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An Efficient Broadcast Technique for Vehicular Networks

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Abstract—Vehicular networks are a promising application of mobile ad hoc networks. In this paper, we introduce an efficient broadcast technique, called CB-S (Cell Broadcast for Streets), for vehicular networks with occlusions such as skyscrapers. In this environment, the road network is fragmented into cells such that nodes in a cell can communicate with any node within a two cell distance. Each mobile node is equipped with a GPS (Global Positioning System) unit and a map of the cells. The cell map has information about the cells including their identifier and the coordinates of the upper-right and lower-left corner of each cell. CB-S has the following desirable property. Broadcast of a message is performed by rebroadcasting the message from every other cell in the terrain. This characteristic allows CB-S to achieve an efficient performance. Our simulation results indicate that messages always reach all nodes in the wireless network. This perfect coverage is achieved with minimal overhead. That is, CB-S uses a low number of nodes to disseminate the data packets as quickly as probabilistically possible. This efficiency gives it the advantage of low delay. To show these benefits, we give simulations results to compare CB-S with four other broadcast techniques. In practice, CB-S can be used for information dissemination, or to reduce the high cost of destination discovery in routing protocols. By also specify the radius of affected zone, CB-S is also more efficient when broadcast to a subset of the nodes is desirable.

Keywords—V2V Communication Protocols, Vehicular Network, Ad Hoc Network, Broadcast, Broadcasting Storm, Routing

1. INTRODUCTION

A vehicular network is a form of mobile ad hoc network. In a vehicular network, nodes are vehicles equipped with wireless communication devices. Nodes roam within the confines of a road network and communicate with each other wirelessly. Many vehicular applications can benefit from an efficient broadcast protocol. One example is message dissemination in a disas-

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trous situation where the communication infrastructure may not be available. In [1], we propose an intelligent transportation system that utilizes specialized traffic signals to guide traffic away from an incident. To communicate without traffic signals, an ad hoc network can be used to inform nearby motorists about the incident and the associated evacuation plan. On-board intelligent navigation systems would be able to process the evacuation plan and guide the motorists away from the incident in a coordinated manner. Another example application is reducing control overhead in routing protocols [2-7]. In these routing protocols, establishing a connection with a node requires either querying a location service [8, 9] or broadcasting a message to search the entire network for the node. The location service requires ongoing maintenance that is sensitive to the effect of high mobility and not needed when routing protocols such as [3, 4, 10] already provide a location update mechanism. For obtaining the location of a destination for the first time, these routing protocols can benefit from an efficient mechanism other than a simple Plain Flooding technique [11] that can cause a broadcast storm, especially in a high density environment [12].

A vehicular network in a street environment with relatively narrow streets surrounded by large buildings provides a very short window of time for communication between any two nodes moving at high speed on different streets. This short window means the network topology among nodes changes very fast when dealing with general protocols that are not sensitive to a street environment. For example, in the island of Manhattan in New York City, many streets are 20 meters wide, and measure in length from approximately 60 meters to 180 meters. Vehicles traveling in parallel in different streets that want to communicate only have a very short 20 meter window to do so every 60 to 180 meters, assuming that the cross street is sufficiently short to allow the communication to occur. Broadcast protocols [13-17] that rely on one or two hop neighborhood information either suffer from topology information that quickly becomes outdated, or need to exchange neighborhood information more frequently, which can cause congestion in the wireless medium.

In addition to changing topology, large buildings limit the coverage of a broadcast. A node's broadcast often cannot reach a node on another street. Earlier broadcast protocols such as Counter Based [12] and Probabilistic Based [18] provide simple ways to reduce overhead in a plain terrain environment without neighborhood information. These 0-hop protocols, however, usually fail to choose broadcasting nodes optimally in a street environment. The problem is that not all nodes should be treated equally in a street network due to obstacles. Nodes at intersections have better reachability to other nodes, compared to nodes in road segments. Techniques developed for an open space, not taking this factor into consideration, would not be able to achieve good performance in a street environment.

Another challenge present in a street environment is constraints in node mobility. In plain terrain, advanced protocols such as Angle Based [19], PANDA [20], Border Aware [21], and Cell Broadcast [22] use distance delay and geographic relationship as their rebroadcast criteria. With these strategies, many nodes can refrain from rebroadcasting because a message can be more efficiently rebroadcast by some neighboring node. As an example, a node in the Angle Based technique would not rebroadcast if the range of its rebroadcast is completely covered by some of the recent node broadcasts for the same message it overhears in the neighborhood. This strategy cannot be used for a street environment since most nodes would rebroadcast. This happens because the radio range of any node cannot be covered completely even if all its neighbors broadcast the message. According to the protocol, this node should rebroadcast even though its rebroadcast will not likely reach additional nodes.

MAC-layer protocols, such as [23-25], focus on reducing interference to improve the use of the wireless medium. These protocols modify the broadcast mechanism of the underlying MAC protocol that a routing protocol operates on. While this eliminates the need to modify the networking-layer protocol, these protocols have disadvantages (over a network-layer approach) such as relying on expensive repeaters [23], added delay due to sequential directional broadcast in intersections [24], or reduced spatial reuse of the wireless medium due to larger busy tone broadcast [25].

The broadcast protocol proposed in this paper is a network-layer approach that focuses on improving the use of network bandwidth through a reduction in the number of nodes needed in order to propagate a network wide message, such as a route or location request message used in many routing protocols. We assume each node is equipped with a GPS (Global Positioning System) unit. The terrain is divided into cells to allow nodes to easily determine their geographic relationship with a sender and decide whether to rebroadcast the message. The design is an adaptation of a broadcast technique, called Cell Broadcast (CB) proposed in [22] for an open terrain environment. Although CB provides high reachability and involves fewer nodes in message dissemination, it does not work well in a street environment due to similar issues that arise in other wireless broadcast models not specifically adapt for the street model. We name the new technique Cell Broadcast for Street Environment (CB-S). The new design addresses a number of challenges found in this environment, including faster topology change, limited radio coverage, and constrained node mobility.

The remainder of this paper is organized as follows. We introduce the proposed Cell Broadcast for Street Environment (CB-S) in Section 2. The simulation setting is presented in Section 3, with the simulation results discussed in Section 4. Then we analyze the CB-S in Section 5 and finally, we present our conclusions in Section 6.

2. CELL BROADCAST FOR STREET ENVIRONMENTS (CB-S)

With increasing availability of on-board navigation systems, more and more vehicles are equipped with GPS and map systems. Many works such as driver assistance [26], routing [5], and traffic condition dissemination [27] leverage such systems to improve safety and communications in vehicular networks. The proposed CB-S technique focuses on improving vehicular communications, and can have many important applications. It can be used to reduce the high cost of request packets in routing protocols such as [3-5]. CB-S can also be used to reduce the overhead of disseminating network wide information, such as information about a particular event [1], to vehicles within a radius. The initiator of such messages can be one of the vehicles or a roadside unit connected to a venue such as an arena. A street terrain is first divided into intersections and street segments. An intersection is a cell and a street segment can be one cell or several cells depend on the length and other characteristics of the segment. Fig. 1 shows an example street terrain and the cells on the local streets used by CB-S. When a street segment is longer than the nominal radio range of nodes or has a curvature that prevents a rebroadcast from covering the entire segment, the segment is divided into several cells. Compared to nodes on street segments, nodes on intersections are better candidates to relay packets as they can reach nodes on intersecting streets. Thus, nodes on intersections are used whenever possible to relay packets. In addition to reach nodes on more streets, rebroadcasts from intersections can also eliminate or reduce rebroadcasts from street segments in between intersections. In this section,

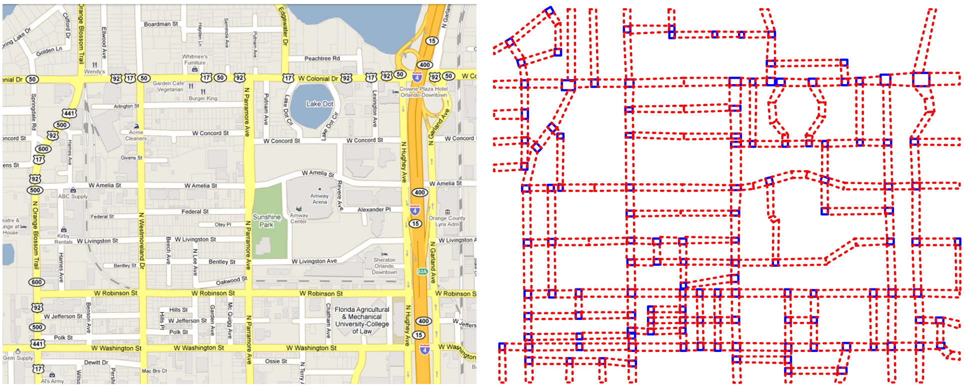


Fig. 1. A street network and the cells specific to the street environment.

we first describe our street environment and then present the proposed technique. For the sake of clarity, we refer to the rebroadcast of a data packet from a single node as a *rebroadcast* or a *node broadcast*. The entire process of disseminating a data packet to all the target nodes in the network is referred to as a *broadcast*. Thus, a broadcast consists of many node broadcasts working together to disseminate a message to the target nodes in the wireless networks.

2.1 Cell in Street Environment

To support a street environment, we divide streets into cells according to intersections and blocks (i.e., the street segment in between two adjacent intersections). An example is given in Fig. 2 Cell A and Cell C at the intersections are called *intersection cells*. Cell B is a street segment spanning an entire block and is called a *segment cell*. In this paper, we assume that all nodes or vehicles have a radio range sufficient to cover any three consecutive cells (e.g., Cells A, B, and C in Fig. 2). With this requirement, any node in Cell A can communicate with any node in Cells B and C.

The configuration, shown in Fig. 2, is typical for most streets in cities. A street segment that exceeds the nominal radio range R can be further divided into multiple cells. This is illustrated in Fig. 3, in which the road segment of length sl is divided into multiple cells of length cl. When sl is not evenly divisible by cl, the last cell (the rightmost cell in Fig. 3) can have a length less than cl. Let sw be the width of the street segment. To ensure that the nominal radio range R can cover any three consecutive cells, we have the following constraint:

$$\sqrt{sw^2 + (3 \times cl)^2} \leq R \quad \text{or} \quad cl \leq \frac{\sqrt{R^2 - sw^2}}{3} \tag{1}$$

We will show later how this cell configuration allows us to design a technique to allow a node in a farther downstream cell to rebroadcast the message and prevent rebroadcasts from any node in cells closer to the last broadcasting node. This way, the number of rebroadcasts for any message is approximately half the number of cells in a particular street regardless of the total number of nodes in the street. This characteristic provides two highly desirable properties: (1) the number of node rebroadcasts is very small, and (2) the performance is predictable and consistently good for all broadcasts. We will discuss these properties further when we present the si-

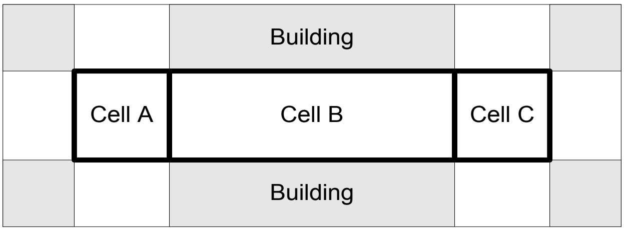


Fig. 2. Intersection and segment cells.

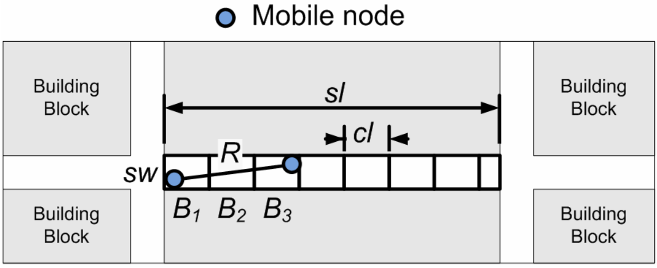


Fig. 3. Multiple cells in a street segment.

mulation results in Section 3 and overhead analysis in Section 4.

We assume that each node has a map that includes information on all the cells including their identifier and the coordinates of the upper left and lower right corners. Note that information about the streets is not needed, and that the cell map is very small in size. As an example, consider a large city with 5,000 cells. If 64 bytes are required to record information for each cell, the cell map is only 0.25 gigabytes. There are many ways to disseminate a map [28], such as downloading the map from a server in advance, from other nodes in the streets, or via mobile cellular network. This topic is beyond the scope of this paper but has many existing solutions can be used.

2.2 Broadcast Procedure

To broadcast a packet for a destination, a source node includes the following information in the packet: *Source Node ID*, *Destination Node ID*, *Packet ID*, *Current Node Position*, *Incident Location*, and *Dissemination Radius*. The *Source Node ID* and *Destination Node ID* fields are the node IDs of the source and destination nodes, respectively. The *Destination Node ID* can be set to a broadcast address if the message is intended for all the nodes, as in message dissemination. The *Current Node Position* is the position of the node about to rebroadcast this packet. Thus, each intermediate node updates the *Current Node Position* header field before rebroadcasting the packet to downstream nodes. The *Incident Location* and *Dissemination Radius* indicate the location of an incident and radius of the affected zone, respectively. These two fields can be used to disseminate information related to an incident such as an evacuation [1]. Such information often is of interest only to the vehicles within a certain radius of the incident. The *Incident Location* can be the location of the source or a nearby incident observed by the source.

When a node *n* receives a packet from another node *m*, it will first find the cell containing *m*'s position as indicated in the packet header. It then determines if it needs to rebroadcast the packet according to the following algorithm:

Algorithm I:

1. If *n* is outside the dissemination area, it drops the packet.
2. If *n* has broadcast the packet before, it drops the packet.
3. If *n* is not on a downstream cell of *m*'s cell, it drops the packet.
4. If *n* has heard the same packet broadcast from another node in its cell, it drops the packet.
5. If *n* has heard the same packet broadcast from its overtaking neighboring cells, it drops the packet.
6. If all previous conditions fail, *n* sets the delay.
7. If at the end of the delay, one of the previous conditions satisfies, *n* drops the packet.
8. Otherwise, *n* rebroadcasts the packet.

In Steps 5 and 6 of the above algorithm, *n* determines its overtaking neighboring cells and delay based on whether *m*'s radio range can reach the next intersection cell. If *m* can reach at least one intersection cell in the downstream as in Fig. 2, then *n* uses Algorithm II to determine its overtaking neighboring cells and delay.

Algorithm II:

1. If *n* is in an intersection, its overtaking neighboring cells are the nearest intersection at each incoming direction of its intersection cell and its delay is $rand_n \times t$ seconds.
2. If *n* is in a street segment, its overtaking neighboring cells are the adjoining intersection at each end of its segment cell and its delay is $rand_n \times t + t$ seconds.

In Step 1 of Algorithm II, if an incoming road is a dead-end street (i.e., there is no nearest intersection in the direction), then the overtaking neighboring cell for this particular direction is the street segment of the dead-end street. The $rand_n$ in Algorithm II is a pseudo-random number generator which produces a number from the range *[0, 1)* and is seeded uniquely for node *n*. The delay *t* can be adjusted based on node density derived from historical data collected by intelligent transportation systems such as [29]. When node density is high such as before a concert event or sports game, *t* can be set longer to reduce the radio contention. The value of *t* can be included in the message packet initiated by the event organizer.

The significance of Algorithm II is that nodes in intersections rebroadcast first and thus eliminate the need for rebroadcasts from the segment cells between the intersection cells. A rebroad-

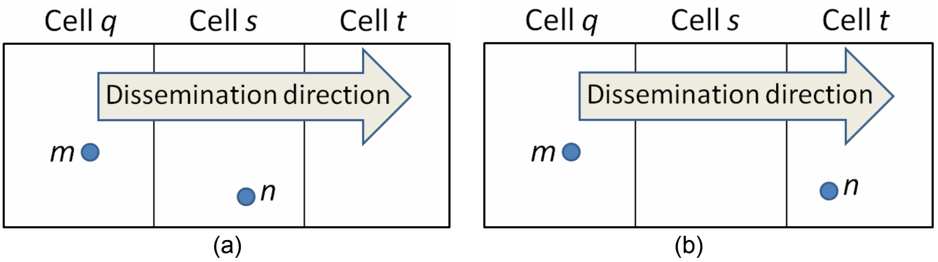


Fig. 4. Two scenarios for delay computation in Algorithm III.

cast from an intersection also has the advantage of propagating the packet to the intersecting street in addition to the street the packet is currently on and thus reaches more nodes than a rebroadcast from a segment cell.

In rare cases where *m*'s radio range is too small to reach the next intersection due to a long road segment (as in Fig. 3), *n*'s overtaking neighboring cells are the adjoining cell at each end of its cell and *n* uses Algorithm III to determine its delay.

Algorithm III:

1. If *n* is in the downstream segment cell *s* adjoining the cell of *m* (see Fig. 4 (a)), *n* sets its delay as $rand_n \times t + t$ seconds.
2. If *n* is in the segment cell located immediately downstream of *s* (see Fig. 4(b)), *n* sets its delay as $rand_n \times t$ seconds.

In Algorithm III, $rand_n$ is the same pseudo-random generator previously described.

When nodes on intersections cannot be utilized, Algorithm III takes advantage of information about node location to reduce delay and overhead. It allows far away downstream nodes to rebroadcast with little delay. It also eliminates unproductive rebroadcasts from nodes closer to the last broadcaster, as they will not reach additional downstream nodes.

3. SIMULATION SETTING AND PERFORMANCE METRICS

To evaluate our approach, we perform simulations using the network simulator called GloMoSim [30]. This simulator is a packet-level simulator specifically designed for ad hoc networks. It follows a layered network communication model and provides comprehensive simulation for each of the layers.

Since the proposed CB-S protocol is a network layer protocol that does not rely on easily outdated neighborhood knowledge, we simulated and compared CB-S and other network layer 0-hop broadcast protocols discussed in Section 1 including Plain Flooding, Counter Based, Angle Based, and Cell Broadcast (CB). These protocols do not assume the additional requirements by the MAC layer protocols [23-25] and thus can provide better insight to the performance result. All the protocols use 60 milliseconds for each delay period. For Counter Based, we set the value of the counter threshold to C = 3 in accordance with [12]. For Angle Based, we set the value of $\varepsilon = 2$ according to [19].

We consider 1,640 mobile nodes. The field configuration is a 1000m × 1000m space, with a street width of 10 meters and street block size of 100m × 100m. There are 81 street blocks in total. Each simulation emulates 15 minutes of time. Before the simulation begins, 10% of the nodes are randomly picked to be the set of nodes which initiates broadcasts. Each node initiates a broadcast one time during the simulation run, and this single broadcast occurs at a random time. A broadcast is 500 bytes long. We assume the broadcast messages are intended for all the nodes in the terrain, similar to request packets used by routing protocols [3-5]. Each node has a radio range of about 120 meters. Initially, nodes are placed uniformly with 2 nodes per intersection and 8 nodes per segment cell. The nodes then move in the directions permitted in the streets. Upon arriving at an intersection, a node probabilistically changes its direction of movement -

turns left, turns right, or continues in the same direction.

We performed sensitivity studies for mobile node speed, openness of the terrain (in terms of signal obstruction), and dissemination radius. The protocols are compared under three performance metrics: (i) **average overhead** measures the average percentage of nodes participating in *relaying* each broadcast message in the entire terrain (a higher percentage indicates more rebroadcasts, and therefore more overhead); (ii) **average reachability** measures the average percentage of nodes *receiving* each broadcast message within a dissemination area (90% means, on average, 90% of the nodes receive the broadcast message); and (iii) **average delay**, measured in seconds, is the average interval from the time the first node initiates a message to the time the last node receives the message within a dissemination area. Unless otherwise noted, the dissemination area refers to entire area of the terrain.

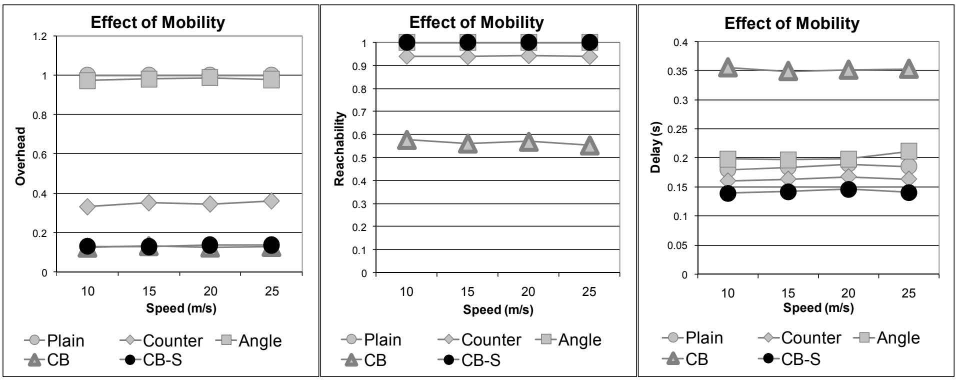
4. SIMULATION RESULTS

We present the simulation results in this section. We study the effects of mobile speed, openness of the terrain (in terms of signal obstruction), and dissemination radius on performance.

4.1 Effect of Speed

The simulation results for mobile node speed are shown in Fig. 5. We observe that all the protocols, except CB-S, make a tradeoff between reachability and overhead (see Fig. 5 (a) and Fig. 5 (b)). The naïve Plain flooding offers good reachability by making every node rebroadcast. This results in very high overhead. The more advanced Angle Based protocol also has a high overhead because it is nearly impossible for any node to fail its rebroadcast criteria as we have discussed in Section 1. Protocol CB suffers from low reachability because the cells are not tailored to a street network. In this environment, the terrain is partitioned into grid cells regardless of the street network topology. As a result, nodes in intersections often do not rebroadcast because they have overheard another rebroadcast from the same cell but from a node in a street segment. Such rebroadcasts cannot forward the packet onto the intersecting street, therefore affecting the overall reachability performance. While the Counter Based protocol reduces overhead, it negatively affects reachability. This occurs because it fails to take into account the advantage of rebroadcasts at intersections. Consequently, the message does not always reach nodes near the edge of the terrain. In contrast to the aforementioned protocols, the proposed CB-S technique offers high reachability with low delay and low overhead. The high reachability can be attributed to the high percentage of rebroadcasts from the intersections of the streets. More nodes can therefore be reached in this environment. The low overhead is attributable to rebroadcasts occurring in every other cell in CB-S, thus usually skipping road segments in-between intersections. The low overhead contributes to the very low delay in CB-S (Fig. 5(c)).

We also observe that mobility does not have a significant impact on the protocol performance since they are all 0-hop protocols that do not rely on 1- or 2- hop neighborhood information. For Plain and Angle based approaches, the mobility has completely no effect on overhead since every node rebroadcasts as explained above. With no change in overhead, the protocols' delay and reachability remain the same. For other protocols, the delay between the time a node initiates a packet to the time last node in the terrain receives the packet is less than half a second, and thus, the topology during this time period remains fairly static. During this time, a node



(a) (b) (c)

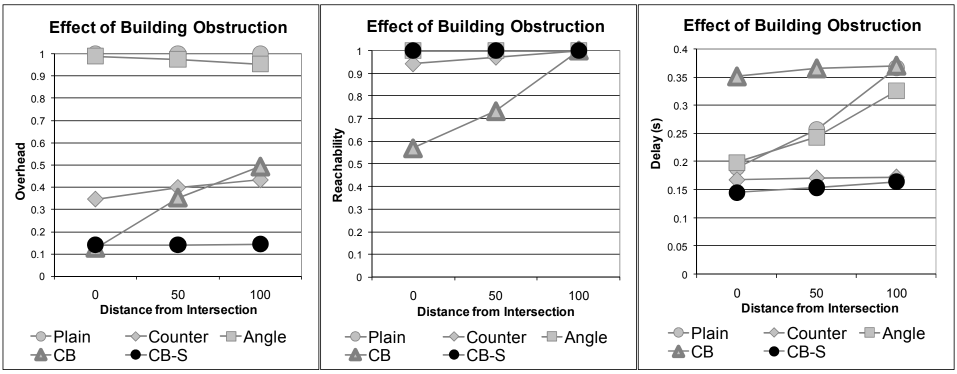
Fig. 5. Effect of Mobility: (a) Overhead, (b) Reachability, and (c) Delay.

moves at most 9 meters with the fastest mobility speed in Fig. 5; this distance is only enough for a node to traverse from one intersection to a street segment or vice versa without making turns. For Counter based protocol, a node decides whether or not to rebroadcast base only on number of packets it overhears. This simple mechanism does not require high accuracy of nearby topology. As long neighbors do not move too far away, the perceived neighborhood serves its purpose. For CB protocol, its performance fluctuation is due to interaction between node distribution and its cells. A long narrow street allows CB to drop a packet only if there is already a rebroadcast from the same cell. This makes CB very sensitive to node distribution. If more nodes on a street segment are included in the CB cell overlaying an adjacent intersection, the lower probability a node on the intersection broadcasts. As result, the performance of CB fluctuates. For CB-S, a node on a street segment drops a packet if it overhears a packet has been rebroadcast from all its adjacent intersections. With a short interval of less than 0.16 second (a node can move at most four meters with the fastest mobility setting), a node deciding to rebroadcast can safely assume the topology does not change drastically over this period of time. When a node decides to drop a packet based on the overheard locations of rebroadcasting neighbors, the node can assume that the rebroadcasts cover all its neighboring nodes.

4.2 Effect of Building Obstruction

In this section, we examine how the presence or lack of buildings affects the performance of the protocols. We simulated this effect by specifying how far away a node can be from an intersection and still be able to communicate with another node on the intersecting street of the intersection. We call this parameter *Communication Distance from Intersection* (CDI). A low CDI value characterizes an urban environment where many tall buildings block the radio between two nodes on two different streets. A high CDI value represents a suburban environment where smaller buildings are farther apart and away from the streets, allowing for nodes on two different streets to be able to communicate. The simulation results are shown in Fig. 6.

The highest CDI in Fig. 6 represents a street environment without any buildings. This setting is used to exclusively show the effect of the constraint on node mobility (i.e., mobility is constrained to the road network) alone on the protocols. Again, we observe that only the proposed CB-S technique performs well under all three performance metrics. The performance of the oth-



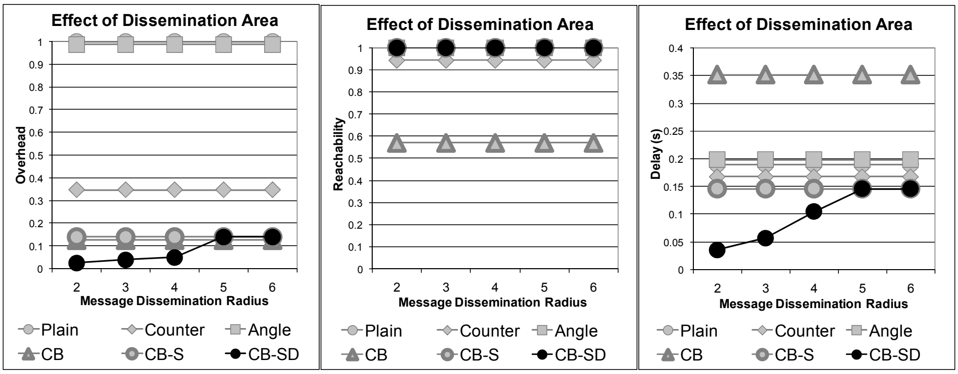
(a) (b) (c)

Fig. 6. Effect of Building Obstruction: (a) Overhead, (b) Reachability, and (c) Delay.

er techniques is similar to the results shown in Fig. 5 with the following differences. CB improves as the building obstruction decreases. This is due to the fact that CB is very effective for an open terrain environment. When the obstruction is minimal, it has the same reachability as that of CB-S. In terms of delay (Fig. 6(c)), both the Plain and Angle Based techniques experience longer delays with decreases in building obstruction (i.e., increases in CDI). This is due to the high overhead in these two techniques (Fig. 6 (a)). Almost every node rebroadcasts, resulting in severe contention on the wireless medium. This contention increases with corresponding decreases in building obstruction because radio signals from more nodes on different streets can interfere with each other. As a consequence, nodes must wait longer before rebroadcasting each packet.

4.3 Effect of Message Dissemination Radius

In this section, we compare the performance of the protocols in disseminating messages to nodes in the proximity of the source node of the broadcast. A message is initiated near the center of the terrain. The *dissemination radius* (DR) is defined as a multiple of the nominal radio range and defines the dissemination area. This smaller area is only applicable to CB-S, whose *reach-*



(a) (b) (c)

Fig. 7. Effect of Dissemination Radius: (a) Overhead, (b) Reachability, and (c) Delay.

ability and *delay* metrics involve only the nodes within the area.

The simulation results are shown in Fig. 7. We observe that only CB-S responds to changes in DR. While other protocols utilize the nodes within the dissemination zone, they do not limit the broadcast to the dissemination region. Only CB-S utilizes less rebroadcast nodes for a smaller dissemination zone. Hence it incurs less overhead (Fig. 7 (a)). Since only nodes in the dissemination area are reached, the delay is also reduced under CB-S. When the dissemination radius becomes very large (e.g., 5 or 6 times the radio range), almost covering the entire terrain, CB-S performance levels off.

5. ANALYSIS OF CB-S

In this section we analysis the overhead, delay (in terms of number of hops), and reachability of the proposed protocol. CB-S can be viewed as a dual-layer design as illustrated in Fig. 8, which consists of a logical layer and a physical layer. The physical layer is the actual mobile ad hoc network with the physical nodes. The logical layer consists of the cells, each treated as a virtual node. If every two adjacent virtual nodes are considered as connected in the logical layer, we have a special kind of overlay network formed over the mobile ad hoc network. From this perspective, a rebroadcast from a physical node in one virtual node to another physical node in the next virtual node can be seen as a broadcast from the first virtual node to the next virtual node. That is, a virtual node derives its communication functionality from the capability of the physical nodes currently within its area of operation.

To disseminate a message to all the nodes in the physical layer, the algorithms in Section 2 are used to implicitly construct a *broadcast graph* in the overlay network, on demand. This is possible because the virtual nodes in the logical overlay layer, unlike the physical nodes, are stationary. This broadcast graph connects every other virtual node (Fig. 8) to include half of the virtual nodes in the overlay of one street. During data dissemination, the rebroadcasts are carried out at each virtual node in the broadcast graph starting from the source node (i.e., the virtual node in the logical cell where the broadcast is initiated). Each rebroadcast, however, is an actual node broadcast occurring in the physical layer. The rebroadcast data can reach all physical nodes in the next two virtual nodes. The second of these two virtual nodes is part of the broadcast graph, and it in turn relays the message to its own two next virtual nodes. This process transmits the data packet to all the physical nodes inside these two virtual nodes. With the data relay proceeding in this manner, the data packet will eventually propagate downstream to eventually cover all virtual nodes in the broadcast graph, and will therefore reach every physical node in the

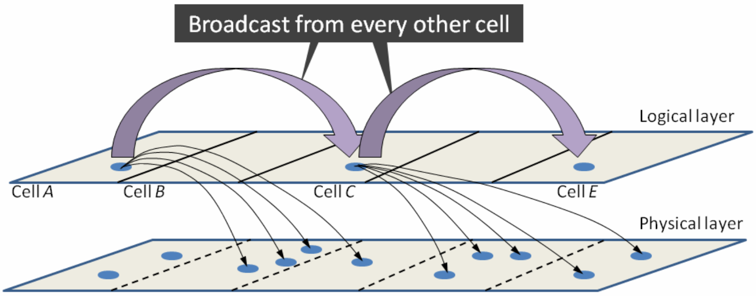


Fig. 8. Two layers of the CB-S approach.

physical layer.

From the above description of the broadcast operation, we observe that a broadcast utilizes k physical nodes, where k is approximately half the number of cells in one particular street and one third of cells in an entire street terrain. Given the length of each cell is about one third of the nominal radio range, k is nearly minimal. We will discuss this property further when we analysis the overhead in Section 5.4.

5.1 Desirable Properties of Broadcast Protocol in a Street Environment

Protocols [13-17] rely on neighborhood information are not considered desirable in high speed environments because of their large overhead to maintain the neighborhood information. Protocols such as Plain Flooding and Angle Based that require every node to rebroadcast the packet are not considered desirable because of large overhead. A protocol such as CB optimized for open terrain is not desirable for street environments because it does not reach all the nodes easily. Protocols like Counter and Probabilistic Based are not desirable because they do not reach all the nodes in minimal hops by not utilizing nodes in intersections whenever possible.

In this section, we will consider the desirable properties to broadcast a packet in a street environment and provide analysis that demonstrates that CB-S possess these properties. Consider a nominal radio range that is about the size of three consecutive cells (or two intersections and the segment in between) as defined in Section 2.1, a desirable relaying pattern is illustrated in Fig. 9. For simplicity of the analysis we consider the nominal radio range to be not much larger than the three consecutive cells as defined in Section 2.1. In practice, one can increase the radio range to reach more nodes in one rebroadcast with tradeoff of increased power consumption. This desirable pattern uses a small number of rebroadcasts to transmit a packet to a large number of nodes and do so with little delay. More formally, for physically absolute optimality, the time t_n at which a node n (at distance d_n from the source node) receives a message originating at the source node at time $t_0=0$ should be the same time required by electromagnetic radiation to traverse said distance d_n. This distance cannot be the minimal Euclidean distance in the street model for any broadcast technique because signals are assumed not to propagate through occlusions such as buildings. Therefore, in the street model, the distance between the origin and any node n

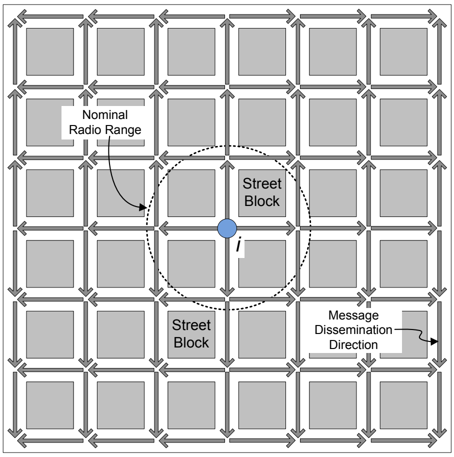


Fig. 9. Desirable message relaying pattern.

is calculated using the Manhattan distance metric (also known as the taxicab metric and rectilinear distance). Also, for the simplicity of the analysis, we assume that nodes are distributed evenly across the terrain.

5.2 Proof of Minimal Delay and Full Reachability of the Desirable Relaying Pattern

In this section, we prove that the desirable relaying pattern can reach each of the nodes in minimal number of hops. From the desirable pattern in Fig. 9, a diamond shape can be drawn to indicate the area where nodes are within *h* hops from node *i* in the desirable pattern. We call this shape a Minimum Hop Count Diamond as this diamond indicates the minimal number of hops to reach an enclosed node near the edge of the diamond. For examples, diamond 1 in Fig. 10 indicates an area where nodes are 1 hop away from node *i* and the area between diamonds 1 and 2 indicates an area where nodes are 2 hops away from *i*.

We can prove by induction that the nodes in between diamond *h* and diamond *h-1* required at least *h* hops from Node *i* to reach. We use the following equation to denote this:

$$\text{hop}(h) = h \tag{2}$$

$$\text{Basis: } \text{hop}(1) = 1. \tag{3}$$

From Fig. 9 and the definition of the nominal radio range defined in Section 2.1, nodes can hear *i*'s broadcast are located on the segment cells adjoining *i*'s cell and their adjoining intersection cells. Hence, they require at least one hop from the initiating node *i* to be reached and hop(1)=1.

$$\text{Induction Hypothesis: } \text{hop}(k) = k \ \text{ for } 1 \le k \le n \ \text{ and } n \ge 1. \tag{4}$$

$$\text{Induction Step: We want to show that } \text{hop}(n+1) = n+1. \tag{5}$$

The nodes between diamond n+1 and diamond n are within radio range of the nodes on the intersection cells at the edge of diamond n. Thus we can rewrite the hop(n+1) expression as follows:

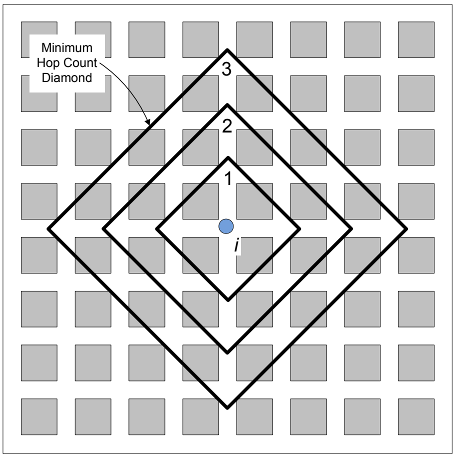


Fig. 10. Minimum Hop Count Diamond.

$$\begin{aligned} \text{hop}\,(n+1) &= \text{hop}\,(n)+1 \\ &= n+1 \quad \text{by Induction Hypothesis} \end{aligned} \tag{6}$$

In Section 5.3, we will also empirically show that CB-S exhibits this message relaying pattern by demonstrating that CB-S requires a similar number of hops as this desirable message relaying pattern to reach every node.

Since every node can be reached by the minimum number of hops indicated by its minimum hop diamond, we also show that the desirable relaying pattern can reach every node.

5.3 Reachability and Hop Count Analysis of CB-S

From the simulation result in Section 4, it is clear that CB-S can consistently broadcast a packet to every node in the network. In the rest of this section, we verify that nodes are reached in a relaying pattern similar to the one in Fig. 9 by analyze the number of hops a packet travels before reach a node in the terrain. Fig. 11 shows the minimal hop count to reach each node using CB-S to broadcast a packet initiated by a node in the middle of the center diamond. The result is obtained from a simulation run with even node distribution and the nominal radio range allows a node in one intersection to communicate with a node in another intersection. The hop count is represented with different node colors, with red being 1-hop away from the initiate node in the middle of the red diamond and navy blue being 10-hops away. The figure shows the following: the majority (76%) of the nodes are reachable by the minimal hop count depicted by their encompassing diamond, 21% are reached by 1 more hop than the minimum, 2% are reached by 2 or 3 hops, and no node requires more than 3 hops than the minimum to be reached.

In the most ideal scenario of broadcast that does not include stochastic delay, 100% of the nodes should be reachable by the minimum hop count. However, we do not require such high levels of minimal hop count recipients, nor can they be realistically achieved under many circumstances. What impedes having all nodes receive packets at the minimal hop count is the

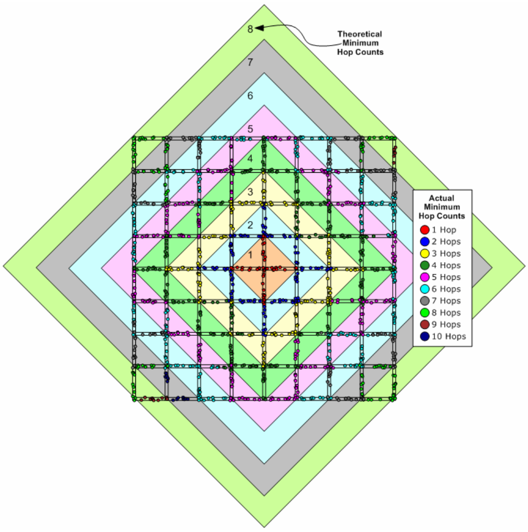


Fig. 11. Minimal number of hops to reach each node.

need to do probabilistic collision avoidance using random delays. This constraint is a core assumption of this method and of many other broadcast protocols [12, 18-22] where the goal is to reduce message reception delay and attempt to minimize retransmissions without requiring precise control using a distributed deterministic collision avoidance mechanism. Such a mechanism is more feasible for fixed wired or wireless networks using circuit switching, where communication parameters are well known. However, the feasibility drops significantly when mobility is introduced, when packet switching (and associated message time origination non-determinism) is used, and when reducing the cost of communication devices such as radios is desired.

Fig. 12 represents the minimal hop count to reach each cell in Fig. 11. The hop count of a cell is the lowest hop count required to reach a node on the cell. The hop count is represented with different cell colors with red being 1-hop away from the source in the middle of red diamond and navy blue 10-hops away. The figure shows that the majority (82%) of the cells are reached by the minimal hop count depicted by the diamond they are in, 16% are reached by 1 more hop than the minimum, 2% are reached by 2 more hops, less than 1% by 3 hops, and no cell requires more than 3 hops than the minimum to be reached. Fig. 11 and Fig. 12 show that CB-S is very close to the desirable low delay by reaching nodes and cells with a nearly minimal number of hops. We summarize the result of the figures in Table 1 with the result from Fig. 11 listed under "Percentage of nodes reached by" column and Fig. 12 under "Percentage of cells reached by", respectively.

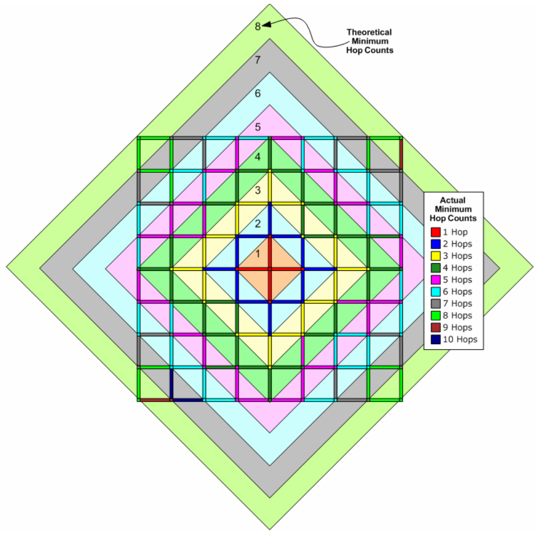


Fig. 12. Minimal number of hops to reach each cell.

Table 1. Percentages of nodes and cells reached by minimal hops

Additional hops to the minimal	Percentage of nodes reached by	Percentage of cells reached by
+ 0	76%	82%
+ 1	21%	16%
+ 2	1%	2%
+ 3	1%	0%
> 3	0%	0%

The percentage ($p_{minimal}$) of nodes that is reached by the minimal number of hops will vary depending on many factors. These include topological information on nodes, radio signal propagation environment due to buildings and other occlusions, travel speed of individual vehicles, the minimum desired number of retransmissions due to collisions among simultaneous radio transmissions, and various others. A controllable parameter that can be adjusted that will affect this number is the node transmission delay range or t as discussed in Section 2.2. Adjusting this parameter needs to be done carefully to match the given scenario. Setting the value of t too high causes an increased message reception time across the network because nodes are waiting longer to retransmit. Setting the value too low also causes an increased message reception time because the collision probability due to nodes broadcast at same time increases with a smaller value of t. Also as mentioned in Section 2.2, this value can be adjusted based on historical data on node density. Tuning this parameter in the simulation runs has allowed for the relatively high 76% value of $p_{minimal}$ in the result in this section.

5.4 Proof of Minimal Overhead of the Desirable Relaying Pattern

In this section, we study the overhead required by the desirable relaying pattern. From the relaying pattern in Fig. 9, one can see the minimal overhead is one rebroadcast from every intersection. This is approximately half of the cells in one particular street. For a terrain with HS horizontal streets and VS vertical streets similar to Fig. 9, the number of intersections I and segments S can be computed as following:

$$I = HS \times VS \quad \text{and} \quad S = (HS-1)\times VS + (VS-1)\times HS = 2\times HS\times VS - HS - VS \tag{7}$$

We can compute the percentage of cells needed for broadcast as percentage of intersection cells in all the cells. Thus, we have the following equation :

$$\frac{I}{(I+S)} = \frac{HS\times VS}{HS\times VS + 2\times HS\times VS - HS - VS} = \frac{HS\times VS}{3\times HS\times VS - HS - VS} \tag{8}$$

The above function has a limit as the following:

$$\lim_{HS\to\infty, VS\to\infty} \frac{HS\times VS}{3\times HS\times VS - HS - VS} = \frac{1}{3} \tag{9}$$

The above equation shows that about one-third of cells in Fig. 9 are intersections. The following equation computes the minimal overhead needed for a terrain with C cells and N nodes:

$$\frac{I}{N} = \frac{HS\times VS}{N} = \frac{C}{3N} \tag{10}$$

5.5 Overhead Analysis of CB-S

In this section, we verify CB-S has an overhead close to the low overhead of the desirable relaying pattern. Using the terrain and the initiating node in the middle of the terrain as in Fig. 11, we study the overhead of the protocols discussed in Section 4 and the desirable relaying pattern. We vary the number of nodes or N in Equation (10) and show the result obtained from the simulation in Fig. 13. For clarity, the number of nodes is shown as multiples of the node count of the fewest node setting. The overhead of the protocols are obtained from simulation result and the overhead of the desirable relaying pattern is obtained using Equation (10) with different number of nodes in the terrain. Only protocols with full reachability are shown in the figure. The figure shows that among all the protocols with full reachability, CB-S has the lowest overhead and thus is closest to the overhead of the desirable relaying pattern. Like the desirable relaying pattern, CB-S also exhibits a decreasing trend in overhead as the number of nodes increases. Both Plain and Angle Based use all the nodes to rebroadcast and do not respond to the node increase. Countered Based shows an unstable trend when the number of nodes becomes large. Counter Based also has a higher overhead than CB-S in all node density settings.

6. CONCLUSION

In this paper, we proposed the CB-S broadcast technique for street environments. We defined a desirable message dissemination pattern and proved how such pattern can reach each node with the minimal overhead and the minimal number of hops away from the initiate node of the message. Our analysis of simulation result shows that CB-S is able to reach every node in a minimal or almost-minimal number of hops. We also performed simulation studies to compare it with four other techniques. The results indicate that only CB-S performs well under all three performance metrics, namely reachability, overhead, and delay. Its reachability results are consistently at 100% for all simulation settings, always successfully disseminating a message to every node in the street network. This perfect coverage is achieved with the least overhead. In fact, the analysis indicates that its overhead is closed to the overhead of the desirable relaying pattern (i.e., the number of nodes needed to disseminate a message is small, and the number of hops is also small). This efficient property gives CB-S the advantage of very small delay. In summary, CB-S can always disseminates messages to all the nodes in the least amount of time using the least number of rebroadcast nodes.

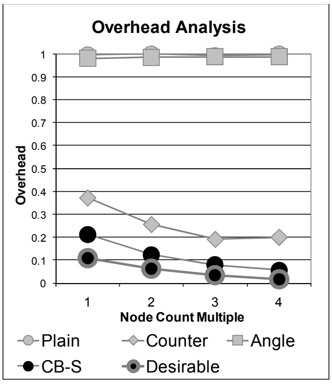


Fig. 13. Overhead analysis.

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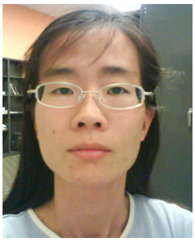

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