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Department of Computer Science & Engineering

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1. Introduction

The rapid reduction in the size and cost of computation, communication, and sensing units is ushering in an era of sensor network computing. Large-scale wireless sensor networks are expected to be deployed in various physical environments to support a broad range of applications such as precision agriculture, habitat monitoring, battle field awareness, smart highways, security, emergency response and disaster recovery systems [8]. These applications typically involve collecting data from sensor networks, aggregating it inside the network, and communicating preprocessed information to users over multi-hop ad hoc networks. Data aggregation in sensor networks is often driven by the locality of environmental events and entails coordination activities subject to spatial constraints. Furthermore, oftentimes the information about the environmental event is more relevant to users close to where the event is taking place than to those farther away. For instance, many sensor network applications (e.g., habitat monitoring [5] and intruder tracking [16]) involve monitoring mobile physical entities that move in the environment. Only sensors close to an interesting physical entity should participate in the aggregation of data associated with that entity as activating sensors that are far away wastes precious energy without improving sensing fidelity. To continuously monitor a mobile entity, a sensor network must maintain an active sensor group that moves at the same velocity as the entity. Achieving this energy-efficient operation ([5, 19]) requires two fundamental building blocks. The first is a protocol for activating and deactivating (i.e., putting to sleep) sensors whenever necessary. Usually, only a small number of sensors need to be active to provide continuous coverage. Most sensors should sleep and only wake up periodically to poll active sensors and to re-enter the active mode, if necessary. The second building block is a communication mechanism that enables sensors to actively push information about a known entity to other sensors or actuators before the entity arrives in their vicinity, in order to wake up sleeping sensors in time or prearm actuators for better monitoring and action. The combination of entity mobility and spatial locality introduces unique spatiotemporal constraints on the communication protocols. While several protocols have been developed to manage the activation and deactivation of sensors, the problem of spatiotemporal communication in sensor networks has received less attention.

We propose a new multicast communication paradigm called "spatiotemporal multicast" for supporting spatiotemporal coordination in applications over wireless sensor networks. The distinctive trait of this new form of multicast is the delivery of information to all nodes that happen to be in a prescribed region of space at a particular point in time. In other words, the set of multicast message recipients is specified by an area of delivery that may continuously move, morph, and in general, evolve over time. This provides a powerful mechanism for application developers to express their needs for spatial and temporal information dissemination (e.g., just-in-time multicast delivery) directly to the multicast communication layer and simplifies application development.

In this paper, we focus on a constant velocity mobile multicast called *mobicast*, a special class of spatiotemporal multicast whose delivery zone is of some fixed shape that translates through space at a constant velocity $\vec{v}$. A key challenge we tackle in this paper is to achieve a strong just-in-time spatial delivery guarantee over a wide range of network topologies. The key contributions of this work include: (1) the specification of mobicast and its performance metrics, (2) the introduction of four different mobicast protocols along with the analysis of their delivery guarantee and overhead trade-offs, (3) the introduction of two topological compactness metrics for geometric networks designed to facilitate the analysis of information propagation behaviors across such networks, and (4) experimental results about the compactness properties of random sensor networks, and their effect on protocol performances.

The remainder of the paper is organized as follows. We specify *mobicast* formally in Section II. A protocol to achieve reliable *mobicast* in sensor networks and its analysis are described in Section III. We present our study of the compactness of random networks and its implications for spatiotemporal protocols in Section IV, followed by a simulation study of a optimistic mobicast protocol in section V. Discussion, related work and conclusions appear in sections VI, VII and VIII, respectively.

2. Spatiotemporal Multicast and Mobicast

Spatiotemporal multicast is a new multicast paradigm that caters to the class of applications that need to disseminate their multicast messages to the "right-place" at the "right-time". A spatiotemporal multicast session can in general be specified by a tuple, $\langle m, Z[t], T_s, T \rangle$, where m is the multicast message, $Z[t]$ describes the expected area of message delivery at time t, T_s and T are the sending time and duration of the multicast session, respectively. As the delivery zone $Z[t]$ evolves over time, the set of recipients for m changes as well. Clearly, conventional geographical/spatial multicast can be viewed as a special case of spatiotemporal multicast. Note that in conventional spatial multicast [22, 12, 15] the delivery area Z is fixed (i.e., does not change over time) for each multicast session, and there is no explicit specification of when the session terminates. The key characteristic of the spatiotemporal multicast service is giving applications explicit control over both the spatial and temporal perspectives of multicast information delivery.

Fig.1 shows two examples of spatiotemporal multicast with different kinds of delivery zones. Fig.1(a) depicts a rectangle-shaped zone (shaded) that moves from the source located at the bottom of the figure to the top. As the delivery zone moves, some nodes enter the zone and some others leave the zone. The delivery specification of spatiotemporal multicast may require that a node be delivered the message m at the time the delivery zone reaches the node. Note that the shape and evolving behavior of a delivery zone are defined/specified by *mobicast* users (for their spatiotemporal delivery requirement of information m). A spatiotemporal multicast protocol then needs to achieve this spatiotemporal delivery requirements efficiently in various network topologies. Fig.1(b) shows a more general example where the delivery zone assumes an arbitrary shape, with both its shape and location evolving over time. This may be the case when the delivery requirements change in response to dynamic context observed in the mobile delivery zone.

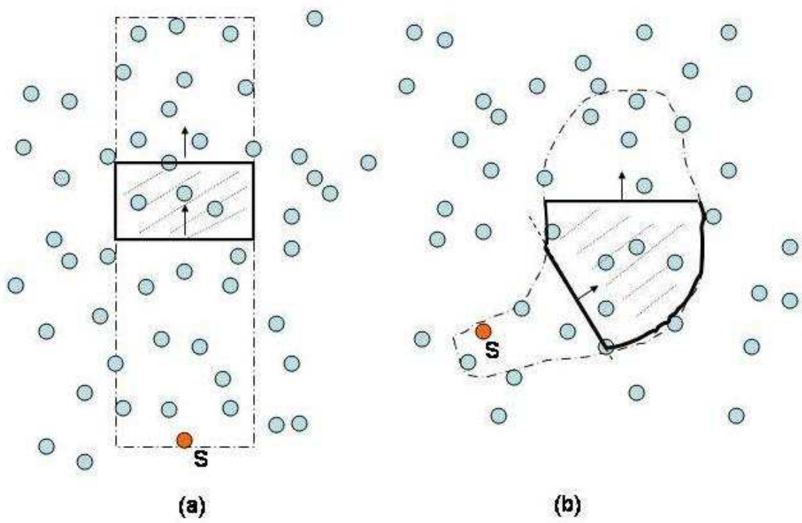


Figure 1: Spatiotemporal Multicast Examples

2.1. Mobicast

A special class of spatiotemporal multicast of interest in this paper is one that has the following special behavior: its delivery zone is some fixed convex polygon P that translates through a 2-D space at some constant velocity $\vec{v}$, i.e.,

$$Z[t] = P[\vec{r}_0 + \vec{v}(t - T_s)]$$

with $P[\vec{r}_0]$ being the polygon centered at $\vec{r}_0$. We call this specific class of spatiotemporal multicast "constant velocity mobile multicast", abbreviated as "CV-mobicast", or "mobicast" in this paper. A mobicast session example is shown in Fig.(2), in which the solid rectangular area $Z[3]$ represents the current delivery zone (at time $t = 3$), and the two dashed rectangles $Z[1]$, $Z[2]$ represent two instances of the same delivery zone at times $t = 1$ and $t = 2$, respectively.

Note that there are many other mobicast scenarios besides the constant velocity mobicast. For instance, some applications may like the delivery zone to move on a path under a specific speed schedule, or on a path with maximum information gain [18].

2.2. Application Examples

Mobicast can be used for sensor network applications such as intruder tracking [4, 18] or information scouting, as shown in Fig 3. On the left we have an intruder tracking example. A set of sensors discovers an enemy tank, they send an alert message to sensors and actuators (e.g., camera control

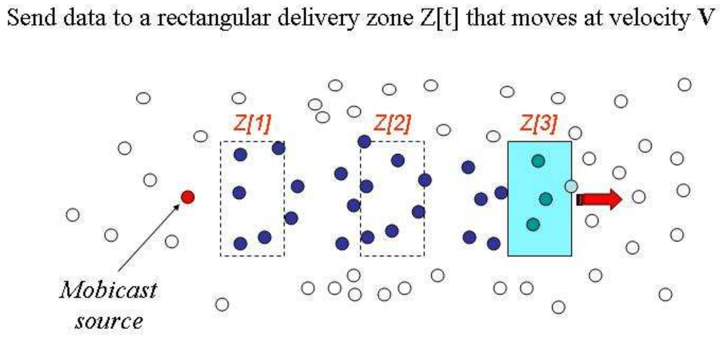


Figure 2: Mobicast example: A Moving Rectangular Delivery Zone

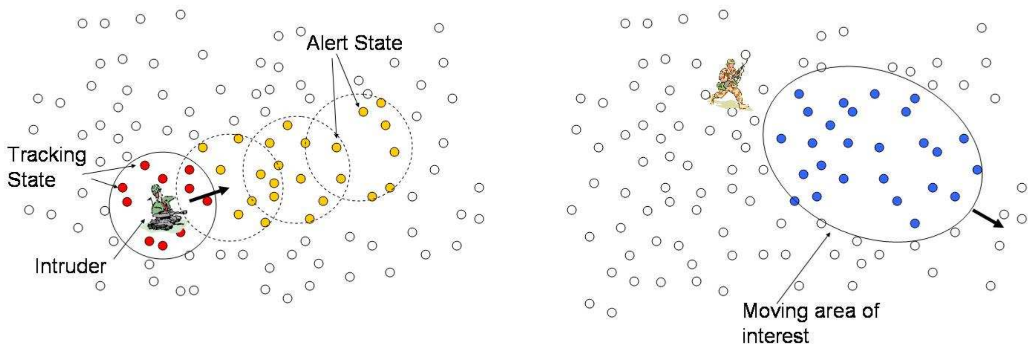


Figure 3: Tracking and Scouting Applications

units) on the intruder's expected path to wake them up, alert them, or pre-arm them for better tracking and actions. This alert message can be sent by a mobicast service, using a delivery zone of desired size that moves at certain distance ahead of the intruder, with a speed approximating that of the intruder's, thus creating an evolving alert "cloud" just in front of it. The right side of Fig 3 depicts an information scouting example. A solider is running to the southeast area. For safety and/or action efficiency, he would like to know the field information ahead on his path, so as to adjust his action accordingly. His area of interest changes in front of him as he runs. One can see that this is another natural application scenario for mobicast. The solider can send a scouting request to a delivery zone that moves on his path in front of him. Only the sensors that enter the delivery zone (receive the scouting message) will pool their currently sensed information and send aggregated data back to him. The use of mobicast naturally delivers the spatial and temporal locality requirements of information dissemination and gathering exhibited by these applications.

A key observation here is that if the mobile event does not change its motion very often, the system alert or scouting message does not need to be issued all the time. But rather, one can let the message roll on its own according to a motion plan. If the mobile event changes or the old mobicast expires, one can always issue a new mobicast reflecting the new information.

2.3. Specification of Spatiotemporal Delivery Guarantees

As we have pointed out earlier, application developers can encode their spatiotemporal information delivery requirements via the delivery zone behavior. The complexity of a *mobicast* protocol in general depends on the delivery guarantees it is required to achieve. A straight-forward delivery specification may demand that once a node α is in a delivery zone $Z[t]$, it receives the information m immediately. Here we will first try to define and refine this specification formally, and discuss its feasibility and implications. Let Ω be the set of all nodes in space, let $\vec{r}(j)$ be the location of node j, and let $D[j,t]$ denote the fact that j has been delivered the information m at time t. Let the time when the *mobicast* is initiated be T_s. This *mobicast* delivery property can be formally stated as

$$\langle \forall j, t : j \in \Omega \wedge T_s \le t \le T_s + T :: \vec{r}(j) \in Z[t] \Longrightarrow D[j,t] \rangle^1 \quad (1)$$

This statement can be interpreted as "During the *mobicast* session, all nodes inside zone Z at time t should have information m."

Unfortunately, the delivery property (1) is practically impossible to realize in most wireless ad hoc networks. The reasons include:

- First, communication latency is often not negligible in wireless ad hoc networks. This is especially true in wireless sensor networks where sensor nodes might have a sleeping schedule in order to save energy. Note that (1) implies instantaneous delivery to all nodes at the initial delivery zone $Z[0]$. If $Z[0]$ contains a node other than the sender node, it is impossible for the node to receive information D instantly when considering the communication latency.
- Second, a wireless ad hoc network may be partitioned. A delivery zone, specified by some geometric property alone, might cover nodes in multiple network partitions, which in turn renders the delivery impossible.
- Third, we did not put any restrictions on the speed of the delivery zone. One can imagine cases where a user-specified delivery zone moves so fast that it exceeds the maximum delivery speed a network can support.

As such, we are forced to weaken the ideal *mobicast* delivery property in the following practically-minded manner: *mobicast* satisfies property (1) only after some initialization time t_{init} on a connected network. That is

$$\langle \forall j, t : j \in \Omega \wedge t_{init} < t \le T :: \vec{r}(j) \in Z[t] \Longrightarrow D[j,t] \rangle \quad (2)$$

Thus, each *mobicast* session has two phases. The first, from time 0 to t_{init}, is an initialization phase in which no delivery guarantee is specified. The second phase, from time t_{init} to T, is a stable phase in which the strong spatiotemporal guarantee is required. We also implicitly assume the speed of delivery zone is smaller than the maximum speed the network can support. (The upper-bound for a feasible speed is addressed by theorem 3 in Section 3)

[1] The three-part notation $\langle \mathbf{op}\, quantified\_variable : range :: expression \rangle$ used throughout the text is defined as follows: The variables from *quantified_variables* take on all possible values permitted by *range*. If *range* is missing, the first colon is omitted and the domain of the variables is restricted by context. Each such instantiation of the variables is substituted in *expression* producing a multiset of values to which **op** is applied, yielding the value of the three-part expression.

2.4. Optimization Concerns

Note that specification (2) addresses only the functional requirement for mobicast, and does not address any performance optimization perspectives. Yet, performance is an indispensable dimension of protocol design. Here we discuss three optimization dimensions for mobicast protocols.

Note that, since communication latency is a random variable, it is impossible for one to deliver a message to a node at an exact time. In order to achieve the delivery property (2), one has to consider the worst case scenario and schedule the delivery of *mobicast* messages ahead of time.

Let $t_r(j)$ denote the time node j receives the *mobicast* message for the first time, and let $t_{in}(j)$ be the first instant of time j enters the delivery zone. We call the time difference $t_{in}(j) - t_r(j)$ the "slack time" associated with the message delivery. It measures how early the message is delivered to a node with respect to its requisite deadline (to be at the specific node). Note that specification (2) implies that t_{in} is the deadline of message delivery. In general, one would like to have as many expected recipients as possible meet the delivery deadline. Let Θ be the set of the "delivery zone nodes" that is defined as the set of all nodes that are expected to receive the mobicast message in a mobicast session. Let Ξ be the set of delivery zone nodes that received the mobicast message on or before the deadline, i.e.,

$$\Xi \equiv \{j | (j \in \Theta) \wedge (t_{in}(j) - t_r(j) \geq 0)\}$$

One obvious optimization dimension is to make the initialization phase as short as possible. A smaller t_{init} means more nodes will meet the delivery deadline. In general, the length of the initialization time depends on the size of the delivery zone, the network connectivity pattern within the region, and the protocol execution behavior. While a *mobicast* protocol has no control over the former two factors, it can try to make t_{init} as short as possible by optimizing its execution strategy.

Another optimization concern for any *mobicast* protocol is to reduce the overall time interval between the reception of a message and its required delivery to the application, i.e., the slack time. Minimizing the average slack time t_{slack} for all nodes that were ever in the delivery zone improves the timeliness of mobicast message delivery, and means less time in "holding" the message before it is needed. Small t_{slack} is also desirable as it potentially leads to less energy consumption and better locality in spatial data aggregation. So, a *mobicast* protocol should seek to minimize the average slack of the delivery zone nodes:

$$\overline{t_{slack}} = \frac{\sum_{j \in \Xi}(t_r(j) - t_{in}(j))}{|\Xi|} \tag{3}$$

where $|\Xi|$ denotes the cardinality of the set Ξ. The ideal case for a mobicast protocol involves reducing $\overline{t_{slack}}$ to zero, i.e., a node only receives the *mobicast* message (from its neighbors) precisely at the time it enters the delivery zone. Yet, this may not always be possible due to the randomness of the communication latency.

The third optimization dimension for *mobicast* is to reduce the total number of retransmissions needed for each *mobicast* session while delivering the spatial and temporal guarantees. This concerned is shared with most broadcast and multicast protocols for ad hoc networks.

2.5. Simple Mobicast Solutions

To help see more clearly the complexity of the mobicast, we present first two simple mobicast protocols that succeed and fail in different ways. In both protocols, mobicast packets are always marked by the sender with a description of the packet delivery zone and a life time (for the downstream nodes to determine their delivery and forwarding behavior).

The first simple mobicast protocol is based on flooding. Once a node receives a mobicast call from the application, it floods the mobicast message to the whole network. The rest of the nodes in the network, in addition to participating in the flooding, behave as follows: once a mobicast message is received, they schedule the delivery of the mobicast message to the respective interested applications at the time when the delivery zone reaches them. If a node finds itself to be never in the delivery zone of a mobicast, it drops the message after having fulfilled its forwarding responsibility, without delivering the message to application layer. Note that even though this protocol can achieve the spatiotemporal delivery specification (2), it is not desirable in at least two respects. The first is that the global flooding has a large overhead, especially when the cumulative (union) delivery zone area is much smaller than the span of the whole network. The second is that the average slack time of the mobicast reception is higher than necessary, especially when the mobicast delivery zone speed is much smaller than the maximum information propagation speed on the network.

The second protocol examined here employs a hold-and-forward strategy, and only nodes on the path of the delivery zone will participate. For convenience, we call it the "Delivery-Zone Constrained" (DZC) protocol. The DZC protocol exhibits minimal delivery overhead and has good slack time characteristics on "good networks," but is not entirely reliable. For simplicity, Fig 4 shows a mobicast example on a one-dimensional network with a rectangular delivery zone moving at a constant velocity. The DZC protocol works as follows. Once a node receives a new mobicast

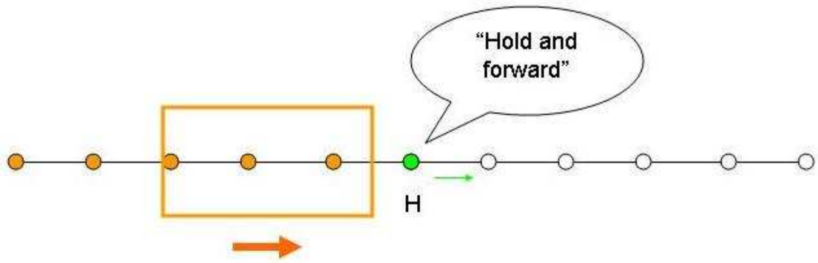


Figure 4: Greedy Hold-and-Forward Mobicast Protocol

packet, it first checks if the packet has expired. If not, the node checks to see if it finds itself in the current delivery zone for the packet. If this is the case, the packet is delivered to the application immediately and is forwarded as soon as possible; otherwise, if the node is not currently in the delivery zone but expects to be in the delivery zone in the future, as the node H in Fig 4, the packet is held and scheduled for delivery and forwarding at the time the delivery zone reaches the node. In all other cases, nodes will ignore mobicast packets. One can see that the hold and forward behavior of nodes in front of the running delivery zone makes the packet delivery and forwarding "just-in-time," and creates a self-sustained mobile message wave. Note that only nodes that find themselves in the delivery zone path will join the forwarding. This delivery-zone constrained forwarding keeps the forwarding overhead at a minimum. Yet, the protocol fails to deliver the mobicast message to delivery zone nodes that are not directly connected to the source through a path fully contained in the area which the delivery zone covers over time. Fig 5 shows such an example. DZC protocol fails to deliver the mobicast message to node X because the nodes outside of the delivery zone do not participate in the forwarding process.

From the drawbacks of the DCZ protocol we can see that in order to guarantee mobicast delivery for all delivery zone nodes, some nodes that are not in the delivery zone have to participate in message

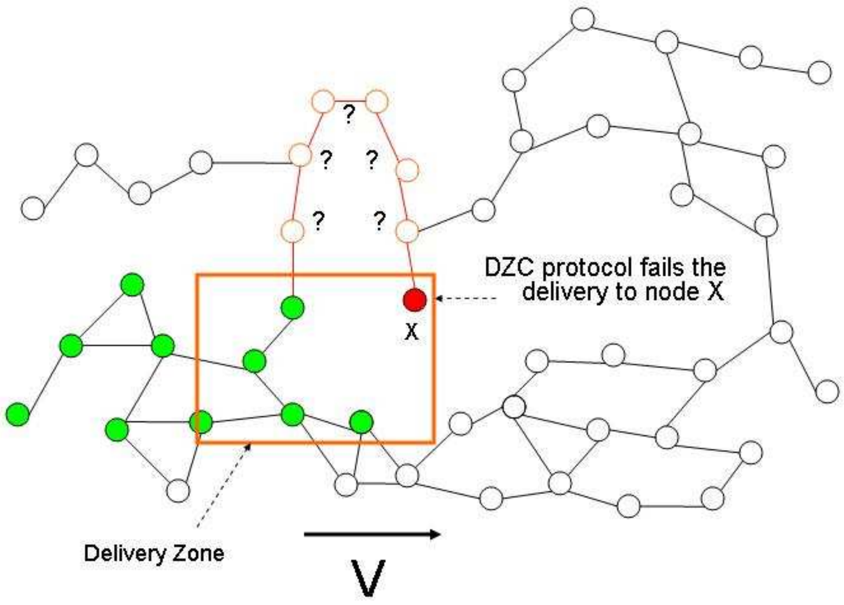


Figure 5: DZC protocol cannot guarantee delivery

forwarding. An important question is: how to determine who should participate without knowing the detail of the global network topology? Furthermore, potential holes in the network (as in Fig 5) show that two nodes close in physical space can be relatively far away in terms of network hops. This presents a serious challenge for timely delivery of mobicast messages, i.e., a mobicast protocol needs to consider potential propagation latency in physical space due to long underlying network paths in order to achieve timely delivery across the physical space. In the next section, we further investigate these challenges under the backdrop of random sensor networks and propose a reliable mobicast protocol.

3. A Reliable Mobicast Protocol

As alluded earlier, a key challenge we want to tackle in this paper is the reliable mobicast delivery, as specified by (2), on networks of arbitrary topology while using only limited information about the network topology. In this section, we explain the key assumptions regarding the network, describe the framework for a reliable mobicast protocol, and offer an analysis and proof of reliability for this protocol. Our effort in deriving the protocol yields new insights and concepts useful in the study of spatiotemporal information dissemination strategies across sensor networks.

3.1. Sensor Network Model

The sensor network model for our protocol is as follows. The network does not have any partition, and all nodes are location-aware, i.e., they know their location $\vec{r}$ in space with reasonable accuracy. The maximum clock-drift among the sensors in the system is small enough to be negligible. All nodes support wireless communication and are able to act as routers for other nodes. Local wireless broadcast is reliable, i.e., once a local broadcast is executed, it will be heard by all its neighbors within latency τ_1.

3.2. The Forward-Zone Constrained (FZC) Mobicast Protocol

In this section we propose a mobicast protocol featuring a "forwarding zone" that cruises in front of the moving delivery zone at a certain prescribed distance. Only nodes in the path of the forwarding zone will participate in the mobicast forwarding. We call this protocol the "Forward-Zone Constrained" (FZC) mobicast protocol. In order to describe the FZC *mobicast* protocol more concisely, we need to introduce some terminology. The reader is reminded that the delivery zone, specified by the application itself, is an area where the delivery of messages to the application takes place. Our protocol creates and uses a "forwarding zone" $F[t]$ that is moving at some distance ahead of the delivery zone, as shown in Fig. 6. We call the distance between the forwarding zone and its associated delivery zone the "headway distance" (of the forwarding zone). The shape of the forwarding zone is related to the shape of the delivery zone, and the topology of the underlying network. More specifically, in our protocol, the shape of the forwarding zone is generated from a "seed shape" which we call the "core" of the forwarding zone with a metric of the network topology. The choice of the headway distance and the size of the forwarding zone is such that it guarantees that all nodes entering the delivery zone will have received the *mobicast* message in advance, even if some of them are not directly connected (1-hop) to any nodes already in the delivery zone. The forwarding zone limits retransmission to a bounded space while ensuring that all nodes that need to get the message will do so. We will discuss how the forwarding zone is determined in the next section. While nodes

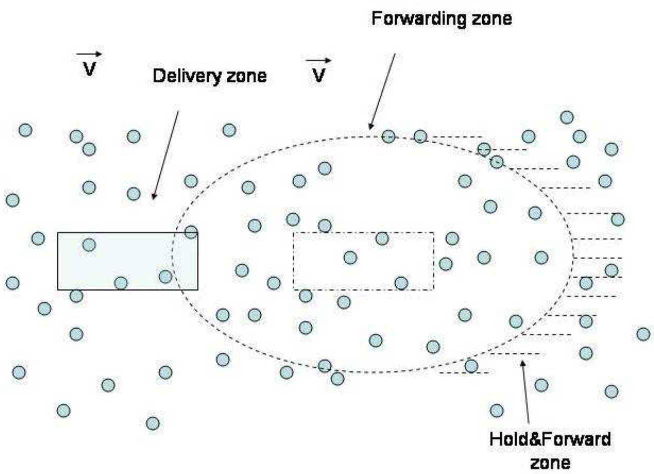


Figure 6: Mobicast example

in a forwarding zone retransmit the *mobicast* message as soon as they receive it (for the first time), the nodes in front of the forwarding zone enter a "hold-and-forward" state whenever they hear the *mobicast* message. They will retransmit the message only after becoming members of the forwarding zone. As we pointed out earlier, the action of the nodes in the hold-and-forward zone implements the "just-in-time" feature of the *mobicast* delivery policy while keeping the average slack time t_{slack} small. This behavior results in a virtual "hold-and-forward zone" in front of the forwarding zone, as also indicated in Fig.6.

When a request $\langle m, Z[t], T_s, T \rangle$ is presented to the *mobicast* service, it constructs and broadcasts a *mobicast* message to all the neighbors at time T_s. A *mobicast* packet $\tilde{m}$ contains the following information: a unique message identifier, a delivery zone descriptor, a forwarding zone descriptor, the session start time T_s, the session lifetime T, and the message data m. The unique message identifier is created from the combination of the location of the source and the time T_s of the request. The delivery zone descriptor encodes the original location, the shape of the zone, and its velocity. The forwarding zone descriptor encodes the shape and the original location of the forwarding zone, which is computed using some knowledge about the network and the shape of the delivery zone. We will discuss in detail the computation of the forwarding zone in later sections.

Upon hearing a mobicast message $\tilde{m}$ at time t.

```
if (m̃ ) is new and t < t_0 + T
    if (I am in F[t]) then
        broadcast m̃ immediately ;                    // fast forward
        if (I am in Z[t]) then
            deliver the message data D to the application layer;
        else
            compute the earliest time t_in for me to enter the delivery zone;
            if t_in exists and t_in < t_0 + T
                schedule delivery of data D to the application layer at t_in;
            end if
        end if
    else
        compute the earliest time t' for me to enter the forwarding zone;
        if t' exists
            if t_0 ≤ t' ≤ t
                broadcast m̃ immediately ;            // catch-up!
            else if t < t' < t_0 + T
                schedule a broadcast of m̃ at t';     //hold and forward
            end if
        end if
    end if
end if
```

Figure 7: The FZC mobicast protocol

The FZC *mobicast* protocol is described in Fig.7. While not explicitly shown in the code, this *mobicast* protocol exhibits two phases in its spatial and temporal behavior. The first is an initialization phase, in which the nodes are trying to "catch-up" with the spatial and temporal demands of the *mobicast*. When a node in the path of the forwarding zone receives a message for the first time, it rebroadcasts the message as soon as possible. This phase continues until a stable forwarding zone that travels at a certain distance d_s ahead of the delivery zone is created.

The second phase is a cruising phase in which the forwarding zone moves at the same velocity as the delivery zone. The protocol enters this phase after the delivery zone and the forwarding zone reach the stable headway distance d_s. This cruising effect is achieved by having the nodes at the moving front of the forwarding zone retransmit the *mobicast* message in a controlled "hold-and-forward" fashion to make the forwarding zone move at the velocity $\vec{v}$. The initialization and the cruising phases together establish *mobicast* property (2) with t_{init} being the time required by the initialization phase.

In the next section we turn our attention to explaining how the forwarding zone and its stable headway distance are computed, what is the value of t_{init} given a specific *mobicast* request and the spatial properties of the underlying network, and how the protocol delivers on its guarantees.

3.3. Analysis

The key elements in the FZC *mobicast* protocol (Fig.7) are the forwarding zone and its headway distance d_s from the delivery zone. As we mentioned earlier, the purpose of the forwarding zone and its headway distance is to ensure that all the nodes entering a delivery zone will receive the *mobicast* message in advance, while minimizing the total number of nodes participating in each mobicast session.

The shape of the forwarding zone depends on the following three factors: the shape of the delivery zone, the spatial distribution of the network nodes, and the topology of the network. Fig.8 illustrates this point for a rectangle *mobicast* delivery zone (solid rectangle). The source node S initiates a mobicast. For node A to be able to deliver the message (to the respective application layer) when it becomes a member of the delivery zone, it should have received the message by that time. In scenario Fig.8(a), the message is required to have gone through G (in order for it to reach A). This requires A and G to be in the forwarding zone together at some point in time before A can receive the message (otherwise, the mobicast message will not be forwarded to A, as A is in a "past" location comparing to G, with respect to the delivery zone velocity direction). On the other hand, if the network connectivity is "denser," as in Fig.8(b), the width of forwarding zone (e.g., the dashed rectangle, comparing to the one in Fig.8(a)) can be relatively smaller. Furthermore, in

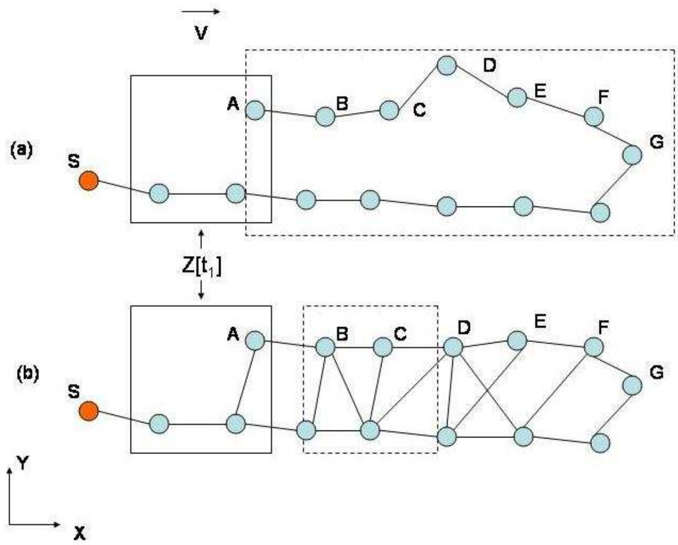


Figure 8: Spatial and connectivity configuration of the network influence the size of forwarding zone

Fig.8(a) the height of the forwarding zone has to be bigger than the height of the delivery zone so as to include D. Otherwise, nodes A, B and C will be effectively partitioned from the rest of the nodes in the network, because node D will not participate in the routing process. This is just one special example with an ad hoc choice of forwarding zone. The question we would like to address is, in an arbitrary sensor network, how to determine the forwarding zone and its headway distance for a specific delivery zone.

We found that the minimum size, shape, and headway distance for a mobicast protocol that provides a strong spatial and temporal delivery guarantee (in the presence of an arbitrary network topology) depend on two network metrics we call "Δ-compactness" and "Γ-compactness." These two metrics capture the spatial and temporal information propagation properties of sensor networks in Euclidean space, respectively, and are related to the following three distance metrics between two nodes i and j in a network:

- Euclidean distance, denoted as $d(i, j)$;
- Shortest network distance, in terms of smallest network hops, denoted as $h(i, j)$;
- S2 distance, defined as smallest Euclidean path length among the set of shortest network paths between nodes i and j, denoted as $\tilde{d}(i, j)$.

Next we formalize these network compactness metrics and discuss how they relate to the computation of the forwarding zone and its headway distance. Then we show that our protocol provides the desired spatiotemporal guarantees given the proper choice of the forwarding zone and its headway distance.

3.3.1. Computing the Forwarding Zone. In order to describe how the minimum forwarding zone can be determined for a specific delivery zone in an arbitrary network, we first introduce the definition of the "Δ-compactness" measure for the network.

Δ-compactness. Given a geometric graph/network $G(V, E)$, Δ-compactness seeks to quantify the relation between the Euclidean distance and the S2 distance among network nodes. We denote the Euclidean distance to shortest path distance ratio between two nodes i and j as $\delta(i, j)$, i.e.,

$$\delta(i, j) = \frac{d(i, j)}{\tilde{d}(i, j)} \tag{4}$$

We call $\delta(i, j)$ the pairwise "Δ-compactness" between nodes i and j. The Δ-compactness of a geometric graph $G(V, E)$ is defined as the smallest Δ-compactness of all node pairs of the network:

$$\delta = \min_{i,j \in V} \{\delta(i, j)\} \tag{5}$$

Note that Δ-compactness has a close relation with the terms "dilation"[9], "spanning ratio"[3], and "stretch-factor"[21] used in the graph and computational geometry community. "Dilation" is defined as the maximum ratio between Euclidean path distance and geometric distance, while Δ-compactness is defined as minimum ratio between the geometric distance and the corresponding S2 distance. They have more than an inverse relationship. For instance, for nodes A and B in Fig 9, path $\overline{ACB}$ contributes to the computation of Δ-compactness while path $\overline{ADEB}$ contributes to the computation of dilation. The reason is that Δ-compactness is computed on the set of shortest network paths (path of minimum hops) only, while dilation is computed on the set of all paths. Path $\overline{ADEB}$ has 3 hops and is not a shortest network path between A and B, even though it is a shortest Euclidean network path between them. (As a result, the Δ-compactness of this graph is $\sqrt{2} = 1.414$, while the dilation is $3/\sqrt{5} = 1.342$). For convenience, we will call the inverse of Δ-compactness Δ-*dilation* .

THEOREM 3.1. *Let i, j be any two nodes in a network with Δ-compactness δ. Let $E(i, j, \delta)$ be an ellipse using i, j as two foci and with eccentricity δ. There is at least one shortest path between i and j inside the ellipse $E(i, j, \delta)$.*

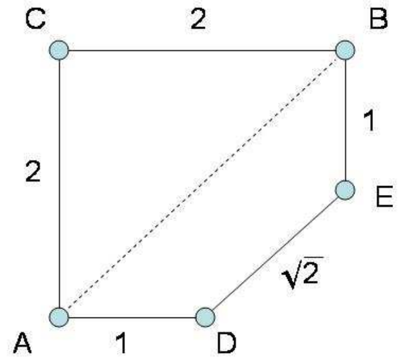


Figure 9: Dilation and Δ-compactness

Proof: We prove this theorem by contradiction.

Assume the theorem is not true. There must be at least one pair of nodes i and j, whose shortest paths all have at least one vertex outside the ellipse $E(i, j, \delta)$. Using the fact that for all points k on the ellipse, $d(i, k) + d(j, k) = d(i, j)/\delta$, it is easy to prove in this case

$$\tilde{d}(i,j) > \frac{d(i,j)}{\delta}$$

that is

$$\delta > \frac{d(i,j)}{\tilde{d}(i,j)}$$

this directly contradicts the definition of Δ-compactness (5).

This theorem is very useful for limiting the forwarding region while guaranteeing point to point message delivery in a geometric network. In our case, this metric helps us decide the shape and size of the forwarding zone, which turns out to relate to a notion called "k-cover".

K**-cover.** We introduce the notion "k-cover" of a polygon to simplify the mathematical description of the forwarding zone. The k-cover of a convex polygon P is defined as *the locus of all points p in the plane for which two points q and r in the polygon P exist such that*

$$d(p, q) + d(p, r) \leq kd(q, r) \tag{6}$$

where the $d(x, y)$ is the distance between points x and y.

Theorem 3.2. *Let i, j be two nodes in a Δ-compact network, and assume that i and j are inside a convex polygon P. The $\frac{1}{\delta}$-cover of P contains at least one shortest path between i and j.*

Proof: (The proof is similar to that of theorem (3.1), and thus omitted.)

One may view an ellipse to be a special case of k-cover. An ellipse of eccentricity e is a $\frac{1}{e}$-cover of the line segment between the two foci of the ellipse. In other words, the k-cover is a generalization for the ellipse.

The Forwarding Zone. Given a *mobicast* delivery zone of convex shape P, if the *mobicast* is executed on a network with Δ-compactness value δ, then we choose the shape of the forwarding zone's core to be P and the shape of the forwarding zone to be the $\frac{1}{\delta}$-cover of its core.

COROLLARY 3.1. *Let i, j be two nodes in the core of a forwarding zone on a network whose Δ-compactness is δ. The forwarding zone contains at least one shortest path between i and j.*

Proof: This results from theorem (3.2) and the construction of the forwarding zone.

3.3.2. Computing the Stable Headway Distance. The headway distance of the forwarding zone is a way to tell the protocol how far ahead to prepare the message delivery in order not to miss the delivery deadline as a result of some unexpected distortions on related network paths. It should be intuitively clear that a network with more "indirect" network paths requires a longer headway distance than one whose paths are more "direct." In order to capture this notion more precisely, we introduce the "Γ-compactness" metric.

Γ-compactness. Γ-compactness quantifies the relation between the shortest network distance and the Euclidean distance among the nodes in a geometric network. We define the Γ-compactness of a geometric graph $G(V, E)$ to be the minimum ratio of the Euclidean distance to the shortest network distance between any two nodes in the network, i.e.,

$$\Gamma = \min_{i,j \in V} \frac{d(i,j)}{h(i,j)} \tag{7}$$

Intuitively, if a network's Γ-compactness value is γ, then any two nodes in the network at a distance d have a shortest path no greater than d/γ hops.

THEOREM 3.3. *Let N be a network with a Γ-compactness value γ and let τ_1 be its maximum 1-hop communication latency. The lower bound of the maximum message delivery speed over the space on N is $\frac{\gamma}{\tau_1}$.*

Proof: Let $d(i, j)$ be the distance between two arbitrary nodes i and j in the network. We know that the shortest network path h between the two nodes is bounded by

$$h(i,j) \leq \frac{d(i,j)}{\gamma} \tag{8}$$

We also know that a message sent from one node to another node h-hops away takes no longer than $h\tau_1$ if each intermediate node forwards the message immediately after receiving it. Let t be the time it actually takes for the message to go from i to j. In this case we have

$$t \leq h(i,j)\tau_1$$

From this we know that the average speed v of this information propagation over distance $d(i, j)$ is

$$v = \frac{d(i,j)}{t} \geq \frac{d(i,j)}{h\tau_1} \geq \frac{\gamma}{\tau_1} \tag{9}$$

Note that the bound $\frac{\gamma}{\tau_1}$ is not dependent on $d(i, j)$. This inequality (9) is true for any two nodes in any network with Γ-compactness value γ, when all nodes in the network relay the message as soon as possible. That means $\frac{\gamma}{\tau_1}$ is a lower bound on the maximum spatial message delivery speed on networks with Γ-compactness value γ.

Theorem (3.3) states that, given a geometric network, there is a clear limit to how fast spatiotemporal information dissemination can be achieved. For instance, given a geometric network with Γ-compactness value γ, one can not guarantee the delivery zone to move at a speed higher than $\frac{\gamma}{\tau_1}$ in all areas.

3.3.3. The Headway Distance. The stable headway distance d_s must be large enough to ensure that when the delivery zone reaches a node, the message has been received already, i.e., $t_{in} > t_r$ is achieved for all nodes.

THEOREM 3.4. *Let S_d be the maximum distance between the boundary points of the delivery zone, let v be the speed of the delivery zone, let τ_1 be the 1-hop maximum network latency of the network and let γ be its Γ-compactness . If we let $d_s = v\tau_1\lfloor\frac{S_d}{\gamma}\rfloor$, then all the nodes in the core of the forwarding zone will have received the the mobicast message by the time delivery zone reaches them, assuming there is at least one node in the core that has received the message.*

Proof: Let us consider a snapshot of the mobicast at some time t and the core of the current forwarding zone. Let i denote the node in the core that already has the message. Its distance to all other nodes in the core is less than S_d, because S_d is the maximum size of the delivery zone, as well as that of the core. The longest of the shortest network paths from i to all other nodes in the core of is less than $\lfloor\frac{S_d}{\gamma}\rfloor$ hops. In turn, at most $\tau = \lfloor\frac{S_d}{\gamma}\rfloor\tau_1$ time is needed for a message to traverse the core if all nodes forward the message as soon as possible. We can conclude that after τ, all nodes in the core of the forwarding zone will get the message, because in the protocol all nodes inside the forwarding zone forward *mobicast* messages in as soon as possible, and there is always a shortest path inside the forwarding zone for any two nodes inside its core. Since the speed of the delivery zone is v, a distance $d_s = v\tau_1\lfloor\frac{S_d}{\gamma}\rfloor$ takes exactly τ time to be traversed.

Hence, it is true that all the nodes in the core of the forwarding zone will have received the the mobicast message when the delivery zone reaches them, assuming at least one node in the core has received the message and given the headway distance $d_s = v\tau_1\lfloor\frac{S_d}{\gamma}\rfloor$.

Given the headway distance d and the shape F of the forwarding zone, a node can easily determine the current forwarding zone using velocity v, current time t, sending time t_0 and the source location r_0. Note that t_0 and r_0 can be obtained from the mobicast protocol message header.

3.3.4. Duration of Initialization Phase. As we pointed out earlier, it is in the cruising phase that the *mobicast* protocol guarantees on-time delivery. In the initialization phase, the timing constraint of *mobicast* is realized in a best-effort manner. It is possible that in the initialization phase, some nodes may not get the messages in time. The initialization phase continues until one node inside the core of the forwarding zone that is d_s ahead of the delivery zone receives the *mobicast* message. From theorem (3.4), we know that after this, the timing constraint of *mobicast* is always satisfied.

The time (t_{init}) it takes for the *mobicast* protocol to enter the cruising phase is related to the stable distance needed, the delivery zone speed, and the maximum admissible spatial propagation speed of the network.

THEOREM 3.5. *Let d_s be the required headway stable distance between the forwarding zone and the delivery zone. Let w be the width of the delivery zone. Let v be the speed of the delivery zone and u be lower bound on the maximum message delivery speed achievable in the network. The mobicast protocol initialization time t_{init} is no greater than $\frac{(d_s+w)}{u-v}$*

Proof: In the protocol, the nodes in the forwarding zone and between the forwarding zone and the delivery zone retransmit the message immediately the first time they receive it. As such, the protocol achieves a maximum message propagation speed v_{max} in this phase. This message propagation speed relative to the delivery zone is $v_{max} - v$. Meanwhile, the end-to-end distance between the delivery zone and the core of the forwarding zone is $d_s + w$, which can be covered by a message propagating at the speed $v_{max} - v$ in $t = \frac{d_s+w}{v_{max}-v}$ time. When a message from the delivery zone reaches the core of the forwarding zone d_s distance ahead of the delivery zone, by definition the initialization phase is over. Hence we have

$$t_{init} \leq t = \frac{d_s + w}{v_{max} - v} \leq \frac{(d_s + w)}{u - v} \tag{10}$$

in the above we also used $u < v_{max}$, which by definition is true.

The Spatiotemporal Guarantees of the Protocol. The spatiotemporal guarantees of the FZC *mobicast* protocol (7) are addressed by the following theorem:

THEOREM 3.6. *If at any instant of time in a mobicast session, its (user-defined) delivery zone covers at least one node in the network, our mobicast protocol delivers property (2) with*

$$t_{init} \leq \frac{v\tau_1 \lfloor \frac{S_d}{\gamma} + w \rfloor}{\frac{\gamma}{\tau_1} - v}$$

.

Proof: If a delivery zone covers at least one node in the network at any instant of time, then whenever the last node in a delivery zone is leaving a delivery zone, there must be another node entering it. The same is true for the core of the forwarding zone, because it is of the same shape as the delivery zone and moves on the same path. If at one point in time, a node in the core of the delivery zone has received the mobicast message, it will always be able to pass the message on to all others nodes on the path because our protocol and the way we choose the forwarding zone guarantees that if two nodes ever appear together in the same core of the forwarding zone, one having the message means the other will get it too.

By using theorems (3.4) and (3.5), it is easy to see that property (2) is satisfied.

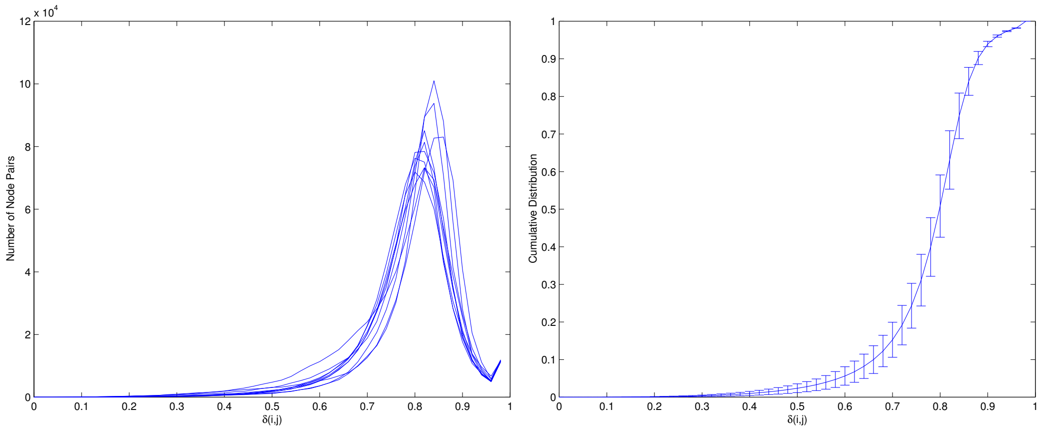
3.4. New Questions

So far we have proved that FZC mobicast protocol is able to achieve the strong mobicast delivery guarantees specified in Section 2 given a proper choice of the forwarding shape and its headway distance, under a set of necessary assumptions. Note that for the FZC mobicast protocol, the forwarding zone size is the $\frac{1}{\delta}$-cover of the delivery zone. A small value for Δ-compactness implies a relatively big mobicast overhead, defined as the number of nodes participating in the mobicast message forwarding. Note also that in the previous protocol, the network compactness values are used because of the need for strong delivery guarantees, captured by the concern with the worst case path distortion in a network rather than the average case. Several new questions arise: (1) What is the typical compactness value for common sensor networks? (2) Can we make a network more compact to support better spatiotemporal communication? (3) The previous protocol used the worst case compactness among all paths, as it was geared towards 100% delivery guarantee. This choice might be pessimistic if the worst case is rare. How will an optimistic choice of forwarding zone perform in reality? (4) Can we use a local notion of compactness and can the mobicast session and the forwarding zone be adaptively adjusted to the local compactness values? Next, we will turn our attention to addressing the first three questions. An investigation of the last question is reported in a separate work [11].

4. Properties of Random Networks

In the previous section, we showed that a network with higher compactness admits a more economic FZC mobicast protocol, i.e., fewer nodes need to participate in mobicast forwarding. Notice that Δ-compactness is the minimum ratio of the Euclidean distance and the shortest path distance distance, which accounts for the worst case "indirect" path among all nodes. An immediate question is, how typical is the worst case scenario? The answer to this question is very important to applications which may not need 100% delivery guarantee. If most of the pairwise ratios among nodes are much larger than the minimum, then a choice of a much smaller forwarding zone may be able to practically guarantee mobicast delivery most of the time with only a small number of nodes needing to participate in each session. Energy can be saved by sacrificing the delivery guarantee on rare occasions. This is desirable for sensor networks as they are typically resource limited.

Motivated by these observations, we carried out several experiments to see the potential distribution of the pairwise Δ-compactness value $\delta(i,j)$ in randomly distributed networks. We found that, indeed, in random networks of uniform distribution, most $\delta(i,j)$ are close to one while the minimum $\delta(i,j)$ is close to zero. Fig 10(a) shows the distribution of pairwise compactness value $\delta(i,j)$ in



(a) (b)

Figure 10: Pairwise Compactness distribution

10 different randomly generated uniformly distributed networks. Fig 10(b) shows the average case (averaged over the above 10 network instances) in a cumulative distribution view with standard deviation bars. Note that more than 90% of node pairs have a $\delta(i,j)$ greater than 0.6, while the minimum $\delta(i,j)$ (i.e., the value of Δ-compactness of the network) is less than 0.2. Note also that a mobicast protocol using Δ-compactness value $\delta = 0.2$ to construct its forwarding zone results in a forwarding zone size 25 ($= (1/\delta)^2$) times bigger than the delivery zone, while using $\delta = 0.6$ results in a forwarding zone less than 3 times bigger than the delivery zone. So more than 200% $\sim(\frac{1/0.2-1/0.6}{1/0.6})$ of the forwarding cost may be saved by slightly sacrificing the delivery guarantee if one uses $\delta = 0.6$ rather than the minimum pairwise compactness value δ in the construction of the forwarding zone. (Note that in the above calculation we use a linear rather than a quadratic relation of $1/\delta$ in estimating overhead because, while the forwarding zone size is quadratic to $1/\delta$, its integral volume over the path of a mobicast is proportional to $1/\delta$).

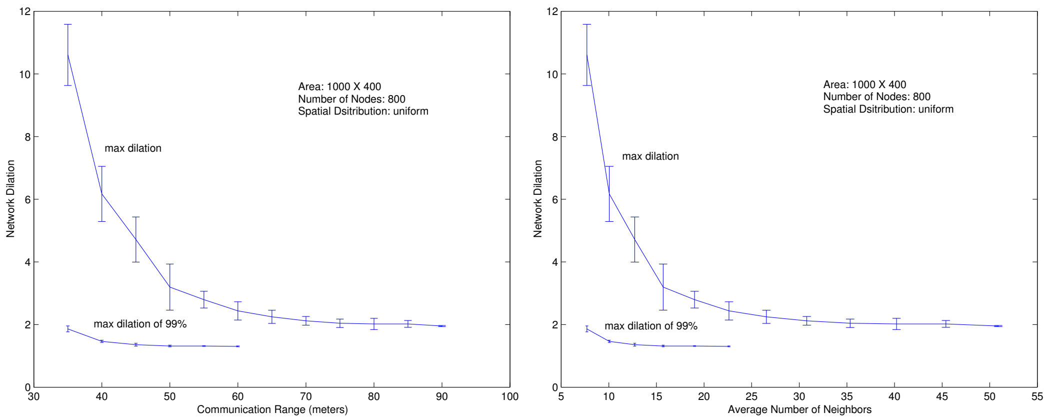
These results suggest three approaches to improve the efficiency of mobicast. The first is to design a sensor network with high compactness to support spatial temporal communication. The second is to use a smaller forwarding zone than the one needed for an "absolute" delivery guarantee. The third is to use a protocol that adapts to the local compactness conditions rather than the global one. In this paper, we focus on examining the first two approaches, with some preliminary results about the third approach. Investigation of the first approach is presented next. An investigation of the second approach appears in section VI. The third approach is presented in a separate publication [11].

4.1. Impact of Node Density on Network Compactness

As we pointed out earlier, for a specific delivery zone, the more "compact" a network is, the smaller the forwarding zone needs to be. An immediate question is, can we design the sensor network so as to make its Δ-compactness value as close to the maximum value of one as possible? Since we want to continue with the random distribution assumption, there is only one design dimension left: the sensor node density. Note that we define sensor density as the average number of immediate network neighbors for each node, rather than number of nodes in a unit area.

Intuitively, the higher the sensor density, the "better" connected the sensor network is and the larger the corresponding network Δ-compactness is. To verify this observation, we designed the following experiment. We scatter 800 sensors uniformly distributed in a 1000x400 rectangular area and select only configurations which are not partitioned for a communication range of 35. (Note that because of random distribution, the network is sometimes partitioned. 35 is close to a critical range for connectivity in our experimental configuration). For the surviving configurations, we compute the values of Δ-compactness assuming communication range valuea between 35 and 90. Note that in this experiment we chose to vary the communication range rather than to vary node density directly (by adding more nodes to the area). The reason we chose to vary the communication range as a mechanism to vary the relative sensor density is because this does not change the actual location configuration of the sensors in the experiment and, in turn, makes the corresponding compactness value comparison more meaningful.

The above procedure was repeated for five different configurations and the results (average values and standard deviations) are presented in Fig 11. Fig 11(a) shows the average (across the 5 runs)



(a) (b)

Figure 11: (a)Δ-Dilation vs Range, (b)Δ-Dilation vs Average Number of Neighbors

Δ-Dilation (defined as the inverse of Δ-compactness) versus the change of communication range. Fig 11(b) shows a corresponding figure with the average node degree as the x-axis.

The results show that the network compactness indeed increases when the node density increases. But surprisingly, there appears to have a saturation point at a moderate density. The network exhibits a rapid increase in compactness (rapid decrease in Δ-dilation) when the average number of neighbors changes from 8 to 15 and then starts to saturate. This appears to be an area to increase the compactness of the network with highest efficiency for these randomly distributed networks. This may provide a good heuristic for deploying mobicast/communication friendly sensor networks. For instance, if one wants to monitor a area of 1000x1000 square meters using sensors of average range 50 meters, the total number of sensors should be about $\frac{1000\times1000}{\pi 50^2} \times 15 = 1910$ for a random scattering deployment method. One can also see that after a certain threshold (15 $\sim$ 20 neighbors in this case), increasing the node density no longer introduces much benefit in terms of improving compactness.

In addition, we also examined the value of the majorities of the pairwise Δ-compactness and how they change with node density. The lower curve in Fig 11(a) and (b) shows how the lower bound of the top 99% of the $\delta(i, j)$ of the network changes with node density. One can see that the occurrence of the lower extreme compactness value is a rare event. This further suggests that an optimistic choice of k-cover for the forwarding zone is a good mobicast strategy in practice.

5. Optimistic Mobicast

To verify our observations about the potential benefit of optimistic mobicast on random networks with uniform distribution, we implemented an extended mobicast protocol on the ns-2 network simulator. Our implementation was extended with a mode to let the user specify the parameter (delta) for determining the forwarding zone. This allows us to test the trade-off between the message[2] forwarding cost and the delivery guarantee.

The header of our mobicast protocol packet contains the following information:

- message type
- sender packet sequence number
- sender location (x and y coordinates)
- sending time
- message lifetime
- delivery zone size (radius)
- delivery zone velocity (x and y components)
- delta factor
- gamma factor

Our protocol only provides support for a circular delivery zone. We also assume that the initial delivery zone is centered at the sender. One may augment the header with the information about the initial delivery zone center to allow applications to explicitly set the initial delivery zone location. Because this is not essential for our validation and verification test purposes, we simply default the sender location as the center of the initial delivery zone.

The mobicast protocol is depicted in Fig 16 (modified from Fig 7, with additional compactness information processing). In this paper we omit the detail about the geometric computation involved in determining if and when a node is in a forwarding zone and delivery zone, as it is not conceptually essential. The mobicast protocol also maintains a transient message cache (it is periodically cleaned by throwing out expired messages).

To minimize the dependence of simulation results on the network configuration used, our experiments were run on five different connected network configurations generated via uniformly distributing 800 sensor nodes on a 1000x400m area. Fig 12(b) shows one such configuration example used. (the network connectivity pattern is shown Fig 12(a)). One node close to the left is chosen as the mobicast sender. Our results are averaged over multiple runs on five network configurations. For all

[2]Note that we use “packet” and “message” interchangeably here. In the simulation, we only deal with cases where a mobicast message can be fit in one mobicast packet.

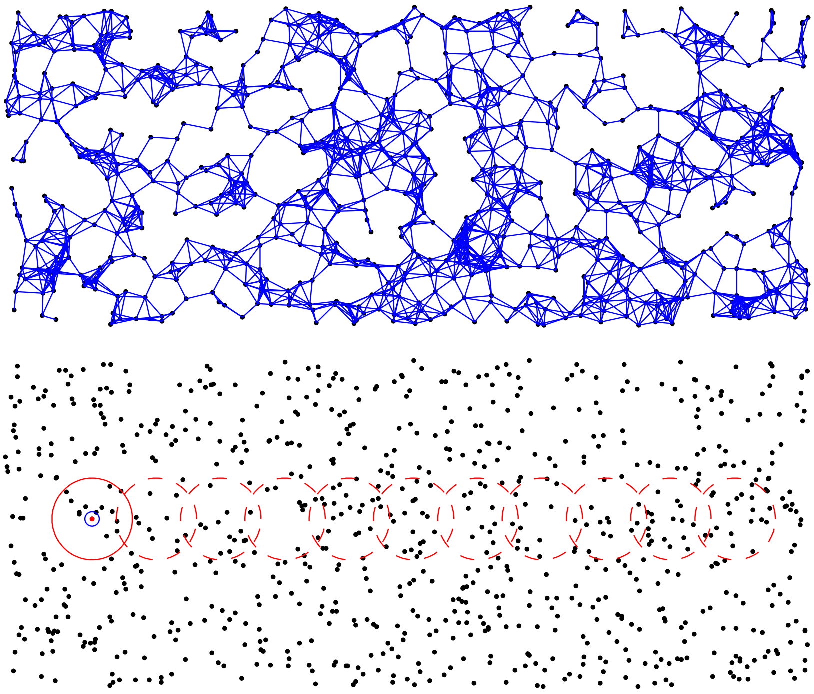


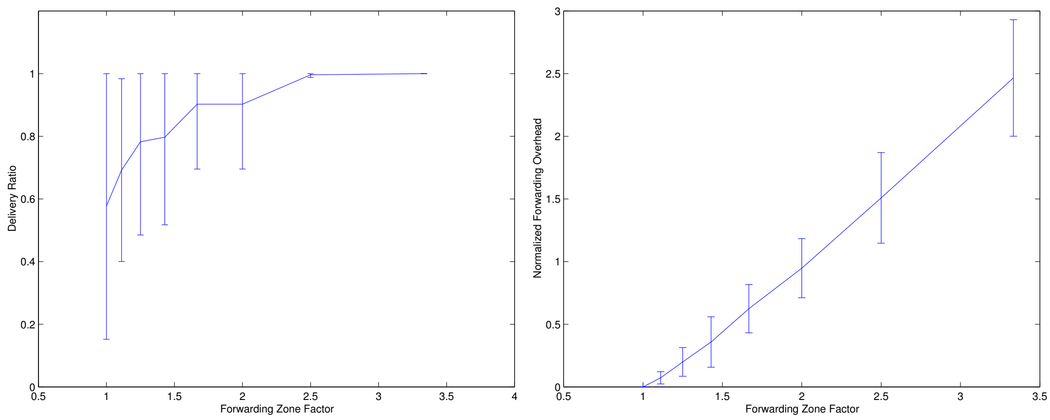
Figure 12: Optimistic Mobicast Simulation Example

runs, the delivery zone velocity is 40m/s, from left to right, and each mobicast session has a lifetime of 20s. For all the configurations used, the critical communication range for all the nodes to form a connected graph is between 30 to 35 meters. We chose the delivery zone radius to be 45 meters.

We designed two sets of experiments. The first one intended to investigate how mobicast delivery ratio and forwarding overhead changes with the size of the forwarding zone on these uniformly distributed networks. Delivery ratio is defined as the percentage of delivery-zone nodes (those that are in the virtual delivery zone at some point of time during a mobicast session) that actually received the mobicast message. Forwarding overhead is defined as the number of extra message transmissions per node delivery, i.e., the total number of retransmissions divided by the number of delivery zone nodes that actually received the message. Fig 13(a) shows the simulation results of delivery ratio versus the normalized forwarding zone size (the actual k used in forwarding zone computation.) One can see the delivery ratio improves when the forwarding zone becomes bigger. The high variance in delivery ratio value is due to random distribution of holes across different configurations, which causes each mobicast session to stop prematurely at different locations across different configurations. The limited number of network configurations used also contribute to this. Fig 13(b) shows how the forwarding overhead changes with the forwarding zone factor. Clearly the message forwarding overhead increases almost linearly with the increase of forwarding zone factor.

The second set of experiments were designed to investigate how the delivery ratio is affected when the network becomes more compact. Due to the limited scalability of ns-2, we again use the change of the communication range to change compactness, rather than by adding more nodes. In the experiment, the delivery zone radius used is 45 meters. The communication radius varies from 35 to 45 meters. We collected results from multiple runs of mobicast using different forwarding zone factors over the five configurations and results are summarized in Fig 14.

From these results we can see that indeed the delivery ratio increases when the node density



(a) (b)

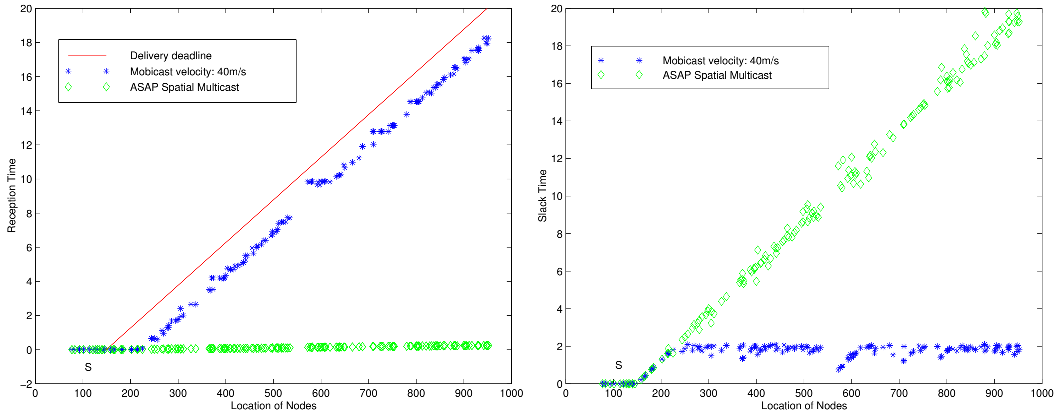
Figure 13: (a) Delivery ratio vs Forwarding Zone Size; (b) Normalized Forwarding Overhead vs Forwarding Zone Factor

R \ δ	1.0	0.9	0.8	0.7	0.6	0.5	0.4
35	0.69± 0.29	0.78± 0.29	0.80± 0.28	0.90± 0.21	0.90± 0.21	0.99± 0.10	1
40	0.90± 0.21	0.90± 0.21	0.90± 0.21	1	1	1	1
45	0.998± 0.003	1	1	1	1	1	1

Figure 14: Delivery ratio v.s. node density and forwarding size

increases, and when the size of the forwarding zone increases. Again the high variance in the value is due to random distribution of holes across different configurations and each mobicast session stops prematurely at different locations across different configurations. These results also in a sense demonstrate that the forwarding zone in the FZC protocol (based on the value of worst case network compactness) is indeed sufficiently large to guarantee the reliable delivery on a connected network of random topology.

In our simulation, we also examined the timeliness of mobicast delivery on these networks. More specifically, we wanted to see how far ahead a node received the mobicast message before entering the delivery zone (or how late after entering the delivery zone). Fig 15 shows one typical result of a mobicast session, when the communication range is 35m, the delivery zone radius is 45m, δ is 0.7, d_s is 0, and the mobicast speed is 40m/s. Fig 15(a) shows the mobicast packet reception time relative to the sending time, for all the nodes that were ever in the delivery zone. The solid line is the expected reception deadline for nodes in each location, i.e, the first time they are expected to enter the delivery zone. The star dotted line is the actual reception time of the mobicast packet for each node. For comparison, we also included a simulation result (the diamond dotted line) of a spatial multicast on the same path with "as soon as possible" delivery. (Note that in this case the spatial propagation speed exceeds 1600m/s, i.e., 800m is traversed in less than half a second). We can clearly see the temporal locality property of mobicast. The packet reception time is very close to the deadline specified by the delivery zone semantics. These results also suggest the benefit of mobicast over a more conventional spatial multicast like geocast, which assume implicit as-soon-as-possible temporal delivery semantics, i.e, using mobicast one can control information propagation speed to better satisfy application needs while without overwhelming spatiotemporally unrelated nodes. We believe this "just-in-time" delivery nature of mobicast is a powerful mechanism for resource utilization optimization for related applications in sensor network.



(a) (b)

Figure 15: Slack Time of Mobicast Delivery

Upon hearing a optimistic mobicast message $\tilde{m}$ at time t.

```
if (m̃ ) is new and t < T
    cache this message
    if the value of the delta field is zero
        use local knowledge of delta for later computation
    else
        use the value in the packet for later computation
    end if
    if (I am in current forwarding zone F[t]) then
        broadcast m̃ immediately ;                  // fast forward
        if (I am in current delivery zone Z[t]) then
            deliver the message data D to the application layer;
        else
            compute the earliest time t_d[in] for me to enter the delivery zone;
            if t_d[in] exists and t_d[in] < T
                schedule delivery of data D to the application layer at t_in;
            end if
        end if
    else
        compute the earliest time t_f[in] for me to enter the forwarding zone;
        if t_f[in] exists
            if t_0 ≤ t_f[in] ≤ t
                broadcast m̃ immediately ;          // catch-up!
            else if t < t_f[in] < T
                schedule a broadcast of m̃ at t′;   //hold and forward
            end if
        end if
    end if
end if
```

Figure 16: Optimistic Mobicast Protocol

6. Discussion

For reliable mobicast, we introduced two network compactness metrics to help us choose the right forwarding zone and its headway distance for a given delivery zone so as to achieve the *mobicast* delivery guarantee without unnecessary flooding. These compactness values must to be computed for supporting the FZC mobicast protocol. Calculating them involves computing the shortest path and Euclidean distances of each pair of nodes in a given network. The all-pair shortest path of a graph $G(V, E)$ can be computed in $O(VE \log V)$ time by using Johnson's algorithm [7]. All-pair distance can be computed in $O(V^2)$ time. Therefore, we can compute the Γ-compactness of the graph in $O(VE \log V)$ time. Δ-compactness can also be computed in $O(VE \log V)$ time. It is not feasible for individual sensor nodes to compute these values in a large network. In practice, one may have a central server collect all the location and connectivity information, do the computation and use one broadcast to inform all the nodes this value. However, for the local compactness values, it is possible for the sensor nodes to compute the metric values as they involve only a relatively small number of nodes in their respective neighborhood.

While we chose the shape of the forwarding zone to be a $\frac{1}{\delta}$-cover of the shape of the delivery zone, this was done only for the purpose of analysis. Computing an exact k-cover for an arbitrary polygon P can be difficult. Yet one can always choose some approximation techniques such as using the k-cover of P's bounding box or bounding circle, which is computationally much simpler, but still has the required property (a shortest path between two nodes inside a specific instance of the delivery zone exists in the cover). The tradeoff is that the resulting forwarding zone is bigger than necessary, and thus may entail more re-transmissions for the same delivery goal. We should note that in the FZC protocol the forwarding zone only needs to be computed once by the sender. The nodes that receive the mobicast message only need to translate the forwarding zone with respect to their distances from the sender.

An important aspect of mobicast is that applications have control over the velocity of the information dissemination over the space. This brings many new spatial and temporal coordination and interaction possibilities across a network. For instance, an application might use a mobicast to send some information to the east at a speed of 40 miles per hour. One second later, it may find a change in that information, (e.g., there is a change in the intruder's expected path) and may want to send the new information and stop further propagation of the old information in the network. Note that stopping previous information dissemination is impossible in conventional protocols which have explicit or implicit "as-soon-as-possible" delivery semantics. Yet, in mobicast, a "stop that message" message can be sent at a much higher speed, say 120 miles per hour, (or even more than 1000 miles per hour which we found possible in our simulation), with a same-size delivery zone along the previous path. Clearly, this new mobicast recall message can easily catch up with its target message which propagates at a much lower speed.

As spatiotemporal protocols are relatively new, there are many research questions waiting to be answered. For instance, our ns-2 simulations are run without background traffic. When there is background traffic, the one-hop latency will change and will have a higher variance. Also, more collisions will happen and more packets will be lost. How background traffic will affect the delivery ratio and timeliness of the spatiotemporal protocols and how the protocols should be adjusted accordingly are questions we hope to answer in the near future.

Furthermore, for simplicity of presentation, our protocol essentially carries out flooding inside the forwarding zone. If the nodes have an accurate picture about the locations of their one-hop or two-hop neighbors, one can reduce the number of re-transmissions by using this knowledge in a manner similar to techniques proposed for improving broadcast efficiency [24, 25]. In a probabilistic guarantee scenario, one may also use probabilistic retransmission-reduction techniques such as the one proposed in [23]. A review of these and other related methods can be found in [27]. Our protocol, by only using the compactness values of the network, tries to use minimum number of bits to capture the relevant topology. If the nodes have local knowledge about the network topology in the neighborhood, (e.g., know the locations of all nodes within certain distance) more communication efficient mobicast protocols can be designed.

Finally, while we are focusing on constant velocity mobicast in this paper, the concept of spatiotemporal multicast in general applies to a much wider set of spatiotemporal constraints. The delivery zone can exhibit any evolving characteristics as long as it is sustainable by the underlying system. While they may all require ideas similar to the notion of forwarding zone and headway distance to maintain the spatiotemporal properties inherent in *mobicast*, different types of delivery zones may require different protocol handling details. Classification of a useful set of mobicast delivery zone scenarios and the design of the corresponding mobicast protocols are also important elements in our future work.

7. Related Work

Mobicast is motivated by the need for coordination activities related to moving entities in the physical environment. In [5], Cerpa et. al. proposed a Frisbee model in which an active sensing zone moves through the network along with the target. [16] and [6] proposed several data service protocols for improving the accuracy of distributed sensing in mobile environments. Both protocols entail communication schemes that push information about the object to the nodes close the projected location of the object in the future. The EnviroTrack group management protocol [1] dynamically creates and maintains a group that tracks mobile entities in the environment. However, neither of the aforementioned projects include communication mechanisms geared toward meeting explicit spatiotemporal constraints related to mobility. *Mobicast* can be viewed as complimentary to these projects by providing a convenient underlying communication mechanism that allows applications to push information with specified spatiotemporal requirements.

The idea of disseminating information to nodes in a geographic area is not new. Navas and Imielinski proposed geographic multicast addressing and routing ([12, 22]), dubbed "geocast," for the Internet. They argued that geocast was a more natural and economic alternative for building geographic service applications than the conventional IP address-based multicast addressing and routing. In a geocast protocol, the multicast group members are determined by their physical locations. The initiator of a geocast specifies an area for a message to be delivered, and the geocast protocol tries to deliver the message only to the nodes in that area. Ko and Vaidya investigated the problem of geocast in mobile ad hoc networks [15] and proposed to use a "forwarding zone" to decrease delivery overhead of geocast packets. Other mechanisms A([26, 17, 2]) have been proposed to improve geocast efficiency and delivery accuracy in mobile ad hoc networks. Zhou and Singh proposed a content-based multicast [28] in which sensor event information is delivered to nodes in some geographic area that is determined by the velocity and type of the detected events. While different in style and approach, all these techniques assume the delivery zone to be fixed. They also assume the same information delivery semantics along the temporal domain, i.e., information is to be delivered "as soon as possible." However, local coordination often requires just-in-time delivery in sensor networks.

Data aggregation is an important information processing step in sensor networks. Several techniques have been proposed to support data aggregation in sensor networks. For example, both directed diffusion ([14, 13]) and TAG [20] allow data to be aggregated on their route from the sources to a base station. No explicit local coordination is supported by these techniques. LEACH [10] organizes sensors into local clusters where each cluster head is responsible for aggregating the data from the whole cluster. However, there is no notion of mobility and the clusters do not move in space following a physical entity. In contrast, supporting local coordination for mobile physical entities is a primary goal of mobicast.

8. Conclusion

Spatiotemporal multicast represents a new multicast paradigm for disseminating information which has intrinsic spatial and temporal value. Mobile multicast is a special case of spatiotemporal multicast which has a promising application potential in sensor networks. To demonstrate the feasibility of *mobicast*, we developed a protocol and explored its ability to meet strong spatiotemporal guarantees. The key element in the protocol is a dynamic forwarding zone moving ahead of the delivery zone. Furthermore, we introduced two new notions of network compactness and proved several related theorems useful in the analysis of information propagation in wireless sensor networks. Using these results we were able to determine the shape of the forwarding zone and the headway distance needed in theory for our protocol to ensure strong multicast delivery guarantees in space and time while keeping retransmission overhead and average slack time small. The strong spatiotemporal guarantee differentiates mobicast from existing multicast protocols. We also investigated the network compactness properties of randomly distributed sensor networks and their implication on performance of mobicast protocols. We found the distribution of values for the compactness metric in randomly distributed sensor networks to be highly concentrated around a peak close to one with a very small portion close to zero. This leads to the identification of a fundamental tradeoff between probabilistic delivery guarantees and communication overhead in spatiotemporal multicast. Via analysis and simulation, we found that mobicast can indeed significantly reduce its communication overhead via a propitious choice of forwarding zone size by only a slight relaxation of its delivery guarantee.

The powerful just-in-time spatial delivery semantics of *mobicast* can be used to optimize resource utilization for multicast tasks in sensor networks and enables application programmers to address both spatial and temporal perspectives of communication and coordination explicitly, in a manner atypical of current multicast models. We hope this work will facilitate a broad research effort in spatiotemporal communication mechanisms and sensor network applications.

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