Human Mobility in Shopping Mall Environments

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ABSTRACT

The need for a network when there is no infrastructure is no longer limited to military and emergency applications; ad hoc networks can support private and public applications as well. Ad hoc networking has been a dynamically growing research area in recent years. In order to conduct informed and realistic design of forwarding policies and algorithms for mobile ad-hoc delay tolerant networks, it is important to gather appropriate real human mobility data. In this paper we study human mobility in a shopping mall environment. In such an environment, people using network devices such as mobile phones, PDA, etc. could be willing to communicate in a variety of ways, without the mediation of routing across the global Internet. The ultimate goal is to enable a multitude of users at any place in the shopping mall to access/receive appropriate local information at any time. We discuss the implications of our results and make recommendations for the design of opportunistic forwarding algorithms for shopping mall environments.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design – *Wireless communication*;
C.4 [**Performance of Systems**]: Modeling techniques

General Terms

Measurement, Experimentation, Human Factors.

Keywords

Delay-tolerant Networking, Human Mobility Patterns, Network Measurements, Mobile Networking, Wireless Networking.

1. INTRODUCTION

Pervasive computing has entered the backpack, purse, and coat pocket in the form of mobile devices. Pervasive computing devices are very tiny devices, either mobile or embedded in almost any type of object imaginable, including cars, tools, appliances, clothing and various consumer goods, all communicating through increasingly interconnected networks. Such devices will actively participate as part of an autonomic network, sharing wireless resources, providing local connectivity to other devices, and possibly offering local mobility management, persistent storage and forwarding services. They will provide connectivity based upon cooperation incentives or rewards, individual mobility and social patterns. A key point for growth and robustness of such network is the willingness to cooperate. Sometimes autonomic networks can be a better solution with respect to traditional networks which could be more expensive, involve installation issues, incur customer cost factors and particular policy restrictions, and may be inapt for wireless people-centric networks where services are established on the fly. The ultimate goal is to create a system that is pervasively and unobtrusively embedded in the environment, completely connected, intuitive, effortlessly portable, highly scalable, and constantly available. In this context mobility plays a key role in the forwarding of data as it is mobility which gives rise to local connection opportunities when access to network infrastructure is not available. For this reason studying human mobility in different environments for extended period of time is essential. It is likely that successful forwarding algorithms will be based on locally learned information. Thus we need to measure what we can statistically learn locally and then use those measurements to drive the development and evaluation of appropriate forwarding algorithms. Recently, several significant efforts have been made to collect data reflecting human mobility [1], [2]. However, these traces are from specific scenarios and their validity is difficult to generalize.

Figure 1: Map of the shopping mall - 11 shops, 1 store, 1 bar and 18 mobile devices, 7 fixed devices involved in the experiment

We have been considering applications in shopping mall environments and therefore decided to collect real-world Bluetooth contact data from shop employees of a shopping mall over six days. This data will allow us to conduct informed design of forwarding policies and algorithms for such scenarios, and determine the effects of users' mobility patterns on the prevalence of networking opportunities. This paper, which follows from our previously introduced work [3], has three main contributions. First we introduce in section 2 our analysis of shopping mall activity based on three main entities which shape this environment. In section 3 we describe the research we conducted in a shopping mall, which was a deployment of 25 smart phones only active in Bluetooth mode in order to measure the human mobility patterns in this environment. Ultimately, we present in section 4 some implications of these results for the design of forwarding algorithms for mobile ad-hoc delay tolerant network applications in environments such as this.

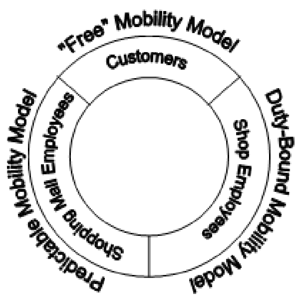

Figure 2: Main Classes of Mobility in Shopping Mall Environments

2. SHOPPING MALL NETWORKS

Nowadays shopping malls look more and more like a world in microcosm. Like Tom Hanks character in The Terminal, someone could even spend the whole day there without necessarily doing shopping. Such environments offer all of the elements required to build large-scale people-centric network applications. A mobile ad-hoc delay tolerant network is an autonomous system of mobile devices intermittently connected by wireless links forming an arbitrary graph. Because of the devices' intrinsic mobility the topology of the network is time varying. Such a network may operate in a standalone fashion, or may be connected to the larger Internet. Note that connectivity to traditional networks is not always better than local connectivity; local networking can be better if the corresponding party is nearby, either because one or both of the terminals do not have access to the network infrastructure, or because this is expensive. Ad-hoc networks are fully decentralized and can work in any place without any infrastructure. In fact, mobile nodes that are in radio range of each other can directly communicate, whereas others need the aid of intermediate nodes to route their packets. This property makes these networks flexible and robust. However, the dynamic nature of the network topology introduces problems for the design of ad-hoc networks. Mobility compromises the communication between users, as forwarding paths may be unstable and receiver reachability may be very variable. We believe that different environments are characterized by different patterns of mobility and should be supported by suitable embedded routing protocols. Therefore collecting data reflecting human mobility is important to design suitable routing protocols for applications for mobile ad-hoc delay tolerant networks. We suggest that a number of environments are characterized by a similar mobility structure including Trade Fair, Music Festival, Automobile race track, stadium, etc. Stores and shops in shopping malls correspond to stands, kiosks, booths, tents, bars, pubs, and so on in trade fairs, music festivals, automobile race tracks, stadiums, etc. Customers, audience, partygoers and any attending individual are the main actors who might be supported. Unfortunately, to date little work has been done to determine human mobility in this kind of scenario. We conducted our experiment in a shopping mall aiming to provide some base-line data to support the design of forwarding algorithms for such scenarios. A shopping mall is a place where a collection of shops all adjoin a pedestrian area or an exclusive pedestrian street. In many cases, shopping malls are tens of thousands of square meters in area and crowded much of the time. Here, we distinguish three main classes of individuals with different mobility patterns (as illustrated in Figure 2). First, shop employees in charge of particular tasks (i.e. shopkeepers, sellers, clerks, shop assistants, etc.) co-located in well defined locations whose mobility is defined by their duties. Second, customers who are free to move "wherever" they like and for their own specific purposes within the whole area. Finally, groups or single individuals mainly responsible for maintaining safety and in order the mall area (i.e. safety guards, cleaners, stewards, etc.). As such they have specific duties and relatively predictable mobility.

3. EXPERIMENTAL SETUP

We have conducted an experiment aiming to gather data about contacts between devices carried by humans. Similar experiments have been done in different settings: conference environment which involved conference attendees at *Infocom 2005* [2], in research lab and university in Cambridge [1],[9] and MIT [10] by involving researchers and students, during the Paris roller blading [11], in a typical office environment [12], from traces collected in the Wi-Fi access network of Dartmouth College [13] and ETH Zurich campus [14]. We are focusing on human mobility in shopping mall environments. Setting up an experiment in such places is not easy: local regulations may prevent such an experiment, and even if permitted there are problems of privacy, security, mistrust, etc. Unfortunately, not all the employees participated in the experiment but the ones who did are sufficient to obtain valuable results. Our experiment aimed to collect data on the frequency and duration of contact between devices carried by people (inter-contact time and contact duration). Gathering such a data set also presents many practical issues: dealing with deployment of mobile devices to a certain number of shopkeepers, the battery life of the devices, and minimizing the inconvenience of carrying the devices so that they are willing to do so at all times. The devices used to collect data in this experiment are smart phones running symbianOS and using Bluetooth technology. We carried out neighbor discovery approximately every 120 seconds. The Bluetooth 1.1 specification states that an inquiry process for neighbor discovery should last about ten seconds. The experiment involved twenty-five mobile devices, seventeen of which were carried by shopkeepers and shop employees and eight of which were static, placed in fixed locations. For six days these devices were given to the participants at around the same time, 9:15am, and collected at 8:45pm. They carried the devices throughout the working day (from 09:00am to 01:00pm and from 04:30pm to 09:00pm). All the twenty-five devices yielded useful data. The phones were deployed in one store, eleven shops and one bar. The floor plan in Figure 1 shows

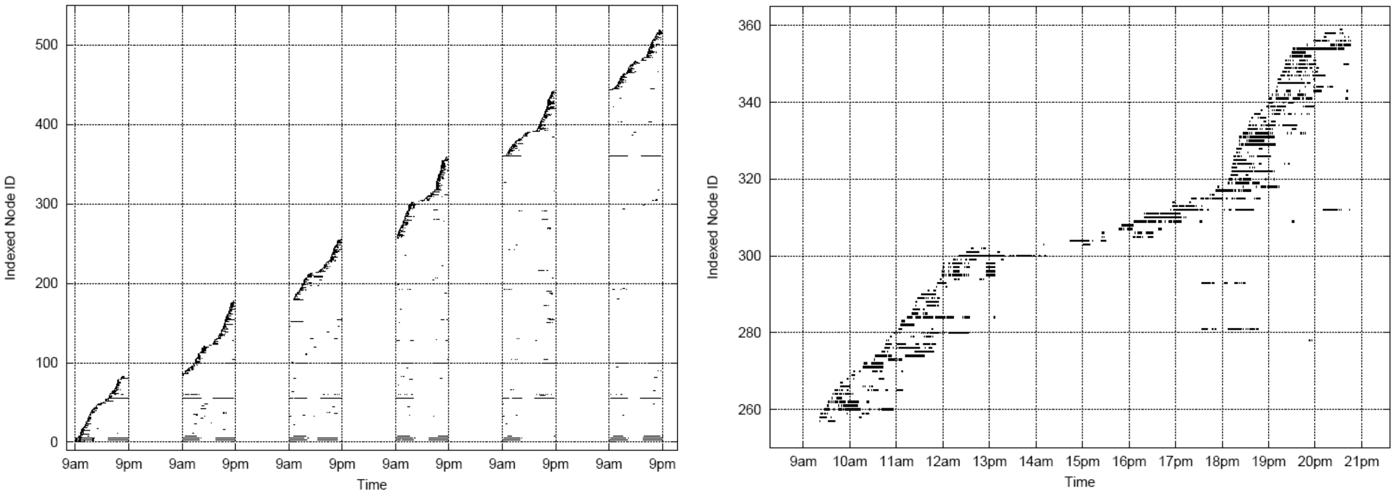

Figure 3: Time series of external contacts seen by all of our Smart Phones over six working days (left) and over the fourth day (right)

the shopping centre, which has a surface area of 10,880 m^2 (without considering the parking area).

4. ANALYSIS OF SHOPPING MALL MOBILITY PATTERNS

We have deployed twenty-five smart phones as described in section 3. We identify contacts between two of our smart phones as “internal” whilst all the other contacts are “external”. Internal contacts are all the contacts between shop employees. External contacts are much greater in number than internal contacts and represent a valuable source of data: they are the other Bluetooth devices seen in the vicinity of our smart phones, and allow us to estimate the deployment and movement of other Bluetooth devices. A typical log file is visualized in Figure 3 where the X-axis shows the time and the Y-axis identifies Bluetooth unique MAC addresses seen. Clock synchronization was checked manually. The smart phone taken into account for this analysis is the one whose MAC address ends with “c3a4” located in shop 4 (highlighted in Figure 1). The left plot in Figure 3 shows the external Bluetooth devices seen by “c3a4” as seen by all the twenty-five smart phones (519 external devices), while the right plot in Figure 3 zooms into the fourth day of the experiment. These last two plots show that most of the customers spend less than two hours in the shopping mall. Our devices recorded 60223 external contacts with 749 detected external devices and 284492 internal contacts between each other. There are significantly more external devices than internal ones, but they are seen less often. The maximum number of internal and external nodes seen by one of our devices at one time was respectively 18 and 11. Following the ethic principals, an anonymised version of our data will be available to other research groups on request.

4.1 Inter-Contact and Contact Time

We analyze connection opportunities in terms of contacts by considering inter-contact time. This is related to the frequency with which packets can be transferred between networked devices (as defined by the authors in [1]). Inter-contact time is the elapsed time between two non-consecutive sightings of the same node. It (with contact time) determines the frequency and the probability of being in contact with the recipient of a packet or a potential forwarder in a given time period. Contact time is the duration of a single set of consecutive sightings of the same node, i.e. a presumed period of continuous contact. These parameters are particularly relevant in opportunistic mobile networks, such as mobile ad-hoc delay tolerant networks [1]. Our results are necessarily constrained by the duration and granularity of the experiments. In particular, observation of short event lengths is limited by the granularity of measurement (around 134 seconds). Similarly, events lasting longer than the experiment cannot be observed. In Figure 4 we plot the inter-contact time distributions of two smart phones with different sets of people for the six days of the trial. The y-axis identifies the probability that the sender will be in contact with the receiver after a certain time. One of the two smart phones has been used as fixed node and left next to the cash register (in the Figures 4-5 labeled as FX) and one has been carried by a seller over the working time in the same shop (in the Figures 4-5 labeled as M). In Figures 4 and 5 we show contact and inter-contact times between the two above mentioned smart phones and four groups of devices; customers (i.e. external devices); all contacts; all the 25 smart phones (i.e. all shop employees participating in the experiment); and only neighboring smart phones (those allocated in the dashed circle in Fig. 1). In the plots these groups are numbered from (1) to (4). The figures also show that the fixed and mobile device have very similar distributions. This could be explained by employees being mainly located in the shop where they are during the working day and thus having the same contacts in sight. All of them exhibit a strong heavy tail property which can be observed as an approximate power law for the time scale [2min:1hour] for the first three groups (i.e. customers, all contacts and all shopkeepers) with power law coefficients respectively 0.57, 0.76 and 0.92, and an approximate power law for the time scale [2min:30min] for neighboring shopkeepers. Note that the distribution for neighboring shopkeepers in Figure 4 shows a power law with coefficient 1.30. This may be significant because, using multiple intermediate relays, this is sufficient for stateless forwarding algorithms to converge [1]. After about one hour all of the graphs

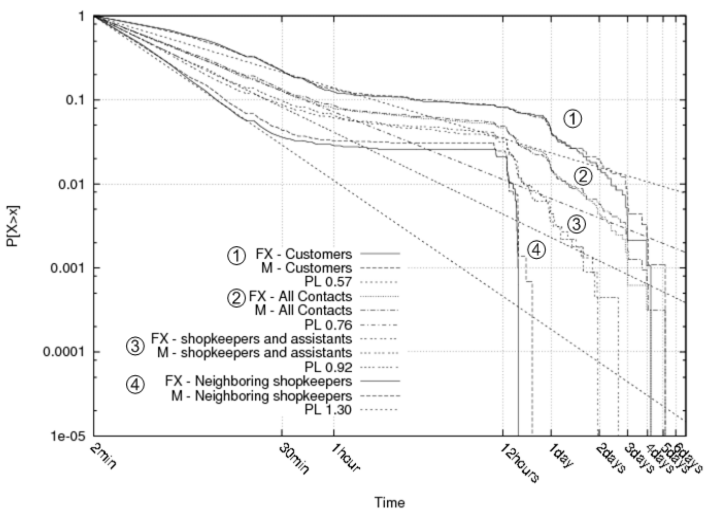

Figure 4: Tail Distribution Functions of the Inter-Contact Time over six days of the internal node "c3a4" with: customers, all contacts, all 25 internal phones, and neighboring smart phones only.

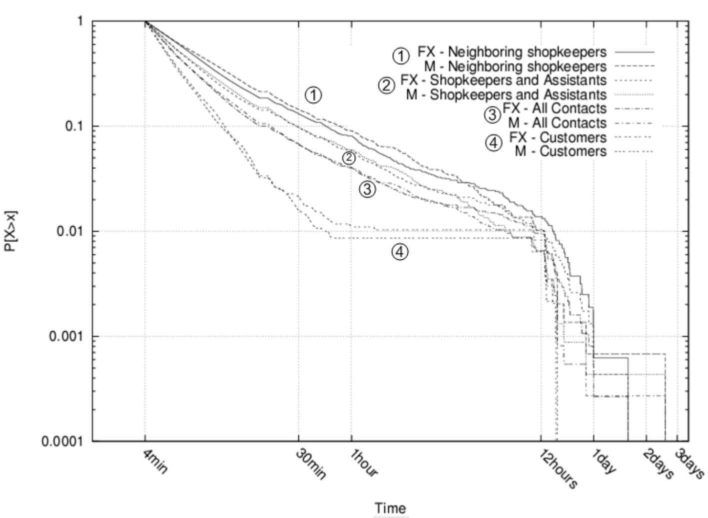

Figure 5: Tail Distribution Functions of the Contact Duration over six days of the internal node "c3a4" with: neighboring internal phones only, all 25 internal phones, all contacts, and customers.

tend to plateau until the end of the working day. The shape of the distributions in Figure 4 shows us that inter-contact times tend either to be smaller than one hour or larger than twelve. This is most evident in the neighboring shopkeepers' distribution (4) which is almost flat from around 60 minutes to 12 hours. This suggests that shopkeepers, sellers and shop assistants in the shopping mall are in contact with each other most of the time allowing MANET-like connectivity. Longer inter-contact times are larger than twelve hours (the time between two consecutive working days). This implies that customers commonly spend up to an hour in any one part of the shopping centre and some come back the next day. The distributions in Figure 4 also suggest that a seller tends to meet subgroups of people from the same organization (i.e. neighboring sellers (4)) more often than people from a different organization (i.e. customers (1)). This suggests a promising strategy to identify forwarders for message delivery. We imagine that the union of these clusters of neighboring sellers could form a reliable mobile ad-hoc network backbone in a shopping mall environment. This is backed up by Figure 5 which shows that the contact time distributions also approximate a power law distribution. Contact durations for customers are almost all smaller than 1 hour. It is worth noticing that a few "customers" (i.e. external devices) have very long contact durations which suggest that they could in fact be shop employees working close by rather than customers. Notice that the order of the distributions in Figure 5 is reversed with respect to the order in Figure 4. The contrast between the distributions in Figures 4 and 5 and the corresponding distributions from previous experiments [1] and [2] suggest that the nature of the environment and the individuals has a significant impact. We suggest that in campus and conference environments people have more freedom to move without particular constraints and boundaries, giving rise to longer inter-contact time than the ones seen in the shopping mall, where individuals follow certain motions strictly related to the surrounding environment and their aims. Figures 4 and 5 show that customers have distinct mobility pattern with compared to employees. In addition, customers tend to spend shorter periods in the shopping mall compared to people in campuses and conferences. Because of the purpose of their presence in the mall, customers tend to stay close to sellers and the majority of them do not return on the same day. This behavior gives rise to shorter inter-contact times than in [1] and [2].

4.2 Inter-Any-Contact and Any-Contact Times

In the previous section we have analyzed contacts between pairs of devices, in terms of to frequency and duration of the contact. In this section we study the frequency (*inter-any-contact time*) and duration (*any-contact time*) of transfer opportunities for a subset of customers (those seen by the node 'c3a4') with any of our smart phones. We do not show the "inter-any-" and "any-"contact times for all smart phones as for neighboring sellers because it appears that sellers are almost always in contact with neighboring sellers. Figure 6 shows the any-contact time distribution for all of the customers seen by 'c3a4' with any internal node. As expected, any-contact times with customers are much longer than contact times but with the same distribution shape. It is also clear that some customers spend much more than one hour in the mall in total, even if they spend less than an hour near any single seller. Figure 7 shows inter-any-contact time for the same customers with any internal node. Compared to Figure 4 the best fit power law coefficient increases from 0.57 to 1.16. This difference is quite relevant, in particular if compared to the results of [2]. As one might expect, a node willing to communicate with any member of a group of other nodes has much better forwarding possibilities. More generally, information about other groups of people could be exploited in application layer protocols. For example, a group of nodes subscribing to be "shop-members" might receive benefits in exchange for involvement in communication.

4.3 Studying Contacts among Nodes

A lot of work has been done to build the mobility models on which much ad hoc network research is founded. The majority of

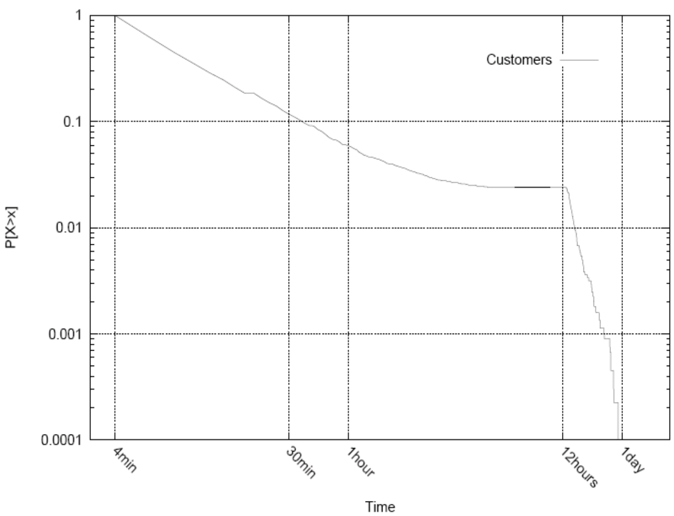

Figure 6: Distribution Function of Any-Contact Duration over six days for the customers seen by the node 'c3a4' with any internal node.

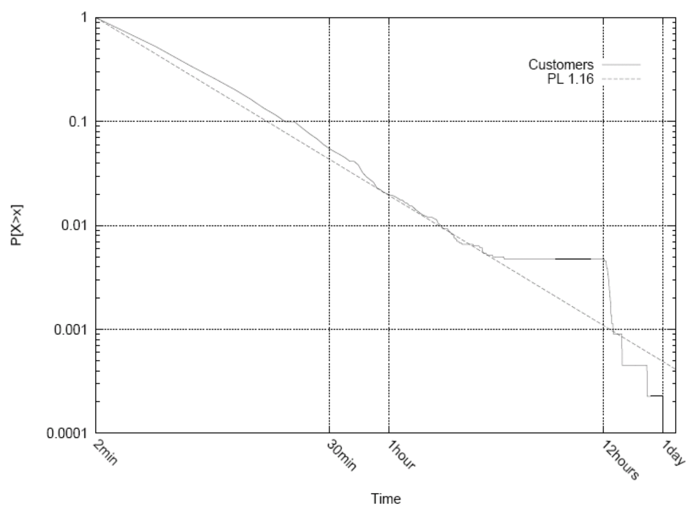

Figure 7: Distribution Function of Inter-Any-Contact Time over six days for the customers seen by the node 'c3a4' with any internal node.

work to date has been based on "unnatural" mobility models such as Random Walk Mobility Model and its derivatives [4]. Such mobility models seem to be unrealistic for everyday scenarios, and do not exhibit the kind of characteristics found in [1] or here. Consequently, network research based on such models must be considered unproven for real-world situations. Other mobility models have been proposed based on social network theory [5]-[7], but the mobility models which most closely reflect real life are the ones founded on accurate real trace data, i.e. trace-driven mobility models. In this section we examine the data gathered to identify possible implications which are worth to consider in building forwarding algorithms as well as mobility models for network applications in shopping mall environments. The Figure 8 shows the distribution of the number of times each node was seen by one of the internal devices, distinguishing between internal and external nodes. Considering internal nodes, during the experiment, 14 of our smart phones were sighted between 340 and 1685 times, nine of our smart phones were sighted between 5 and 63 times, and one was sighted just once. These distributions suggest that different nodes have different contact-relationships and that many of them (14 of the 25 smart phones) have good contact-relationship. This might reflect an employees' mobility being mostly localized around the shop they work in, and sometimes moving away for scheduled and toilet breaks. The gap between first and second group might suggest the difference between neighboring sellers and the rest of the sellers. Considering external nodes, the mode is 1 and the vast majority of external devices have less than 32 sightings, except for three of them which have between 169 and 224 sightings. But recall that "external" nodes could also be personal devices carried by sellers and/or shopping mall employees (i.e. safety guards, sweepers, stewards, etc.). From these results we can see significant differences between customers and shop employees. From this, we can argue that mobility models in which all the nodes have the same mobility patterns cannot adequately represent shopping mall environment. The Figure 9 shows the number of times that pairs of (internal, internal) and (internal, external) nodes come in contact with each other. This distribution shows a considerable variability in the number of times pairs of smart phones saw each other. Unlike the results in [2], in our case pairs of internal nodes are uniformly spread along the number of contacts from 0 to the range (513-1024). This strengthens our conjecture that sellers, who are positioned within the shopping mall according to its structure and following a certain order (i.e. some are in charge of a specific area, others have particular tasks, etc.), have "duty-bound" mobility that links them to the shop where they are employed. The Figure 9 also suggests that sometime sellers move away from their working place to satisfy their needs. In contrast, in conference environments [2] most or all of the nodes are "free" to move without any boundaries. The plot also shows that the majority of pairs with external nodes have less than 16 contacts. Unlike internal pairs, the pattern of visibility with external devices does seem to reflect that in [2], for example, the number of pairs that never come into contact with each other is almost half of them. These results could not be reproduced by mobility models that give all nodes the same probability of meeting each other. Figure 10 shows how many internal nodes saw a particular device over the whole six days (the plot does not tell us how many times the same device was seen). These two distributions highlight the difference between internal and external nodes. Unlike the graph in [2] where iMotes carriers saw all but a few of the other iMotes and external devices were seen by only a couple of iMotes, here the majority of the customers meet more than half of the sellers, while almost all of the sellers meet at some point. We imagine that in a conference environment [2] the internal nodes are not always together; external devices could be seen by an internal device when distant from the conference and thus would be unlikely to be seen by any other internal device. But in shopping mall environments internal nodes are mainly duty-bounded to the shop in which they are employed (during the day at least) moving away from time to time. Note also that six of the internal fixed nodes (out of seven) see between 20 and 24 other internal nodes. This suggests a possible role for fixed nodes to forward data contrary to the preference for mobile nodes in [8] (where the use of mobile nodes increases the capacity of the ad-hoc wireless networks). The analysis in [8] is based on

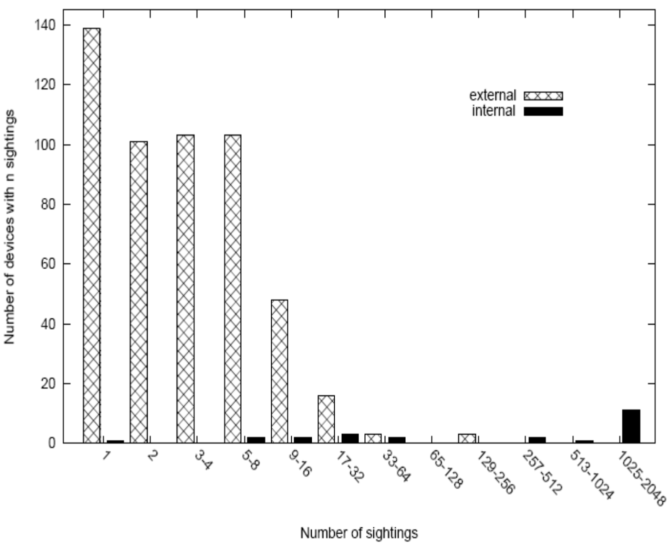

Figure 8: Distribution of the number of sightings by one device.

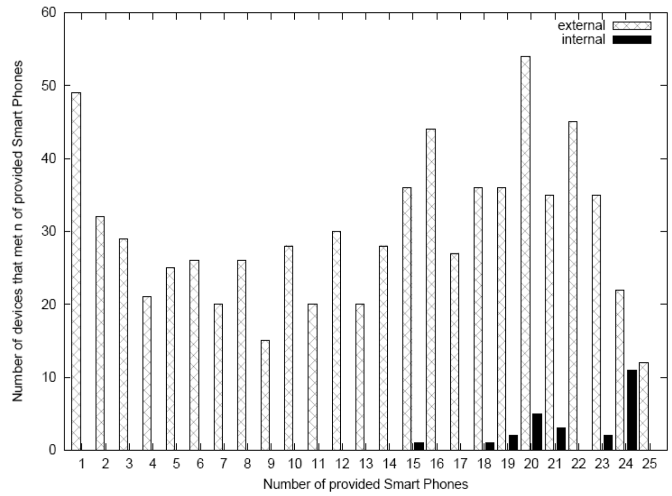

Figure 10: Distribution of the number of provided smart phones met by each device in the experiment.

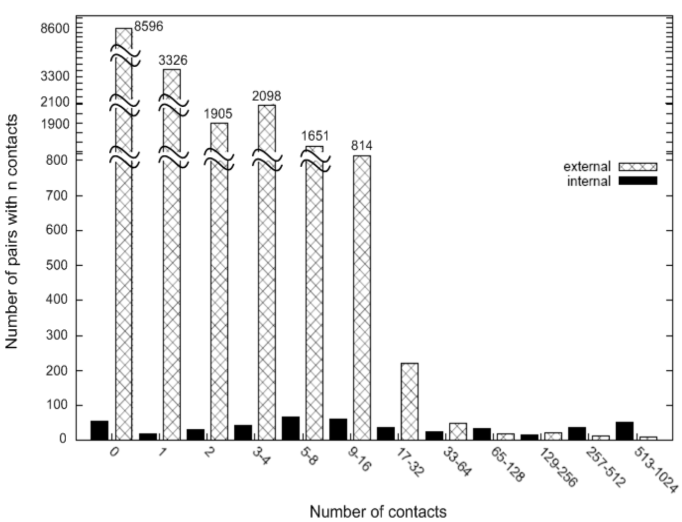

Figure 9: Distribution of the number of contacts between pairs of devices.

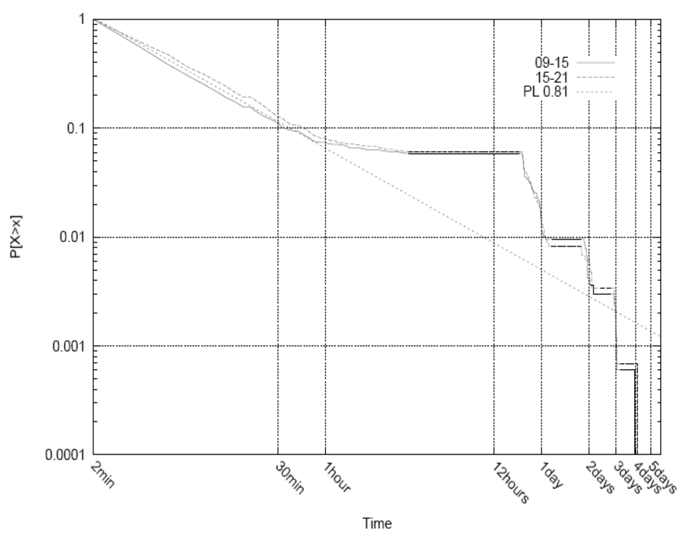

Figure 11: Distributions of inter-contact times during two working times only (9am-3pm and 3pm-9pm).

the assumptions that all nodes are identical and uniformly visit the entire network area according to an ergodic mobility model based on independent and identically distributed trajectories. From our previous observations these assumptions do not hold for some real life scenarios such as shopping malls (in particular the assumption that the mobility of each node uniformly covers the entire space over time, making all nodes basically indistinguishable from each other).

4.4 Influence of the Time of Day

In here we look at distributions of contacts over the working day. Employees in the shopping mall where we ran the experiment work from 9am till 9pm. A few of them close the shop from 1pm till 3pm to take a break or/and tidy the merchandise. We split the working time in to two intervals, from 9am to 3pm and from 3pm to 9pm, to see whether there were different contact distributions during the working time. Figure 11 shows the distributions of the inter-contact time for these six hours periods. It shows that the contact distribution has no visible time dependence during opening time of the shopping mall. As such, there is no evidence here for future forwarding algorithms for shopping mall environments to take into account temporal patterns.

5. CONCLUSION

Bluetooth technology offers several opportunities, including interoperability, scalability, low cost, voice/data compatibility, the formation of ad-hoc networks and low power consumption. Communication services that rely on this technology (and others like it) will strongly depend on human mobility characteristics.

We have presented real-world measurement results from the mobility of people in a shopping mall environment. Although the distinction of classes of mobility in practical situations within shopping malls is somewhat obvious, we have presented evidence and provided certain quantification degrees which identify their nature. Such measurements will be considered in the future to validate our empirical mobility models. These results are quite different from previous studies in workplace, university campus and conference scenarios, where power law coefficients approximate the inter-contact time distributions for longer periods of time. From our results, communication services might require specific networking protocols depending on the environment in which they are used. For a shopping mall network protocol we propose to exploit the three main entities' mobility patterns to route data: customers, shop employees and shopping mall employees (see Figure 2).

We have identified groups of people who exhibit higher power law coefficients but only for short time periods. The neighboring shopkeepers' distribution, (4) in Figure 4, reveals a PL with coefficient 1.30. This is significant in that using multiple intermediate relays may be sufficient for stateless forwarding algorithms to converge. Indeed, if the power law coefficient is located between 1 and 2 the algorithm introduced by [8] would exhibit infinite delay. Nonetheless, [1] has shown that it is possible to build a forwarding algorithm that achieves a bounded delay, using a number of duplicate copies of the packet.

Our results also show that inter-contact time between shopkeepers in a working day is typically small and contact durations are long which suggests that shopkeepers will be more reliable for forwarding data. The observed distributions suggest that forwarding to neighboring sellers and shop assistants might increase significantly the likelihood of timely contact. We believe that shopkeepers could form a mobile ad-hoc network backbone and the starting point from which to build wider networks in shopping mall environments. The identification of such groups of people could help greatly in forwarding data.

We have explored various characteristics of the collected data, from the sellers' point of view, which might be used to design improved forwarding algorithms. Firstly, when forwarding to neighboring shopkeepers the power law coefficient is more than 1; identifying neighboring shopkeepers would be a great help in forwarding data between two shop employees. Secondly, we observed that nodes do not behave the same; for example, sellers and some "customers" are much more active and see each other more often than others. Thirdly, we observed that forwarding algorithms do not appear to need to take into account broad temporal patterns in this environment.

In future work we intend to create mobility models which will accurately represent the observed human mobility patterns, and design and evaluate forwarding algorithms for different pervasive applications in this type of setting.

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