic simulation of noisy and unstable environments, the environment noise can be varied for different medium accesses. On the other hand, interference is the received signal power calculated as described above for other frames received by the receiver simultaneously.

Based on the aforementioned discussions and the product specification of the Intersil HFA3861B radio chip (Intersil, 2007a), we are able to calculate the BER as shown in Fig. 4(a), which models the QPSK modulation with 2 Mbps. Note that the BER-E_b/N_0 curve given in (Intersil, 2007a) is simply converted into the BER-SINR curve since SINR = $E_b/N_0 \times R/B_T$, where E_b is energy required per bit of information, N_0 is interference plus noise in 1 Hz of bandwidth, R is system data rate, and B_T is system bandwidth that is given by $B_T = R$ for QPSK in the Intersil chipset (Intersil, 2007b). In an IEEE 802.11 frame, physical layer convergence protocol (PLCP) preamble, PLCP header and payload (data) may be transmitted at different rate with different modulation method. Hence, BER should be calculated separately for the three parts of a frame.

Once BER is obtained, *frame error rate* (*FER*) can be calculated, which determines the percentage that a frame is received correctly. For example, given α-bit preamble, β-bit PLCP header and γ-bit payload with BER of p_a, p_b and p_c, respectively, FER is obtained by $1 - (1 - p_a)^{\alpha}(1 - p_b)^{\beta}(1 - p_c)^{\gamma}$. For comparison, Fig. 4(b) also shows the FER curve used in unmodified *ns*-2. As discussed earlier in this section, if SINR is larger than CPThresh, *e.g.,* 10 dB as in Fig. 4(b), the frame succeeds (FER = 0.0). Otherwise, it fails (FER = 1.0). Our performance evaluation study modifies *ns*-2 so that FER is not deterministically but probabilistically determined based on SINR, making our evaluation more realistic and convincing.



(a) BER versus SINR



(b) FER versus SINR

Fig. 4. BER and FER for QPSK with 2 Mbps in the Intersil HFA3861B radio chip. (The PHY frame size for calculating FER is assumed to be 864 bits, *i.e.*, 144-bit preamble, 48-bit PLCP header and 84-byte payload.)

4.2 Simulation environment

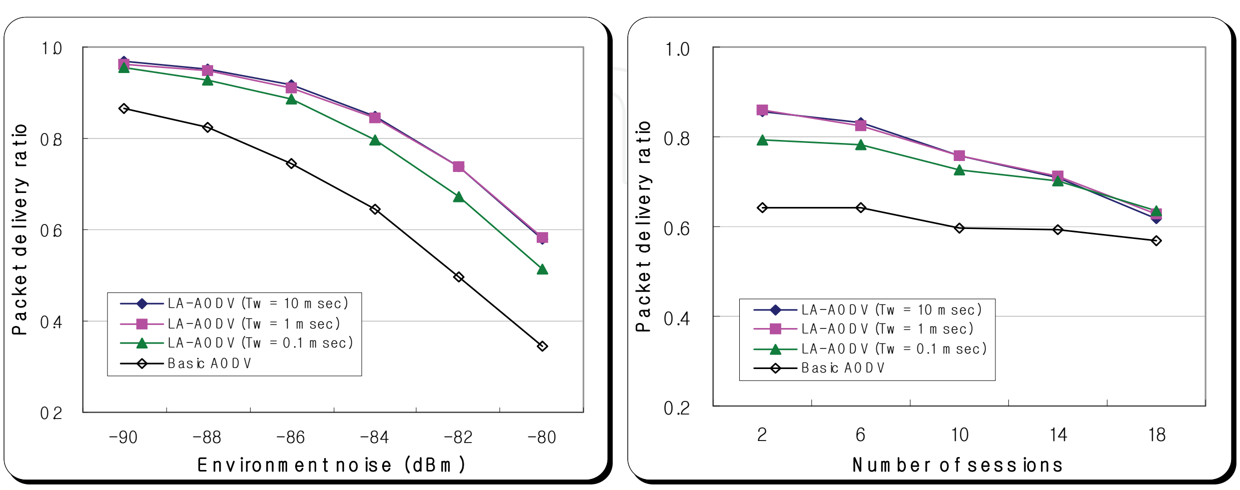
In our simulation study, it is assumed that 50 mobile nodes move over a square area of 300*m* × 1,500*m*. The propagation channel of *Ricean fading* model is assumed with a data rate of 2 Mbps. As mentioned in Section 2.2, the SINR-based rate adaptation scheme based on RBAR (Holland et al., 2001) is modeled and used in *ns*-2 (NS-2, 2008; CMU, 2008), where the data rate of RTS is set at a base rate of 1 Mbps to safely cope with dynamically changing link quality in MANETs. The constant bit rate (CBR) source of 2 packets per second is assumed with UDP-based traffic and the data payload of the packets is 512 bytes long. Mobile nodes are assumed to move randomly according to the *random waypoint model* (Broch et al., 1998), where two parameters of maximum node speed and pause time determine the mobility pattern of the mobile nodes. Each node starts its journey from a randomly selected location to a target location, which is also selected randomly in the simulation area, at a randomly chosen speed (uniformly distributed between 0 and maximum speed). The maximum speed is set as 5 *m/sec* throughout the simulation. When a node reaches the target location, it stays there during the pause time and then repeats the mobility behavior.

As for performance metrics, we evaluate the followings: *Packet delivery ratio* is the ratio of the number of data packets successfully delivered to the destination over the number of data packets sent by the source. *Per-route goodput* is the application level throughput excluding protocol overhead and retransmitted data packets, which is sometimes given by the inverse of the averaged end-to-end data packet delay. *Normalized control overhead* is the ratio of the total number of control packets transmitted for medium access and routing over the number of data packets successfully delivered to the destination, where each hop-wise transmission of a control packet is counted as one transmission.

For measuring the performance metrics, the simulation factors of the environment noise level, the number of sessions, and the pause time are varied in a meaningful range; *i.e.,* the environment noise level of -90 ~ -80 dBm (*i.e.,* -90, -88, -86, -84, -82, and -80dBm) modeled as a Gaussian random variable with the standard deviation of 1 dB, the number of sessions from 2 to 18 (*i.e.,* 2, 6, 10, 14, and 18), and the pause time of 100 ~ 900 *sec* (*i.e.,* 0, 20, 50, 100, 200, 300, 600, and 900 *sec*) are applied. While one simulation factor is varied during a simulation, the others are fixed as follows: the environment noise level of -84 dBm (which represents a relatively harsh environment), the number of sessions of 4, and the pause time of 100 *sec*. Note that the number of sessions is the number of connections. Source-destination pairs are randomly selected. Each run has been executed for 900 *sec* of simulation time.

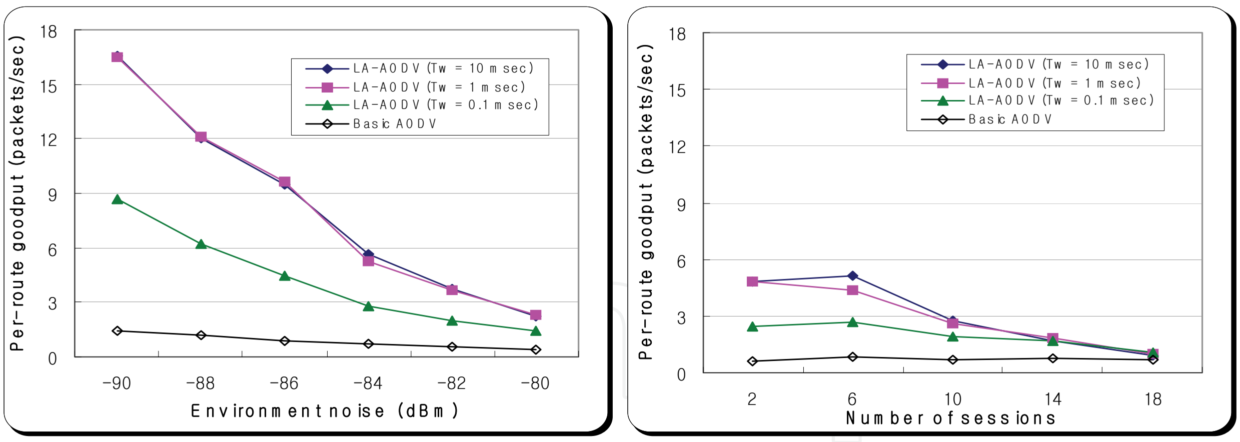
4.3 Simulation results and discussion
4.3.1 Packet delivery ratio.
Fig. 5 shows the packet delivery ratio for varying the environment noise and the number of sessions. It is shown that the proposed LA-AODV outperforms the basic AODV by up to 70 % and 34% for the environment noise and the number of sessions, respectively. Note here that LA-AODV shows almost the same performance for the two different values of *RREQ waiting time* (T_w) of 1 *msec* and 10 *msec*. The two cases with T_w of 1 *msec* and 10 *msec* outperform LA-AODV with T_w of 0.1 *msec*. Therefore, it can be easily inferred that T_w of 1 *msec* is long enough to achieve the most robust delivery in the given environment. As the environment noise increases, PDR is decreased as expected. It is slightly decreased with the increased number of sessions.

4.3.2 Per-route goodput.
Fig. 6 shows the per-route goodput for varying the environment noise and the number of sessions. It is shown that the proposed LA-AODV outperforms the basic AODV by a factor of up to 12 and 8 for the environment noise and the number of sessions, respectively. As in Fig. 5, LA-AODV shows almost the same performance for the two different values of *RREQ waiting time* (T_w) of 1 *msec* and 10 *msec*, and the two cases with T_w of 1 *msec* and 10 *msec* outperform LA-AODV with T_w of 0.1 *msec*. Hence, T_w of 1 *msec* is long enough to achieve the highest performance in the given environment. As the environment noise increases, the per-route goodput of LA-AODV is rapidly decreased compared with the basic AODV. It is also decreased with the increased number of sessions.



(a) Varying environment noise (b) Varying the number of sessions

Fig. 5. Packet delivery ratio.

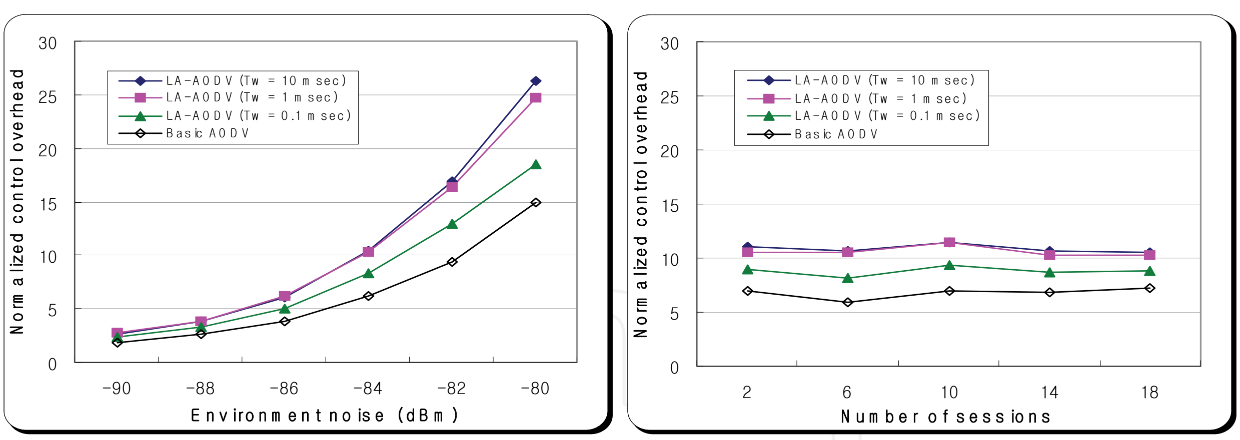


(a) Varying environment noise (b) Varying the number of sessions

Fig. 6. Per-route goodput.

4.3.3 Normalized control overhead.

Fig. 7 shows the normalized control overhead for varying the environment noise and the number of sessions. As can be expected, LA-AODV incurs more control overhead compared to the basic AODV for both the environment noise and the number of sessions. This is a kind of side effect paid to achieve robust delivery and high performance. As the environment noise increases, the normalized overhead is increased as expected. It is almost constant with the increased number of sessions. This mainly due to the fact that, as the number of sessions increases, the number of delivered data packets is also increased while the number of control packets is increased.

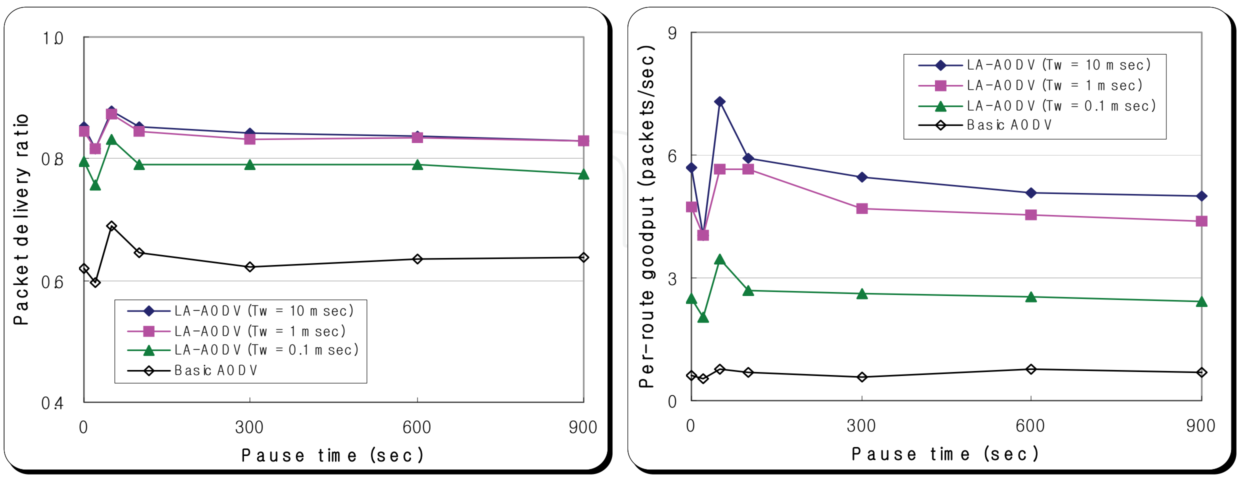


(a) Varying environment noise (b) Varying the number of sessions

Fig. 7. Normalized control overhead.

4.3.4 Impact on node mobility in the harsh environment.

In general, the network performance is highly affected by node mobility in the normal operation environment and it is degraded with increased mobility. Fig. 8 shows the impact on node mobility in the harsh environment with the noise level of -84 dBm. LA-AODV outperforms the basic AODV in terms of packet delivery ratio and per-route goodput for different pause time. However, the packet delivery ratio and per-route goodput are almost constant with increased pause time except for very high mobility. In other words, it is inferred from the results that the node mobility is not a major factor affecting performance in the harsh operation environment.



(a) Packet delivery ratio (b) Per-route goodput

Fig. 8. Effect of varying pause time in the harsh environment.

5. Conclusions

In this paper, the *link quality aware AODV* (*LA-AODV*) has been presented by devising the *RREQ forwarding algorithm*, resulting in robust packet delivery and high network performance. The RREQ forwarding algorithm finds out a reliable path with strong links. During route discovery, the strong links are effectively exploited by forwarding the route request (RREQ) packet with the highest *link quality* or *signal to interference plus noise ratio* (*SINR*) among the multiple RREQ packets received. Some tolerance is applied to the link quality in choosing an RREQ to be forwarded in order for coping with the dynamic behavior of SINR. Compared to the basic AODV, the proposed scheme may not have the minimum hop-count route but the one with more number of hops. However, the discovered route is a reliable path with high data rate because it consists of strong links, resulting in high performance as well as robust routing. The performance study shows that *packet delivery ratio* is improved by up to 70% and *per-route goodput* is dramatically increased by a factor of up to 12. It is also shown that the acceptable value of the *RREQ waiting time* (T_w) is 1 *msec* in the simulated environment, which is enough to achieve fairly good performance.

The proposed mechanism can be easily applied to other routing protocols using *broadcast-based route discovery*. To extend the LA-AODV principle to hierarchical routing protocols and multicast protocols is another future work. Our future work includes the exploration of a new link quality aware routing protocol for MANETs with asymmetric links as well, which should be a very challenging work.

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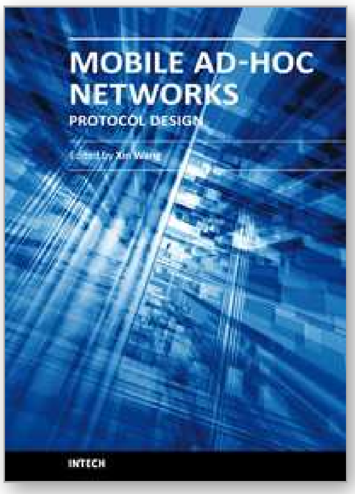

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Being infrastructure-less and without central administration control, wireless ad-hoc networking is playing a more and more important role in extending the coverage of traditional wireless infrastructure (cellular networks, wireless LAN, etc). This 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.