Survivable Bluetooth Location Networks

F. J. González-Castaño
Departamento de Ingeniería Telemática
Universidad de Vigo
ETSI Telecomunicación, Campus, 36200 Vigo Spain
Email: javier@det.uvigo.es

J. García-Reinoso
Departamento de Ingeniería Telemática
Universidad Carlos III de Madrid
Escuela Politécnica Superior,
Av. de la Universidad 30, E-28911 Madrid Spain
Email: jgr@it.uc3m.es

***Abstract*— In this paper, we analyze survivability issues of Bluetooth Location Networks (BLN) for location-aware or context-driven mobile networks, such as m-commerce environments or e-museums. We assume that, in any of those scenarios, there exist *service servers* that need to know user location in real-time, to send context-oriented information to user handhelds when necessary. The BLN transmits position information to service servers, without user participation. It is not subject to line-of-sight constraints and is supported by existing commercial handhelds. BLN users carry either a Bluetooth-enabled handheld or any mobile data terminal and a Bluetooth *badge*. The BLN is composed by wireless Bluetooth nodes, which establish an spontaneous network topology at system initialization. The BLN can coexist with other Bluetooth systems.**

I. Introduction

A. Motivation

This paper analyzes survivability issues of Bluetooth Location Networks (BLN) for location-aware or context-driven mobile networks [1].

M-commerce (mobile e-commerce [2], [3]) has a promising future. In a typical m-commerce scenario, customers walk around a large commercial area or mall carrying wireless PDAs. A PDA client allows its user not only to purchase items, make reservations or request information, but also to receive (possibly context-driven) store coupons, advertisements and advice. Another interesting application field is electronic guidance. Exhibition visitors receive specific information associated to their current location [4].

In any of those scenarios, there exist service servers that need to know user location in real-time, and send context-oriented information to user handhelds when necessary.

The BLN transmits position information to the service servers, without user participation. It is not subject to line-of-sight constraints and its base technology is supported by existing commercial handhelds [5], [6]. As a fully operational data network, the BLN admits alternative uses as a security network when the target area is closed to the public, or as a spare network for emergencies.

BLN users carry either a Bluetooth-enabled handheld or any mobile data terminal and a Bluetooth badge (thus, the BLN may provide location services to *any* mobile data terminal). We must remark that we simply rely on Bluetooth responses to inquiry cycles and, as a consequence, we do not need specific client programming. The BLN is composed by wireless Bluetooth nodes, which establish an spontaneous network topology at system initialization. The BLN can coexist with other Bluetooth systems, such as printers.

B. Background

Many user-positioning solutions have been proposed in previous research, but they are based on specialized devices that are not supported by commercially available data terminals [7], [8], [9], [10]. If we review positioning systems supported by commercial terminals, we find the following:

- Cell phone location services [11] and GPS are quite effective for outdoor applications (specially GPS), and possibly the best choice. However, they are useless indoors.
- HP's Cooltown [12] is based on IR *beacons*, which push position-dependent URLs into handheld IR ports (included in most state-of-the-art PDAs and WAP phones). Cooltown is user-dependent, because the user must aim the infrared port to location beacons. It could be argued that this is not a drawback, since automatic detection of location information (without user participation) may have severe consequences in terms of nuisance value. For example, when users are annoyed because the Web page they are viewing is suddenly supplanted by one advertising frozen peas from a grocery store nearby. Cooltown is one of the key technologies in the Electronic Guidebook Research Project [4]. Other examples of IR-based systems are described in [13], [14].

User-independence is only a disadvantage in *aggressive* systems, which are not a desirable scenario. Consider, for example, a museum, where updates could only take place when users enter new halls, and imagine that the update shows the previous page with a tiny flashing icon at its bottom meaning "do you want to update context information?" Also, asking the user to locate IR beacons each time he enters a room full of visual distractions may be tiring, and signaling IR beacons with large red arrows unsightly.

We can conclude that, depending on the specific application, user-dependent line-of-sight IR systems may be more advantageous than user-independent RF ones or vice versa. *In fact, they are complementary*. For example, in a museum, an iPAQ H3870 could use Cooltown to retrieve information on a single object (e.g. "Celtic *fibula*"), and Bluetooth-assisted context awareness to retrieve information on the surrounding hall (e.g. "Iron Age").

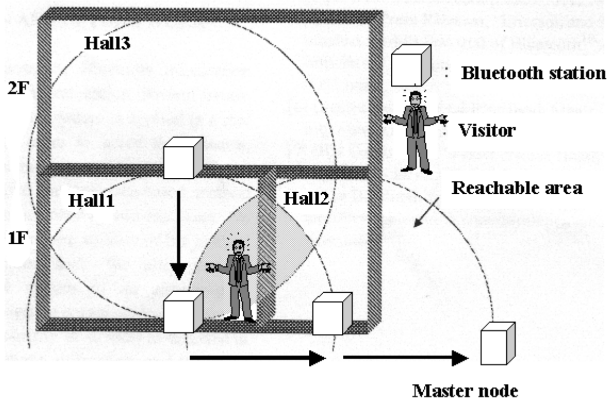

Fig. 1. Cooperative Bluetooth location

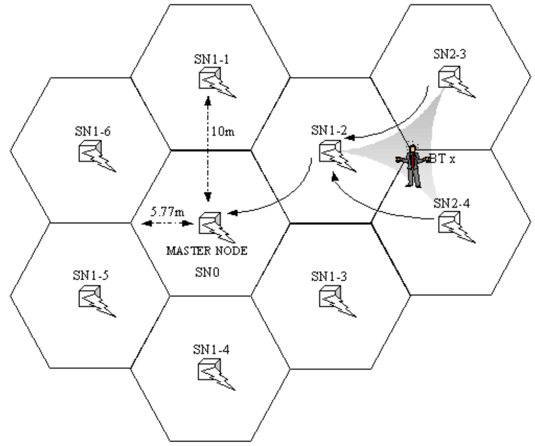

Fig. 2. Bluetooth Location Network

C. Bluetooth location networks

In this paper, we evaluate the survivability capabilities of Bluetooth Location Networks (BLN), which satisfy the requirements in section I-A. We assume that the users carry a Bluetooth-enabled terminal, or any mobile data terminal and an independent Bluetooth location badge. The users must access the Web/WAP service servers from their handhelds, and enter their badge address. By doing so, the Bluetooth address of the badge becomes *valid* from the BLN's point of view (obviously, the location network must work even if invalid addresses are present, as we will see later). The service server associates the user' IP address or WAP session to his badge number, for all subsequent transactions. The badge (or the Bluetooth modem in the user's terminal) interacts with the BLN, which provides service servers with real-time user position. The service servers may use this information to push URLs into user terminals via TCP/IP sockets, or to update WAP cards. Thus, no user action is involved in context-driven updates.

Bluetooth was also selected as the base technology for the information offering system in [15]. Although the authors claimed some of the advantages we enumerate in section I-A, they also stated that Bluetooth range does not provide enough location precision. Consider the example in figure 1. In principle, if the three Bluetooth stations detect the user modem, the user could be located in any hall if considering full range. The key point in our philosophy is establishing a *cooperative location network*. The network transmits user modem addresses and the addresses of the Bluetooth stations that detect those modems to a *master node*. In the example in figure 1, the master node would determine that the user is located inside the gray region. Note that most of that region is part of the hall were the user is actually located. This is interesting, because this particular arrangement could not be solved by the non-cooperative system in [15]. The cooperative BLN in this paper is intended to cover 2D target areas, although it can be generalized to cover 3D ones.

The rest of this paper is organized as follows: the next section describes BLN protocols. Section III analyzes BLN survivability. Finally, section IV concludes.

II. BLN PROTOCOLS

A. BLN configuration

The BLN is composed by mobile badges and static Bluetooth units (located at the ceiling, for example). We will refer to the latter as *static nodes*. Static nodes (SNs) are arranged in a network that covers the whole target area. Hexagonal tiling is a typical solution in 2D cellular network planning, which we have followed in this research (figure 2). Other arrangements where any SN has at most seven closest neighbors within its range could be used as well ($\sim$ 10 m for class 2 Bluetooth modems [17]). For example, meshes for 2D areas or k-ary 3-cubes [19] for 3D areas.

Each cell in the ideal case in figure 2 has an area of 86.55 m^2. SN units scan their surroundings periodically, by means of Bluetooth inquiry calls [16]. All SNs are organized in a radial scatternet around a master node, SN0, connected to the service servers (not shown). The remaining SNs are arranged in "circular" layers around SN0. The notation SNX-Y is used to support the explanation and stands for the Bluetooth address of SN Y in layer X. In any layer, SNX-1 is placed right above SN0, and the remaining Y values are increased clockwise. Our example shows the six cells in the first layer, SN1-1 to SN1-6, and two cells in the second layer, SN2-3 and SN2-4. Each SN is a slave of its six neighbors.

All SNs perform inquiry cycles periodically, to publish their existence. If SN a detects an inquiry from SN b, and b is not currently listed in a's routing table, a must send its *minimum distance to the master node* in number of hops to b (in a *distance packet* with a 8-bit *control field* and a 8-bit *distance field*, which fits in a DM-1 packet [16]). All SN minimum distances are set to ∞ at power up, excepting the master node's, which is set to 0. Thus, the master node initiates the configuration by sending 0-hop distance packets to its neighbors on demand. Later, if a SN performing an inquiry cycle does not receive an answer from one of its neighbors that was previously listed in the routing table, it deletes the

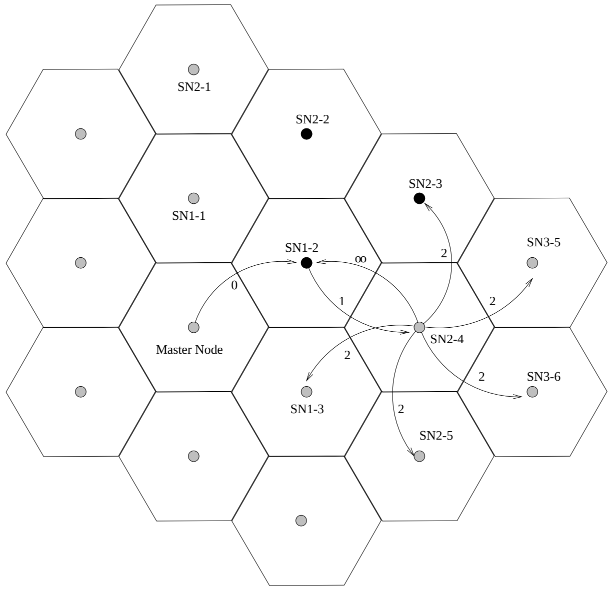

Fig. 3. BLN configuration

corresponding entry. If this changes its minimum distance to the master node, the SN transmits a new minimum distance packet to all its slaves.

Whenever a SN receives a distance packet, it searches its routing table to check if the corresponding distance is lower than its current lowest distance to the master node. If so, the SN builds a new distance packet and transmits it to all its slave SNs, excepting those included in minimum-distance routes to the master node. This algorithm is similar to the *split horizon* algorithm.

Therefore, the configuration process also restarts in case of SN failures, and propagates changes from the failure neighborhood (possibly only affecting a BLN region).

If a SN receives a distance packet, it must update its routing table. The routing table stores pairs of neighbor SN addresses and their distances to the master node, and is sorted by distance. The best path to the master node is always the first table entry.

Figure 3 depicts a BLN region. We describe two configuration steps to illustrate the general procedure.

1) Once the master node initiates the process, the distance from SN1-2 to the master node changes. Node SN1-2 transmits the new minimum distance (1) to all its slaves, on demand.
2) SN2-4 receives the distance packet from SN1-2. Since this distance plus 1 is lower than the current local minimum distance (∞), SN2-4 increments the received distance by 1, stores it in its routing table, and sorts the table again.

As we said previously, if a SN detects that the minimum distance to the master node has changed, it builds a new distance packet with this minimum distance, and transmits it to its slaves (neighbors) except to those who are in the minimum distance path. Those SNs receive an *infinite* distance packet, to prevent loops (see figure 3).

	Before inq.		After inq.	
Bluetooth addr.	Detected	New	Detected	New
BD-3	NO	NO	YES	NO
BD-7	NO	NO	NO	NO
BD-11	NO	NO	NO	NO
BD-13	NO	NO	YES	NO
BD-17	NO	NO	YES	NO
BD-19			YES	YES

TABLE I
SN CACHE EVOLUTION

Remark 1: If a SN has less than seven neighbors within its range, it is possible to implement permanent links with them (the seven-slave transmission constraint holds). This is valid for hexagonal-tiling, mesh and k-ary 3-cube BLNs.

Remark 2: A simple authentication handshake avoids connection establishment with invalid Bluetooth modems, which are considered invalid badges for simplicity. Typically, invalid badges will answer inquiry cycles with FHS packets, which is relatively harmless (see section II-B). However, in case they answered with another kind of packet, they would be easily detected by the authentication handshake and rejected.

Remark 3: Badges do not try to establish data connections with SNs. They simply answer inquiries with FHS packets, which does not violate the seven-slave constraint.

B. BLN location protocol

The main goal of the BLN is user tracking. To meet that goal, all SNs have to send inquiries and collect badge responses. Every SN has a cache where it stores badge addresses. When it detects a response from a badge whose address was not in the cache, it builds a *location packet* (which fits in a DM-1 packet) with its own address, the badge address (64+64 bits) and a 8-bit control field, and transmits it to the SN on top of its routing table.

For example, table I (second and third columns) shows the current SN cache state (BD-X identifies the badge with address X) when the SN is performing an inquiry cycle. Before the cycle starts, the *detected* and *new* columns are unmarked (set to NO).

When a badge detects an inquiry, it answers with a FHS packet. The SN extracts the badge address from the FHS packet and checks it in the cache. If the address is already listed, the corresponding *detected* column is marked (set to YES). Otherwise, a new row with the address is added and both the *detected* and *new* columns are marked with YES. When the inquiry cycle ends, (i) all marked (YES) *new* columns are switched to unmarked (NO) state, and location packets for the corresponding entries are transmitted to the master node to report that new badges have entered SN range. (ii) All entries with unmarked (NO) *detected* column are deleted, and generate location packets to report that the corresponding badges have left SN range.

Location packets carry two Bluetooth addresses: SN address and badge address. The packets have a bit to report if the badge arrives to or leaves the cell.

It should be understood that the SN that detects a badge is in charge of building location packets. All SNs placed along the transmission path to the master node simply forward them to the SN on top of their routing tables.

The fourth and fifth columns in table I represent a possible SN cache state after an inquiry cycle. A new badge, BD-19, has been detected. Thus, a location packet with BD-19 payload will be sent to the master node. The corresponding *new* column will be unmarked. Two badges, BD-7 and BD-11, have left the cell. Therefore, two location packets will be sent to the master node with the *detected* bit set to 0, and the corresponding entries will be removed. Badges BD-3, BD-13 and BD-17 are still around, but do not generate location packets.

Remark 4: SN responses to SN inquiry cycles are ignored by the location protocol, because answering SNs are listed in the routing table of the requesting SN.

Remark 5: Obviously, invalid badges will answer to SN inquiries, and will generate location packets. However, those packets will be filtered by the master node. The results in [1] suggest that, even if a large target area is crowded, the BLN can carry a large number of location packets, valid or invalid. Moreover, note that, if invalid badges correspond to static devices (such as printers), they will generate only *one* location packet, because their *new* column in SN location caches will be unmarked afterwards.

C. Location zones

The master node (or a service server attached to it) estimates that badge x is placed in a *location zone* that depends on the SNs that send location packets containing address x. Room-scale precision may be enough for many context-driven services in the scenarios in section I, while keeping SN complexity reasonably low. So far, we do not take signal strength nor signal delay into consideration. Location precision depends on the number of SNs that detect a given badge, and on the range of their modems. In a hexagonal tiling topology without SN failures, badge position is determined with worst precision if *only* four SNs detect it. In this case, the estimated location area has 18.12 m^2. For example, when *only* SN2-2, SN2-3, SN3-2 and SN3-3 in figure 4 detect a badge (zone II).

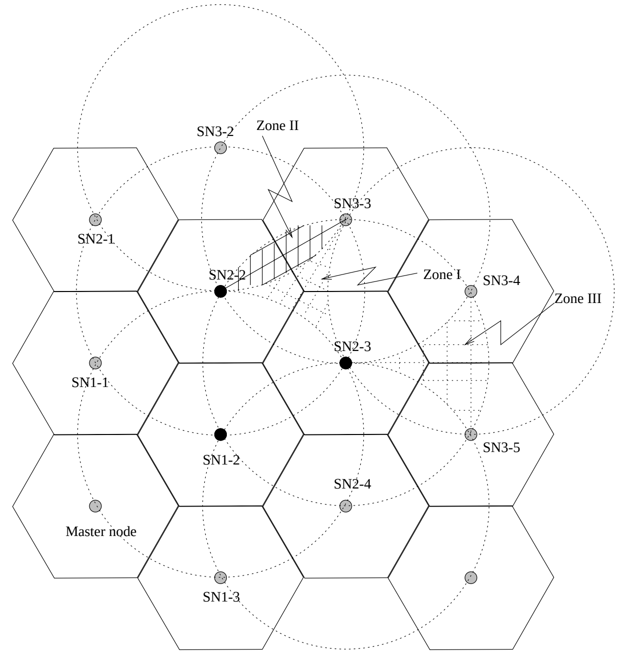

Fig. 4. Location zones

SN2-1 routing table					
Beginning		SN1-2 down		SN1-1 down	
Route	Dist.	Route	Dist.	Route	Dist.
SN1-1	2	SN1-1	2	SN2-12	3
SN2-2	3	SN2-2	3	SN3-18	4
SN2-12	3	SN2-12	3	SN2-2	∞
SN3-18	∞	SN3-18	∞	SN1-1	∞
SN3-1	∞	SN3-1	∞	SN3-1	∞
SN3-2	∞	SN3-2	∞	SN3-2	∞
SN1-6 down		SN1-5 down		SN1-4 down	
Route	Dist.	Route	Dist.	Route	Dist.
SN2-2	5	SN2-2	5	SN2-2	5
SN3-2	6	SN3-2	6	SN3-2	6
SN3-18	6	SN3-18	∞	SN3-18	∞
SN3-1	∞	SN3-1	∞	SN3-1	∞
SN2-12	∞	SN2-12	∞	SN2-12	∞
SN1-1	∞	SN1-1	∞	SN1-1	∞

TABLE II
ROUTING TABLE OF SN2-1

III. SURVIVABILITY

A. BLN reconfiguration

BLN detection capabilities survive in case of failures, due to spontaneous reconfiguration when a SN dies, which keeps as many SNs connected to the master node as possible. Survivability is inherent to the BLN configuration protocol. Suppose SN a does not respond to an inquiry from SN b. If, as a consequence, the minimum distance changes, b transmits its new minimum distance to its slaves, propagating the change to the outer layers.

As an example, table II shows the evolution of the routing table of SN2-1, when all SNs in the first layer but one fail successively. When SN1-3 finally crashes, all SNs in the first layer (and therefore all SNs in higher layers) are isolated. Only after all SNs in the first layer die, SN2-1 will be isolated from the master node.

B. Badge detection survivability

As SNs crash, it could happen that a badge crosses a region of the target area undetected. We performed different simulations of a three-layer BLN to evaluate survivability of BLN detection capabilities in multiple failure scenarios. Figure 5 shows the results, for a single, two or four symmetrically distributed master nodes. The simulations were made for a quality of 90 % and a tolerance of 5 %, using the Batch Means Method [20].

In our simulation, master nodes are protected against failure. This is certainly realistic, since the whole BLN relies on them. It is important to mention that, in a real scenario, no more than 5%-10% of the SNs should be ignored if dead (in other words, if they are maintained as frequently as light bulbs. A

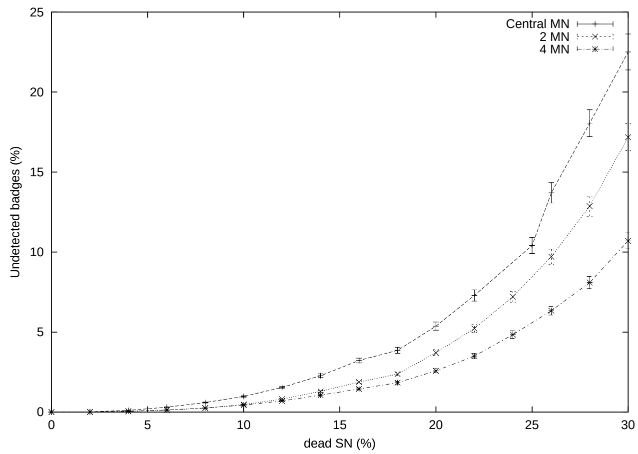

Fig. 5. Undetected badges

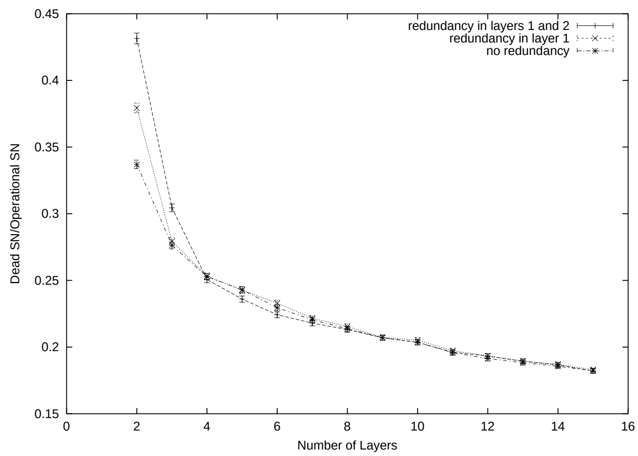

Fig. 6. Dead SNs to isolate a single operational SN

percentage of over 30% dead SNs means that the target area is simply not properly maintained). Note that, for as many as 10% dead SNs, only 1% of the badges were undetected.

C. Isolated SNs in case of failure

As another survivability measure, we evaluated the percentage of SNs that must die to isolate a single operational SN (it is impossible to establish a path between that SN and the master node), for a single master node. Figure 6 shows the simulation results. Note that, in the three-layer BLN of the previous example, more than 20% of the SNs should die to isolate a single operational SN.

IV. Conclusions

In this paper, we have evaluated survivability in Bluetooth Location Networks for context-driven services. These networks have the following characteristics:

- The BLN transmits position information to the service servers without user participation.
- Its RF technology is available in commercial handhelds.
- The BLN can be used as a general-purpose data network.
- The spontaneous topology configuration is scalable, by placing as many master nodes as necessary.
- The BLN can coexist with Bluetooth devices that are not part of the location system, such as printers or headphones.

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