Encounter-based Message Broadcasting in Ad Hoc Networks with Intermittent Connectivity

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I. Introduction

Most works on performance analysis studies on packet delivery mechanisms in ad hoc networks are done in scenarios in which nodes are always on. In this work we revisit this assumption and find that nodes display on-off usage pattern in current wireless networks. Such on-off usage pattern could significantly hinder packet delivery in the network. It is also well studied that mobility of nodes in ad hoc networks has significant influences on protocol performances [2]. Both on-off usage pattern and mobility pose difficulties for traditional path-based routing protocols, such as DSR or AODV, to work efficiently. These path-based routing protocols first try to find an end-to-end path to the packet receiver before sending out the packet. In highly mobile scenario route discovery and maintenance becomes increasingly difficult due to frequent topology changes. In scenarios with on-off usage pattern, a node could be off-line and path leading to the node does not exist.

Therefore, end-to-end path-based routing paradigm may not be the best one in these scenarios. The delay tolerant network (DTN) paradigm has been proposed to deal with message delivery in scenarios where network partition is a normal network dynamics rather than abnormality [1]. In DTN paradigm, packets are sent from the sender without knowing any path leading to the receiver. Instead, the sender delivers the packet to other nodes that may have a chance to deliver the packet to the receiver at a later time. This is a different paradigm to traditional path-based routing as follows: In path-based routing paradigm packets are delivered only in space domain during a short time interval, while in DTN packets are disseminated through node mobility and pair-wise encounters followed by packet exchanges between nodes during a longer time frame.

In this work we revisit a simple application of delivering broadcast messages in a wireless ad hoc network. Instead of assuming always-on scenario with synthesis nodal mobility patterns, we adopt a more realistic network model derived from wireless network traces. The network trace captures both underlying on-off usage pattern and mobility pattern of nodes. In such realistic environment, we discover that message broadcasting is no longer trivially achievable by simple flooding in space domain since off-line nodes can't be reached. Repeated flooding could be used, but it incurs high overhead to give intermediate delivery success rate. On the other hand, DTN paradigm is more suitable in this realistic setting as it increases the success rate of disseminating a broadcast message at a reduced transmission count, in comparison to traditional flooding in space domain. In addition, DTN paradigm also has the strength that its does not suffer severe performance degradation even if 40% of nodes in the network are selfish and uncooperative in message forwarding. The robustness of DTN paradigm stems from the underlying SmallWorld structure of encounter patterns in the network model.

The closest work to ours in the literature is [5], in which the authors give out PDAs to students to carry and study their encounter patterns. They capture all encounters among nodes using always-on devices, in contrast to our trace-based approach, which only captures encounters when nodes are turned on and observed in the trace.We argue that on-off usage pattern will still be unavoidable in the foreseeable future and putting usage patterns into consideration will more realistically reflect the behavior of users. Another benefit of the trace-based approach is that it allows larger campus-wide scale study than the experiment in [5], which focus on about 20 students taking the same class.

II. Network model of encounters

2.1 Building encounter model from wireless network trace

In this work, we build a network model with focus on nodal encounter pattern. We make use of the on-off and association pattern with access points (APs) of mobile nodes (MNs) in an 802.11 wireless network trace to derive the encounter pattern. We use the following simple definition of encounters between MNs: If 2 MNs appear at the same AP during overlapped time we refer to this as an *encounter* between 2 MNs in this paper. We also use the coordinates of the AP a MN is currently associated with as an approximation for the coordinates of the MN when we derive space distance between MNs.

In this work we use wireless network traces from Dartmouth University [4]. We use 2-week's worth of trace from Dartmouth University between March 1st and March 14th 2004. There are totally 4618 nodes in the trace during this time frame.

2.2 On-off usage pattern and spatially limited visit pattern

We first observe the on-off usage pattern from the trace. Online time fraction of mobile nodes is quite uniformly distributed, ranging from less active users who are online for only several minutes to aggressive users who are online almost all the time. There are about 65% of nodes being online for less than 50% of total time. This supports the argument that on-off behavior is an essential characteristic of current wireless network users. We also observe that in any of the network snapshots taken every 30 minutes at most only about half of the nodes are simultaneously online and the online user population displays clear diurnal pattern. This indicates a single-shot flooding in space domain can at most reach only half of the total population, if there is no network partition. Hence single-shot flooding in space domain is certainly not enough to effectively send out a broadcast message.

We further look into the number of APs a MN visits. It turns out that most MNs do not access a large portion of APs during the trace time frame.Among the total of 623 APs, the most aggressive MN visited 93 APs through the 2-week trace period, and on average a node visits 9.17 APs during this time frame. It indicates that current wireless network users are quite spatially limited in locations where they use the devices.

2.3 SmallWorld by encounters

Given that mobile nodes do not stay online for large time fraction, and they visit only a small portion of APs when they are online, one may doubt that if it is possible to have enough encounters among mobile nodes to propagate messages. To investigate this question, we define static *encounter relationship graph* as follows: During the 2-week trace period, if 2 nodes have encountered as least once, we draw a link between them on the static encounter relationship graph. This link indicates a potential chance to exchange messages between these 2 nodes, and we use the concept of encounter relationship graph to study the structure of encounters between MNs. The methodology we chose to analyze these encounter relationship graphs follows the SmallWorld concept introduced by Watts et al. first in [4].

The result of this analysis is encouraging since it indicates encounters of MNs form a connected network with SmallWorld property. The largest connected part of the graph contains 4586 nodes, with average out degree 183.21. The clustering coefficient and average path length are 0.4293 and 2.3291, respectively. Clustering coefficients for regular and random graphs with the same node degree are 0.7459 and 0.0401, respectively. Average path lengths for regular and random graphs with the same node degree are 12.5157 and 1.6167, respectively. This implies although nodes display diurnal on-off usage pattern and visit small portion of APs, the underlying structure of encounters among nodes still provide a network with rich inter-connections that could be utilized to deliver messages.

III. Comparison of message broadcasting mechanisms

3.1 Message broadcast mechanisms in ad hoc network

In this paper we focus on a specific type of application: Broadcasting a copy of announcement message to every node within the network. We compare three different mechanisms of propagating broadcast messages in a network and compare their performances using the network model derived from the wireless network trace. The first mechanism is simple message flooding from the sender through connected part of the network in space. We use the simple disk model to determine connectivity of nodes in space. If two nodes are within a certain threshold distance, we assume that they are able to communicate with each other through space. In the performance analysis we assume the threshold to be 200 meters. To overcome the problem of some nodes are off at the time when the broadcast message is sent, the sender will try to rebroadcast the message every 2 hours if it is online.

The second mechanism in the comparison is to propagate the message via encounters only. In this mechanism, the sender and nodes that already received the announcement message keep looking for potential recipient when they are online. If they encounter another node that has not got the message yet, they forward the message to the recipient. In this mechanism the message follows the nodes movement and gets disseminated via encounters, but they are not propagated in space via long-range transmission. (i.e. Nodes can only send messages to others if they are at the same location) We refer this mechanism as encounter-based forwarding below.

The third mechanism is to propagate the message in both space and time, referred as 2-dimensional forwarding below. The nodes that have received the message keep looking for recipient of the message, not only via encounter at its current location, but also in other neighboring locations in space within its 200 meter radio transmission range. This mechanism is a combination of the 2 above mechanisms and is the most aggressive one.

We compare the performances of the three mechanisms by observing broadcast delivery percentage and total message transmission counts. We use the following traffic patterns to compare the mechanisms for broadcast message delivery: We pick the top 500 nodes in online time ranking as senders of broadcast messages and each of them send out one broadcast message when they first come up online. We ignore the constraints such as collision of transmission and storage space of nodes at this stage, and focus on the performance of message delivery mechanisms in ideal case.

3.2 Performance evaluation of announcement mechanism

The average number of announcement messages received for all nodes in the network and the total number of transmissions performed to deliver these messages for each mechanism are shown in Table 1. As we can observe from the figures, 2-dimentional forwarding achieves the highest message delivery rate. Encounter based forwarding has performance close to 2-dimentional forwarding. Flooding in space domain, on the other hand, has lower message delivery rate. This is because periodical broadcasts miss those potential receivers who are not on line at sending times, and this is likely to happen for nodes that are online with small time fraction. Of course, one could propose to shorten re-broadcast period to increase the message delivery rate. However, this introduce even more transmission count, aggravating the overhead that already makes flooding a less preferable choice among the three mechanisms, especially for mobile networks in which nodes have stringent power constraint. Encounter-based forwarding and 2-dimensional forwarding by far outperform flooding in terms of transmission count. This is due to the inherent wastage in flooding that a node can receive duplicate copies of the same message for many times in order to propagate the message in space. On the other hand, in the other two forwarding mechanism each message is received only once for each receiver.

Forwarding mechanism	Average messages received per node	Total transmission count
Repeated flooding	447.776	199566725
Encounter-based	493.711	17335680
2-dimentional	498.726	4485040

Table 1. Comparison of performance metrics

3.3 Robustness of encounter-based forwarding

In this section we look further into encounter-based forwarding. Specifically, we study the impact of selfish users on message delivery performance. In the simulation experiment, we make a portion of users selfish such that it sends message for itself and receives message from others but never forward messages for other sources. We find that performance of encounter-based message forwarding is quite robust to the reduction of transmission opportunity due to user selfishness as follows.

In the following simulation we change up to 40% of nodes to selfish mode and show the distribution of number of message transmissions required to deliver the message in encounter-based forwarding. In Fig. 1 we observe that although messages are forced to take longer alternative path as number of selfish nodes increases, performance does not degrade much. The performance degrades gradually when the percentage of selfish node increases. The average unreachable node for a given sender increases from 58.1 to only 120.21 when selfish nodes increase from 0% to 40% and this translates to decrease of average received message for a receiver from 493.711 to 486.985. At meantime, the average transmission count from sender to receiver count increases from 7.60 hops to 8.77 hops. This result is mainly due to the SmallWorld structure of encounters of MNs. One property of SmallWorld network is its robustness in terms of connectivity against node removal. Hence in encounter-based forwarding, even if some nodes are not cooperative to forward the broadcast messages, it is still likely for the messages to reach a large portion of the network through other encounter chances.

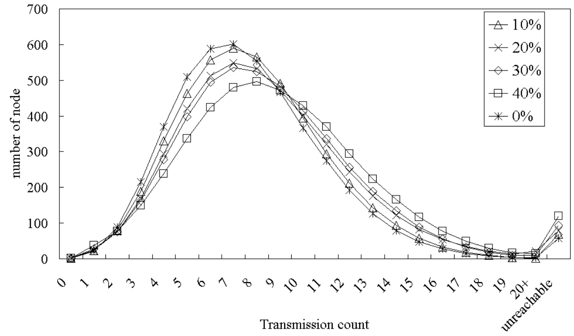

Fig. 1. Distribution of average transmission count with increasing percentage of selfish nodes

V. Conclusion and future work

In this work we investigate the mechanisms of delivering broadcast messages in ad hoc network. We use a realistic wireless network trace to derive the network model of the ad hoc network, which encompasses all of underlying factors such as node movement, on-off usage pattern, etc. From the wireless network trace, we first observe on-off usage pattern is an important characteristic of current users, and flooding in spatial domain alone fails to deliver broadcast messages to the majority of nodes, even if flooding is performed repeatedly. On the other hand, encounter-based forwarding schemes that fall into the DTN paradigm are able to deliver messages to much larger proportion of nodes at a reduced transmission overhead. We further show performance of such encounter-based forwarding scheme does not degrade too much when an intermediate proportion of nodes are selfish.

In the future we plan to study the influences of mobility and usage patterns on encounter patterns in wireless networks, and build models for encounter based on the study.

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