Abiding Geocast: Time–stable Geocast for Ad Hoc Networks

Christian Maihöfer, Tim Leinmüller and Elmar Schoch,
DaimlerChrysler AG, Research Vehicle IT and Services
P.O. Box 2360, 89013 Ulm, Germany
Christian.Maihoefer|Tim.Leinmueller|Elmar.Schoch@DaimlerChrysler.com

ABSTRACT

Abiding geocast is a time stable geocast delivered to all nodes that are inside a destination region within a certain period of time. Services like position–based advertising, position–based publish–and–subscribe, and many other location–based services profit from abiding geocast. For vehicular ad hoc networks, abiding geocast allows realization of information and safety applications like virtual warning signs. Similar to real traffic or warning signs, they are attached to a certain geographical position or area. When a vehicle enters such an area, the virtual warning sign is displayed for the driver.

This paper discusses the design space, the semantics, and three reasonable approaches for abiding geocast in an ad hoc network. The first one is a server solution to store the messages. The second approach stores the messages at an elected node inside the geocast destination region that temporarily acts as a server. The last one complements the exchange of neighbor information necessary for many unicast routing protocols with abiding geocast information.

We compare the proposed protocols with a probabilistic network load and delivery success ratio analysis. The results show that the approaches with local message storage cause less network load. However, we also observed that in some cases the delivery success ratio of the approaches with local message storage is lower.

Categories and Subject Descriptors: C.2.2 [Computer-Communication Networks]: Network Protocols

General Terms: Performance, Theory, Verification.

Keywords: Abiding Geocast, Geocast, Geographic Routing, Stochastic Analysis, Stored Geocast.

1. INTRODUCTION

Geocast, the transmission of a message to a predefined geographical region, opens the way for new applications and location–based services, where position awareness plays the key role. While in traditional networks like the Internet, position awareness is hardly given, many ad hoc networks and their protocols are based on position aware nodes.

Promising new services and applications require a geocast service that allows to specify a geocast message lifetime. Instead of delivering a geocast message only once to all nodes that are at the time of delivery inside the geocast destination region, they require the delivery of geocast messages to all nodes that are sometime during the geocast lifetime inside the geocast destination region. We call such a geocast service *abiding geocast*. Services and applications like position–based advertising, position–based publish–and–subscribe, and many others profit from abiding geocast. Of particular interest is abiding geocast in the automotive domain. It is envisaged that in some years vehicles will form a position aware ad hoc network since many necessary conditions are complied with: many vehicles are already equipped with a navigation system (i.e. are position–aware) and triggered by the introduction of automatic toll systems many will be equipped with communication systems in the near future. Abiding geocast allows the realization of virtual traffic signs in order to increase road safety, like local hazard warning [1]. For example, an abiding geocast fixed to a certain geographical area could warn approaching vehicles about an icy road.

Obviously, abiding geocast can be realized by periodical delivery using a usual geocast routing protocol. However, there are more options to realize it, for example on–demand delivery whenever a new node enters a geocast message destination region. In this paper, we aim at giving a detailed overview of these options and evaluate them by analysis.

In the next section background of geocast and related work is discussed. Section 3 gives an overview and introduces the semantics and design space of abiding geocast. In Section 4 three approaches are described and analyzed in more detail. Numerical results are presented in Section 5 and finally, the paper is concluded with a brief summary.

2. BACKGROUND AND RELATED WORK

2.1 Unicast Routing

Mobile ad hoc routing protocols can be classified into topology– and position–based or geographic approaches [2, 3]. Topology–based approaches use only information about existing neighborhood links rather than additional physical (geographical) position information of the participating nodes. Geographic routing protocols usually refrain from setting up routes to forward packets, which decreases overhead. Instead, the forwarding decision of a node is based on the destination's position and the position of the forwarding node's neighbors (i.e. nodes with a one hop distance).

For geographical unicast routing protocols, three basic

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forwarding strategies can be identified: 1) greedy forwarding, 2) restricted directional flooding, and 3) hierarchical forwarding. In the context of this paper only the first strategy is of interest. With greedy forwarding a node forwards a packet to a neighbor that is located closer to the destination. If this forwarding strategy fails, since there may be situations in which there is no closer node to the destination than the forwarding node, recovery strategies have to deal with it.

2.2 Geocast Routing

Besides the unicast delivery described so far, the following approaches allow geocast addressing and routing. We refer to the *destination region* of a geocast packet as the geographical area to which a packet has to be delivered. Geocast protocols belong to one of the classes: 1) directed flooding, or 2) explicit route setup approaches without flooding.

Geocast directed flooding approaches are quite similar to the unicast directed flooding approaches. They define a forwarding zone that comprises a subset of all network nodes. The forwarding zone includes at least the target area and a path between the sender and the target area. An intermediate node forwards a packet only if it belongs to the forwarding zone. If the target area is reached, they differ from unicast approaches, since they apply a flooding of the whole target area. A node broadcasts a received packet to all neighbors provided that this packet was not already received before and that the node belongs to the target area. Finally, a node accepts a packet and delivers it to its application if the own location is within the specified target area. Examples of geocast directed flooding protocols are Location Based Multicast (LBM) [4, 5] and GeoGRID [6].

The second geocast scheme, explicit route setup without flooding, requires either a fixed network like the Internet, which is exemplified by the GeoNode approach [7]. Or, in the GeoTORA approach [8], for each geocast group a directed acyclic graph comprising all network nodes is maintained, which shows the routing direction to the destination. These acyclic graphs are initially created with a flooding scheme, too. However, their maintenance is achieved without flooding.

More complete overviews of geocast routing protocols can be found in [9] and [10].

2.3 Discussion and Contribution of this Work

Currently, no abiding geocast solution for ad hoc networks exists. The only approach that allows periodical delivery of a geocast message, GeoNode, is designed specifically for infrastructure–based networks. Their assumption is that the network has a fixed cellular architecture with a GeoNode assigned to each cell. Routing is done in two steps, the first between sender and GeoNode and the second between GeoNode and destination region. GeoNodes are able to store the packets they receive for periodical delivery. In contrast to GeoNode we will discuss how to achieve abiding geocast for ad hoc networks.

Besides basic network analysis work [11], interesting results for ad hoc networks and mobility models have been published recently [12, 13]. We took them into account where appropriate.

3. OVERVIEW OF ABIDING GEOCAST

3.1 Abiding Geocast Semantics

Before we begin to discuss the abiding geocast approaches we have to define what semantics a solution should have. Most important is here to differentiate abiding geocast from reliability mechanisms. Although abiding geocast is bound to an area over time, our proposed solutions do not try to achieve reliability. For some applications, in particular safety–related applications to which class the virtual traffic sign service belongs to, reliable abiding geocast is bound to be desirable. However, we know from other group communication research areas like reliable multicast that it is not trivial or even impossible to define a semantics suitable for most or all applications. Therefore, reliability mechanisms are not discussed in this paper.

An inherent question of the abiding geocast semantics is the duration of storage and delivery availability. As discussed above, we provide a best effort service without guarantees, which means that we cannot provide guarantees ab-out the duration availability, i.e. we cannot guarantee to reach the full lifetime. However, we assume that we have a mechanism in place to limit the lifetime to a user defined time.

Besides the natural definition of lifetime corresponding to physical clock time, it is possible to define lifetime based on some sort of hop count, similar to the IP approach or some sort of delivery count. For abiding geocast it would make sense to limit the number of deliveries or the total number of hops (we will see that for some approaches abiding geocast has to hop in order to keep stored). Another approach would be to limit the lifetime by an opposing event which fits well to our virtual traffic sign scenario. This means, if a virtual traffic sign is put up, say for example an accident warning sign, it is difficult to fix a lifetime since it is unknown when the crashed cars will be removed. In such a case it seems better to remove the virtual traffic sign by an opposing event.

3.2 Design Space of Abiding Geocast

In this section we discuss and structure the design space of abiding geocast before we present detailed approaches in the following section. For an abiding geocast solution we identify four building blocks: 1) the underlying geocast routing protocol, 2) the storage of geocast messages within their lifetime, 3) the hand over of abiding geocast messages to other nodes, and 4) the delivery of geocast messages to their intended destination nodes.

The underlying geocast routing protocol is necessary for most approaches to deliver the first geocast message to its destination region and possibly for the delivery of all following geocast messages to new nodes entering the destination region later.

The second building block is the storage of geocast messages. This can be done either infrastructure–based by a central server or infrastructure–less, which means distributed on some or all nodes participating in the network.

With the third building block, the hand over of abiding geocast messages, we refer to the problem that a node used for message storage may change its state so that it is no longer considered a suitable node and transfer the message to another, suitable node. For example, the principle of locality may make it desirable to store a geocast message only on nodes inside the destination region. If a storing node leaves the destination region, the stored message is then transferred to another node that is inside the destination

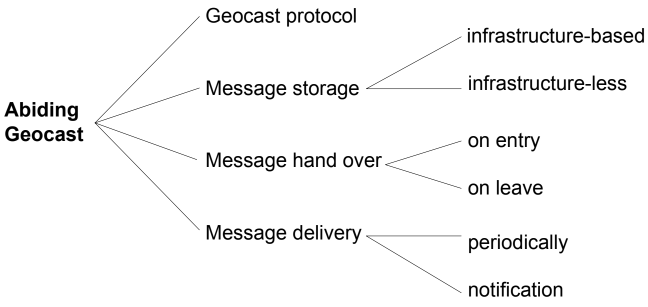

Figure 1: Design space of abiding geocast

region. Transferring a message to another node can be triggered when a new node enters the destination region or when a node inside the destination region is going to leave it.

Finally, the last building block is the delivery of an abiding geocast message to new nodes inside the destination region. This can be done either by blind periodical resending of abiding geocast messages or on demand, by a notification scheme, when a new node enters the destination region. Figure 1 summarizes the design space. Basically, these four building blocks have to be combined to realize abiding geocast. In the next section we will discuss three reasonable combinations.

4. ABIDING GEOCAST APPROACHES

We discuss in the following three reasonable abiding geocast approaches in more detail. For each approach we start with a short overview followed by the detailed description. Then we discuss possible optimizations and the lifetime management. Finally, we analyze the message overhead of each approach and the probability for successful geocast delivery.

4.1 Server Approach

4.1.1 Overview

A server is used to store geocast messages. Hand over of messages is not necessary. Message delivery is done either periodically or by notification.

4.1.2 Description

The geocast message is first unicasted to the geocast server provided by the infrastructure. Then the geocast server uses a geocast routing protocol to deliver the message to the destination region. After the first delivery, further deliveries can be done either periodically by the geocast server or by notification from moving nodes. Note that this approach has some similarities to the geocast proposal of [14].

If the server periodically delivers the geocast message, the delivery frequency has to depend on the maximum or average velocity of the network's nodes.

Assume that the message frequency is denoted as λ_r, the maximum velocity as v_{max} and that the shortest crossing distance within the geocast region a node has to cover in order to receive the abiding geocast message is denoted as c, the following holds:

$$\lambda_r \quad \geq \quad \frac{v_{max}}{c} \quad , 0 < c \leq s.d \tag{1}$$

s denotes the abiding geocast message and $s.d$ the diameter of the destination region. If the message frequency is decreased below the obtained λ_r, fast moving nodes and nodes crossing less than the assumed distance c within the geocast destination region may cross it without receiving a geocast message. If the message frequency is higher than obtained by λ_r, a certain number of message losses can be tolerated since the probability for receiving at least one of the messages increases.

Besides the periodic delivery a notification from moving nodes can trigger the message delivery. However, as a moving node does not know about the defined destination region of geocast messages stored on the server, this requires moving nodes to periodically send their position to the geocast server. To realize an efficient location notification approach, it should depend on the distance between the current position and the position of the last report to the server rather than on time. The distance between two reports d has to be not greater than the minimum required crossing distance c within a geocast's destination region (which has to be not greater than the minimum diameter of geocast destination regions):

$$d \quad \leq \quad c \quad , 0 < c \leq s.d \tag{2}$$

A consequence of the location notification approach is that the geocast server cannot be implemented stateless, since it has to remember requesting nodes and already delivered geocast messages to these nodes.

4.1.3 Optimizations

A reasonable optimization of the notification approach would be to suppress location notifications if an abiding geocast message for the current location is received before, which means that another node has recently reported its presence in the same region. Another optimization would be to synchronize several nodes with similar movement patterns and to send just a single location notification for the synchronized group. Finally, the location information of a node could be sent to the server and additionally as a geocast message to the surrounding of the current location in order to suppress further location notifications of other nodes in the same region.

The decision about the most adequate scheme depends on the frequency of node movements. If nodes move frequently, the node penetration is high, or only few abiding geocast messages with small destination regions are active, the periodic sending scheme may be more efficient, otherwise, the notification scheme. Note that with position calculations of dead reckoning approaches [15], overhead of too frequent message delivery may be further decreased.

4.1.4 Lifetime Management

The server approach allows a simple management of the lifetime of abiding geocast messages. The lifetime is checked on the server before a message is resent. If it is expired, resending is suppressed and the message discarded. Implementing an opposing event to discard an abiding geocast is straightforward, too. It is realized with a discard message sent by unicast to the server. We assume here that abiding geocasts are tagged with a unique sequence number in order to identify them. Either the initial sender can tag geocasts with a unique sequence number, then the sender identifier is part of the sequence number to make it globally unique, or the server can assign a unique sequence number.

In summary, the server approach offers a simple and robust mechanism for abiding geocast. One disadvantage,

Table 1: Notations for the analysis

ν_n	-	Total number of nodes in the network.
ν_b	-	Average number of nodes in one hop wireless transmission range.
ν_g	-	Average number of nodes in geocast destination region.
τ_l	-	Average geocast lifetime.
λ_r	-	Periodic geocast retransmission rate.
λ_c	-	Geocast region change rate.
L	-	Distance between two points in a square region.
p_u	-	Probability for successful unicast transmission from a sender to a receiver.
p_f	-	Probability for successful flooding in geocast destination region.
p_e	-	Probability that a geocast destination region has at least one node.
p_n	-	Probability for successful dissemination inside geocast destination region.
B	-	Bandwidth requirement in terms of number of messages for initial send (B_i), for server send (B_s), for flooding (B_f), for handover (B_h), for neighbor exchange (B_e), and total number of messages to send (B).
R	-	Successful geocast delivery ratio.

the large communication distance between the server and the destination region of geocast messages can be relaxed by distributed geocast servers close to the destination region of their stored messages. Note that a large distance results not only in high overhead but may also result in low robustness, especially in ad hoc networks where network partitioning and message loss may occur frequently and successful delivery of messages incorporating too many hops become unlikely. Now, we will analyze this in more detail.

4.1.5 Network Load and Delivery Success Ratio Analysis

In the following we give a detailed network load and delivery success ratio analysis of the server approach with periodical delivery. We assume a random–waypoint model for the nodes' movements and a square–sized network, which is our assumption for the most common network structure. As our protocols are based on unicast routing protocols, we assume a position–based greedy routing protocol [16]. For simplicity, we assume that no perimeter mode is used, i.e. no backtracking mechanism is in place if a packet transmission reaches a dead end. In such a case a message is simply lost. Table 1 summarizes the most frequently used notations from our analysis.

The message overhead of the server approach encompasses the following three phases:

- initial unicast forwarding from sender to server with bandwidth requirements (i.e. network load) B_i
- unicast forwarding from server to geocast destination region with bandwidth requirements B_s
- flooding inside geocast destination region with bandwidth requirements B_f.

The initial sender is an arbitrary node in the network, while the server is assumed to be placed at the geographical center of the network. This means, the initial unicast forwarding is from an arbitrary node to the center node of the network. Later we will relax this assumption and allow randomly placed servers.

In order to obtain the distance between sender and center node, we consider the random placement of a sender in the two dimensional network area. As ν_n denotes the total number of nodes in the network, the square area has the size $\sqrt{\nu_n} \times \sqrt{\nu_n}$. The sender node's spatial distribution $P = (P_x, P_y)$ is given by two uniform distributions with probability density function (pdf):

$$f_{P_x}(x) = \begin{cases} \frac{1}{\sqrt{\nu_n}} & , 0 \leq x \leq \sqrt{\nu_n} \\ 0 & , else. \end{cases} \quad (3)$$

Since both dimensions are independent from each other, the joint pdf of a node's spatial distribution is:

$$\begin{aligned} & f_{P_xP_y}(x,y) = f_{P_x}(x) f_{P_y}(y) \\ & = \begin{cases} \frac{1}{\sqrt{\nu_n}\sqrt{\nu_n}} \\ 0 \end{cases} = \begin{cases} \frac{1}{\nu_n} & , 0 \leq x, y \leq \sqrt{\nu_n} \\ 0 & , else. \end{cases} \end{aligned} \quad (4)$$

If we divide the network area in four identical squares, the centrally placed server is located at one edge of each square. Using one of these squares, the distance between the center and a random node is given by:

$$L = \sqrt{x^2 + y^2}. \quad (5)$$

Using the pdf from Eq. 4 and the length computation from Eq. 5, the expected value of the distance L is:

$$\begin{aligned} E(L) &= \int_0^{\frac{\sqrt{\nu_n}}{2}} \int_0^{\frac{\sqrt{\nu_n}}{2}} \frac{1}{\nu_n} \sqrt{x^2 + y^2} dxdy. \\ &= \frac{\sqrt{\nu_n}}{6} \left(\sqrt{2} + \ln(1 + \sqrt{2}) \right). \end{aligned} \quad (6)$$

The number of nodes in the wireless transmission range of a node is denoted ν_b. With the expected mean length $E(L)$ between an arbitrary sender and the center node, we have the number of hops which is identical to the bandwidth requirement for the first phase $E(L)$ divided by the radius of a node's wireless transmission range as:

$$B_i = \frac{E(L)}{\sqrt{\frac{\nu_b}{\pi}}}. \quad (7)$$

In the second phase, the center node sends a stored message to the geocast destination region. For an arbitrary node, which is by our definition the geocast destination center, the message overhead is identical to B_i. However, since this phase delivers a message only to the edge of the destination region rather than to the destination region center, the distance from geocast center to edge is subtracted. The resulting message overhead B_s yields to, where ν_g denotes the number of nodes in the geocast destination region and $E(L) \geq \sqrt{\nu_g/\pi}$:

$$B_s = \frac{E(L) - \sqrt{\frac{\nu_g}{\pi}}}{\sqrt{\frac{\nu_b}{\pi}}}. \quad (8)$$

If $L < \sqrt{\nu_g/\pi}$, then the server is already inside the geocast destination region. Consequently, the message overhead B_s is 0.

For flooding the geocast destination region, every node inside the destination region sends a one hop broadcast. The resulting message overhead is then:

$$B_f = \nu_g. \quad (9)$$

The total bandwidth requirement (i.e. network overhead) B for the server approach in terms of messages to send is

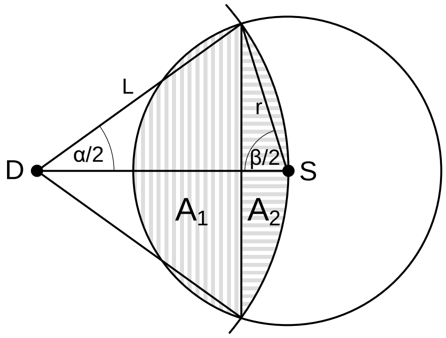

Figure 2: Intersection area for greedy unicast forwarding

then:

$$B = B_i + (1 + \tau_l \lambda_r)(B_s + B_f), \tag{10}$$

where λ_r denotes the rate of periodical resending and τ_l the average geocast lifetime.

If the server node is not placed in the center of the network but is rather a randomly selected node, B_i and B_s are different. For both B_i and B_s we have now the situation that a message is sent from an arbitrary sender to an arbitrary server or from an arbitrary server to an arbitrary geocast destination node, respectively. The expected mean length $E(\tilde{L})$ of two randomly placed nodes in a lattice is already analyzed in the literature [12]. Adapted to our scenario it is given by:

$$E(\tilde{L}) = \frac{\sqrt{\nu_n}}{15}(2 + \sqrt{2} + 5arccosh(\sqrt{2})). \tag{11}$$

Using this modified $E(\tilde{L})$ in Eq. 7 and Eq. 8 yields the message overhead of a randomly placed or randomly moving server. In case of a central server (see Eq. 6) $E(L)$ is approximately $0.3819\sqrt{\nu_n}$ where here $E(\tilde{L})$ is approximately $0.5214\sqrt{\nu_n}$. As a result, a central server requires less bandwidth than a randomly placed server.

For obtaining the delivery success ratio, we distinguish between unicast forwarding and flooding. During a single unicast transmission to the next hop, the delivery ratio depends on the probability that a neighbor node closer to the destination exists. In more detail, the neighbor must be within the sending node's (S) wireless transmission range and within the current distance to the destination node (D), which is the intersection area of two circles (see Figure 2). If such a neighbor exists we assume that the message can be successfully delivered, which is a reasonable assumption as transmission errors can be handled by the 802.11 ACK scheme on ISO OSI layer 2.

From the intersection area depicted in Figure 2, divided into A_1 and A_2, the probability for a successful transmission step can be obtained. The area is given by:

$$\begin{aligned} A(l) &= A_1(l) + A_2(l) \\ &= \frac{r^2}{2}(\beta - sin\beta) + \frac{l^2}{2}(\alpha - sin\alpha) \qquad (12) \\ \alpha &= 2\arccos(1 - \frac{r^2}{2l^2}) \qquad (13) \\ \beta &= 2\arccos(\frac{r}{2l}), \qquad (14) \end{aligned}$$

with distance l between sender and receiver taken from Eq. 6 or 11, respectively. We normalize the wireless transmission range to be $r = 1$. From the intersection area, the probability of a successful single transmission step follows to $1 - (1 - A(l)\nu_b/(\pi\nu_n))^{\nu_n}$. After the first transmission step, the distance l between sender and receiver is decreased. Finally, the probability for a successful transmission from a sender to a receiver yields to:

$$p_u(l) = \prod_{i=0}^{l} 1 - (1 - \frac{A(i)\nu_b}{\pi\nu_n})^{\nu_n}. \tag{15}$$

The probability for successful flooding p_f depends on the probability that the set of neighbor nodes is not empty:[1]

$$p_f = (1 - \frac{\nu_b}{\nu_n})^{\nu_n}. \tag{16}$$

Finally, the total probability for successful reception in the server approach yields to:

$$R = p_u(B_i)\left(1 - (1 - p_u(B_s)p_f)^{1 + \frac{\tau_l \lambda_r}{\lambda_c}}\right). \tag{17}$$

The rate λ_c at which a node enters and leaves the geocast destination region is obtained later in Eq. 26.

Now we have described and analyzed the server approach in detail. Numerical results will be given in Section 5. We continue with describing a second reasonable combination of the design space building blocks which we call election approach.

4.2 Election Approach

4.2.1 Overview

A node in the destination region of a geocast message is elected to store geocast messages. Hand over of messages is done when this node leaves the destination region. Message delivery is done periodically or by notification.

4.2.2 Description

Instead of relying on a fixed server infrastructure, a dynamically elected node within the destination region of the geocast message is responsible for storing and delivering the message.

Basically, each node in the destination region is a candidate for the election process. However, to avoid frequent hand over, it is desirable to choose one that stays as long as possible in the destination region. Such a node is characterized by low velocity and closeness to the center of the destination region. For example, the unique tuple <velocity * center_distance, node_id> can be used in the election process. A suitable election algorithm is for example described in the GeoGRID approach [6]. Note that in contrast to general election algorithms in distributed systems, the outcome of the election requires no consensus among all nodes about a *single* winner. It is sufficient to have *at least* one elected node, which is less costly to achieve than the strict requirement of a single winner. If more than one node is elected, elected nodes hear from each other during the resending of their abiding geocasts and can decide to give up their role.

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[1] Note that we make here an optimistic assumption that no broadcast collisions occur. Although not difficult, we refrain from a collision consideration for simplicity reasons and because the resulting probability for complete message loss at a node from all neighbors in uncongested networks is negligible.

Geocast message delivery is done as follows. The initial sender of a geocast message uses a geocast routing protocol to deliver the message for the first time. Inside the destination region, all nodes receive the geocast message and start the election process. The elected node stores the message and periodically or on request delivers the message as in the previous server approach. Note that here a simple algorithm for electing a node is assumed. We simply elect the first node on the unicast path from sender to destination region that is inside the destination region and switches from unicast to flooding. If the elected node leaves the destination region, a new election round is started and the message is handed over to the new elected node.

In case of periodical delivery, our calculations from the previous approach are effective for the election approach, too. In case of on request delivery, the location notification report is sent as a geocast message to a circular destination region with the actual position as the center.[2]

The configuration of important parameters like diameter of the location notification geocast and frequency of location notifications requires consideration. A basic observation is that the diameter of the location notification $n.d$ must be no smaller than the doubled maximum diameter of the geocast messages $s.d$, because with $n.d$ smaller than $2 \cdot s.d$ it would be possible to miss the elected node:

$$n.d \quad \geq \quad 2 \cdot max(\forall s \in \{\text{abiding geocasts}\} : s.d) \tag{18}$$

Besides the destination region's diameter of location notifications, the frequency of location notifications is of interest. The distance between two reports d has to be not greater than the minimum required crossing distance c within a geocast's destination region identical to the server approach.

If the elected node leaves the destination region, a new election round is started and the message is handed over to the new elected node. Fault tolerance can be increased by electing not only a single node but several ones that keep message replicas.

4.2.3 Optimizations

Location notification suppression schemes as briefly discussed in the server approach are feasible, too. The geocast based location notification makes it quite simple to suppress an own location notification if another one for the same region has been received before. Fault tolerance can be increased by electing not only a single node but several ones that keep message replicas.

4.2.4 Lifetime Management

Lifetime management is more complex in the election approach. While checking whether the lifetime has expired before resending a message is simple, too, the opposing event mechanism requires a modification. Sending an opposing event requires knowledge of the elected node in order to address the destination. As this is not always given, unicast cannot be used to send the opposing event. Instead, for the opposing event geocast is used to address (at least) the whole destination region of the abiding geocast message that is to be discarded. This ensures that the elected node is usually enclosed in the opposing event's addressed region. However, if a hand over takes place at this very moment, the elected node might be outside the destination region and missed by the opposing event. Therefore, the diameter of the opposing event o should be:

$$o.d \quad \geq \quad s.d + \frac{1/\lambda_r}{v_{max}}, \tag{19}$$

with λ_r denoting the rate at which retransmissions take place and at which the elected node checks whether it is still inside the geocast destination region or initiates a hand over, otherwise.

4.2.5 Network Load and Delivery Success Ratio Analysis

The message overhead of the election approach with periodical delivery encompasses the following three phases:

- initial unicast forwarding from sender to destination region with bandwidth requirements B_i
- unicast handover from current server to a new server with bandwidth requirements B_h
- flooding inside geocast destination region with bandwidth requirements B_f.

For simplicity we assume here that no special election mechanism is used. Instead the first node on the unicast path from sender to destination region that is inside the destination region is the elected node. In the first phase sender and receiver of the message are arbitrary nodes. The distance between both arbitrary nodes is reduced by the radius of the geocast destination region. This yields to (see Eq. 8 and 11):

$$B_i \quad = \frac{E(\tilde{L}) - \sqrt{\frac{\nu_g}{\pi}}}{\sqrt{\frac{\nu_b}{\pi}}}. \tag{20}$$

If an elected server node detects that it is outside the geocast destination region, a geocast message is handed over by a single packet to a neighbor inside the destination region. The resulting message overhead is:

$$B_h \quad = \quad 1. \tag{21}$$

Finally, we have to obtain the rate at which a node enters and leaves the geocast destination region, which is denoted as change rate λ_c. A precise change rate analysis has to take into account mainly the shape of a geocast destination region and the properties of the random waypoint model. For obtaining λ_c we consider a random node inside a geocast destination region. According to the random waypoint model, this node selects a random destination inside the network area. With probability ν_g/ν_n the random destination is again inside the geocast destination region and with probability $1 - \nu_g/\nu_n$ it is outside. If the next destination is outside the geocast region, the node crosses the border of the destination region after time period $\frac{1}{v}\sqrt{\frac{\nu_g}{\pi}}$, where v is the average velocity. Otherwise, the node stays for a certain time period T inside the geocast region and then again a new destination inside or outside the geocast region is selected. T is the expected transition time from one waypoint to another. In the random waypoint model, T and v are (see [12]):

$$v \quad = \quad \frac{v_{max} - v_{min}}{ln(v_{max}) - ln(v_{min})} \tag{22}$$

$$E(T) \quad = \quad \frac{E(\tilde{L})}{v}. \tag{23}$$

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[2] Note that this is feasible for a random walk scenario. In case of a directed walk like in a vehicular scenario, optimizations by sending a geocast location notification to the region in front of the vehicle may be worthwhile.

Note that according to $\tilde{L}$, which is the number of hops, consequently v is defined here as the number of hops per second. In summary, the expected change rate is then:

$$p = \frac{\nu_g}{\nu_n} \tag{24}$$

$$\lambda_c = 1/\int_{i=0}^{\frac{\tau_l}{E(T)}} p^i(1-p)\left(\frac{1}{v}\sqrt{\frac{\nu_g}{\pi}} + iE(T)\right) di \tag{25}$$

$$\begin{aligned}\lambda_c = {} & 1/\frac{(p-1)}{(\ln(p))^2}\Bigg(E(T) - E(T)p^{\frac{\tau_l}{E(T)}} + \ln(p) \\ & \cdot\Big(\frac{1}{v}\sqrt{\frac{\nu_g}{\pi}}(p^{\frac{\tau_l}{E(T)}} - 1) + E(T)p^{\frac{\tau_l}{E(T)}}\frac{\tau_l}{E(T)}\Big)\Bigg).\end{aligned} \tag{26}$$

The total bandwidth requirement B for the election approach is then:

$$B = B_i + \tau_l\lambda_c B_h + (1 + \tau_l\lambda_r)B_f. \tag{27}$$

The successful reception probability for the election approach is:

$$R = p_u(B_i)\left(1 - (1-p_f)^{1+\frac{\tau_l\lambda_r}{\lambda_c}}\right), \tag{28}$$

with p_u and p_f given in Eq. 15 and Eq. 16, respectively. Note that the handover of a message to a new server is not considered since it does not decrease the reception probability. It is done by reliable layer 2 unicast or if handover fails, because no neighboring node is closer to the destination region, the geocast message is kept at the current server until a new one is found.

4.3 Neighbor Approach

4.3.1 Overview

Each node stores all geocast packets destined for its location and keeps a table of all neighbor nodes and their location. If a node within a geocast destination region detects a new neighbor it delivers the geocast packet to it, i.e. hand over is done on entry and message delivery is done by notification. As an option, the message delivery can also be done periodically with a one–hop broadcast.

4.3.2 Description

The initial abiding geocast message is sent using a regular geocast routing protocol to the destination region. After the first delivery, geocast information is exchanged between neighbors inside the destination region if message delivery by notification is used.

Many location–based unicast routing protocols like NFP [17] or DREAM [18] proactively and periodically exchange neighbor information containing their location in order to forward a packet to a neighbor closer to the destination. The neighbor approach simply extends the exchanged neighbor information for the unicast routing with abiding geocast information. The following alternative schemes to extend the exchanged neighbor information are reasonable: 1) each node maintains a list of neighbors and already exchanged abiding geocast messages 2) with neighbor information all abiding geocast messages relevant for this location are exchanged, 3) with neighbor information a list of already received abiding geocast identifiers relevant for this location is exchanged.

In the first scheme, for most unicast routing protocols the exchanged neighbor information does not require any extension, since it is sufficient to learn about the identifiers and positions of neighbors. Each node maintains a list of <neighbor_identifier, delivered_geocasts> that contains for each neighbor node which abiding geocast messages are already delivered. Note that this is not a global view but only a local one, from each node's individual perspective. If a node detects a new neighbor that is not in its list or to whom not all abiding geocast messages relevant for the neighbor's location has been forwarded, then all relevant abiding geocast messages are forwarded by means of unicast. As the maintained list does not have a global view, in general a node receives an abiding geocast message more than once from some or even all neighbors.

The second scheme, blindly exchanging abiding geocasts with all neighbors, is the most simple but also most bandwidth wasteful one. The resending is done by each node individually with a one hop broadcast instead of joint flooding triggered by a single node. After receiving an abiding geocast, a node has to check whether its location intersects with the geocast destination region. If so, the geocast is delivered to the higher protocol layer and stored for later exchange with neighbors. Otherwise, the geocast is discarded.

With the third scheme, filtering of geocast messages is done before they are exchanged. The exchanged list of geocast identifiers contains unique tuples, for example <initial_geocast_sender, sequence_number> to identify a geocast message. If a node detects that it has stored a geocast message relevant for a neighbor node's location but unknown to the neighbor, the abiding geocast is sent to this neighbor.

4.3.3 Optimizations

As an optimization of all last three schemes, a two round protocol can be introduced. In the first round, only information necessary for most location based unicast routing protocols is exchanged with neighbors. This includes the own identifier and location. If this results in detecting a new neighbor inside a geocast's destination region, a second information exchange round is triggered including the abiding geocast information according to one of the three schemes from above.

4.3.4 Lifetime Management

Lifetime management in the neighbor approach is similar to the election approach. Before a message is sent to neighbors its lifetime is checked. If it has been expired, the abiding geocast is discarded.

An opposing event is sent with geocast to the whole destination region of the abiding geocast message that is to be discarded. This allows for all nodes inside the destination region to receive the opposing event and discard their corresponding abiding geocast messages.

4.3.5 Network Load and Delivery Success Ratio Analysis

For the analysis we assume that the neighbor approach uses the first discussed scheme, maintaining a list of already delivered geocast messages. At the end of this section we will briefly show the differences if periodical broadcasting instead of unicasting is used. The message overhead of the neighbor approach encompasses the following three phases:

- initial unicast forwarding from sender to destination region with bandwidth requirements B_i
- flooding inside geocast destination region with bandwidth requirements B_f

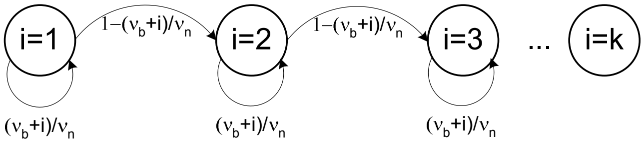

Figure 3: State transitions of the Markov chain

- unicast exchange of geocast messages with neighboring nodes with bandwidth requirements B_e.

In the first phase sender and the first receiver inside the geocast destination region are arbitrary nodes. The distance between both arbitrary nodes is reduced by the radius of the geocast destination region. This yields to the same result for B_i as already depicted in Eq. 20.

The number of necessary unicast message exchanges with neighboring nodes depends on the rate neighbor nodes change. This rate is obtained with Eq. 26 for λ_c by replacing ν_g with the wireless transmission range of a node, ν_b.

If a node n_1 enters the wireless transmission range of another node n_2, which frequency is given by the rate λ_c, n_2 checks whether n_1 was not seen before and geocasts have not been delivered before. For example, if n_1 leaves n_2's wireless transmission range after geocasts have been delivered and reenters it later again, this is detected by n_2. Geocasts are delivered only if they have not been previously delivered to the entering node.

The probability that an entering node is new is obtained by a discrete–time Markov chain. The number of states k is given by the rate a node is entering the wireless transmission range λ_c multiplied by the number of nodes inside the wireless transmission range ν_b and the geocast lifetime τ_l, which is the total number of neighbor changes:

$$k = \begin{cases} \tau_l \lambda_c \nu_b & , \tau_l \lambda_c \nu_b \leq \nu_n - \nu_b \\ \nu_n - \nu_b & , else. \end{cases} \tag{29}$$

The Markov state–transition probability matrix $P = [p_{ij}]$ is given by the following formula (see Figure 3). The index of a state denotes the number of unseen nodes that have entered the wireless transmission range. For each state i, the probability for entering the next stage $i+1$ is given by $1 - (\nu_b + i)/\nu n$. If eventually all nodes have been in the wireless transmission range before, the probability for entering the next state becomes 0. Consequently, the probability for retaining in a state is $(\nu_b + i)/\nu n$, which eventually becomes 1. The probability matrix is given by:

$$p_{ij} = \begin{cases} \frac{\nu_b + i}{\nu_n} & , i = j \\ 1 - \frac{\nu_b + i}{\nu_n} & , j = i + 1 \\ 0 & , else \end{cases} \tag{30}$$

With the initial probability vector $\underline{p}(0)$ of size k, the probability vector $\underline{p}(k)$ after k steps is:

$$\underline{p}(0) = (1, 0, 0, ...0) \tag{31}$$

$$\underline{p}(k) = \underline{p}(0) P^k. \tag{32}$$

The expected number of nodes entering the geocast destination region for the first time, which corresponds with the bandwidth requirement B_e after multiplication with the number of nodes in the geocast destination region ν_g, is:

$$B_e = \nu_g E(P) = \nu_g \sum_{i=0}^{i=k} i p_i. \tag{33}$$

The total bandwidth requirement B for the neighbor approach is then:

$$B = B_i + B_f + B_e. \tag{34}$$

If the neighbor approach uses periodical broadcast instead of unicast for sending geocasts to neighboring nodes, B_i and B_f are unchanged. The total bandwidth requirement B yields to:

$$B = B_i + B_f + \tau_l \lambda_r \nu_g. \tag{35}$$

When analyzing the delivery success ratio we have to take into account that a geocast message can get lost if no node is inside the destination region. The probability p_e that the destination region is not empty is:

$$p_e = 1 - (1 - \frac{\nu_g}{\nu_n})^{\nu_n}. \tag{36}$$

With probability ${p_e}^i$ that the destination region is not empty during i steps and p_f that a message is received from at least one neighbor node (see Eq. 16) the total probability that a message is received is then:

$$p_n = 1 - \prod_{i=0}^{\frac{\tau_l \lambda_r}{\lambda_c}} (1 - {p_e}^i p_f). \tag{37}$$

Finally, taking into account the necessary delivery of a message to the destination region and dissemination inside the destination region, the delivery success ratio for the neighbor approach is:

$$R = p_u(B_i) p_n. \tag{38}$$

5. NUMERICAL RESULTS

We examine the network load and the delivery success ratio of the analyzed abiding geocast protocols by means of some numerical examples. For most results we assume an ad hoc network consisting of $\nu_n = 1000$ nodes. The average number of neighboring nodes within a node's wireless transmission range is $\nu_b = 8$. The average number of nodes in a geocast destination area is $\nu_g = 25$, the average geocast lifetime is $\tau_l = 30s$ and the retransmission rate is $\lambda_r = 1/s$. The average node wireless transmission range is $250m$ and the average velocity is $v = 25m/s$.

Figure 4.a shows the expected total network load in terms of number of sent packets with varying number of network nodes. All other parameters are constant according to the description above. With increasing number of nodes, the distance between sender and geocast destination region becomes larger. As a result, the network load of all approaches increase. In more detail, we observe that there is a significant increase for the server approaches, while the election and neighbor approach show only a slight increase. This is because for each retransmission event, the server approach has to bridge the distance between server and geocast destination region again, while the election and neighbor approach store the geocasts inside the destination region.

Figure 4.b gives an example for the expected delivery success ratio resulting from a varying number of network nodes. We can see that all abiding geocast approaches show similar behavior. If the number of network nodes is increased, the longer distances result in decreasing successful deliveries. By comparing the quantitative results, we observe that the central server outperforms the other approaches in some cases. This is remarkable, since in the

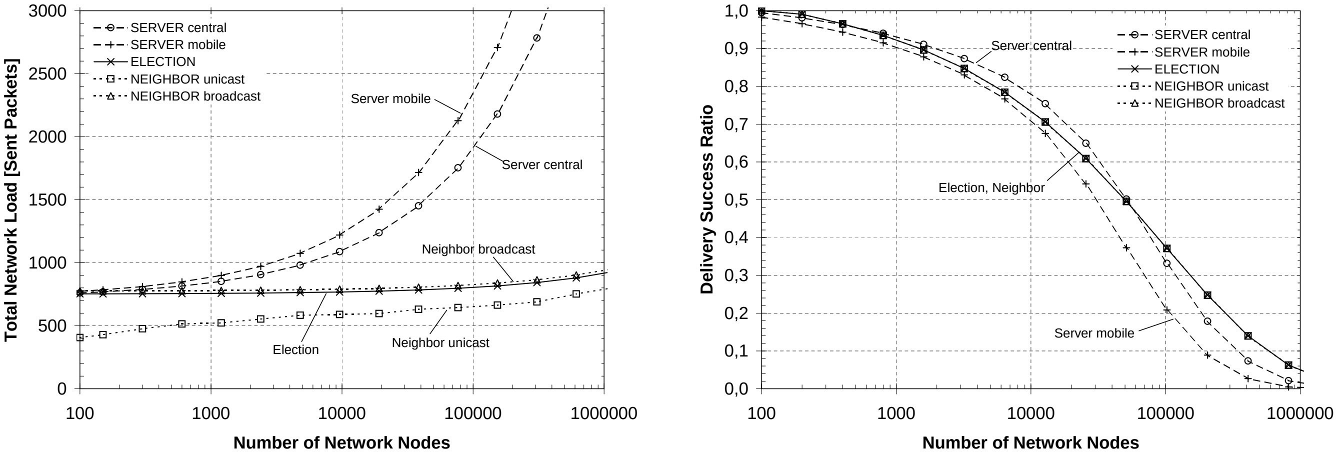

Figure 4: a) Expected network load and b) expected delivery success ratio with varying number of network nodes

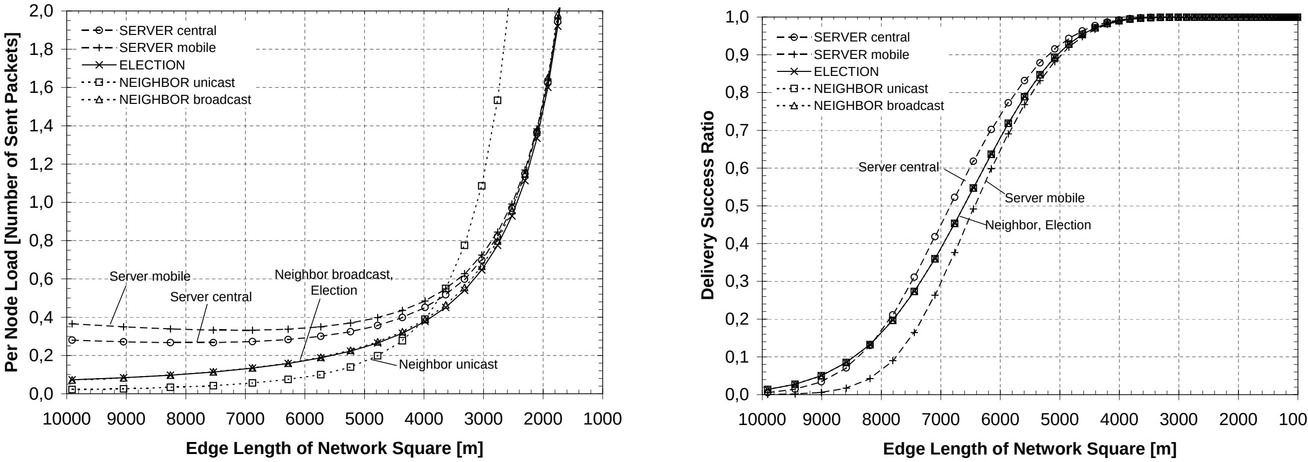

Figure 5: a) Expected network load and b) expected delivery success ratio with varying network density

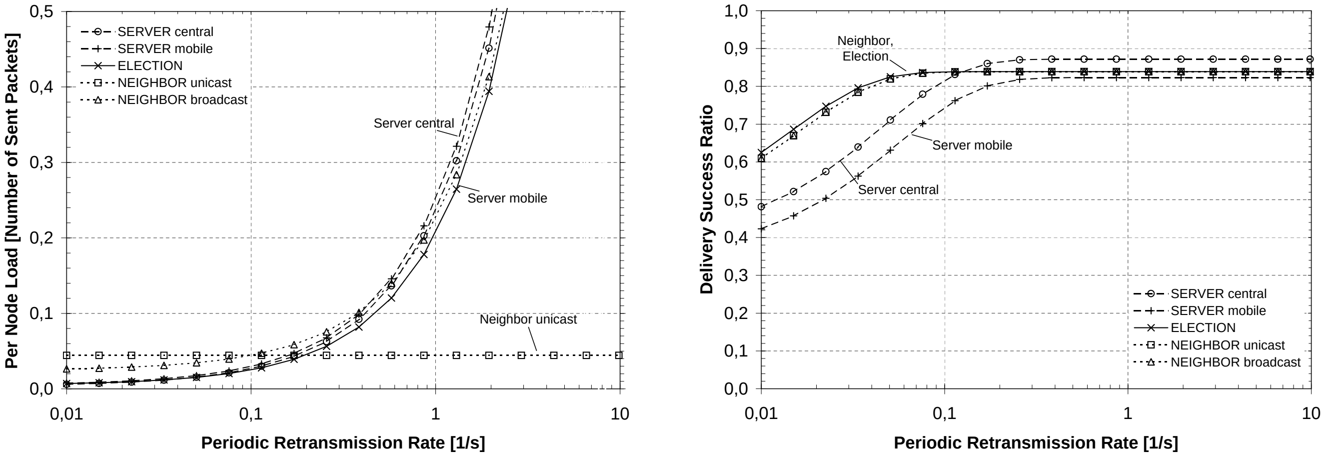

Figure 6: a) Expected network load and b) expected delivery success ratio with varying periodic retransmission rate

previous paragraph we noted that the server approach has to bridge the distance between server and geocast destination region for each retransmission step, which should decrease successful deliveries. On the other hand, the most critical path is from the sender to the server, or from the sender to the geocast destination region for the other approaches, respectively. This path is more critical than from the server to the geocast destination region since in the latter periodical retransmissions from the server can cope with a certain number of message losses while a loss on the former path means that the geocast message is not delivered at all. The central server approach benefits from this, since its critical path is shorter than that of the other approaches (compare with Eq. 6 and 11).

Figure 5 shows the per node load and delivery success ratio with varying network area size, i.e. from sparse networks with an edge length of $10000m$ to dense networks with an edge length of only $1000m$. In our assumed scenario with $250m$ wireless transmission range and 1000 nodes this results in $\nu_b \approx 2..200$, i.e. between 2 and 200 neighbor nodes in the wireless transmission range. We assumed for the geocast destination region a constant diameter of $250m$. Obviously, in a denser network more nodes are inside the destination region, hence the load increases. In a sparse network and sparse destination region, the neighbor approach using unicast results in the lowest network load. However, in denser networks the delivery using broadcast outperforms the unicast approach. With respect to the delivery ratio, we observe that a reasonable reliable delivery can only be achieved in dense networks. With $\nu_b > 8$ (approx. edge length of $5000m$ in our scenario) all approaches achieve more than 90% delivery success.

An example for analyzing the influence of the periodic retransmission rate on the per node load and delivery success ratio is given in Figure 6. Obviously, a low retransmission rate results in low network load. However, in particular the server approaches suffer from low retransmission rates since the delivery success ratio is significantly lower compared with the other approaches. This results from the longer communication distances between server and destination region and therefore higher message loss probabilities, which are more dominant if only a few or even no retransmissions are made. On the other hand, increasing the retransmission rate increases the network load, too.

6. SUMMARY

Abiding geocast is a time stable geocast delivered to all nodes that are inside a destination region within a certain period of time. Many vehicular information and safety applications profit from abiding geocast as it releases the applications from blind periodical retransmissions and saves bandwidth.

We have discussed the design space of abiding geocast and have described three reasonable combinations in more detail. The first approach is a server solution to store the messages. The second approach elects a node inside the geocast destination region to act temporarily as a server. The last approach uses local message storage inside the destination region, too, and complements the exchange of neighbor information necessary for many geographic unicast routing protocols with abiding geocast information.

A detailed probabilistic network load and delivery success ratio analysis has shown the protocols' behavior in more detail. We have observed that in many cases the approaches with local message storage cause less network load.

Currently we are working on simulations of our approaches with vehicular traffic traces from highway scenarios. Preliminary results show high correlation with our analysis.

7. REFERENCES

[1] C. Maihöfer and Reinhold Eberhardt, "Virtual warning signs: A geocast enabled service for ad hoc networks," *Special issue of Computer Communications*, 2004.

[2] E. Royer and C. Toh, "A review of current routing protocols for ad-hoc mobile wireless networks," *IEEE Personal Communications*, vol. 6, no. 2, pp. 46–55, Apr. 1999.

[3] Martin Mauve, Jörg Widmer, and Hannes Hartenstein, "A survey on position-based routing in mobile ad hoc networks," *IEEE Network*, vol. 15, no. 6, pp. 30–39, Dec. 2001.

[4] Young-Bae Ko and Nitin H. Vaidya, "Geocasting in mobile ad hoc networks: Location-based multicast algorithms," in *Proceedings of the 2nd Workshop on Mobile Computing Systems and Applications (WMCSA 99)*, New Orleans, USA, Feb. 1999, pp. 101–110.

[5] Young-Bae Ko and Nitin H. Vaidya, "Flooding-based geocasting protocols for mobile ad hoc networks," *Mobile Networks and Applications*, vol. 7, no. 6, pp. 471–480, 2002.

[6] W.-H. Liao, Y.-C. Tseng, K.-L. Lo, and J.-P. Sheu, "GeoGRID: A geocasting protocol for mobile ad hoc networks based on GRID," *Journal of Internet Technology*, vol. 1, no. 2, pp. 23–32, Dec. 2000.

[7] T. Imielinski and J. Navas, "GPS-based addressing and routing," Internet Engineering Task Force, Network Working Group, Request for Comments, RFC 2009, Nov. 1996.

[8] Y.-B. Ko and N. H.Vaidya, "GeoTORA: A protocol for geocasting in mobile ad hoc networks," in *Proceedings of the 8th International Conference on Network Protocols (ICNP)*, Osaka, Japan, Nov. 2000, pp. 240–250.

[9] X. Jiang and T. Camp, "A review of geocasting protocols for a mobile ad hoc network," in *Proceedings of the Grace Hopper Celebration (GHC)*, Vancouver, Canada, Oct. 2002.

[10] C. Maihöfer, "A survey on geocast routing protocols," *IEEE Communications Surveys and Tutorials, 2nd quarter issue*, vol. 6, no. 2, 2004.

[11] John A. Silvester and Leonard Kleinrock, "On the capacity of multihop slotted aloha networks with regular structure," in *IEEE Transactions on Communications, COM. 31, No 8*, Aug. 1983, pp. 974–983.

[12] Christian Bettstetter, Hannes Hartenstein, and Xavier Perez-Costa, "Stochastic properties of the random waypoint mobility model," *ACM/Kluwer Wireless Networks, Special Issue on Modeling and Analysis of Mobile Networks*, 2003.

[13] Olivier Dousse, Patrick Thiran, and Martin Hasler, "Connectivity in ad-hoc and hybrid networks," in *INFOCOM*, New York, USA, June 2002.

[14] Tomasz Imielinski and Julio C. Navas, "GPS-based geographic addressing, routing, and resource discovery," *Communications of the ACM*, vol. 42, no. 4, pp. 86–92, Apr. 1999.

[15] O. Wolfson, A. P. Sistla, S. Chamberlain, and Y. Yesha, "Updating and querying databases that track mobile units," *Distributed and Parallel Databases Journal*, vol. 7, no. 3, pp. 1–31, 1999.

[16] B. Karp and H.T. Kung, "Greedy perimeter stateless routing for wireless networks," in *Proceedings of the Sixth ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 2000)*, Boston, USA, Aug. 2000, pp. 243–254.

[17] T. Hou and V. Li, "Transmission range control in multihop packet radio networks," *IEEE Transactions on Communication*, vol. 34, no. 1, pp. 38–44, Jan. 1986.

[18] S. Basagni, I. Chlamtac, V. R. Syrotiuk, and B. A. Woodward, "A distance routing effect algorithm for mobility (DREAM)," in *Proceedings of the ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom)*, Dallas, USA, Oct. 1998, pp. 76–84, ACM Press.