A Link Stability Model and Stable Routing for Mobile Ad-Hoc Networks*

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Abstract. When using shortest-distance routing for mobile ad-hoc networks (MANETs), the physical distances of links that constitute such paths tend to be very long since this leads to fewer hops between source and destination nodes. However, if the physical distance of a wireless link becomes so long that it approaches its transmission range, packet transmission error rates can increase drastically, resulting in an unstable link. Furthermore, packets are more likely to be lost due to external environment factors such as white noise and wireless interference if the signal strength is not strong enough. Therefore, it would be desirable for routing algorithms for MANETs to be able to select paths that are more likely to be stable. With this objective in mind, we propose an enhanced stability model (ESM) to estimate link stability based on signal strength. A routing algorithm based on this new model is also proposed. Simulations of the proposed ESM and previous link estimation models validate the superiority of the proposed approach. Simulations also show that the proposed routing algorithm performs particularly well when there are unreliable links.

1 Introduction

A routing algorithm for mobile ad-hoc networks (MANETs) should not only route using short-distance paths, but should also be adaptable to highly dynamic changes in network topology since the network topology can change frequently and wireless communication channels are inherently unreliable. Given a routing algorithm targeted toward finding optimal (in terms of distance) paths, the physical distance between two neighboring nodes within a path tends to be very long since this results in fewer hops. Such distances may even be close to the effective transmission range between nodes as shown in [1]. In this case, a small movement of any of the nodes involved may cause packet loss due to link disconnection. Furthermore, packets can be lost due to noise or interference in the wireless channel if the signal strength is very weak. Therefore, a MANET routing algorithm should not only seek to find short-distance paths, it should

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also strive to find stable paths that take into account the mobility of nodes, low signal power and interference in the wireless channel.

In this paper, we propose a new link stability estimation model and a routing algorithm based on this new model. Section 2 reviews previously proposed routing methods that take into account link stability. Section 3 discusses various link stability estimation models and the proposed link stability model. Section 4 discusses routing algorithms that are able to support stable routing, and Section 5 shows simulation results for various link stability models on top of the target routing algorithm. Finally, conclusions are presented in Section 6.

2 Related Works

Signal stability-based adaptive routing(SSA)[2] estimates link stability based on signal strength. Each node measures signal strengths from other nodes. If a node receives a strong signal from a neighbor, which typically results if two nodes are close to each other, the link is considered as stable. If possible, SSA tries to find a path using only stable links. If it fails to find a stable path, then it tries to find a path using all possible links, resulting in an ordinary path. When a failed link is detected, an intermediate node sends an error message to the source node to notify it that the path is broken. Then the source reinitiates another path search process in order to find a new path – this causes undue overhead and is thus undesirable.

Associativity-based routing(ABR)[3] tries to find long-lived paths to destinations using estimations of link stability based on beacon messages. ABR searches all possible paths to find a path with strong links. Therefore, a path is selected for each destination based on link stability. However, the link stability model that ABR uses is not accurate for some mobility patterns.

Link life based routing protocol(LBR)[4] is another stability-based routing protocol. LBR converts signal strength into distance using a free space propagation model assumption. Based on estimated distance and maximum speed of nodes, LBR estimates link lifetime. When the source node initiates a route request, each intermediate node attaches its estimated link lifetime to the route request message. When the destination receives a route request message, it can calculate the path lifetime for that path based on the estimated link lifetimes in the path. Therefore, the destination can select a path that is expected to have the longest lifetime. In order to react to path breakage, proactive and reactive maintenance is proposed in LBR. In reactive maintenance, the source node needs to reinitiate a route request to the destination, which results in increased delay and control overhead. In proactive maintenance, a backup path is found prior to path breakage. However, the estimated path lifetime is not valid when a path is broken. Therefore, the backup path may be unstable.

The approaches discussed above require the delivery of an error message to the source node followed by reinitiation of route discovery when path breakage is detected. However, reinitiating route discovery is a very costly operation that may not be acceptable for time critical applications such as those requiring QoS routing. Furthermore, the stable routing algorithms discussed above attempt mainly to reduce routing overhead. Even if a stable path is selected when the path is initially discovered, the probability of successful packet delivery (packet delivery ratio) can decrease because the signal strength of links in the path can weaken. The purpose of stable routing should be not only reducing routing overhead but also increasing packet delivery ratio. Therefore, we propose a new stable routing algorithm that is aimed at increasing packet delivery ratio.

3 Link Stability Models

In order to support stable routing, proper estimation of link stability is required. In [5], link stability is modeled in a statistical manner based on node movement models. However, statistical approaches are not adequate for general applications because the mobility patterns of nodes cannot be known a priori. In [3], a link stability estimation model is proposed using periodic beacon signals. In order to estimate link stability, every node sends beacon messages periodically. If the number of continuous received beacon messages are beyond a certain threshold from its neighbor, then the link is considered as stable since ABR is based on the idea that nodes that have been stationary for a threshold period are less likely to move. However, this idea is not so accurate because not all nodes follow the mobility patterns that ABR assumes. The other approaches are based on signal strength. The basic idea is that signal strength weakens if the distance between two nodes grows farther apart. A path composed of weak links can easily become broken. Therefore, a signal strength-based estimation model marks a link as stable if the signal strength of the link is greater than a certain threshold.

Let us use the following notation in discussing link stability models. v_i represents a node with a unique identifier i and $e_{i,j}$ is the link between node v_i and v_j. SS_j is the signal strength of a packet received from node v_j and $SScum_j$ is the cumulative signal strength of packets received from v_j. DSS_j is the differentiated signal strength (i.e., the change in signal strength from the value measured during the previous measurement period) of neighbor v_j. ρ is an weight factor of $SScum_j$ that defines how much previous signal strength affects current $SScum_j$. Finally, Thr is the signal strength threshold above which a signal is considered to be stable.

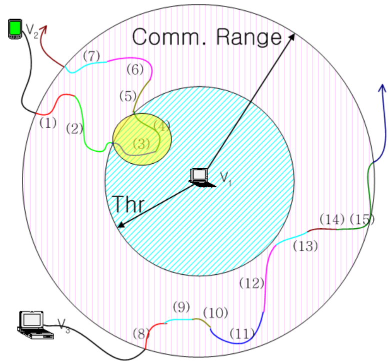
3.1 Signal Strength-Based Link Stability Estimation Model(SBM)

SBM, proposed in [2], estimates link stability using signal strengths. Each node monitors signals from its neighboring nodes. If the signal strength of a received packet is higher than a certain threshold, the link to that neighbor is considered stable. Figure 1(a) shows the pseudocode for the procedure followed by SBM when v_i receives a packet from v_j.

Figure 1(b) shows estimation results for link stability when SBM is used. The circle with 45 degree slash marks (the stable zone) is the area where the signal strength is greater than Thr. Only nodes in the slashed area can be considered as

$SScum_j = \rho SScum_j + (1-\rho)SS_j$
if($SScum_j > Thr$) {
    $e_{i,j}$ is stable.
} else {
    $e_{i,j}$ is unstable.
}

(a) Pseudocodes



(b) Estimation results

Fig. 1. Pseudocodes and estimation results of SBM

nodes connected by stable links. The vertically slashed circle area (outer circle) is the maximum communication range of v_1. When mobile nodes are inside the small ovals, the link between those nodes and v_1 can be considered as stable. Link $e_{1,2}$ when v_2 is on path segments (1), (2), (5), (6) and (7) is considered as unstable because the signal strength received from v_1 is less than Thr. However the link $e_{1,2}$ is considered as a stable link when v_2 is on path segments (3) and (4) because the signal strength received is greater than Thr. Link $e_{1,3}$ is always considered as unstable because the signal strength received by v_3 is less than the threshold Thr throughout its journey.

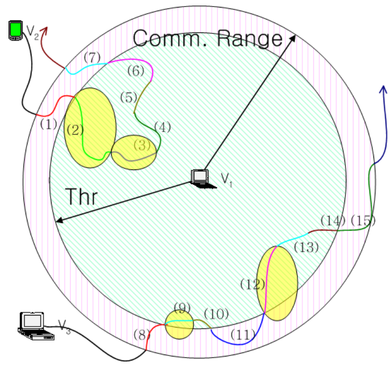
3.2 Advanced Signal Strength-Based Link Stability Estimation Model(ASBM)

ASBM, proposed in [1], takes differentiated signal strength (DSS) values into account when estimating the direction of node movement. DSS indicates whether the signal strength is getting stronger or weaker. If the signal strength is getting stronger, this means that the two nodes are getting closer together and the link is getting stronger. Therefore links with increasing signal strengths are considered as stable. If the signal strength is getting weaker, this means that the two nodes are getting farther apart and the link may become disconnected. In addition, a very weak initial signal strength between two nodes also indicates a weak link. Thus, a link in which the signal strength is getting progressively weaker or is less than a threshold is considered as unstable. Since ASBM takes DSS into account, it can detect movements of nodes that can weaken link stability. Therefore, the threshold for ASBM can be set lower than the threshold for SBM, which means that the stable area is larger than with SBM. Figure 2(a) shows the pseudocode for ASBM.

Figure 2(b) shows estimated results for link stability when ASBM is used. Note that the area of the stable zone for ASBM is larger than that for SBM because Thr of ASBM is less than Thr of SBM. When v_2 is on path segments

$SScum_j = \rho SScum_j + (1-\rho)SS_j$
$DSS_j = SScum_j - prevSScum_j$
if($SScum_j > Thr$) {
  if($DSS_j > 0$) {
    $e_{i,j}$ is stable.
  } else {
    $e_{i,j}$ is unstable.
  }
} else {
  $e_{i,j}$ is unstable.
}
$prevSScum_j = SScum_j$

(a) Pseudocodes



(b) Estimation results

Fig. 2. Pseudocodes and estimation results of ASBM

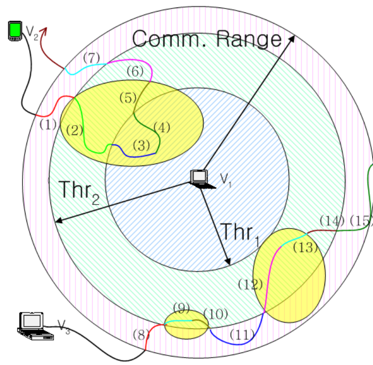
(2), (3), (4), (5) and (6), v_2 is inside the stable zone. DSS_2 is positive when v_2 is on path segments (2) and (3) because v_2 and v_1 are getting closer. Therefore, the link $e_{1,2}$ is considered as stable when v_2 is on path segments (2) and (3). However, DSS_2 is negative when v_2 is on path segments (4), (5) and (6) because v_2 and v_1 are getting farther apart. Therefore, link $e_{1,2}$ is considered as unstable when v_2 is on path segments (4), (5) and (6). Note that when v_2 is on a path segment (4), the distance between v_1 and v_2 is very close. Even if v_2 starts to move out immediately, it can be considered as stable because it may need a lot of time to move out of the communication range of v_1. Therefore, ASBM may result in fewer stable links than SBM. Based on similar reasoning, link $e_{1,3}$ is considered as stable when v_3 is on path segments (9) and (12).

3.3 Enhanced Stability Model (ESM)

A major shortcoming of ASBM is that it considers the link $e_{1,2}$ as unstable when v_2 is on a path segment (4) in Fig. 2(b). In order to overcome this shortcoming of ASBM, we propose a new link stability estimation model, termed the Enhanced Stability Model (ESM), that uses two thresholds. In ESM, a link is considered as stable when two nodes are located very close to each other. ESM uses two threshold Thr_1 and Thr_2 with the property $Thr_1 > Thr_2$. If the signal strength is greater than Thr_1, then the link is always considered as stable because the distance between the two nodes is very small. However, if the signal strength is less than Thr_1 but greater than Thr_2, then DSS is used to estimate link stability as in ASBM. In addition, due to external environment factors like obstacles, interference and white noise, signal strength can decrease even when the locations of both nodes are fixed. Suppose that signal strength is slightly decreased by

$SScum_j = \rho SScum_j + (1 - \rho) SS_j$
$DSS_j = SScum_j - prevSScum_j$
if($SSCum_j > Thr_1$) {
  $e_{i,j}$ is stable.
} else if($SScum_j > Thr_2$) {
  if($DSS_j > \mu$) {
    $e_{i,j}$ is stable.
  } else {
    $e_{i,j}$ is unstable.
  }
} else {
  $e_{i,j}$ is unstable.
}
$prevSScum_j = SScum_j$

(a) Pseudocodes



(b) Estimation results

Fig. 3. Pseudocodes and estimation results of ESM

external environment factors. In this case, ASBM considers the link as unstable because DSS becomes negative even though the actual link may still be stable. Therefore, we add a parameter μ where $\mu < 0$ to address this problem. A link is considered as unstable in ESM only when $DSS < \mu$. Figure 3(a) shows the pseudocode for ESM.

Figure 3(b) shows the estimated results for ESM. Path segments (2) and (3) are considered as stable because the signal strength is greater than Thr_2 and $DSS_2 > 0$. However, a path segment (4), which was considered as an unstable link in ASBM, is considered as a stable link in ESM because the signal strength for v_2 is greater than Thr_1 even two nodes are getting farther apart. In addition, a path segment (5) is also considered as stable in ESM because $DSS_2 > \mu$ even though v_2 is moving toward the outside of the communication range of v_1. However, a path segment (6) is considered as unstable because $DSS_2 < \mu$. Path segments (9) and (10) are considered as stable because $SScum_3 > Thr_2$ and $DSS_3 > \mu$ even though v_3 is moving toward the outside of the transmission range of v_1 when v_3 is on a path segment (10). Furthermore, path segments (12) and (13) are also considered as stable for the same reason.

4 Stable Pseudo-distance Routing (S-PDR) Algorithm

Since link stability continually changes in a MANET, a routing algorithm for such a network should be able to dynamically adapt to link stability changes in selecting a path to each destination. However, most previous algorithms provide only a single path to each destination. Thus, once a path has been selected, new link stability information cannot be used to change the path to the destination. Unlike such rigid algorithms, TORA[6] and PDR[7] provide multiple paths, and a path to each destination can be selected on a hop-by-hop basis. The most recent link stability information for each link can be used in making hop-by-hop routing decisions. Of these two algorithms, PDR is chosen as our base routing algorithm because PDR shows better performance than TORA [7].

Note that there are two types of links in PDR. Primary links are mainly used to route packets along shortest-distance paths. Auxiliary links are used when all primary links are broken. User can select whether auxiliary outgoing link can be used to forward packets or not because auxiliary outgoing links tend to be detour to the destination. PRI is abbreviation of primary only routing that auxiliary links are excluded in routing, and AUX is abbreviation of auxiliary routing that auxiliary outgoing links are included in routing. Note that PRI shows shorter path than AUX but route overhead in terms of control messages are increased than AUX.

PDR provides multiple paths to destination, but it does not take link stability into account. Therefore, we need to modify the PDR algorithm to select stable links. This modified algorithm is referred to as the stable pseudo-distance routing (S-PDR) algorithm. Since S-PDR already requires each node to store information for each of its neighbors, we can simply add a variable that represents stability into this neighbor information table. The "estimated" stability of a link $e_{i,j}$ is updated whenever a node receives packets from its neighbors using one of the estimation models discussed in Section 3. When a node selects its next hop, S-PDR selects a neighbor with the minimum height from among the nodes connected by stable links. If there are no stable outgoing links, S-PDR simply selects a minimum-height neighbor in order to reduce the path length as in PDR. Note that S-PDR can be divided into PRI and AUX parts as same as PDR.

5 Simulation Results

Simulations were conducted to evaluate the performance of the various stability models considered and to evaluate the benefits of routing using stable links. The simulation tool used was ns-2[8], which is a discrete event simulator commonly used in networking research. In order to model wireless connections accurately, the distributed coordination function (DCF) of the IEEE 802.11 standard for wireless LANs was used for the MAC and PHY layers. The data rate was set to 11 Mbps as this is a rate supported by the most common IEEE 802.11b devices.

The simulation scenarios used were based on the following setup. The simulation space was a 500m $\times$ 300m area, and the communication range of each node was set to 130m. The mobility of the nodes was controlled by a mobility generator function in ns-2 that uses a random destination model[5] with 5m/s maximum speed. Finally, the simulation time was set to 130 seconds. A source sends 256 bytes of UDP packet data to its randomly chosen destination every 1 second from 10 seconds after the simulation starts to 125 seconds. Data were collected for ten different simulation scenarios.

5.1 Error Model Used in Simulation

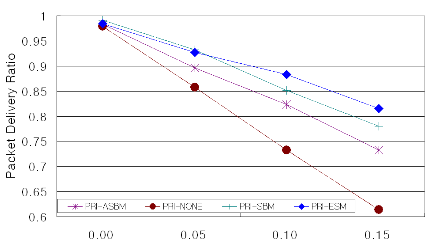
The error model used is a modification of the basic ns-2 error model. Basically, all packets in ns-2 are successfully received if the signal power is greater than the receiving threshold. In ns-2, each node that receives a packet calculates its receiving signal strength $RxPr$ using a propagation model based on a free-space, two-ray ground reflection or shadowing model. If the calculated $RxPr$ is greater than $RXThresh\_$, the threshold of the receiving packet, then the packet is successfully received. However, a packet received with a weak signal strength can easily be corrupted or lost due to various external environment factors such as white noise, wireless interference and other circumstances in actual wireless networks. Therefore, the ns-2 error model was modified to simulate a more reasonable error model. In our implementation, we update the receiving signal strength as $RxPr = RxPr - [0, RXThresh\_ \times MASS]$, where $MASS$ is a floating-point value in [0, 1]that represents the maximum attenuation of the signal strength. If the signal power $RxPr$ is greater than $(1 + MASS) \times RXThresh\_$, the packet is always successfully received. Otherwise, the packet can be lost with a random probability factor. Note that as $MASS$ is increased, the probability of packet loss also increases.

5.2 Performance of Primary Routing (PRI)

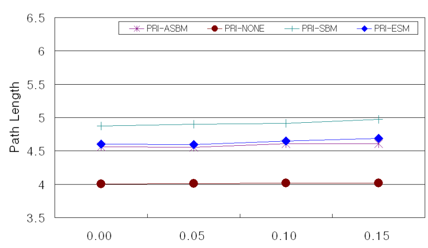
For the simulation, Thr of SBM is set as $1.5 \times RXThresh\_$ and Thr of ASBM is set as $1.2 \times RXThresh\_$. In ESM, Thr_1 is set as $1.5 \times RXThresh\_$, Thr_2 is set as $1.2 \times RXThresh\_$ and μ is set as $-0.3 \times RXThresh\_ \times Thr_2$.

Figure 4(a) shows packet delivery ratio versus $MASS$. The plot for PRI-NONE shows the results for PRI without a stability estimation model, and the PRI-SBM plot shows the results for PRI with the stability estimation model used in SBM. The PRI-ASBM plot shows the results for PRI with the estimation model of ASBM, and the PRI-ESM plot shows the performance of PRI with the estimation model of ESM.

As expected from Section 5.1, the packet delivery ratio is decreased if $MASS$ is increased and vice versa. Because PRI-NONE does not take link stability



(a) Packet delivery ratio



(b) Path length

Fig. 4. Performance comparison of PRI routing using various link stability models

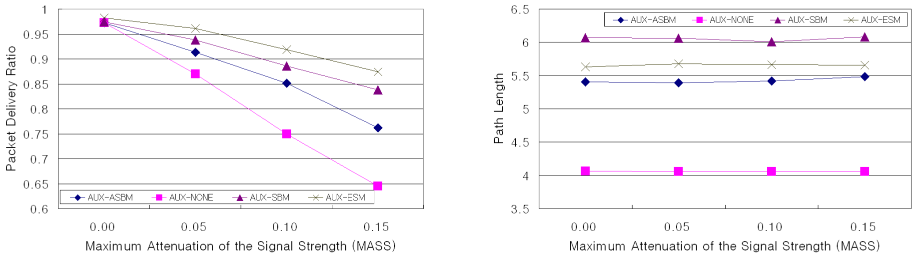
into account, it shows the worst performance in terms of packet delivery ratio. However, since PRI-NONE selects next-hop nodes from among minimum-height neighbors, path lengths produced by PRI-NONE should be the shortest. PRI-ASBM shows the worst performance, in terms of packet delivery ratio, among the stable routing algorithms. Note that the number of stable links are fewer than with other methods because, even if two nodes are very close, ASBM excludes links from the stable link list when $DSS < 0$. The result is that ASBM usually selects its next hop node from among minimum-distance-path neighbors as in PRI-NONE, thereby producing poor performance in terms of packet delivery ratio. However, the performance of ASBM in terms of path length is good. PRI-ESM shows the best performance as $MASS$ is increased because the link stability estimation method used by ESM is very accurate.

Figure 4(b) shows path length versus $MASS$. PRI-NONE shows better performance than all other algorithms because PRI-NONE only selects minimum-distance-path neighbors. As expected, PRI-ASBM shows the best performance among the S-PDR variants in terms of path length because PRI-ASBM tends to select its next hop using unstable links (selecting a minimum-distance-path using those links) because the number of stable links are fewer than with the other methods. Path lengths for PRI-ASBM and PRI-ESM are greater than PRI-NONE because these former algorithms select stable paths even if detours are necessary. PRI-SBM shows the worst performance in terms of path length because the next stable-hop-node is located relatively closer than with other methods. Note that the stable areas for PRI-ASBM and PRI-ESM are larger than for PRI-SBM.

5.3 Performance of Auxiliary Routing (AUX)

Figure 5(a) shows packet delivery ratio versus $MASS$. AUX-NONE performs worst in terms of packet delivery ratio because AUX-NONE does not take link stability into account (like PRI-NONE). AUX-ASBM also performs worst in terms of packet delivery ratio among the stable routing algorithms because the number of stable links is fewer than other methods (like PRI-ASBM). As shown in the figure, AUX-ESM performs best in terms of packet delivery ratio as expected. As $MASS$ is increased, the performance gap between ESM and other methods also increases. ESM outperform all other link stability models considered when the wireless communication channels used become very unreliable. Note that the packet delivery ratio for AUX is greater than that for PRI because AUX routing utilizes more outgoing links — it considers both primary outgoing links *and* auxiliary outgoing links when searching for stable links.

Figure 5(b) shows path length versus $MASS$ for AUX routing. As expected, the path length of AUX-NONE is the shortest, and the path length of AUX-ASBM is the second-shortest as in the PRI case. AUX-SBM performs the worst, in terms of path length, for the same reason as in the case of PRI routing. AUX-ESM performs worse than AUX-ASBM in terms of path length. Nevetheless, the difference in packet delivery ratio, which is our main concern in this paper, favors the AUX-ESM method.



(a) Packet delivery ratio (b) Path length

Fig. 5. Performance comparison of AUX routing using various link stability models

6 Conclusion

In this paper, we propose a new link stability estimation model, termed enhanced stability model (ESM), that can be used to estimate the stability of communication links in MANETs. Analysis of example cases and simulation results show that ESM-based routing tends to perform better than routing using previous link stability estimation models in terms of the ratio of packets successfully delivered to their destinations (packet delivery ratio). Furthermore, as the reliability of the channel gets worse, the relative benefit of ESM-based routing becomes more pronounced.

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