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Hitting time analysis for a class of random packet forwarding schemes in ad hoc networks ☆

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ABSTRACT

In this paper, we study the problem of searching for a node or a piece of data in an ad hoc network using random packet forwarding. In particular, we examine three different methods. The first is a random direction forwarding scheme where the query packet is forwarded along a randomly chosen direction (following an approximate straight line) till it either hits the destination node (the target) or the boundary. It bounces off the boundary in the latter case and the process continues till the target is found. In the second approach, in addition to query packet traversing the network, the target releases an advertisement packet that propagates along a randomly chosen direction so that all nodes visited by the advertisement packet obtain and store the target location information. In the third method the query packet is assumed to follow a random walk type of forwarding. Our primary interest is in comparing the average hitting time under these methods and the memory required to store location information. In particular, we show that under the random direction forwarding the target hitting time is $\Theta\left(\frac{a^2}{b}\right)$, where a and b denote the size/radii of the network and the target area, assumed to be circular in shape, respectively. The hitting time is $\Theta(a)$ with target advertisement, and $\Theta(a^2 \log \frac{a}{b})$ under the random walk type of forwarding. We further show that the target advertisement method achieves mean hitting time on the same order as greedy forwarding schemes with less memory requirement. We compare this class of schemes with the family of Lévy walks and provide simulation results on their performance under more realistic settings.

1. Introduction

In this paper, we consider the problem of searching for a node or a desired piece of data in a wireless ad hoc or sensor network. Specifically, a *querier* or source node sends out a query packet in search of a *target* or destination node located somewhere in the network. The query packet has to traverse the network in some way till it reaches the target, which then responds/replies to the source node. This problem arises in and is motivated by a variety of scenarios, including content location [1], service discovery [2], and data query in a sensor network [3–5].

The primary goal of this paper is to examine a class of query search methods based on random forwarding and attempt to gain a quantitative understanding of their performance in terms of the time it takes to locate the target, as well as the amount of location information required by the network. In particular, we are interested in how the hitting time and information storage scale as the network becomes large (both in terms of the size and in terms the number of nodes in it).

The applicability of random forwarding-based methods primarily lies with scenarios where there is no established

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query or routing infrastructure, e.g., those provided by data caches/replicas, central directory service, or an information gradient field [5,6], and where the queries are simple and one-shot [4]. They are well suited for situations where the data content in the network changes rapidly, when queries occur infrequently, or when nodes are heavily duty cycled as in some sensor networks, all of which make it difficult and costly to keep afresh such infrastructure, be it pre-defined routes, routing tables or gradient field.

These random forwarding schemes can also be applied to navigating a moving vehicle (or robot) in search of a certain target. In this case, there will be no packet forwarding, but the vehicle follows successive random directions in its movement. Therefore, the results obtained here apply to these problem as well.

The main goal of these forwarding schemes is to find the target rather than to maintain a (good) route to it. In this sense, they are more specialized than conventional routing schemes, and are better thought of as "search" rather than "routing" methods. Existing routing protocols designed for ad hoc networks typically accomplish this search (for the destination) task through a route query mechanism using flooding (e.g., DSR [7]), which results in large amount of packet transmission.

There has been extensive study on data query and service discovery in ad hoc networks, and numerous approaches have been investigated. The methods studied here are representative abstractions of a subset of those proposed and studied in the literature. Below we describe these methods within the context of prior work, while noting that our focus in this paper is on the scaling property of hitting time and hitting distance, which is different from most of the work cited below. More literature review on hitting time studies is provided in Section 6.

We start with a scenario where no nodes in the network have the target location information except for the target itself and its neighbors within a certain range. Assuming that nodes have *relative* geographical location information about themselves and their immediate neighbors, the query packet is forwarded along a sequence of approximate straight lines of randomly chosen directions, bouncing off the network boundary, till it reaches the target or its neighbors. This model may be viewed as a special case of the trajectory-based forwarding proposed in [8]. We will refer to this as the *random direction forwarding*, more precisely defined in the next section.

We then consider a second scenario similar to the previous one but with the addition that the target sends out an *advertisement* packet that is propagated along an approximate straight line of a randomly chosen direction. Nodes visited by the advertisement packet store the target location information, and when the query packet reaches one of these nodes, the target is considered found. This model may be viewed as a simplified version of those considered in [1,2], where the target essentially sends out four advertisement packets traveling in four different directions. We shall see that this simplification does not affect our analysis. In [2], a pseudo quorum method was proposed in the context of providing matching service between data producer and subscriber where each producer/subscriber sends out advertisement/subscription messages along four directions (e.g., north, south, east and west) so that a match can be found at intersecting nodes. Similar idea was used in [1] in the context of content location where both content discovery packets and content advertisement packets are sent along these four directions. In [9], a quorum-based location service was proposed where nodes send out position information update along north/south directions with a certain thickness while packets searching for a destination travel along the east/west directions. The same idea of combining query and advertisement, and exploiting the fact that with high probability the two forwarding paths will intersect was proposed in [3] within the context of rumor routing. We will refer to the above method as the *enhanced random direction forwarding*.

We compare these two methods with random walk type of forwarding, where the query packet is randomly forwarded to a neighbor. Examples include [10,11], which studied random walk forwarding on a grid, and [12–14], which applied swarm intelligence by sending out multiple query packets each following an independent random walk. This is a method where no location information is stored in the nodes, and no intelligent processing is required of nodes to maintain a consistent direction, as is required in the previous methods.

As a baseline, we will also compare random direction and enhanced random direction forwarding methods with greedy geographic forwarding method, which assumes that nodes already know the target location. Using this method, each intermediate node selects the neighbor closest to the target as the next hop. Examples include greedy forwarding using precise target location information [15–17], as well as approximate or probabilistic geographical forwarding based on partial target location information [18].

Our principal results are derived under the following assumptions. We consider n nodes uniformly deployed in a disk of radius a. n may increase with a, and the node density is sufficiently high to ensure connectivity. The target node and nodes surrounding it form a *target area* modeled by a circle of radius b, located at the center of the disk.[1] These nodes do not have to be the target's immediate neighbors; they represent the area within which the target information is known. We will assume that $b \ll a$. Under these conditions, our main results are summarized as follows[2]:

- Random direction forwarding achieves a mean target hitting time of $\Theta(\frac{a^2}{b})$ for an arbitrarily located querier/source. Random walk forwarding achieves a mean target hitting time $\Theta(a^2 \log \frac{a}{b})$ when the querier/source is located away (at a distance $\Theta(a)$) from the center of the target area, and $\Theta(a^2)$ when it is located close (at a distance $\Theta(b)$) to the center of target area.
- Enhanced random direction forwarding achieves a mean target hitting time $\Theta(a)$ for arbitrarily located querier/source. This comes at the expense of extra information dissemination and storage of the target location along

[1] In Section 4.3, we consider other target locations.

[2] Notation: $f(n) = O(g(n))$ means $\limsup_{n\to\infty} \frac{f(n)}{g(n)} < \infty$. $f(n) = \Theta(g(n))$ means $f(n) = O(g(n))$ and $g(n) = O(f(n))$. $f(a,b) = \Theta(g(a,b))$ means $0 < \frac{f(a,b)}{g(a,b)} < \infty$ as $\frac{a}{b} \to \infty$.