Every Node Is Born Equal: Attacking Preferential Attachment in Peer-to-Peer Mobile Multihop Networks

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Abstract— A mobile peer-to-peer (P2P) network must guarantee a balanced utilization of the equal-capacity nodes; otherwise it may result in early death of overloaded nodes due to their battery exhaustion. It not only means a discontinuation of certain services offered by them but also causes other services to be disconnected. This is because every node plays an important role as a router in multihop mobile ad hoc networks (MANETs) by participating in a routing protocol to decide the route as well as to forward packets on other nodes' behalf. However, it is observed that mobile nodes in a MANET do not undertake the role of packet forwarding responsibility uniformly. This non-uniformity may incur numerous troubles in the network mostly related to over-dependence of routing functionality on the influential nodes. For example, those influential nodes can be easily exhausted their battery power than ordinary nodes. Anomaly in routing performance which was found but not explained in a number of previous studies is also due to this non-uniformity. This paper defines role number of a node as a measure of the extent to which the node lies on the paths between others, shows the role number distribution in a MANET, investigates why it happens with two most popular routing protocols, Dynamic Source Routing (DSR) and Ad-hoc On-demand Distance Vector (AODV), and poses an open question on how to produce a network with equal responsibility.

Index terms - mobile ad hoc networks; on-demand routing protocols; role number; node degree; network lifetime.

I. INTRODUCTION

Peer-to-peer (P2P) computing over multihop *mobile ad hoc networks* (MANETs) will become an essential part of future computing environment with advances in wireless communication and multihop networking. Equal-capacity nodes collectively share resources and offer services using a multihop routing software such as *Dynamic Source Routing* (DSR) [1] or *Ad-hoc On-demand Distance Vector* (AODV) [2]. However, a mobile P2P network must guarantee a balanced utilization of the equal-capacity nodes; otherwise it may result in early death of overloaded nodes due to their battery exhaustion. It not only means a discontinuation of certain services offered by them but also causes other services to be disconnected. This is because every node plays an important role as a router in multihop MANETs by participating in a routing protocol to decide the route as well as to forward packets on other nodes' behalf.

In an ideal case, each mobile node has complete information on *single-source shortest paths* from the node itself to all possible destinations and they collectively constitute *all-pairs shortest paths*. Practically, each node keeps a subset of the paths in different forms based on the underlying routing algorithm. In AODV, each node keeps the next hop node and the number of hops to the destination. And in DSR, each node maintains the entire path information including all intermediate nodes. It is hoped that a routing algorithm renders the nodes to discover a set of paths that utilize the nodes uniformly with respect to packet forwarding responsibility. In order to quantitatively assess this, we define *role number* of a node as a measure of the extent to which the node lies on the paths between others[1]. The role number can be considered as a measure of the influence, importance or popularity of the specific node when forwarding packets in a MANET. For example, for a MANET with N nodes and an average path length of L hops, there would be a maximum of $N(N-1)$ paths and thus $LN(N-1)$ hops. The best case scenario is that each node undertakes the role of routers for $L(N-1)$ paths.

Based on our simulation study discussed later in this paper, mobile nodes in a MANET do not exhibit uniform role numbers among themselves. One might think it is closely related to *node degree*, the number of direct neighbors within a node's communication range, because having more neighbors generally means more paths leading to the rest of the network. However, as long as the network is reasonably populated, the experimental results show that this is not necessarily true. Closely located two nodes, whose node degree is almost the same, often have an order of different role numbers. Instead, its statistics follow more like a heavy tailed distribution, where some nodes show extremely large role number. This non-uniformity may incur numerous troubles in the network mostly related to over-dependence of routing functionality on the influential nodes. For example,

[1] N. E. J. Newman defines a similar centrality measure called *betweenness* to study the random walk behavior on a random graph [3].

those influential nodes can be easily exhausted their battery power than ordinary nodes. Another undesirable case happens when those influential nodes move. All of its neighbors have to go through time-consuming route discovery procedure all at once because most of routing information becomes obsolete since the key node is missing. It is also bad for network security because the influential node makes up the single point of failure and offers a highly effective target of the attack.

This paper shows the role number distribution in a MANET, investigates why it happens with two most popular routing protocols, DSR and AODV, and poses an open question on how to produce a network with equal responsibility. The paper is organized as follows. Section II overviews the two on-demand routing algorithms. Section III introduces the concept of role number and shows the corresponding statistics as well as correlation between the role number and node degree based on experimental results. Many undesirable outcomes due to unbalanced role number distribution as well as possible solutions are also discussed. Finally, Section IV makes concluding remarks and describes future work.

II. BACKGROUND

A MANET consists of autonomous, self-organizing and self-operating nodes, each of which communicates directly with the nodes within its wireless range or indirectly with other nodes via a dynamically computed, multi-hop route. Routing is one of the key issues in MANETs due to their highly dynamic and distributed nature. In order to facilitate communication within a MANET, an efficient routing protocol is required to discover routes between mobile nodes. The routing protocols proposed for MANETs are generally categorized as *table-driven* and *on-demand driven* based on the timing of when the routes are updated. With table-driven routing protocols, each node attempts to maintain consistent, up-to-date routing information to every other node in the network. This is done in response to changes in the network by having each node update its routing table and propagate the updates to its neighboring nodes. Thus, it is *proactive* in the sense that when a packet needs to be forwarded the route is already known and can be immediately used. Many routing protocols including *Destination-Sequenced Distance Vector (DSDV)* [4] and *Fisheye State Routing (FSR)* protocol [5] belong to this category. With on-demand driven routing, routes are discovered only when a source node desires them. Since it reduces the routing overhead significantly particularly when data traffic is light, we concentrate on on-demand routing protocols. The following two subsections describe DSR and AODV, which are the most popular and highly efficient on-demand protocols.

A. *DSR routing protocol*

When a node has a data packet to send but does not know the routing path to a destination, it initiates the *route discovery procedure* by broadcasting a control packet called RREQ (*route request packet*). When a RREQ reaches the destination, it prepares another control packet called RREP (*route reply packet*) and replies back to the source with complete route information. Upon receiving a RREP, the source begins transmitting data packets to the destination but at the same it saves the route information in its *route cache* for later use. Since data transmission in wireless networks is broadcast in nature, intermediate relaying nodes as well as other nearby nodes also learn the path to the destination via overhearing. Therefore, the number of RREQ packets can be minimized because a node may have a learned path to a destination in its route cache. Route cache reduces the number of RREQ packets even further by allowing an intermediate node to reply to a RREQ if it has a path to the destination. This prevents network-wide flooding of RREQ packets.

Since nodes move unpredictably in a MANET, link errors occur and the route information that includes a broken link becomes obsolete. When a node detects a link error during its communication attempt, it sends a control packet called RERR (*route error packet*) to the source and eliminates the stale route out of its route cache. On the way to the source, RERR informs nearby nodes about the erred link so that they can also eliminate the path including the broken link.

B. *AODV routing protocol*

AODV [2] uses the concept of route discovery and route maintenance mechanisms from DSR but uses the concept of sequence numbers, hop-by-hop routing and periodic beacons (i.e. *Hello* messages) from DSDV [4]. As in DSR, routes to the destination are only discovered when required but, unlike DSR, nodes do not maintain a route to a node until the two nodes need to communicate with each other. AODV uses destination sequence number, which is generated by the destination node for each route entry to ensure loop-free routing path and freshness of the route. It uses RREQ, RREP and RERR as in DSR.

A key differentiating feature of AODV apart from DSR is that it maintains *route table* instead of route cache. The route table of a node maintains entries for each destination the node is interacting with or forwarding packets to. The routing table has the following fields: *Destination IP address*, *Active neighbors*, *Number hops*, *Next hop*, *Destination Sequence Number*, and *Expiration time for the routing table entry*. They help the node to maintain the connectivity of the network. The expiration time associated with the route depends on the size of the ad-hoc network and indicates the time after which the route to that associated destination in the route table is to be removed. The node maintains the list active neighbors that are the next hop to the destination associated in the route table, thus if a link to this active neighbor is broken the node can immediately broadcast RERR messages.

In AODV, a node broadcasts Hello messages periodically at a default rate of one per second, to maintain connectivity. These messages contain the nodes identity and sequence number to its neighbors so that its neighbors can update their local connectivity to the node that broadcasted the Hello message. It can assume the link is broken and can broadcast a REER packet to its neighbors regarding the link failure.

Other methods to maintain link connectivity are used, like physical and link layer methods to detect link breakages to nodes that it considers neighbors.

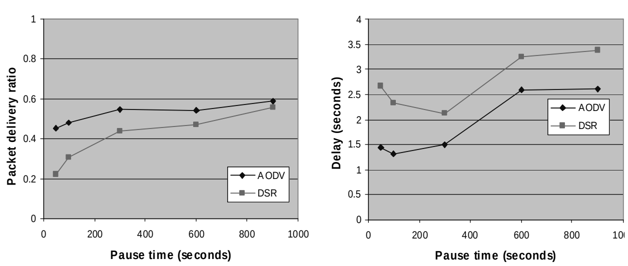
III. ROLE NUMBER AS A MEASURE OF PACKET FORWARDING FUNCTIONALITY

In this section, the role number distribution is uncovered using the *ns-2* network simulator [6], which simulates node mobility, a realistic physical layer, radio network interfaces, and the IEEE 802.11 *medium access control* (MAC) protocol [7, 8]. Section III.A discusses an anomaly found but was not understood clearly in previous studies. We argue that this is due to the non-uniformity of role number among the nodes. Sections III.B and III.C describe simulation results using a small, dynamic and a large, static network, respectively.

The radio transmission range is assumed to be 250 m and a *two-ray ground propagation channel* is assumed with a data rate of 1 Mbps. The *Request-to-send/Clear-to-send* (RTS/CTS)-based MAC algorithm is used with the conventional backoff scheme. The AODV and DSR routing algorithms are used to find and maintain the routes between two end-nodes. Mobility pattern of mobile nodes follows the *Random Waypoint Model* [1], where node speed is chosen randomly between 0 to 20 meters/second and pause time is 50, 100, 300, 600 and 900 seconds. Total simulation time is 900 seconds and thus, 900 seconds of pause time means a static network. These parameters are the same as used in [9]. Buffer queue is 64 bytes.

A. Anomaly in routing performance

In this subsection, we assume that the network consists of 50 mobile nodes located over an area of 1550×300 m^2. Data traffic simulated is *constant bit rate* (CBR) traffic: 40 CBR sources generate three 512-byte data packets every second and the corresponding destination nodes are randomly selected.



(a) Packet delivery ratio (%) (b) Packet delay (seconds)
Figure 1: Network performance with varying pause times (50 nodes in 1550×300m^2 area).

Figure 1 shows the general network performance, packet delivery ratio and packet delay with varying pause times. An interesting observation with this simulation result is that packet delay increases as node mobility decreases as shown in Figure 1(b). The same phenomenon was also reported in [9] and the authors explained that this is due to a higher level of network congestion and multiple access interferences at certain regions of the ad hoc network. However, this explanation is not enough. If it is due to a particular node placement, it should not happen with every simulation instance. However, a number of simulation runs offer the similar phenomenon leaving us wondering the cause of this anomaly in routing performance.

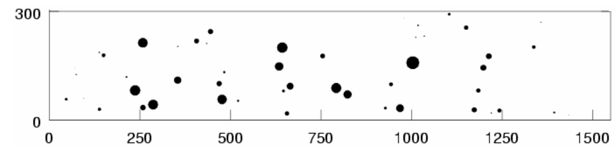
B. Construction of route information

Now, we explain that this anomaly is caused by non-uniform role number distribution. And, in turn, the ingredient of the non-uniform role number distribution is "*preferential attachment*" [10] in the dynamics of routing information construction together with the *expand ring search* algorithm used in both AODV and DSR protocols. Assume that a node, say node *S*, has built a large routing table that includes routing information to a number of destination nodes. When a neighboring node, say node *T*, wishes to discover a route to one of those destinations, node *S* would supply the desired information to node *T*. Thus, node *S* becomes an intermediate node for the route from node *T* to the destination and node *S* becomes to have an additional entry from itself to node *T*. In other words, an influential node becomes more influential as time goes by.

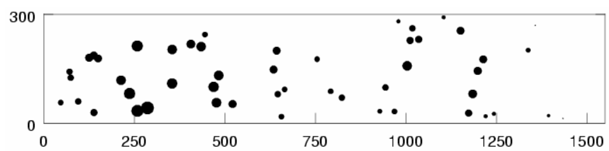
Before presenting the experiment results on the role numbers, we discuss the dynamics of route information in AODV and DSR routing protocols. AODV is basically a pessimistic approach in the sense that any route information is abandoned as invalid if that information is not used for a short predefined amount of time (6 seconds in our simulation). Upon a route discovery request, AODV at first causes single-destination shortest paths (from all nodes to the source) because of the reverse path setup by intermediate nodes, and thus adds (*N-1*) role numbers. However, all those information is dropped after a certain time period (6 seconds in our simulation) but the nodes along a selected route keep the path information to the destination. Therefore, for a route discovery, AODV adds on the average *L* role numbers (one each from an intermediate node to the destination).

On the other hand, DSR is an optimistic algorithm where every route information, obtained during its route discovery process as well as via overhearing, is kept until it becomes invalidated by receiving a corresponding link error message. In addition, since DSR uses the source routing, it also extracts many partial routes from a given source route. In DSR, one route discovery generates *(N-1)* route request messages (excluding the destination) and each node receives the messages from all of its neighbors, say *d*. Since each message includes a source route from the source node, DSR adds *dL(N-1)* role numbers per route discovery.

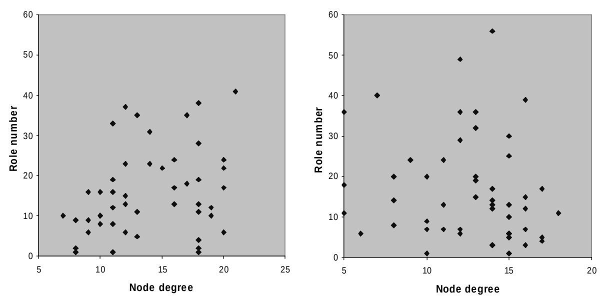
Both AODV and DSR facilitates the process of preferential attachment via the expand ring search. In DSR, upon a route discovery request, a node first requests to its direct neighbors whether or not they have the route to the destination. If one of them replies with the desired route, the node uses the route and thus the answering node becomes more influential. Otherwise, the node floods the request to the entire network. In AODV, since nodes do not keep many routing information in their routing table, expand ring search starts with more than one hop neighbors (5 hops in our simulation). Then, expand the searching ring a little bit more (7 hops in our simulation) and finally, resort to the network-wide flood. This process again facilitates the non-uniform role number distribution even though it is not as much intensive as in DSR.



(a) Role number distribution (pause time=50 sec.)



(b) Node degree distribution (pause time=50 sec.)



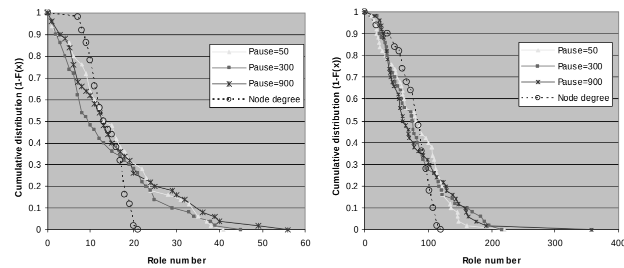
(c) Pause time=50 sec. (d) Pause time=900 sec.

Figure 2: Node degree and role number distribution (AODV, 50 nodes in 1550×300m^2 area).

C. *Experiments with a small, dynamic network*

Figure 2 shows the simulation results on role number distribution. The role number of a node is calculated in the following manner. At the end of the simulation, each node's routing table (or route cache) is searched to find intermediate nodes when a packet is delivered to every possible destination. In case of AODV, since only the next hop node is stored in the routing table, we only count one node per route. In DSR, since entire path information is stored in the route cache, we count on the average of L nodes per route leading to larger role numbers than AODV. Figure 2(a) depicts the role numbers, represented by the size of the circle, with AODV when pause time is 50 seconds. Figure 2(b) shows the node degree distribution with AODV and pause time of 50 seconds. Comparing Figures 2(a) and 2(b), a higher degree node does not necessarily have a higher role number, which is clearer with Figure 2(c). Figure 2(d) shows the same relationship with pause time of 900 seconds (static network). Comparing Figures 2(c) and 2(d) shows that the situation can be worse with the static network because of the node with an extremely high role number. Simulation with DSR shows the similar results.

Figure 3 shows the cumulative density function of role number distribution while contrasting with of node degree. As in Figure 2, some nodes possess very high role number with pause time of 900 seconds for both DSR and AODV but the cumulative distribution of node degree drops sharps showing that it follows conventional Poisson distribution.



(a) With AODV (b) With DSR

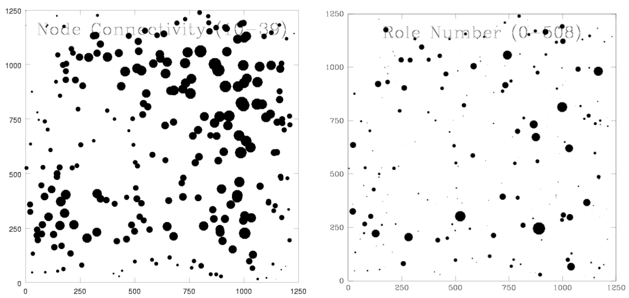
Figure 3: Cumulative distribution with varying pause times (50 nodes in 1550×300m^2 area, Node degree measured with pause time of 50 seconds and normalized to have the same mean value as role number).

D. *Experiments with a large, static network*

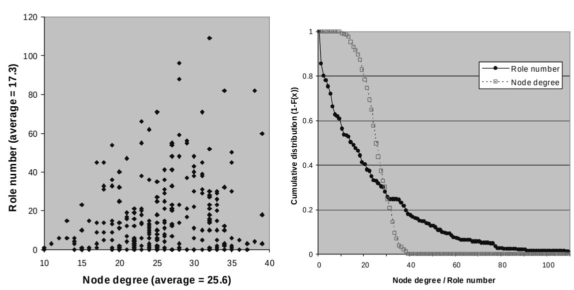
The role number distribution would be much more unbalanced if network size is large and ode mobility is low. This subsection focuses such a case. The static network consists of 250 mobile nodes located over an area of 1250×1250 m^2. 250 CBR sources generate 256-byte data packet every 5 second. A light traffic is used in our experiment because our primary interest is route pattern established in each node rather than general network performance. Every node generates the CBR traffic and the corresponding destination node is randomly selected among the rest 249 mobile nodes.

Fig. 4 shows the spatial location of the 250 static nodes as well as their node degree and role numbers. In Fig. 4(a) shows the node degree with ten different sizes of circles; i.e., each node is connected to 10~39 neighbors depending on their location in the network. Nodes with 10~13 neighbors are drawn with the smallest circle, nodes with 14~16 neighbors with a bit larger circle, and so on. It is clear that nodes in highly populated area usually have a high node degree. Fig. 4(b) shows the role number of the 250 mobile nodes. Again, nodes are marked with the circle whose size corresponds to its role number: The largest circle denotes the most influential node with respect to routing (role number between 90~109). A node whose role number is in between 0~10 is not drawn in the figure (circle size = 0) but the number of nodes in this category is 123, about the half of total number of nodes. Nodes in sparse area hardly have a large role number but the reverse is not always true. In other words, nodes in densely populated area may have a large role number but many of them have a very small role number as shown in Fig. 4(b).

This is clearly shown in Fig. 5. According to the scatter plot of the node degree and the role number in Fig. 5(a), it can be concluded that the node degree and the role number of a node are two independent measures. In addition, as depicted in Fig. 5(b), they show a quite different distribution pattern as before. Node degree distribution pretty much follows the Poisson pattern while the role number follows a heavier-tail distribution than Poisson meaning that a few nodes take an extremely big responsibility of forwarding traffic than ordinary nodes. In this particular example, while the average role number is 17.3, there are five nodes whose role number is greater than 80: 109, 96, 88 and two 82's (see Fig. 5(a)).



(a) Node degree distr. (b) Role number distr.
Figure 4: Node degree vs. role number distribution in a static MANET (AODV, 250 nodes in 1250×1250m^2).



(a) Scatter plot (b) Cumulative distribution
Figure 5: Node degree and role number statistics in a static MANET (AODV, 250 nodes in 1250×1250m^2).

IV. CONCLUSION AND FUTURE WORK

Routing is one of the key issues in MANETs due to their highly dynamic and distributed nature. In order to facilitate communication within a MANET, an efficient routing protocol is required to discover routes between mobile nodes. Among them, on-demand routing protocols, such as AODV and DSR, are regarded highly efficient because routes are discovered only when a source node desires them and thus reduces the routing overhead significantly particularly when data traffic is light. This paper observes and proves via simulation that these on-demand algorithms possess an undesirable characteristic; i.e., each mobile node takes the unequal responsibility in terms of packet forwarding functionality. It is also shown that the load unbalance is more significant when the network is large and node mobility is small, which is the case in many potential mobile P2P applications. It is found that the non-uniformity is caused primarily by preferential attachment in the dynamics of route information construction in each node together with the expand ring search algorithm used in AODV and DSR protocols. Numerous troubles may arise due to the existence of overloaded nodes such as the reduction in network lifetime and presence of single point of failure.

The study in this paper opens important problems in mobile multihop networks. First, we are going to investigate the relationship of the role number with other network parameters such as node degree to have a better understanding of the dynamics of routing algorithms. Second, since nodes with high role numbers naturally construct a routing backbone, load unbalance leads to a natural clustering of nodes in the network. It is an interesting question how we can exploit this to construct cluster architecture without taking extra efforts. Third, a new routing algorithm needs to make a load balance among the nodes without causing any performance penalty and extra overhead. It should diversify next hop connections when a node decides routing paths to other nodes. It may result in a little longer route but could improve overall performance. Fourth, we will study the similar phenomenon occurs with proactive routing algorithms such as DSDV and FSR.

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