Bridging Nodes Density: A Connection Stability Heuristic for Dynamic Ad-hoc Networks

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Abstract. Wireless ad-hoc networks are commonly supposed to be a key technology for future ubiquitous computing environments. The dynamic nature of such networks demands mechanisms that allow the users to assess the availability of given network connections. In this paper we present a novel connection stability heuristic based on neighborhood information of intermediary network nodes. This heuristic identifies nodes that are able to bridge broken network links and thus improve connection stability. Extensive simulation experiments are presented that show the applicability of the heuristic, even though it does not require any special hardware equipment or exact signal strength measurements. Moreover, it imposes only negligible additional effort for the nodes and for the network.

Keywords: Bridging Nodes, Connection Stability, Quality Assessment, Mobile Ad-hoc Networks, Provider Selection

1 Introduction

Ubiquitous computing environments exhibit a far more decentralized and dynamic structure than traditional computer networks. In order to facilitate ubiquitous network access even in infrastructureless areas, mobile nodes have to form multi-hop ad-hoc networks. Such networks require specialized middleware mechanisms for discovery and selection of suitable providers for needed network services such as internet gateways or peripheral devices.

Due to inevitable radio transmission effects, the Quality-of-Service (QoS) properties of wireless network connections (e.g. available bandwidth or transmission delay) are far more heterogeneous than in fixed networks and should thus be considered for the selection of alternative service providers. Still, existing service discovery systems for dynamic ad-hoc networks (e.g. [1, 2]) do not consider connection properties.

Many popular network services require long-term accessibility of a selected provider. This QoS property is hard to achieve in dynamic ad-hoc networks that generally suffer from instable network connections. However, the authors are unaware of any service discovery or provider selection system that considers connection stability as QoS property. Therefore, a capable connection stability prediction system is needed that reflects the future accessibility of a given service provider. This prediction system can then be integrated into existing service discovery systems to enable stability-aware provider selection.

In this paper, we propose a simple heuristic for the stability prediction of network connections. The heuristic is fairly accurate to support provider selection. The real-world applicability of the corresponding assessment mechanisms was a major design goal. Virtually any mobile node should be able to conduct the assessment procedure independent of its hardware equipment. Moreover, since the bandwidth capacity of multi-hop ad-hoc networks is significantly lower than in wireless infrastructure networks [3, 4], the assessment procedure for the heuristic has been designed to minimize the load it imposes to the network.

The rest of the paper is organized as follows. Section 2 takes a look at existing stability prediction systems and their limitations. In Sect. 3 a path-independent connection stability metric is defined and Sect. 4 presents the actual bridging node heuristic. Section 5 describes an efficient assessment procedure for this heuristic and Sect. 6 demonstrates the applicability for provider selection by simulation of a typical use case. The paper closes with a conclusion and an outlook on future research activities in Sect. 7.

2 Related Works

Over the past years, the stability of network and communication structures in mobile networks has been subject to several research activities. The systems proposed in literature primarily differ in the kind of information they use to assess the stability. In [5] an *affinity* parameter is proposed that tries to predict the lifetime of a communication link, i.e. the direct radio connection between two neighboring hosts, by measuring the corresponding radio signal strength and its variation over time. A strong and relatively constant radio signal indicates a high stability of the link. The stability of a multi-hop communication path is determined by the weakest link of the path, i.e. the link with the smallest affinity. A similar approach is presented and analyzed in [6].

The accuracy of such signal strength measurements suffers inevitably from enormous link quality fluctuations due to transient physical layer effects [7]. These phenomenons are not addressed by the proposed systems and may adulterate the predicted lifetime significantly. The same holds true for the statistical analysis of link and path availability in [8, 9].

In [10] the expiration time of a given link is predicted by the node's location and velocity data. A more sophisticated method for assessing path availability from predicted movement data is presented in [11] (revised in [12]). These approaches circumvent the inaccuracy of signal strength measurements, but assume each node to be equipped with a geolocation system, e.g. a GPS receiver. Although more and more mobile devices have integrated GPS subsystems, especially low-cost devices will most probably miss that feature for the foreseeable future. Besides that, satellite-based geolocation systems tend to fail in indoor environments. Therefore we think that GPS receivers or similar equipment should not be mandatory for stability prediction.

All approaches mentioned above try to estimate the residual time that a given link or routing path will exist. However, if such a path breaks, all relevant routing protocols (e.g. DSR [13] or AODV [14]) for multi-hop ad-hoc networks are able to reestablish the connection over an alternative path – if one is available. Therefore, an instable routing path does not necessarily imply that the communication connection to the destination node is instable as well. Therefore, we distinguish between *path stability*, i.e. the duration that a particular routing path persists uninterruptedly, and *connection stability* which refers to the existence of *any* routing path between two nodes. From the user's or application's point of view the connection stability is obviously far more important than the path stability.

3 Connection Stability Metric

In order to design and evaluate stability prediction procedures, an appropriate metric is needed that reflects the stability of a network connection independent of the actual paths that were used to keep the connection. Figure 1 shows the timeline of a measurement interval starting at t_s and ending at t_e. During this time interval we distinguish between active connection periods where transmissions can take place (marked bold) and passive periods where no route can be established between source and destination. We denote the active period durations by $\Delta t_1, \ldots, \Delta t_k$ for k distinct periods during the measurement interval.

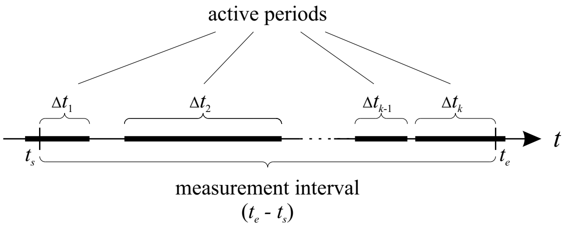

Fig. 1. Transmission timeline

For the following, we propose a connection stability metric $S_c(n_1, n_2)$ that regards the whole measurement interval and describes the fraction of all active period durations within this interval:

$$S_c(n_1, n_2) = \frac{\sum_{i=1}^{k} \Delta t_i}{t_e - t_s} \tag{1}$$

This metric reflects the availability of any communication path between source and destination. The longer a connection can be active during a fixed transmission interval, the more stable is the network connection. Note that the significance of the metric depends on the length of the measurement interval. Too short intervals may result in imprecise stability assessment results. Therefore, we chose a rather long measurement interval of 100 seconds for our simulations.

4 Connection Stability Prediction

In the following, two heuristics will be presented that both allow for efficient and applicable connection stability prediction. They rely on topology information that is available at the nodes of a pre-established network path. The path itself can be determined by an arbitrary routing protocol. This restriction allows for collecting all necessary data by the transmission of a single packet[1] via this path.

4.1 Shortest Path Heuristic

Apparently, the stability of a connection depends significantly on the distance between source and destination. A long distance requires a large number of network nodes to traverse, each of which increases the probability for a – possibly unrepairable – connection failure. We analyzed this interrelationship by simulation of different scenarios with the network simulator *ns-2* [15].

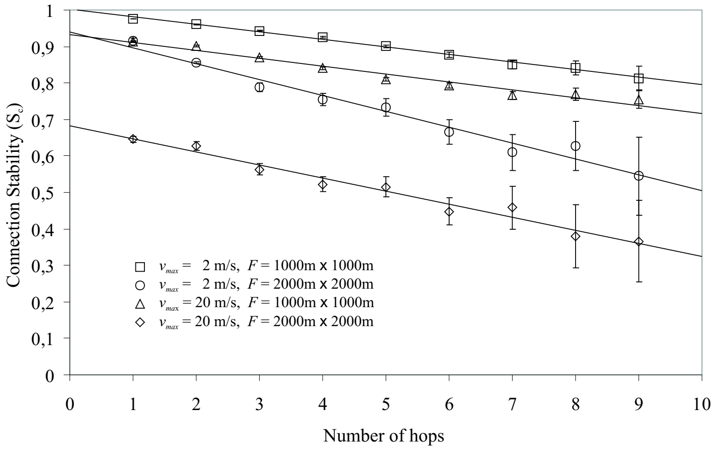

Fig. 2. Impact of path length

For each of the 100.000 simulation runs, 30 nodes were placed randomly on a square area of size F and two of those were picked randomly as source and

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[1] In general, the source node initiates the measurement process and retrieves the result. Therefore, a round trip with two end-to-end transmissions is necessary, but the actual information can be collected by only one of these transmissions.

destination. All nodes move according to the random waypoint mobility model with a maximum speed v_{max} during movement periods and stand still for a maximum pause time of $60s$ in between. After a movement initialization phase a connection is established between source and destination by the DSR routing protocol [13] and the number of hops is counted for the current routing path. In the following 100s, the source node periodically sends packets to the destination node in order to check path availability. Subsequently, the connection stability metric S_c is computed.

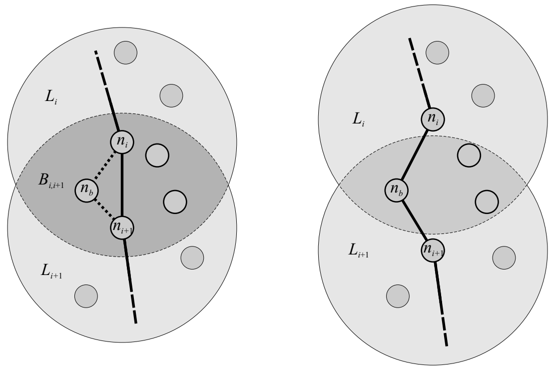
Figure 2 shows the simulation results for four scenarios with an area size of either $F = 1000m \times 1000m$ (dense scenarios) or $F = 2000m \times 2000m$ (sparse scenarios) and a node maximum speed of either $v_{max} = 2m/s$ (pedestrian scenarios) or $v_{max} = 20m/s$ (vehicular scenarios). The error indicators mark the 95% confidence intervals. The connection stability apparently decreases linearly with the number of hops. Hence, the path length heuristic seems to be a viable way to assess connection stability by a single measurement transmission that counts the number of hops between source and destination.

4.2 Bridging Node Density Heuristic

The shortest path heuristic solely relies on direct path information and disregards valuable stability factors that are available at the path nodes. Therefore, we propose a novel *Bridging Node Density Heuristic* which achieves better results throughout all examined simulation scenarios. However, the assessment procedure can still be conducted by a single transmission between source and destination. This reasonable restriction to a single transmission focusses the assessment scope to the neighborhood of the current routing path, i.e. the set of network nodes within the joint transmission range of all nodes the path consists of. However, this neighborhood information allows inference about potential fallback nodes that can fix broken links and thus influence connection stability.

We model a wireless network with N nodes $n_1, \ldots, n_N$ by a set of potential bidirectional links $\{n_i, n_j\}$ for each pair of nodes n_i and n_j that are in each other's transmission range. Without loss of generality we assume the current transmission path to be $p = (n_1, n_2, \ldots, n_P)$ for a path of length $(P-1)$ with source node n_1 and destination node n_P. In order to assess the connection stability between n_1 and n_P, we take a look at each link $\{n_i, n_{i+1}\}$ of the path and identify a set $B_{i,i+1}$ of potential *bridging nodes* that are destined to bridge a potential breakage of this link. Let L_i denote the set of link neighbors of node n_i. Obviously, nodes that are inside the link neighborhood set of both nodes n_i and n_{i+1} are prominent candidates for bridging, so we set $B_{i,i+1} := L_i \cap L_{i+1}$.

Figure 3(a) depicts an active link $\{n_i, n_{i+1}\}$ of a current connection being assessed. The intersection of both transmission areas contains three other nodes including n_b. The node n_b is able to establish links to both n_i and n_{i+1} and is thus a potential bridging node, i.e. $n_b \in B_{i,i+1}$. If n_i and n_{i+1} leave the mutual transmission area (Fig. 3(b)), the link n_i, n_{i+1} breaks, but dynamic routing mechanisms can bridge the resulting gap by replacing it with the links $\{n_i, n_b\}$ and $\{n_b, n_{i+1}\}$. Thus, the bridging node n_b confirms the connection stability.



(a) n_b bridging node for link (n_i,n_{i+1}) (b) n_b bridges interrupted link

Fig. 3. Bridging of link interruptions

The more potential bridging nodes exist, the higher is the probability that a link breakage can be fixed. Hence, the density of potential bridging nodes over the path p is presumably a proper connection stability heuristic:

$$D(p) = \frac{1}{P-1} \sum_{i=1}^{P-1} |B_{i,i+1}| = \frac{1}{P-1} \sum_{i=1}^{P-1} |L_i \cap L_{i+1}| \tag{2}$$

Note that the density is normalized to the path length $P - 1$. This ignores the fact that longer paths are less stable than short path as analyzed in Sect. 4.1. Thus, in order to improve the accuracy of our connection stability heuristic we finally factor in this linear correlation by weighting $D(p)$ with the reciprocal of the path length:

$$D'(p) = \frac{1}{P-1} D(p) = \frac{1}{(P-1)^2} \sum_{i=1}^{P-1} |B_{i,i+1}| \tag{3}$$

The bridging node density heuristic considers the path length as well as the density of potential bridging nodes as stability criterion.

5 Assessment Procedure

As mentioned before, one major design goal was the efficient real-world applicability of the heuristic. For the computation of $D'(p)$, only the path length and the link neighbor sets L_i of all path nodes are needed. The path length can be retrieved by including a counter into the measurement packet and incrementing it at each node of the path. The only information that an intermediary node has to maintain is the link neighbor set. Many routing protocols inherently keep this information for route selection purposes. If the routing protocol does not offer this information, nodes can normally retrieve this information by passively monitoring the network traffic in its vicinity.

As a matter of course, this information has to be propagated to the destination node. If every single link neighbor set is collected and transmitted by the measurement packet, each intermediary node would increase the size of the packet. This might strain network resources significantly – especially for long paths in dense networks. Therefore, we propose to calculate the bridging node density iteratively at each path node, so that only the transmission of a single link neighbor set is necessary.

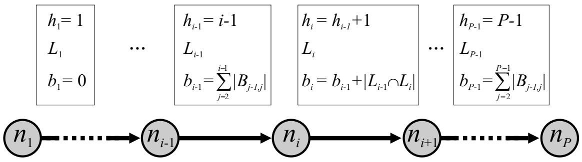


Fig. 4. Measurement Transmission

The procedure is illustrated in Fig. 4. Each path node n_i includes three information entities into the measurement packet: a *hop counter* h_i, the link neighborhood set L_i and a *bridging node counter* b_i. The hop counter is initialized to 1 by the source node and incremented at each intermediary node, so that the destination node n_P retrieves the length $h_{P-1} = P-1$ of the path. Additionally, each node n_i includes its link neighborhood set L_i, which is needed to calculate the bridging node counter. This counter sums up the number of bridging nodes for all path links. Therefore, n_1 initializes $b_1 = 0$. Each intermediary node n_i adds the number of potential bridging nodes $|B_{i-1,i}| = |L_{i-1} \cap L_i|$ for the previous link to the current counter value b_{i-1}. The destination node finally adds $b_P = b_{P-1} + |B_{P-1,P}|$ and is thus able to determine the bridging node density

$$D'(p) = \frac{1}{(P-1)^2} \sum_{i=1}^{P-1} |B_{i,i+1}| = \frac{b_P}{h_{P-1}^2}. \tag{4}$$

The amount of additional data transferred over single links essentially depends on the size of the link neighborhood set of the sending node. This would be a problem only in extremely dense networks which normally do not suffer from stability problems.

6 Performance Analysis

In order to quantify the benefit of the novel stability parameter, we set up a typical use case and analyzed it under different scenarios with the network simulator *ns-2* [15]. The use case is characterized by a user who wants to chose one of ten otherwise identical service providers by the predicted stability of the corresponding connection. Therefore, the user conducts the assessment with each provider and naturally chooses the one with the highest predicted stability.

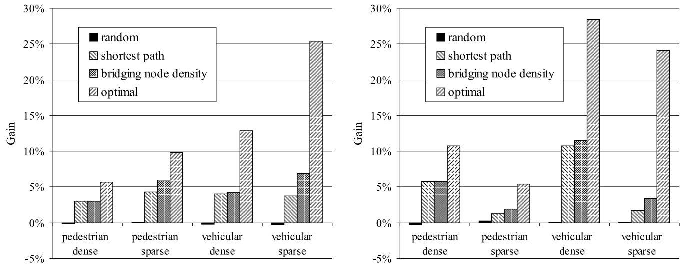
Independently of this choice, we measure the actual stability S_c (c.f. Sect. 3) for all ten connections during an interval of 100 seconds and compare the heuristic's choice to the average stability of the paths.

The general setup of the simulation equals the scenario described in Sect. 4.1, i.e. for each simulation run, 30 nodes with a transmission range of 250m were randomly placed on a square area either of size $F = 1000m \times 1000m$ (dense scenarios) or $F = 2000m \times 2000m$ (sparse scenarios) and were moved according to one of four movement profiles. In detail, we defined a pedestrian scenario (avg. speed $v_{avg} \approx 1m/s$) and a vehicular scenario ($v_{avg} \approx 10m/s$) for the mobility models *random waypoint (RW)* and *manhattan grid (MG)*.

For each simulation run, ten provider nodes and a user node n_u are randomly chosen. After each simulation run, we calculate the actual stability $S_c(n_u, n_i)$ for the connections between n_u and each of the service providers n_i. Let R be the set of providers that are reachable at all during the measurement period and $\hat{n} \in R$ be the provider with the highest predicted stability. Then we can define the gain G of the prediction system for a single simulation run by

$$G := \frac{S_c(n_u, \hat{n}) - (\frac{1}{|R|}\sum_{n_i \in R} S_c(n_u, n_i))}{\frac{1}{|R|}\sum_{n_i \in R} S_c(n_u, n_i)} = \frac{|R| S_c(n_u, \hat{n})}{\sum_{n_i \in R} S_c(n_u, n_i)} - 1. \qquad (5)$$

In order to rank the performance of the bridging node heuristic, we compared its gain to the gain of a system that selects a provider simply by random and a system that solely utilizes the shortest path heuristic (c.f. Sect. 4.1). Furthermore, we calculated the maximum possible gain by considering also a optimal prediction system. This hypothetical system always selects the provider which later proves to offer the most stable connection.



(a) Random Waypoint

(b) Manhattan Grid

Fig. 5. Connection stability gains

Figure 5 shows the simulation results. Unsurprisingly, the random provider selection attains virtually no gain compared to the average S_c stability for any setup. The shortest path heuristic and the bridging node heuristic achieve moderate gains of up to 11.5%. However, the bridging node heuristic achieves about

36% to 61% of the maximum achievable gain for pedestrian networks and 14% to 40% for vehicular networks.

For dense networks, the bridging node heuristic appears to have no noteworthy advantage compared to the shortest path heuristic. Though in sparse networks it significantly increases the gain of the shortest path heuristic by 38% (RW) respectively 58% (MG) for pedestrian scenarios and even by 83% (RW) respectively 96% (MG) for vehicular scenarios. Apparently, the bridging node heuristic reveals its advantages primarily in sparse networks with fast moving nodes, i.e. in highly dynamic networks with very unstable connections. In fact, these are the networks that essentially require a stability prediction system.

The gain of the optimal prediction system varies significantly for different scenarios. The vehicular scenarios apparently allow a higher maximum gain than pedestrian scenarios. The low velocity in pedestrian networks leads to comparatively stable connections: nearly 40% of all connections are available for more than 90% of the interval. Therefore, a stability prediction system has just a small margin for the gain. In contrast, vehicular scenarios exhibit a more instable behavior which allows the prediction systems to achieve higher gains.

Generally, the stability behavior of a connection depends on the mobility profile. For instance, gains increase with the node density in our Manhattan Grid networks, but interestingly decrease with the density in Random Waypoint networks. Anyway, movement scenarios that were used for the analysis distribute the nodes more or less evenly over the specified area. In reality, ad-hoc networks are supposed to exhibit a far more heterogeneous distribution with very dense areas (e.g. crowded city streets) and significantly sparser areas (e.g. backyards). The bridging nodes heuristic obviously prefers stable connections through dense areas. Therefore we can assume that the bridging node heuristic will perform even better in such real-life networks.

7 Conclusions and Outlook

In this paper we proposed a novel connection stability heuristic based on information about nodes that can potentially fix broken transmission links. The main advantage of this heuristic compared to traditional systems is the efficient real-world applicability of the assessment procedure. It neither requires special hardware equipment nor relies on inaccurate and transient signal strength measurements. Moreover, it only needs a single measurement transmission and the iterative calculation procedure additionally saves sparse communication resources.

Simulation experiments demonstrated the applicability of the heuristic for QoS-aware provider selection. Apparently, the bridging node heuristic gives a fair improvement for connection stability in comparison to random provider selection. Especially in sparse networks with fast moving nodes and instable connections, the bridging node heuristic outperforms the path length heuristic and legitimates the marginal overhead.

The bridging nodes heuristic inevitably requires information from intermediary nodes. Since transport and application layer protocols generally have no access to intermediary node information, routing layer support is needed. Therefore, future work will include the practical integration of the assessment procedure into existing ad-hoc routing protocols and the approvement of accuracy by the consideration of spatial and temporal density fluctuations.

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