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RESEARCH ARTICLE

Performance analysis of geography-limited broadcasting in multihop wireless networks

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ABSTRACT

In multihop wireless networks, delivering a packet to all nodes within a specified geographic distance from the source is a packet forwarding primitive (geography-limited broadcasting), which has a wide range of applications including disaster recovery, environment monitoring, intelligent transportation, battlefield communications, and location-based services. Geography-limited broadcasting, however, relies on all nodes having continuous access to precise location information, which may not be always achievable. In this paper, we consider achieving geography-limited broadcasting by means of the time-to-live (TTL) forwarding, which limits the propagation of a packet within a specified number of hops from the source. Because TTL operation does not require location information, it can be used universally under all conditions. Our analytical results, which are validated by simulations, confirm that TTL-based forwarding can match the performance of the traditional location-based geography-limited broadcasting in terms of the area coverage as well as the broadcasting overhead. It is shown that the TTL-based approach provides a practical trade-off between geographic coverage and broadcast overhead. By not delivering the packet to a tiny fraction of the total node population, all of which are located near the boundary of the target area, TTL-based approach reduces the broadcast overhead significantly. This coverage-overhead trade-off is useful if the significance of packet delivery reduces proportionally to the distance from the source. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS
restricted flooding; TTL forwarding; hop distance; broadcasting

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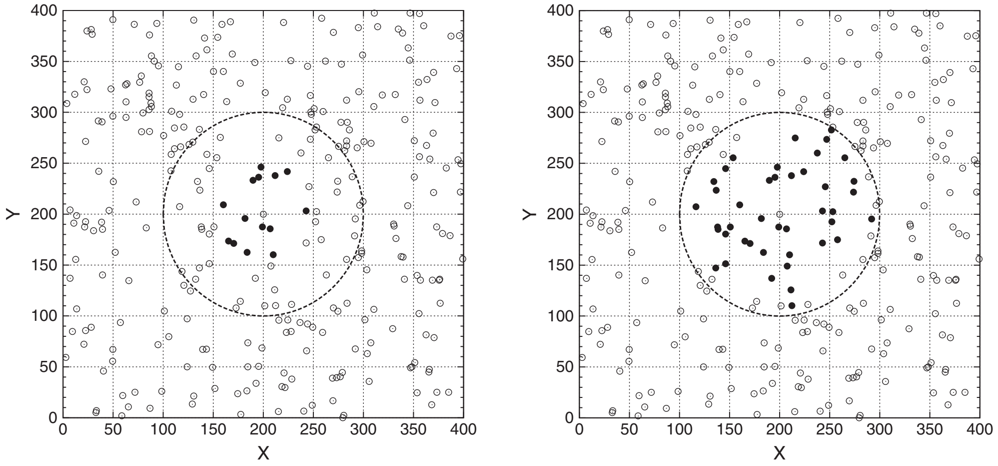
1. INTRODUCTION

In many wireless multihop networking applications, a wireless node often needs to disseminate information to all other nodes within a target geographical distance from it. For example, first responders working in a large-scale disaster site often require broadcasting of warning, help, or discovery messages to other crew members within the geographic jurisdiction of the commanding team [1]. In intelligent transportation system (ITS), road safety applications require vehicles to flood warning messages to other vehicles within an immediate neighborhood to prevent accidents or to warn of traffic hazards [2]. In location-based services [3], a store may wish to broadcast a discount offer to potential customers who are in the neighborhood of the store. Social networking users may want to send a message, for example, "let's meet up for coffee now," to their friends who are in their immediate surrounding [4]. In a wireless sensor network, the sink node (base station) often needs to send various types of queries and command messages to all sensor nodes within a predetermined geographic region around it [5].

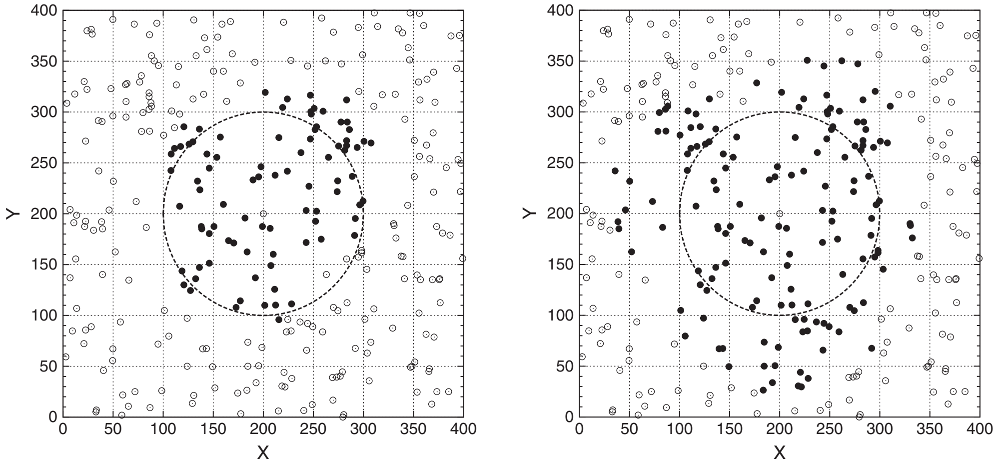
Geography-limited broadcasting is a communication primitive that specifically addresses the communication requirements of the aforementioned applications. The traditional approach of implementing this type of broadcasting assumes that each node has accurate knowledge of its location coordinates. For this reason, in this paper, we refer to the traditional approach as location-based geography-limited broadcasting. The source node broadcasts a packet specifying the target geographical boundary in the packet header. Any node receiving the packet rebroadcasts it only if its own location coordinates were within the geographical boundary and ignores it otherwise. This way, the packet is quickly propagated to all nodes within the target geographical boundary. Packet propagation ceases as soon as the packet travels beyond the boundary.

Although the aforementioned mechanism solves the problem of limiting information propagation within geographic boundaries, it assumes that every node will have access to precise location information at all times. This assumption is valid in general and is well backed up by the falling cost of location sensing hardware, for example, GPS circuits, and advancements in GPS-less localization [6]. There are, however, many practical situations when a particular set of wireless nodes may not have access to reliable location information. For example, it is a known fact that the GPS receivers embedded in mobile devices such as smartphones can rapidly deplete the device battery if operated on a continuous basis [7]. Further, it is well documented that GPS reception can be problematic in built-up urban areas with tall buildings [8]. Previous work [9] shows that the GPS error due to multipath propagation of the satellite signals can reach to 50 m (as illustrated in Figure 1 in [9]). The resulting error in GPS readings can significantly impact location-based services. Examples include applications of sensor actuator systems such as in precision agriculture and broadcasting of safety messages in ITS. Moreover, for vehicles inside a tunnel or in urban roads, access to one or more satellites may be temporarily blocked because GPS requires line-of-sight to at least three satellites. Similarly, a disaster recovery worker trying to discover human bodies under the rubbles may not be able to pick up GPS signals. Because of these, and many other unavoidable circumstances, it is practical to provision for alternate methods of forwarding so that geography-limited broadcasting can proceed in the event that reliable location information is absent.

In [10], the authors propose to use the well-known time-to-live (TTL) forwarding, which limits the



(a) TTL=1 (number of broadcasts=1, coverage=22%) (b) TTL=2 (number of broadcasts=14, coverage=69%)



(c) TTL=3 (number of broadcasts=42, coverage=97%) (d) TTL=4 (number of broadcasts=85, coverage=100%)

Figure 1. Illustrative example of time-to-live-based geography-limited broadcasting (*R* is 50 m and broadcast radius is 100 m).

propagation of a packet within a specified number of hops (TTL)[†] from the source. This is a popular forwarding technique used in both wireless multihop networking, for example, route discovery [11], and in wired networking, for example, IPv4. TTL forwarding is based on a very simple concept. The source node broadcasts a packet with a specified TTL. Upon receiving the packet, each intermediate node decrements the TTL by one. If the TTL is still nonzero, and the node has not received the packet before from another node, the node rebroadcasts the packet. It drops the packet otherwise. A key feature of TTL forwarding, which is of particular interest to us, is that it does not require a node to know its location coordinates.

The main challenge in achieving geography-limited broadcasting with TTL forwarding is the selection of the correct TTL value. This is especially challenging in the context of mobile multihop networking, where the node positions may not follow any regular pattern. A further complexity arises from the randomness in the radio propagation, which can create arbitrary number of hops between nodes irrespective of the geographical distance between them. Obviously, by "overprovisioning" the TTL, we can improve our chances of reaching all the nodes within the target area, but it will be achieved at the expense of increased broadcast overhead in the network, which can be detrimental for resource constrained wireless networks.

The example in Figure 1 illustrates the trade-off between the coverage, that is, percentage of nodes within the geographical boundary receiving the packet, and the broadcast overhead. In this example, the radio range of each node is 50 m, and the required target region is a circle with a radius of 100 m, as depicted in the figure. Figure 1(a)–(d) shows the coverage as the TTL value is varied from 1 to 4. The dark solid circles indicate the nodes that have received the flooding message. The results illustrate that selecting a small TTL value can reduce the broadcast overhead but may compromise the coverage. For example, in Figure 1(a) where $TTL = 1$ is used, the packet is only being broadcast once at the source. Whereas the broadcast overhead is minimum, the percentage of nodes within the target region that receive the packet is only 22%. On the contrary, using a large value can ensure that all nodes will receive the packet but introduces unnecessary broadcasts for nodes beyond the target region. For example, in Figure 1(d), $TTL = 4$ can cover all the nodes within the target region. However, it incurs around 30 unnecessary broadcasts at the nodes outside the target region.

The intent of this paper is to conduct a systematic study exploring the suitability of using TTL forwarding to achieve geography-limited broadcasting in situations when some or all nodes in the target area do not have access to reliable location information. Our objective is to quantify, as a function of the TTL, the achievable coverage, that is, the percentage of nodes in the target area that receive a copy of the original broadcast from the source, and the broadcast overhead, that is, the total number of transmissions needed for each message to achieve the broadcast. This objective is met by developing analytical models, which allow us to derive the geographical distance covered by each hop on average (hop distance) under realistic radio propagation.

Our analytical results confirm that TTL-based forwarding can match the coverage of traditional location-based geography-limited broadcasting without increasing the broadcast overhead. For mathematical tractability, our analysis makes two simplifying assumptions: (i) an idealized media access control (MAC) protocol that does not result in any collisions and (ii) homogenous node distribution that follows a Poisson point process. However, in our simulations, we consider realistic scenarios, wherein we relax the aforementioned assumptions. First, we implement the 802.11 MAC. Second, we consider a real-world VANET scenario, where the node distribution is not only heterogenous but dynamic. We find that despite the simplifying assumptions, our analytical results closely match the results from the simulations, thus confirming that our analysis is valid in realistic settings. Our simulation results also uncover an interesting coverage-overhead trade-off when TTL forwarding is used to achieve geography-limited broadcasting. By selecting a lower than required TTL, which reduces broadcast overhead significantly, it is possible to cover 98% of the nodes in the target geographic region. The 2% of the nodes, which do not receive a copy of the packet, are all found to be located along the edge of the target region. This coverage-overhead trade-off is attractive for applications where the significance of packet delivery is proportional to the distance from the source, for example, in vehicular crash avoidance applications, vehicles farther from the source have less possibility of crashing.

Related work in the literature [12–15] either assume regular network topology (e.g., grid topology) or random topology with high density of nodes. Further, all of these works make the unrealistic assumption, whereby radio coverage at each node is approximated to be a perfect circle. The main contributions of this paper, which distinguish it from prior research, are as follows. (i) We provide an analytical model for TTL-based geography-limited broadcasting that analyzes the broadcasting overhead and coverage trade-off. (ii) The analytical model considers the realistic radio propagation with random fading. (iii) Our simulation results confirm that by selecting the appropriate TTL value based on the analytical model, the TTL-based forwarding can match the performance results of location-based geography-limited broadcasting. (iv) We also show that it is possible to significantly reduce the broadcasting overhead by sacrificing the coverage of the small area near the edge of the target geocasting region.

The rest of the paper is organized as follows. Section 2 reviews the related work in the literature. The analytical model for computing coverage and broadcast overhead is presented in Section 3. Section 4 describes the implementation of TTL-based geography-limited broadcasting in the

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[†] Time-to-live is a misnomer in the sense that it actually specifies the number of hops, not the time, a packet will live.

widely used NS-2 simulation platform. The performance results, obtained from the analytical model and the simulation experiments, are discussed in Section 5. We conclude the paper in Section 6.

2. RELATED WORK

There is a significant body of prior work in multihop networks on a related communication primitive called geocasting. The goal in geocasting is to deliver information to a group of destinations identified by their geographical locations. Prior work in this area has primarily centered on how to efficiently forward a packet to a remote geocast region [16–20]. The fundamental element in those work is to flood the packets within a certain region to avoid global flooding over whole network.

In distance routing effect algorithm for mobility [16], geocasting is used to deliver packets from a source to a destination. A source node first estimates a circular region that the destination may reside in. Then the source nodes floods the packets towards the direction of the geocast region. The flooding region therefore is bounded by the two tangent lines from the source to the circular geocast region. In location-aided routing [17] and its extension in [19], the flooding region is restricted in a rectangle that encompasses the source and the geocast region. Some other work, for example, GeoTORA [18] and GFG [19], use unicast routing to forward packets to further reduce the forwarding overhead. All these works assume the availability of nodes' location information.

Once the packet reaches the geocast region, delivering it to all nodes within the region is usually achieved using simple flooding or some modified version of flooding [21], which uses location information to restrict the flooding within the geocast region.

Note that all those previous works focus on the scenarios that the source is located outside the geocast region. However, the communication primitive, geography-limited broadcasting, considered in this paper is different from geocasting. In geography-limited broadcasting, the source is located at the center of the target broadcast region. In [10], the authors have proposed a middleware design for implementing TTL-based geography-limited broadcasting. Their design seeks to adaptively change the value of the TTL in response to changes in the node density. Our goal is different in that we seek to analytically model and study the trade-off between broadcast overhead and coverage.

In this paper, we develop an analytical model that yields closed-form solutions for the minimum TTL that would achieve complete coverage for the target broadcast region. Prior works that are related to this aspect of our research are those that attempt to derive the geographic distance covered by each wireless hop in multihop networking scenario. Most of the related work on this topic focus on unicast routing protocols. Kleinrock and Silvester [22] presented an approach to approximately estimate the mean hop count for the most forward within radius routing protocol given a source-to-destination distance. Lebedev and Steyaert [23] analyzed the mean hop count assuming a square shape of radio coverage. De *et al.* [24,25] proposed an analytical model to estimate the average hop count incurred in greedy routing given a distance. They also illustrate the hop count distribution by numerical simulation. Zhao and Liang [26] generalized a formula to estimate the hop count based on simulation results. Bettstetter and Eberspaecher [27] derived the probability that two randomly selected nodes are one-hop connected or two-hop connected. For a larger hop count, they assumed that node density is infinite and presented a lower bound. Dulman *et al.* [28] formulated the hop count distribution of the shortest path routing in a one-dimensional network and provided an approximate analysis for the two-dimensional case.

Several work [12–15] have analyzed the broadcasting overhead in TTL-based broadcasting. These work focus on analyzing expanding ring search (ERS) scheme, which is a popular scheme in routing protocols to find a route to destination. In ERS, the source node first set an initial TTL value in a route request packet and broadcast the packet. If the search fails to find the destination when the TTL value expires, the source node increments the TTL value and start the a new search. This process is repeated until the destination is found or the TTL value reaches a threshold. In the second case, a network-wide flooding may be adopted.

In those previous works, Hassan and Jha in [12] aims to find the optimal TTL threshold that can minimize the broadcasting overhead. They considered network with regular topologies including grid topology, circular topology and hexagonal topology. In their another work [13], they took account of random network; however, they assumed that the network topology (connectivity) is a known priori. Chang and Liu [14] used a dynamic programming formulation to find the optimal search strategy (a sequence of TTL value that may not be continuous increased) that minimizes the broadcasting cost. For any given TTL value, they simply assume that the broadcast cost is either a linear or quadratic function of the TTL value with a fixed coefficient. Deng and Zuyev [15] also analyzed the optimal search sequence in a random network. They assume a very dense network where each node can always find neighbors at the edge of its circular coverage range. In other words, the distance that a broadcast packet can propagate from the source is the packet's TTL value multiplied with the radio range. We will show in Section 3 that this assumption does not hold even in a reasonably dense network.

Most works on this topic, including all the work discussed previously and our earlier work [29], assumed only a perfect radio propagation model (random fading was not considered) that, as we have shown later in the paper, significantly overestimates the TTL. Mukherjee *et al.* [30] have considered a more realistic radio model where random fading is present. However, they only provided nonclosed-form formulas for the hop count distribution given a communication pair. Further, because of the nature of unicast routing considered in their work, the calculation of hop count probability requires the knowledge of global topology. Therefore, the analytical model requires an extremely high computation complexity (to enumerate all possible global topologies); as a result, the authors only illustrated the analysis results of two-hop connection probability. In our work, the broadcasting at each hop is essentially a localized routing, which does not rely on the global topology. We exploit this feature and present a time complexity of O(1) formula to derive the hop distance.

3. ANALYSIS

In this section, we first present the system model used in our analysis. Next, we proceed to develop an analytical model for computing coverage and broadcast overhead in geography-limited broadcasting.

Recall that the goal of geography-limited broadcasting is to disseminate the message to the nodes inside a defined geographical boundary, which is a circle of distance d centered at the message source, as shown in Figure 1. Given a distance d, we use $f(h|d)$ to denote the coverage that can be achieved by TTL value of h, that is, the percentage of nodes within the distance radius d that can receive the broadcast message by using h. Similarly, we use $g(h|d)$ to denote the broadcast overhead incurred by using h, that is, the average number of times each message is broadcast (aggregated among all nodes). To select an appropriate TTL value that balances the coverage and the broadcast overhead, it is necessary to accurately estimate $f(h|d)$ and $g(h|d)$. In doing so, the key step is to study how far a packet can progress at each broadcasting, referred to as *hop distance*. In this section, we first focus on analyzing the average hop distance (Section 3.1). Then we analyze the coverage (Section 3.2) and the broadcast overhead given the pair (d, h) (Section 3.3). For simplicity, in our analytical model, we assume that the multihop network employs an idealized MAC protocol, such that there are no collisions. However, this assumption is relaxed in the simulations (see Section 5), wherein we assume that the 802.11 MAC is implemented. The results, therein, demonstrate that despite this simplifying assumption, our analytical model is valid in realistic scenarios.

3.1. Analysis of hop distance

For mathematical tractability, we assume that node distribution follows a homogenous Poisson point process with a density of ρ. This distribution can approximate a large region with uniformly distributed nodes and has been widely used in analyzing multihop wireless networks [31,32]. Note that in our simulations, we have relaxed this assumption and considered a realistic scenario based on real-world traces of a vehicular multihop network.

The hop distance is dependent on the network topology, which again is determined by the radio characteristics at the physical layer. We consider two popularly used radio models here so that we can study the impact of radio model on the performance of geography-limited broadcasting. We first consider an ideal radio model where radio coverage of each node is a perfect circle with a radius of R. This radio model has been proved to be far from realistic [33,34]. Therefore, we also consider a *log-normal shadowing* radio propagation model, which takes account of random signal fading observed in most wireless communication environments. The radio coverage of each node in this model is irregular, which resembles realistic situations [33,34]. More formally, given a distance s that separates two nodes, the probability that these two nodes have a direct connection, referred as link probability [31], is as follows:

$$P_{\wedge}(s) = \frac{1}{2}\left[1 - erf\left(\frac{10}{\sqrt{2}\xi}\log_{10}\frac{s}{R}\right)\right] \qquad (1)$$

where R is referred to as *average radio range*, which is the radio range of a node in the absence of random fading. ξ is the fading randomness parameter and is the ratio of the standard deviation of random fading to path loss rate. The typical values of path loss rate and standard deviation can be found in Tables I, VIII, and IX in [35]. The function *erf*(.) is defined as follows:

$$erf(z) = \frac{2}{\sqrt{\pi}}\int_0^z \exp(-x^2)\mathrm{d}x \qquad (2)$$

As an illustrative example, Figure 2 plots the link probability as a function of distance s for $R = 50$ m and different values of the random parameter ξ. For comparison, we also plot the link probability for ideal radio model, which is a two-state variable (it is 1 when $s \leq R$ and 0 otherwise). Figure 2 shows that in shadowing radio model, the link probability generally decreases with distance s. The slope of decrease is dependent on the randomness parameter ξ. As the value of ξ increases, the rate of decrease in the link probability is less steep. This implies that the node's radio coverage increases.

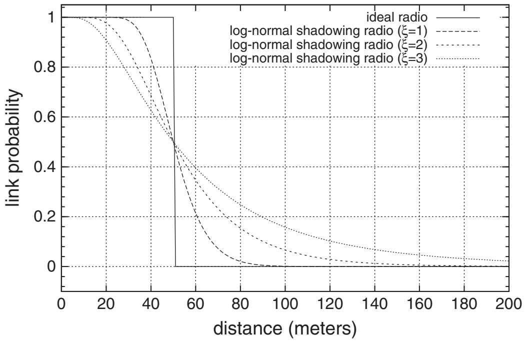


Figure 2. Link probability as a function of internode distance for different radio models ($R = 50$).

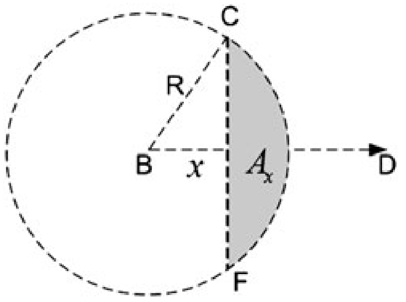


Figure 3. Illustration used to prove Theorem 1.

On the basis of geometric and probabilistic calculations, we can estimate the average hop distance for ideal radio model by the following theorem.

Theorem 1. *In ideal radio model, the average hop distance λ for each broadcasting is given by the following:*

$$\lambda = R\left[1 - \int_0^1 \exp(-\rho R^2(\arccos(t) - t\sqrt{1-t^2})\mathrm{d}t)\right] \tag{3}$$

Proof. Assume that a packet is currently at node B. Let X be the hop distance in the direction of BD (X is a random variable). When node B broadcasts a packet, all neighbors within its radio range can receive the packet. The hop distance in the direction of BD is the largest distance between B and its neighbors' projections on line BD. As shown in Figure 3, the probability that the hop distance is x is the probability that a neighbor is located along line CF and no neighbor exists in the area to the right of CF, referred to as area A_x. Equivalently, the cumulative probability that the hop distance is less than x is the probability that no neighbor exists in the region A_x. We have

$$F_X(x) = P(X < x) = Pr(\text{no nodes in region } A_x) \tag{4}$$

Recall that we have assumed that the node distribution follows a homogenous Poisson point process with density ρ. As a property of this assumption, the number of nodes in any region of area A follows a Poisson distribution with mean ρA. Therefore, the probability that no neighbor exists in the region A_x is $\exp(-\rho A_x)$. The area A_x can be calculated as follows:

$$A_x = R^2 \arccos\frac{x}{R} - x\sqrt{R^2 - x^2} \tag{5}$$

Thus, the cumulative density function (cdf) of X is given by the following:

$$\begin{aligned} F_X(x) &= \exp(-\rho A_x) \\ &= \exp\left(-\rho\left(R^2 \arccos\left(\frac{x}{R}\right) - x\sqrt{R^2 - x^2}\right)\right) \end{aligned} \tag{6}$$

The average hop distance λ follows:

$$\begin{aligned} \lambda &= E(X) = \int_0^R x f_X(x)\mathrm{d}x = \int_0^R x\mathrm{d}F_X(x) \\ &= [xF_X(x)]_0^R - \int_0^R F_X(x)\mathrm{d}x = R \\ &\quad - \int_0^R \exp\left(-\rho\left(R^2 \arccos\left(\frac{x}{R}\right) - x\sqrt{R^2 - x^2}\right)\right)\mathrm{d}x \end{aligned} \tag{7}$$

Replacing x with Rt, we have

$$\lambda = R\left[1 - \int_0^1 \exp\left(-\rho R^2(\arccos(t) - t\sqrt{1-t^2})\right)\mathrm{d}t\right] \tag{8}$$

Hence, the theorem is proved. □

Next, we use a similar approach to analyze the average hop distance for log-normal shadowing radio model. We have the following theorem.

Theorem 2. *Under the consideration of log-normal shadowing radio model, the average hop distance λ is given by the following:*

$$\begin{aligned} \lambda = R'\Bigg[1 - \int_0^1 &\exp\left(-\rho R'^2\left(\arccos(t) - t\sqrt{1-t^2}\right)\right) \\ &\cdot g(t)\mathrm{d}t\Bigg] \end{aligned} \tag{9}$$

where R' is the approximation of maximum radio range and $g(t)$ is as follows:

$$g(t) = \frac{10\int_t^1 \frac{u^2\arccos\left(\frac{t}{u}\right) - t\sqrt{u^2-t^2}}{u} \exp\left(-\left(\frac{10}{\sqrt{2}\xi}\log_{10}\frac{R'u}{R}\right)^2\right)\mathrm{d}u}{\sqrt{2\pi}\ln(10)\cdot\xi\cdot\left(\arccos(t) - t\sqrt{1-t^2}\right)} \tag{10}$$

The theorem is proved in Appendix, along with the approximation of maximum radio range.

According to Theorem 1, hop distance is a function of radio range R and node density ρ for ideal radio model. For the case of log-normal shadowing radio, the hop distance is a function of average radio range R, node density ρ, and fading randomness ξ. Figure 4 illustrates an example of average hop distance as a function of node density

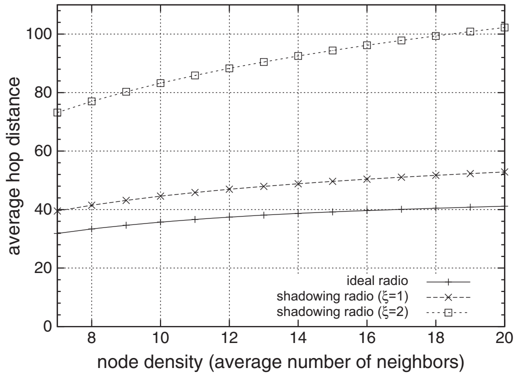


Figure 4. Average hop distance as a function of node density ($R = 50$).

for the different radio models assuming $R = 50$ m (here, the node density is transformed to the average number of nodes within πR^2). It shows that in all radio models, the hop distance increases with the node density. This is due to the fact that each node is more likely to find neighbors at the edge of radio coverage in a denser network. Thus, on average, the packet can progress further in each hop. Comparing different radio models, it is evident that the distance traveled in one hop is greater with the shadowing radio model. Further, this distance increases with an increase in the random fading, ξ. This is a direct result of the link probability distribution as illustrated in Figure 2. Because the link probability curve has a longer tail for a larger value of ξ, each broadcast packet can cover a greater area and therefore has a longer hop distance.

3.2. Analysis of coverage

Next, we analyze the coverage and broadcast overhead as a function of the TTL value. We assume a worst-case scenario where all the nodes in the network do not have access to their location information. In this situation, we assume that all the nodes employ the TTL-based geography-limited broadcasting scheme. Recall that the coverage $f(h|d)$ is defined as the percentage of nodes within the broadcast radius d that can receive the broadcast message by the TTL value of h. To estimate $f(h|d)$, we need to know the number of nodes that can receive the packet by using h and the total number of nodes within the target broadcast region. Given a TTL value h of a packet and the average hop distance λ, the actual distance that the packet can travel on average is λh. Because the node distribution follows a Poisson point process, the average number of nodes within distance λh is given by $\rho\pi\lambda^2 h^2$, which is also the number of nodes that receive the packet. Note that the total number of nodes within the target region is $\rho\pi d^2$. Therefore, the coverage can be calculated as $\frac{\lambda^2 h^2}{d^2} 100\%$. Note that this ratio can be possibly greater than 100% if a very large value of h is used. Hence, we limit the maximum value to 100%, in accordance with our definition of coverage. We have

$$f(h|d) = \min\left\{\frac{\lambda^2 h^2}{d^2}, 1\right\} \cdot 100\% \qquad (11)$$

3.3. Analysis of broadcast overhead

Now, we calculate the broadcast overhead $g(h|d)$, that is, the average number of times that each message is broadcast (aggregated among all nodes) by using h as the TTL value. Note that when a node receives a packet with TTL value of 1, this node is the last recipient of this packet and therefore does not rebroadcast this message. Thus, only nodes that are within hop count $h - 1$ from the source are involved in rebroadcasting the message (if $h = 1$, only the source needs to broadcast). Given λ, the average number of nodes that broadcast the packet, that is, the broadcast overhead, is given by the following:

$$g(h|d) = \rho\pi\lambda^2(h-1)^2 \qquad (12)$$

Note that the aforementioned analysis model is independent of the radio model under consideration. One simply has to substitute the appropriate hop distance λ as derived in Theorems 1 and 2 for the radio model under consideration.

4. PRACTICAL CONSIDERATIONS IN IMPLEMENTING TIME-TO-LIVE-BASED GEOGRAPHY-LIMITED BROADCASTING

In this section, we highlight some of the challenges that may be encountered if TTL-based geography-limited broadcasting is to be implemented in practical networks. We use the popular NS-2 simulator [36] for identifying these implementation challenges and discuss practical solutions to overcome the same. This discussion will be of particular interest to network practitioners who wish to instantiate the ideas presented in this paper in real-world systems. The proposed implementation solutions will be used in the following section as well where we compare the performance of the TTL-based approach with that of location-based geography-limited broadcasting.

Recall that in TTL-based geography-limited broadcasting, a node will immediately broadcast a packet that it has received, if the TTL is nonzero after being decremented. In a practical scenario, this is very likely to cause significant collisions because neighboring nodes that receive a broadcast packet will synchronously rebroadcast the packet. Our simulations have indeed confirmed that this synchronization leads to significant collisions. To avoid this problem, we introduce a small random delay at each node prior to broadcasting. We assume that this delay is a random value, which is uniformly selected from a range $(0, t)$. Note that a similar approach has been used in other protocols that rely on the broadcast primitive. For example, in the Ad hoc on-demand distance vector routing protocol [11], each node waits for a random duration prior to broadcasting the periodic HELLO message to its neighbors.

Note that our mathematical model does not account for this additional random delay incurred at each node. In our analysis, we implicitly assume that a node will always receive the first copy of the broadcast packet along the shortest path between the source and the node. Subsequently, any packets arriving along the other paths (i.e., not along the shortest path) are copies, which are discarded. More importantly, this allows us determine the broadcast coverage $f(h|d)$ that can be achieved when the TTL value is h (see Equation 11). However, with the addition of the random delay at each node, it may be possible that the packet that follows the shortest path to a node may no longer be the first copy to reach the node. In other words, the packet that comes along the shortest path and has the largest TTL will be dropped as it is a copy. On the contrary, the packets with smaller TTL values will be rebroadcast. As a result, the broadcast coverage achieved may be lower than that determined from the analytical model.

However, by introducing a small amount of extra delay for each broadcasting, we can mitigate and even totally eliminate this behavior. For example, if the delay is uniformly selected from range [10, 15] ms, each rebroadcasting of a packet introduces a minimum delay of 10 ms to this packet. Consequently, when a node receives a packet for the first time, this packet is more likely to arrive along the shortest path from the source to this node. In other words, the first copy of packet at each node (which gets rebroadcast) always has the largest possible TTL value, and therefore, the packet can reach to the maximum distance. In our simulation, we have used a random delay between 10 and 15 ms to ensure the maximum coverage.

5. PERFORMANCE RESULTS

In this section, we present results from our simulation-based evaluations. Our goal is twofold. First, we attempt to validate our analytical model. Second, we seek to compare the performance of the TTL-based approach with location-based geography-limited broadcasting in different situations.

We consider three different scenarios. In the first scenario, we simulate a random network topology and validate our analysis by comparing the numerical results derived in Sections 3.2 and 3.3 with the results from the simulations. Recall that (see Section 3) in our analysis, for mathematical tractability, we assumed an idealized MAC, which does not result in any packet collisions. However, we relax this assumption in the simulations. In all the three scenarios, we have implemented the 802.11 MAC at the link layer. This allows us to investigate if our analytical results still hold in realistic settings. In addition, we also compare the performance of our TTL-based approach with location-based geography-limited broadcasting assuming that all nodes have perfect knowledge of their locations. In the second scenario, we investigate if the TTL-based approach can complement traditional geography-limited broadcasting. We consider the same random network topology as in the first scenario but assume that a variable percentage of nodes are unaware of their location coordinates. These nodes employ TTL-based geography-limited broadcasting, whereas all other nodes that know their geographical coordinates use location-based geography-limited broadcasting. In the final scenario, we repeat the aforementioned experiment for a realistic vehicular ad hoc network using mobility traces of a metropolitan public transport bus network.

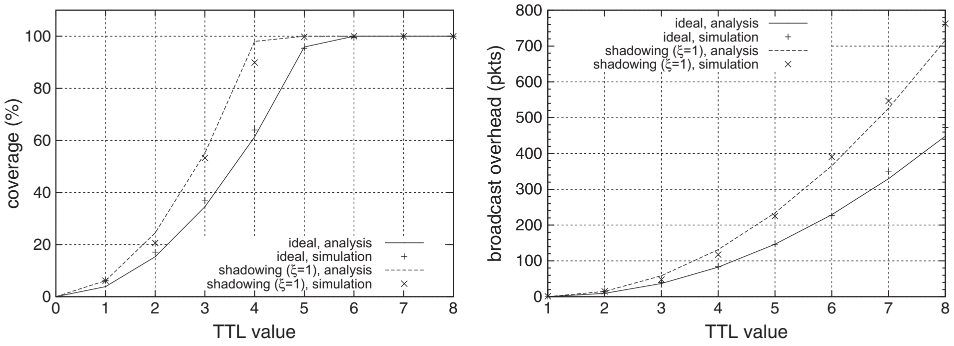
5.1. Comparison with location-based geography-limited broadcasting

In the first scenario, we evaluate the performance of the proposed TTL-based scheme. In particular, we are interested in determining the coverage achieved and the corresponding broadcast overhead as a function of TTL. We also compare the simulation results with the corresponding results from our analysis in Section 3. Finally, we compare our scheme with location-based geography-limited broadcasting, wherein each node in the network has precise knowledge of its location coordinates.

We consider a network of dimension 500 m × 500 m and assume that the node density, ρ, is 0.0019, which results in a total of 475 nodes.[‡] The broadcast source is assumed to be located at the center of the network. We simulate the IEEE 802.11b MAC at the link layer. We simulate the following radio models (to be consistent with our analysis in Section 3): (i) ideal model (i.e., two ray ground) – wherein the received power of a packet depends on the Euclidean distance between the sender and the receiver, the path loss and the transmission power and (ii) shadowing model – wherein the received power is also affected by an additional parameter, random fading. In both cases, the packet is assumed to be successfully received only if the received power is greater than a threshold, $7.69113e-08$ W. The transmit power is set to 0.281 W, and the path loss exponent and standard deviation for the shadowing model are both set to 2. The radio range, R, for each node is set to 50 m, and the broadcast distance, d, is assumed to be 200 m.

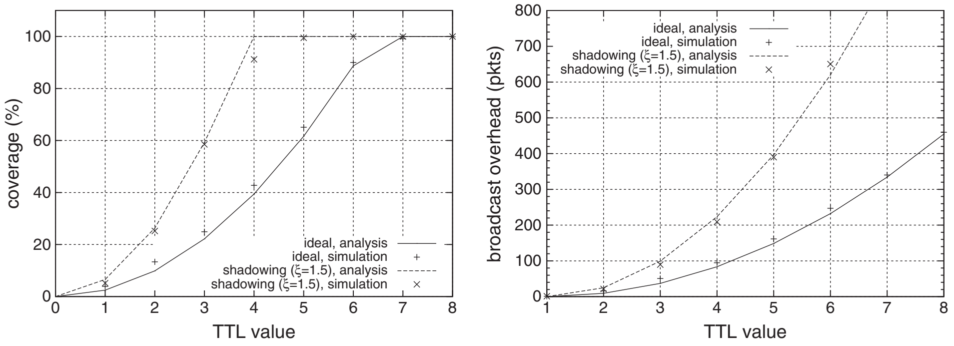
We vary the TTL value from 1 to 8 and observe its impact on the coverage and broadcast overhead in Figure 5(a) and (b), respectively. The coverage increases rapidly with an increase in the TTL, but the rate of increase slows down considerably just before converging to the maximum value of 100% after a certain TTL threshold.

[‡] Note that the radio range is 50 m in our simulations, which results in 15 (directly connected one-hop) neighbors for each node on average. This is not a overly dense network. For some practical vehicular ad hoc networking [37], a single vehicle can have much more than 15 neighbors, particularly during the rush hours in urban area.



(a) coverage (b) broadcast overhead

Figure 5. Comparing analytical and simulation results (assuming a broadcast radius of 200 m, $\rho = 0.0019$, $R = 50$ m).



(a) coverage (b) broadcast overhead

Figure 6. Comparing analytical and simulation results (assuming a broadcast radius of 200 m, $\rho = 0.0030$, $R = 40$ m).

Figure 5(a) also shows that the radio model has a significant impact on the coverage. Particularly, with the realistic shadowing radio model, the coverage converges to its maximum value for a lower TTL threshold than that of the ideal radio model. As expected, the broadcast overhead consistently increases with an increase in the TTL. These results imply that beyond a certain TTL threshold, any further increase in the TTL value does not improve the coverage (beyond 100%) but instead merely introduces additional overhead. To achieve maximum coverage, it is thus prudent to use this threshold value as the TTL. The threshold (for either radio model) can be estimated as $\lceil \frac{d}{\lambda} \rceil$. This is because the average distance traversed in one hop is λ (note that actual value of λ would be different for different radio models as shown in Figure 4), which implies that the total number of hops to cover a distance, d, is d/λ.

To obtain the corresponding analytical results, we substitute the parameters for the scenario under consideration in the appropriate equations (Equation (11) and (12)), derived in Section 3. The analytical results are plotted alongside the simulation results in Figure 5(a) and (b). Observe that the results match closely (for both radio models), thus validating our analytical model. We also simulate another set of network parameters, including $\rho = 0.0030$, $R = 40$ m, and $\xi = 1.5$. The results confirm the correctness of the analytical model, as shown in Figure 6(a) and (b). Note again the difference between the results for the ideal and log-normal models. An important lesson to be learn here is that the results from the ideal scenario are not suitable in realistic situations. For example, the TTL that achieves maximum coverage under the ideal model would be more than what is required in a practical scenario (which is consistent with the log-normal model) and would thus create excessive broadcast overhead.

Next, we compare the performance of our TTL-based scheme with location-based geography-limited broadcasting. We use analytical results in this comparison. In particular, we focus on the broadcast overhead of the two schemes for achieving 100% (or near 100%) coverage. As discussed previously, we select the TTL value for achieving 100% coverage using the formula $\lceil d/\lambda \rceil$. The broadcast overhead given the broadcast radius, d, can be calculated using Equation (12). We also compute the broadcast overhead resulting from using a TTL value that is one less than this threshold (i.e., $\lceil d/\lambda \rceil - 1$). This choice of the TTL value still achieves 98% coverage (according to Equation (11)). In location-based geography-limited broadcasting, because we assume that all nodes have perfect knowledge of their location, the broadcast overhead is simply equal to the total number of nodes contained within the target region. This is because each node that is located within the target region will broadcast the packet exactly once. The broadcast overhead is thus computed as $\pi \rho d^2$. We assume that the physical layer is represented by the log-normal shadowing model.

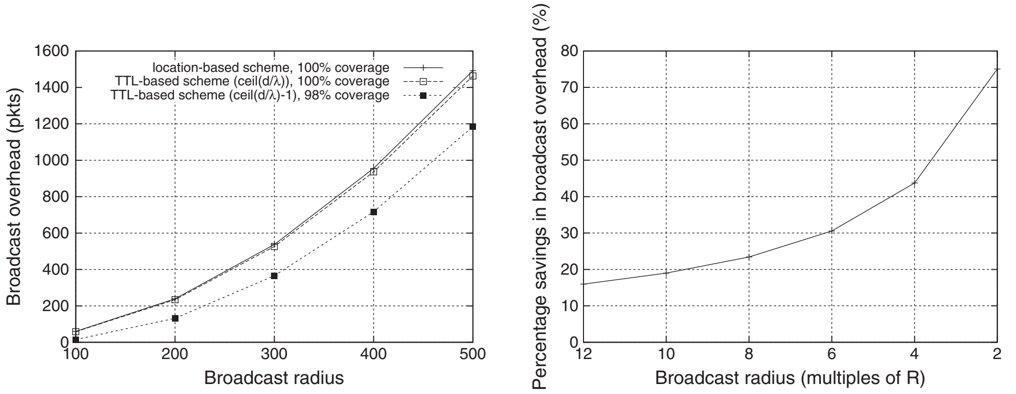
Figure 7(a) plots the broadcast overhead as a function of the broadcast radius for the aforementioned schemes. One can readily observe that the overhead incurred by the proposed TTL-based approach to achieve 100% coverage closely matches that of location-based geography-limited broadcasting. Interestingly, if we choose the TTL to be one less than the threshold, $\lceil d/\lambda \rceil$, then the broadcast overhead can be reduced significantly, while still ensuring that the message is received by 98% of the nodes. The reason is as follows. When a node receives a packet with TTL value of 1, this node is the last recipient of the packet and therefore does not rebroadcast this message. It is expected that when using $\lceil d/\lambda \rceil - 1$, the last recipients of the packet are located near the interior boundary of the geocast region. As a result, some nodes within the goecast region do not broadcast. On the contrary, in location-based scheme, any node that is located within the geocast region must broadcast the packet once, including these node near the edge of geocast region. Therefore, the location-based scheme introduces more overhead than the TTL-based scheme.

Figure 7(b) shows that the percentage savings in broadcast overhead increases exponentially with decreasing broadcast radius, and the actual savings can be as high as 75% when the broadcasting radius is twice the radio range. The exponential increase in broadcast overhead can be explained as follows. When we use a TTL one smaller than the required, we are saving the broadcast near the periphery of the target region. With the decrease of the radius, the ratio of the periphery area to the whole target area becomes larger, boosting the percentage savings in broadcast.

To fully appreciate the coverage-overhead trade-off of TTL-based geography-limited broadcasting, let us further analyze the 2% loss in coverage that yields up to 75% reduction in broadcast overhead. As illustrated in Figure 1(c), the 2% of the nodes, which do not receive a copy of the packet, is found to be located along the edge of the target region. For applications where the significance of packet delivery is proportional to the distance from the source, for example, in vehicular crash avoidance applications (vehicles farther from the source have less possibility of crashing) [38], the coverage-overhead trade-off can be a very useful feature of the geography-limited broadcasting protocol.

5.2. Evaluating the coexistence of time-to-live-based and location-based geography-limited broadcasting

In this scenario, we seek to investigate if TTL-based approach can work hand-in-hand with location-based geography-limited broadcasting. We use the same simulation parameters as in Section 5.1. We assume that a certain variable fraction of the nodes are unaware of their location coordinates. These nodes employ our TTL-based approach, whereas all other nodes in the network, which know their position coordinates, use location-based geography-limited broadcasting. One can readily envision that such situations often arise in realistic ad hoc networks. For example, when vehicles are inside a tunnel or in urban roads, access to one or more GPS satellites may be temporarily blocked. We vary the percentage of nodes that do not have location information from 0% to 100% and observe the effect on the broadcast coverage and broadcast overhead. The results are presented in Figure 8, with the left axis reflecting the coverage and the right axis denoting the overhead. Note that at the two extremes (i.e., 0% and



(a) Broadcast overhead

(b) Percentage savings in broadcast overhead when using a TTL value one less than $\lceil \frac{d}{\lambda} \rceil$

Figure 7. Comparison of time-to-live-based and location-based geography-limited broadcasting as a function of broadcast radius ($\rho = 0.0019$, $R = 50$ m, and $\xi = 1$).

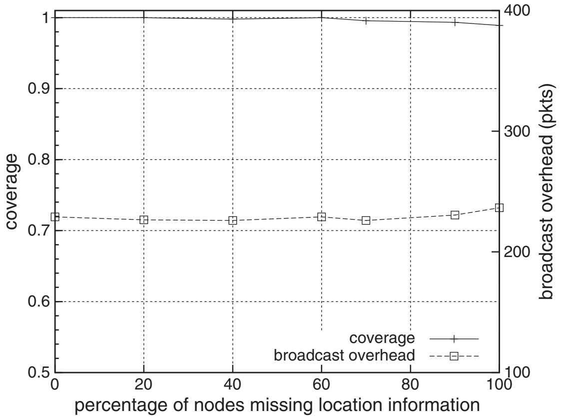


Figure 8. Performance of geography-limited broadcasting when some nodes are missing location information in a random network ($\rho = 0.0019$, $R = 50$, $\xi = 1$, and $d = 200$ m).

100%), all nodes homogeneously use location-based and TTL-based geography-limited broadcasting, respectively. We assume that the broadcast radius is 200 m and the TTL value is equal to the threshold, $\lceil d/\lambda \rceil$.

The graph illustrates that even when a significant fraction of the nodes are not aware of their location, it is still possible to maintain near 100% coverage without any noticeable increase in the broadcast overhead by employing the TTL-based approach. This implies that the TTL-based approach is a simple yet effective strategy for achieving geography-limited broadcasting in practical multihop wireless networks.

5.3. Vehicular network scenario

In the previous simulations, we assumed a random network topology. In this section, we relax this assumption and consider a more realistic scenario. We simulate a vehicular ad hoc network generated from the movement traces of public transportation buses in a metropolitan area. This simulation allows us to study the performance of the TTL-based approach (i) for more practical network topologies and (ii) under a time-varying topology where the topology variations are caused by movements of the nodes.

We have used location traces from the King County Metro bus system in Seattle, Washington [39]. This transport network consists of close to 1160 buses plying over 236 distinct routes and covering an area of 5100 km^2. The traces were collected over a 3-week period in November 2001. The traces are based on location update messages sent by each bus. Each bus logs its current location using an automated vehicle location system [40], its bus ID, and route ID along with a timestamp. The typical update frequency is 30 s. We have not simulated the entire bus network. This is because the network is quite sparse (e.g., only one or two buses) in several regions of the city, which would not lead to meaningful results. Rather, we focus on the business district, which has a consistently high density of buses. In particular, we focus on a rectangular region of size 4 km × 7 km in the central business district. The duration of this trace spans 30 min. We assume that the radio range of each node is 1000 m, which is consistent with that for Dedicated short range communication [38] and the results from [41].

In addition, we simulate a practical road safety application [42]. We assume that municipal workers are conducting road maintenance at certain locations in the business district. The maintenance sites are equipped with wireless devices that periodically broadcast safety messages within the immediate neighborhood of the work zone to warn drivers of the roadwork and revised speed restrictions. We assume that the messages are transmitted periodically every 10 s and that the broadcast radius is 3000 m. As in Section 5.2, we vary the percentage of nodes that do not have location information from 0% to 100%. The nodes without location coordinates employ TTL-based geography-limited broadcasting, whereas all other nodes use the location-based approach. The average node density for the network under consideration is found to be $1.03 \times 10^{(-5)}$. We assume the realistic log-normal shadowing radio model at the physical layer. The TTL value according to $\lceil d/\lambda \rceil$ is 3.

Figure 9 plots the coverage (left axis) and broadcast overhead (right axis) as a function of the percentage of nodes that do not know their location information. The graph again confirms that even when a large fraction of the nodes do not have their location coordinates, TTL-based geography-limited broadcasting ensures that there is no drop in the coverage. However, the TTL-based scheme reduces the broadcast overhead in the network. In fact, the greater the number of nodes employing TTL-based approach, the more the decrease in the overhead. The reason for this is that in the TTL-based scheme, the last hop

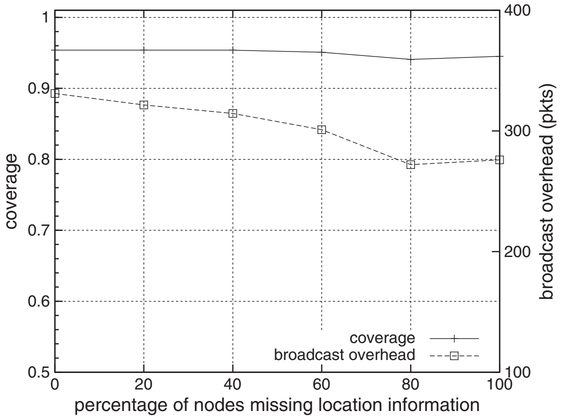


Figure 9. Performance of geography-limited broadcasting when some nodes are missing location information in a vehicular network ($R = 1000$ m, $\xi = 1$, and $d = 3000$ m).

recipients of a packet (i.e., when TTL=1) do not rebroadcast the packet. These last hop recipients are often located near the edge of the target region. Because of the nonuniform distribution of the nodes, we find that more nodes are located near the edge of the target region than in the center (this happened because the edge area was busier than the center, i.e, more buses passed through and stayed longer near the target region boundary). Therefore, the large number of nodes near the edge do not broadcast the packet further if they are the last hop recipients. However, for the nodes that employ location-based scheme, as long as the node is within the target region (including nodes located near the edge), it has to broadcast the packet. Therefore, the broadcast overhead reduces as the percentage of nodes in the network that use TTL-based geography-limited broadcasting increases.

6. CONCLUSION

We have shown that TTL-based forwarding, which does not use location information, can achieve geography-limited broadcasting without sacrificing performance in terms of geographic coverage and broadcast overhead. For a given network density and radio propagation model, we have analytically derived the TTL value required to achieve effective and efficient geography-limited broadcasting. The analytical model has been verified using simulation. Our analysis has shown that TTL-based forwarding supports a coverage-overhead trade-off, which allows us to reduce the overhead significantly at the expense of slightly reducing the coverage near the boundary of the target broadcasting area.

In future work, one can extend the current model in several ways. We used a simple flooding scheme, where each node within the flooding region broadcasts a packet once. It would be interesting to explore more advanced flooding techniques that further reduce the broadcasting overhead in TTL-based geography-limited broadcasting. Another interesting future work would be to apply our analytical model to the well-known ERS scheme that is used to find a specific destination node in a large multihop wireless network. On the basis of the analytical results of TTL-based broadcasting overhead, one would be able to find the optimal search strategy, in terms of a sequence of TTL values, for realistic radio models.

APPENDIX A: PROOF OF THEOREM 2

In log-normal shadowing radio model, the signal attenuation between two nodes is dependent not only on the distance separating the two nodes but also on a random fading value. As a result, the radio range of each node is irregular. However, we can still estimate a large circle around a node, which is large enough to cover all immediate one-hop neighbors of the node with a high probability. Let R' be the radius of such a large circle. Recall that the link probability $P_\wedge(s)$ between two nodes separated by distance s is a decreasing function of s, as illustrated in Figure 2. Given a particular distance R', if $P_\wedge(R')$ is very small (i.e., 0.01), it means that there is rarely a direct link between two nodes if their distance is equal or greater than R'. In this case, R' can be approximately considered as the maximum radio range. Therefore, we can approximate R' as the distance that satisfies $P_\wedge(s) = \alpha$, where α is a very small value.

Now we reuse the Figure 3 to continue the proof and change symbol R to R' in the figure. Similar to the case of ideal radio model, the cumulative probability that the hop distance is less than x is the probability that no direct link exists from B to all nodes within the region A_x. We have

$$\begin{aligned} F_X(x) &= P(X < x) \\ &= Pr(\text{no direct link from } B \text{ to all nodes} \\ &\qquad \text{in region } A_{i,j}) \\ &= \sum_{k=0}^{\infty} \{Pr(\text{k nodes in } A_{i,j}) \\ &\qquad \cdot Pr(\text{no direct link from } B \text{ to} \\ &\qquad \text{any one of those } k \text{ nodes})\} \end{aligned} \tag{13}$$

Recall that the number of nodes within A_x have a Poisson distribution with mean ρA_x. Let $g(x)$ be the probability that there is a direct link from X to a node given that the node is within region A_x. We have

$$Pr(\text{k nodes in } A_x) = \frac{(\rho A_x)^k}{k!} \exp(-\rho A_x) \tag{14}$$

$$\begin{aligned} &Pr(\text{no direct link from } X \text{ to any one of those } k \text{ nodes}) \\ &\quad = (1 - g(x))^k \end{aligned} \tag{15}$$

Thus, the cumulative density function of hop distance, that is, Equation 13, can be rewritten as follows:

$$\begin{aligned} F_T(x) &= \sum_{k=0}^{\infty} \left\{ \frac{(\rho A_{i,j})^k}{k!} \exp(-\rho A_{i,j}) \cdot (1 - g(x))^k \right\} \\ &= \exp(-\rho A_{i,j}\, g(x)) \sum_{k=0}^{\infty} \frac{[\rho A_{i,j}(1 - g(x))]^k}{k!} \\ &\quad \times \exp[-\rho A_{i,j}(1 - g(x))] \\ &= \exp(-\rho A_{i,j}\, g(x)) \\ &= \exp(-\rho \left(R'^2 \arccos \frac{x}{R'} - x\sqrt{R'^2 - x^2} \right) \cdot g(x)) \end{aligned} \tag{16}$$

Here, the cdf function $F_T(x)$ has similar form as Equation 6, which is the case for ideal radio model. Therefore, the average hop distance λ follows:

$$\begin{aligned}\lambda = E(X) &= \int_0^{R'} x f_X(x)\mathrm{d}x \\ &= R'\left(1 - \int_0^1 \exp\left(-\rho R^2 \left(\arccos(t) - t\sqrt{1-t^2}\right)\right)\right. \\ &\qquad \left. \cdot g(t)\mathrm{d}t\right) \qquad (17)\end{aligned}$$

Now, we proceed to solve $g(x)$, that is, the probability that a node has a direct link to B given that the node is within the region A_x. Assume that node M is inside A_x. According to Poisson point process distribution, node M is uniformly distributed within A_x. Let S denote the random variable of distance between M and B. Given a particular value of s, the probability that variable S is less than the value s is the probability that the node M falls within the shaded region depicted in Figure 10. The figure shows that the shaded region has similar shape as A_x but with a reduced size. Let A_s represent the shaded region. The cdf of random variable S can be expressed as follows:

$$\begin{aligned}F_S(s) = Prob(S < s) &= \frac{\text{area of } A_s}{\text{area of } A_x} \\ &= \frac{s^2 \arccos\frac{x}{s} - x\sqrt{s^2 - x^2}}{R'^2 \arccos\frac{x}{R'} - x\sqrt{R'^2 - x^2}}\end{aligned} \qquad (18)$$

Consequently, the probability that there exists a direct link between M and B is

$$\begin{aligned}g(x) &= \int_x^{R'} P_\wedge(s) f_S(s)\mathrm{d}s = \int_x^{R'} P_\wedge(s)\mathrm{d}F_S(s) \\ &= [P_\wedge(s)F_S(s)]_0^{R'} - \int_x^{R'} F_S(s)\mathrm{d}P_\wedge(s) \\ &= P_\wedge(R') + \int_x^{R'} F_S(s)\frac{10}{\sqrt{2\pi}\ln(10)\cdot\xi s} \\ &\qquad \times \exp\left(-\left(\frac{10}{\sqrt{2}\xi}\log_{10}\frac{s}{R}\right)^2\right)\mathrm{d}s \\ &= \frac{10}{\sqrt{2\pi}\ln(10)\cdot\xi\left(R'^2\arccos\frac{x}{R'} - x\sqrt{R'^2 - x^2}\right)} \\ &\qquad \cdot\int_x^{R'} \frac{s^2\arccos\frac{x}{s} - x\sqrt{s^2 - x^2}}{s} \\ &\qquad \times \exp\left(-\left(\frac{10}{\sqrt{2}\xi}\log_{10}\frac{s}{R}\right)^2\right)\mathrm{d}s \qquad (19)\end{aligned}$$

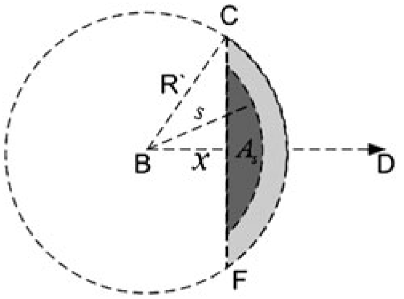


Figure 10. Illustration used to prove Theorem 2.

Replacing x with $R't$ and s with $R'u$, we have

$$\begin{aligned}g(t) &= \frac{10}{\sqrt{2\pi}\ln(10)\cdot\xi\left(\arccos t - t\sqrt{1-t^2}\right)} \\ &\qquad \cdot\int_t^1 \frac{u^2\arccos\frac{t}{u} - t\sqrt{u^2 - t^2}}{u} \\ &\qquad \times \exp\left(-\left(\frac{10}{\sqrt{2}\xi}\log_{10}\frac{R'u}{R}\right)^2\right)\mathrm{d}u \qquad (20)\end{aligned}$$

Finally, combining Equations (17) and (20), the theorem is proved. ☐

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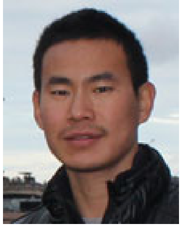

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