Opportunistic Wireless Communication in Theme Parks: A Study of Visitors Mobility

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ABSTRACT

Ad hoc networks of wireless devices carried by theme park visitors can be used to support variety of services. In such networks, links between the devices sporadically appear and disappear with the mobility of visitors. The network performance strongly depends on how often they encounter each other and for how long the contact opportunities last. In this paper, we study the mobility of visitors based on GPS traces collected in an entertainment theme park. We demonstrate and discuss the implications of the observed mobility on the efficiency of opportunistic message forwarding. On an example, we show how arrivals, departures, and spatial distribution of the park visitors affect the delay of a broadcast application.

Categories and Subject Descriptors

C.2.1 [**Computer–Communication Networks**]: Network Architecture and Design – *store and forward networks.*

General Terms

Measurement, Performance, Experimentation.

Keywords

Pedestrian mobility; GPS traces; delay-tolerant networking.

1. INTRODUCTION

For many wireless services, a continuous connectivity and end-to-end paths are not required. Unlike in infrastructure-based networks that provide full wireless coverage, in the so-called ad hoc networks wireless devices communicate directly when within each other's range. This communication mode is useful when infrastructure-based communication is costly or unavailable. When devices are mobile (e.g. carried by people), the ad hoc communication may experience occasional disruptions as links between devices appear and disappear with changes in the distance between the devices. Network applications and protocols need to be delay and disruption tolerant to benefit from such intermittent connectivity [1], [2]. This requires re-design of many protocols, especially routing protocols, since an end-to-end path between devices is not necessarily available throughout a communication session [3]. Therefore, messages are forwarded incrementally through the network in a store-carry-forward fashion when contact opportunities arise. Understanding the mobility of people is crucial because mobility determines the rate and the duration of contact opportunities. Human mobility, however, is not easy to characterize. For example, working-day, shopping, and campus mobility will all result in different encounter patterns. For many practical applications, routing/forwarding algorithms must target specific mobility scenarios, even if this limits the scope of their applicability.

This paper discusses the mobility of theme park visitors and the feasibility of opportunistic store-carry-forward communication in theme parks. A number of services offered to the visitors rely on wireless communication. However, it cannot be assumed that theme parks are fully covered with a wireless (e.g. Wi-Fi) infrastructure. Rolling out extensive infrastructure in a theme park is not an easy task: The largest parks are comparable in size with big cities. The Walt Disney World Resort in Florida spans over ~100 km^2, an area as large as San Francisco. Problems go beyond the obvious deployment and maintenance costs. For example, access points and antennas may be too visible to guests and, therefore, interfere with artistic intentions. For some theme park applications, spotty coverage might be tolerated if supported by store-carry-forward type of communication among visitors. Examples include distribution of park information (waiting times at different attractions, schedules of street parades and other performances), mobile advertising, collaborative localization, participatory sensing, polling/surveying, and multimedia sharing. Some of the application scenarios are described in Section 2. The applications may run on smart phones brought by visitors, or on customized devices handed out to the visitors. The latter could be optimized for opportunistic communication and park-specific applications and mobility scenarios.

In this paper, we study the mobility of park visitors based on a set of collected GPS traces in order to understand network requirements (minimum number and density of mobile devices and supporting infrastructure nodes) for opportunistic communication. On an example of epidemic broadcasting, we analyze the impact of hourly changes in visitors' mobility and density on the speed of content dissemination. Contact-related statistics, such as inter-any-contact time and mean square displacement, are extracted from the traces and their impact on the broadcasting performance is discussed. Theme park mobility could be of significant interest to the community because of the variety of delay-tolerant applications that can be deployed in the parks.

The remainder of this paper is organized as follows: Examples of theme park applications that may benefit from opportunistic communication are given in Section 2. GPS traces are described in Section 3. The performance of opportunistic broadcasting is studied in Section 4. Contact-related statistics are analyzed in Section 5. Section 6 concludes the paper.

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2. APLICATION SCENARIOS FOR DTNs
Some of the application scenarios for opportunistic communication in theme parks are described in the following.

2.1 Mobile Multiplayer Games
Mobile trans-reality games often rely on wireless technologies. Some of them can be supported with a gossip-based communication among players. A simple example is Insectopia [4], a game where players with mobile phones roam Bluetooth-rich environments searching for and catching a multitude of different "insects". Insect types are represented by unique Bluetooth signatures of the devices. In scavenger hunt games, team members often exchange information needed to complete their mission. Kim Possible [5] is a Disney game played in the Epcot theme park where players take roles of secret agents equipped with communication devices to fight evildoers' plans for global domination. Some games however do not revolve around technology and dedicated communication devices (i.e. mobile phones). In those games, gossip-based protocols can be used in real-world to mimic the way game characters (e.g. toys) would communicate with each other in a fantasy-world. For example, in a game designed for young children, a task could be to guide a toy character through missions during which the radio-enabled toy is empowered (e.g. with skills and knowledge) through contacts with other toys and objects in the park.

2.2 Mobile Advertising
Mobile advertising can be used in theme parks to inform visitors about special events (e.g. shows, street performances and fireworks) and shopping/dining opportunities. Advertisements may take form of electronic tips and discount coupons that are distributed wirelessly from a few infrastructure nodes and forwarded epidemically from a device to a device. The advertisements may target the entire park population (flooding), or a sub-population based on visitor's personal profile (multicasting) or current location (geocasting). Long waiting times at popular rides, which are common during summer vacations and holiday weekends, are one of the main reasons for visitors' dissatisfaction. Opportunistic communication can be used to inform visitors about waiting times at different rides so that they can organize their visit time in a best possible way. A network-enabled queue management application would allow visitors to request and obtain an electronic token for a ride on their mobile phones. The token would allow them to enter the ride at a particular time of the day without waiting.

2.3 Collaborative Localization
Opportunistic communication can be useful for guest localization. Many of the theme park applications require knowledge of guests' current location in the park. For example, in mobile games, the game engine often relies on the knowledge of players' positions to control the way in which the game unfolds (e.g. location-specific instructions/clues are send to players' devices). Geocasting of messages/advertisements and other types of location-based services also require mechanisms to localize visitors. Localization solutions can be power demanding. For example, frequent sampling of a GPS receiver would quickly drain the battery on most mobile phones. Besides, not necessarily all devices carried by visitors have the same localization capabilities. Allowing neighboring devices to share their location information via short range radio contacts would help reduce the energy cost and allow less capable devices to localize themselves more accurately. We refer to this type of localization as cooperative/collaborative localization. It relies on opportunistic broadcasting of the location information and smart data fusion algorithms to refine location estimates based on neighbors' locations obtained through the broadcasts.

3. GPS TRACES
Lack of large-scale measurements of human mobility is a big challenge for wireless research communities. It is difficult to organize large-scale measurement campaigns because of financial costs, logistical hurdles, privacy concerns, and government regulations [6]. Those who are able to overcome these problems, often lack incentives to perform such measurements.

Most previous studies of human mobility/encounter patterns for opportunistic communication rely on datasets that are limited in terms of the number of devices and/or time duration. Our dataset (910 GPS traces in total, out of which 825 are used in the analysis) is significantly larger than most datasets used in similar studies. For example, Bluetooth datasets used in [7]-[9], which contain records of discovered peers, are obtained in experiments with at most 100 devices. GPS datasets used in [10]-[13] contain up to 200 mobility traces (one of the dataset in [11] contains 15 GPS traces collected in The Walt Disney World Resort in Florida). Wi-Fi datasets used in [9], [14], [15], which contain SSIDs of access points visible by Wi-Fi devices, are much larger (up to several thousand laptops and PDAs). However, it is difficult to infer contact from such datasets. Typically, two Wi-Fi devices are assumed to be in contact as long as they see the same access point. This is a vague indicator that they may actually be able to connect to each other using short-range radios. Furthermore, some of the Wi-Fi devices were not carried by their owners at all times (e.g. laptops). Hence, observed contacts do not necessarily characterize human mobility.

Our GPS traces were collected as a part of a behavioral research study in the Epcot theme park in Florida. The layout of the park is shown in Fig. 1. The park covers an area of ~1.2 km^2 and receives more than 10 million visitors per years (~ 28000 per day on average, significantly more on weekends and holidays). It consists of two sections, Future World and World Showcase, with approximately 20 themed sub-areas/attractions. The Future World, which is closer to the park entrance, is more popular of the two. Often visitors need to wait in lines to enter attractions located in this section. The World Showcase is centered around a lake. A number of restaurants and stores are located throughout the park.

Over the course of five days, close to 200 smartphones were distributed each day to a total of 910 randomly-selected visitors. In case of groups/families only one of the members was selected. The phones were distributed between 8am and 1pm, and collected when the visitors were exiting the park. The phones ran an application that logged their GPS locations on average every two minutes when the satellite signals were available. In our study, we ignore the dates of the logs, as if all GPS traces were collected on the same day. This is needed to study networks where the number of devices is larger than the number of phones that were available for the experiment. The number of phones in the park at different times of the day is shown in Fig. 2. In addition to geo-coordinates, GPS accuracy was also logged. We discarded waypoints whose accuracy was worse than 25 meters. We also discarded tracks shorter than two hours or containing less than 50 waypoints. Results presented in the following sections are based on the remaining 825 out of 910 tracks. We interpolated the movements of visitors between the remaining waypoints assuming straight-line movements. The tracks may contain gaps, which correspond to the periods when visitors were indoors (e.g. in a building where

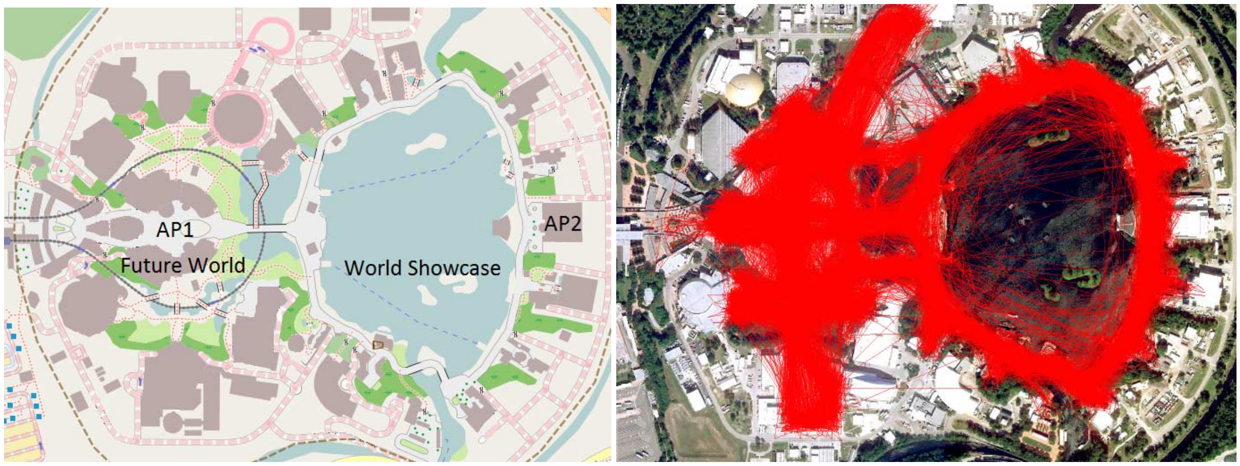

Figure 1: Left: The Epcot park consists of two major sections with approximately 20 themed sub-areas. Right: GPS trajectories overlayed on top of each other illustrate park space utilization.

GPS signal is not available). During such periods, we assume that visitors move slowly from the spot where the last waypoint was recorded before they entered the building to the spot where the first waypoint was recorded after they exited the building. Based on the tracks, a space utilization map is plotted in Fig.1 (right) to illustrate the size and the shape of the area in which visitors move.

4. OPPORTUNISTIC BROADCASTING

Some of the theme park applications are broadcast in nature. Here we investigate how mobility and density of devices affects the speed of opportunistic broadcasting based on the GPS traces. We evaluate the time needed to distribute a message to a certain target percentage of park visitors (e.g. 98% is a tentative target for one of the applications described in Section 2). The setup is as follows: a single infrastructure node (e.g. infostation, access point), labeled as AP1 in Fig. 1 (left), is located in the center of the Future World (later we consider adding AP2). This is one of the spots with the highest flux of visitors: almost all visitors pass by this spot when entering and leaving the park. The transmission range of the access point is 50 m. At time T, the access point starts broadcasting a message to the visitors within the range. The message spreads epidemically among visitors as they encounter each other. Radio aspects (attenuation, interference, energy consumption) and protocol details (device and content discovery, connection setup delay, content caching) are ignored. The only assumption is that the transmission range of mobile devices is 10 m, unless stated otherwise. When a device without the message enters the transmission range of the access point or of another mobile device that possesses the message, it obtains the message instantaneously. The purpose of this simple scenario is to estimate the lower bound on the broadcast dissemination delay for observed mobility and density of the devices, irrespective of wireless technology constraints. This delay might be hard to achieve in practical systems. However, it provides an indication of how delay-tolerant an application should be to benefit from opportunistic communication and what number of devices is needed to meet certain delay constraints. A similar setup has been evaluated in [16] using a much smaller set of mobility traces collected in an office building in a university campus.

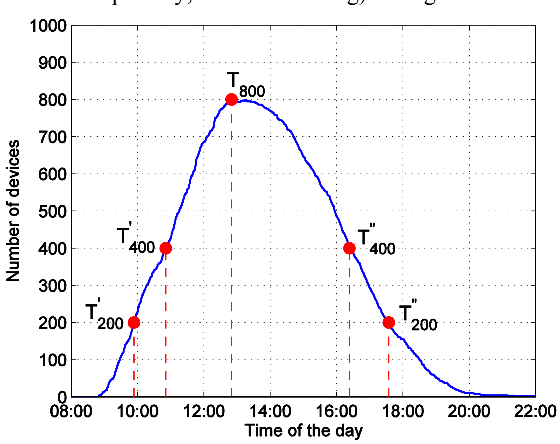

Figure 2. Number of phones in the park at different times of the day. Times when the number reaches 200, 400, and 800 are indicated.

As described in Section 3, the number of visitors with the phones that were in the park at different times of the day when the experiment was carried out is shown in Fig. 2 (we collapsed five days of experiments into a single day by ignoring dates in the GPS traces). The curve closely reflects the way in which the number of visitors in the park changes during a typical day. We assume that, if proprietary devices, such as electronic park guides, would be handed/rented out to the visitors, their number would follow a similar pattern. We assume that broadcasts are initiated at times when there are 200, 400, and 800 devices in the park (Fig. 2). There were two moments when the number of devices reached 200, one in the morning and one in the afternoon, denoted by T'_{200} and T''_{200}, respectively. Similarly, there were 400 devices in the park at T'_{400} and T''_{400}. At the peak of the day, denoted by T_{800}, the number of devices reached 800. The spatial distributions of devices at those moments are shown in Fig. 3. In the morning hours (T'_{200}, T'_{400}), there is a large inflow of visitors into the park, who tend to cram in the Future World section close to the entrance and the access point AP1. It takes several hours until visitors disperse throughout the park. In the late afternoon (T''_{400}, and T''_{200}), there is a large outflow of visitors. Hence, mobility patterns, which affect the efficiency of opportunistic broadcasting, depend strongly on the time of the day. The speed of content dissemination will be different at T'_{200} and T''_{200}, although the number of devices is the same. In the late afternoon, message is disseminated against the flow of crowd—visitors who obtain the content from the access point are likely to take the content out of the park very soon.

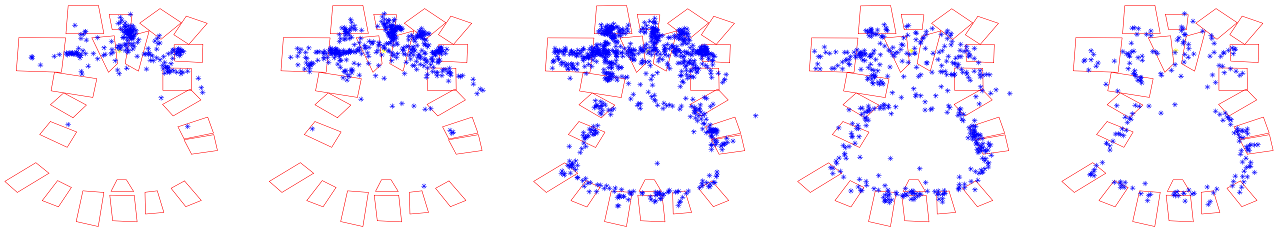

Figure 3. Spatial distribution of visitors with the devices at T'_{200}, T'_{400}, T_{800}, T''_{400}, and T''_{200} (from left to right).

The broadcast performance results are shown in Fig. 4 (left). The curves in the figure show the percentage of visitors in the park that possess the message as a function of time elapsed since the start of the broadcast (at T'_{200}, T'_{400}, T_{800}, T''_{400}, or T''_{200}). We stop the simulation when the possession reaches 98 % and we record the elapsed time ($\Delta T_{98\%}$) in Table 1. In the table, we also show the percentage of visitors that would have received the message by $\Delta T_{98\%}$ if peer-to-peer (P2P) forwarding was not used (hence, connecting to the access point was the only way to obtain the message). We report the following observations:

The time needed to broadly disseminate the message is in the order of tens of minutes. For example, it took 20 and 26 minutes, respectively, to deliver the message to 95 % and 98 % of the devices at T_{800}. At a typical peak hour there are 10000 to 15000 visitors in the Epcot. Therefore, the scenario with 800 devices assumes that 5 to 8 % of the visitors have the devices and run the application, which is a significant number (especially considering that a big proportion of visitors are toddlers). When the range of the devices increases from 10 m to 20 m (at the expense of increased energy consumption), the time to deliver the message to 98 % of devices decreases to 15 minutes, which is still prohibitively long for most applications. To further reduce the dissemination time, more access points are needed and/or the number of devices should be larger.

Apart from the number of devices, dissemination time depends strongly on the spatial distribution of the devices and their residual times in the park after they receive the message. This is obvious when comparing the results for broadcasts initiated at T'_{200} and T''_{200} (former happens in the morning hours while the latter is in the late afternoon). At T'_{200} almost all visitors are located in the Future World section of the park. 98 % of them obtained the message within 30 minutes. Contacts with the access point accounted for 53 % of delivered messages. To the contrary, at T''_{200}, visitors are spread throughout the park. It took 72 minutes to achieve 98 % possession. Contacts with the access point accounted for only 13 % of delivered messages. This illustrates the variety of performances that could be expected with the same number of devices, but at different times of the day. Furthermore, results in Fig. 4 (left) show that the message disseminates faster at T'_{200} than at T'_{400} and T_{800}. Hence, a larger number of devices does not guarantee better performance due to changes in spatial distribution and residual visit times.

We next study the effect of adding the second infrastructure node (AP2 in Fig. 1) on the speed of dissemination. Placing the node in the World Showcase may help reduce the broadcast delay in the afternoon hours, when many visitors are located in this section of the park, as shown in Fig. 3. As expected, the results in Fig. 4 (right) and in the last three columns of Table 1 show that AP2 does not contribute to the message spreading at T'_{200} and T'_{400}. At T_{800} and T''_{400}, the message disseminates somewhat faster compared to the previous setup, as indicate by the slope of the curves in Fig. 4 (left) and Fig. 4 (right). A significant speed-up is achieved at T''_{200} when visitors from the back of the park, where AP2 is located, start to spread the message as they move across the park towards the exit. However, the addition of AP2 has very little effect on the time needed to reach 98 % of devices, regardless of the time of the day. It is hard to deliver the message to the last few percent of visitors since they may be isolated from the rest (e.g. sitting on a boat in the middle of the lake). Another

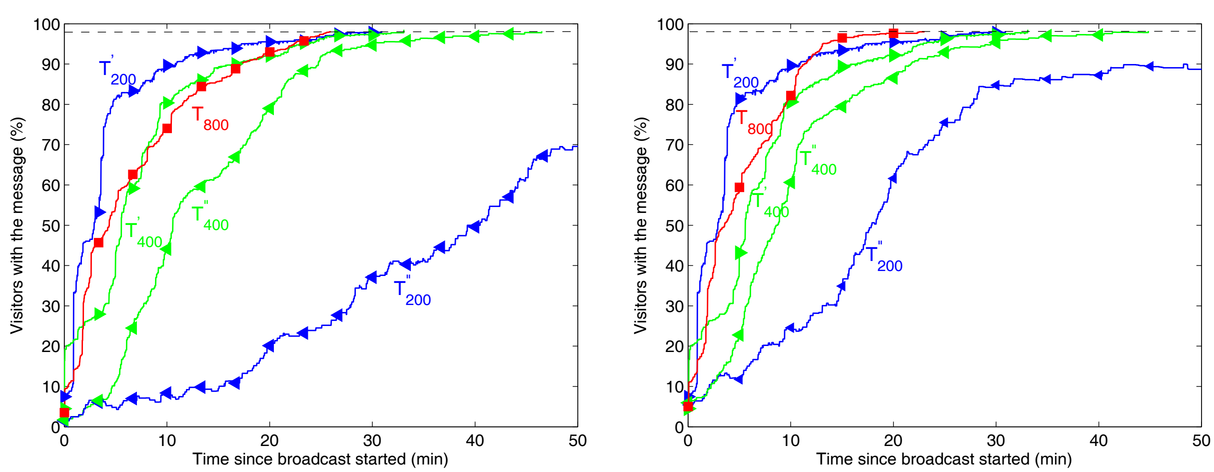

Figure 4. Percentage of visitors with the message as a function of time since a broadcast started. Broadcasts are initiated at T'_{200}, T'_{400}, T_{800}, T''_{400}, and T''_{200}. Left: With one access point (AP1). Right: With two access points (AP1 and AP2).

Table 1. Time $\Delta T_{98\%}$ needed to distribute the message to 98% of the devices and the percentage of devices that would receive the message by $\Delta T_{98\%}$ without P2P forwarding.

T	AP1			AP1 & AP2		
	$\Delta T_{98\%}$ (s)	AP + P2P	AP only	$\Delta T_{98\%}$ (s)	AP + P2P	AP only
T'_{200}	1855	98 %	53 %	1855	98 %	53 %
T'_{400}	1984	98 %	33 %	1984	98 %	33 %
T_{800}	1556	98 %	16 %	1380	98 %	20 %
T''_{400}	2790	98 %	21 %	2690	98 %	39 %
T''_{200}	4320	98 %	13 %	4240	98 %	36 %

reason is constant inflow/outflow of visitors to the park. We evaluated the effect of adding two more APs at the border between the Future World and the World Showcase sections of the park. The additional APs helped speed up the dissemination, but the "last few percent" problem remained. An alternative to increasing the infrastructure coverage (either by adding more APs or by increasing their range) is to enable mobile devices to adapt their range according to the rate of encounters, current dissemination level, and remaining battery power. This alternative is not explored in this paper.

5. ENCOUNTER STATISTICS

We analyze several contact-related statistics that are highly relevant for the performance of opportunistic content distribution (inter-any-contact time, mean square displacement, number of neighbors, and the rate of (new) contacts) and correlate them with the results of the previous section.

Inter-any-contact time (IACT) is the time elapsed between starts of two successive contacts of a device with other devices. IACT determines the frequency of contact opportunities and, therefore, it affects the speed of opportunistic broadcasting. It strongly depends on the devise density (i.e. time of the day). We observed IACTs in 30-minute intervals following T'_{200}, T'_{400}, T_{800}, T''_{400}, and T''_{200}. Their complementary cumulative distribution functions (CCDFs) are shown in Fig. 5 (left). The curve labeled as T'_{200} represents CCDF of IACTs observed in [T'_{200}, T'_{200}+30 min], for example. The distribution of IACTs is best described by the gamma distribution with the shape parameter between 0.6 and 0.7 depending on the time of the day. This is consistent with the results presented in [17], but contradicts the power-law distribution observed in [18]. The Bluetooth sighting traces analyzed in [18] may have failed to capture some contacts since neighbors were searched for every 120 s. Beside, the traces were collected in a conference environment with a lower degree of mobility compared to theme parks. Results in Fig. 5 (left) show that the average IACT corresponds well to the device density illustrated in Fig. 3. It decreases with the number of devices. For the same number of devices, it is shorter in the morning (e.g. at T'_{200}) than in the afternoon (e.g. at T''_{200}).

Beside the density, the number of contact opportunities depends on the level of mobility, which can be measured by the mean square displacement (MSD). Displacement measures how far away a mobile node is from its starting position after some time t. Let $P_\tau \in \mathbb{R}^2$ be the position of a node at time τ (e.g. in an x-y coordinate system). Mean square displacement after time t is given by $\mathrm{MSD}(t) \triangleq \mathbb{E}\{\|P_{\tau+t} - P_\tau\|^2\}$. $\mathrm{MSD}(t)$ increases with t, such that $\mathrm{MSD}(t) \sim t^\gamma$. The exponent γ indicates the speed of diffusion. For Brownian motion $\gamma = 1$. When $\gamma > 1$, the mobility is superdiffusive. For example, when a node moves on a straight line $\mathrm{MSD}(t) \sim t^2$, hence $\gamma = 2$. Nodes whose mobility exhibits stronger diffusion will cover larger area compared to nodes with weaker diffusion. As a consequence, they will encounter more new nodes. The speed of diffusion makes huge impact on the performance of forwarding algorithms [10].

We calculated the $\mathrm{MSD}(t)$ of each park visitor in a 30-minute interval following T (i.e. T'_{200}, T'_{400}, T_{800}, T''_{400}, and T''_{200}) by varying τ from T to $T + 30\,\mathrm{min} - t$. Fig. 5 (right) shows the average $\mathrm{MSD}(t)$ at different times of the day on a log-log scale. The initial slopes of the curves $\gamma > 1$ indicate that park visitors

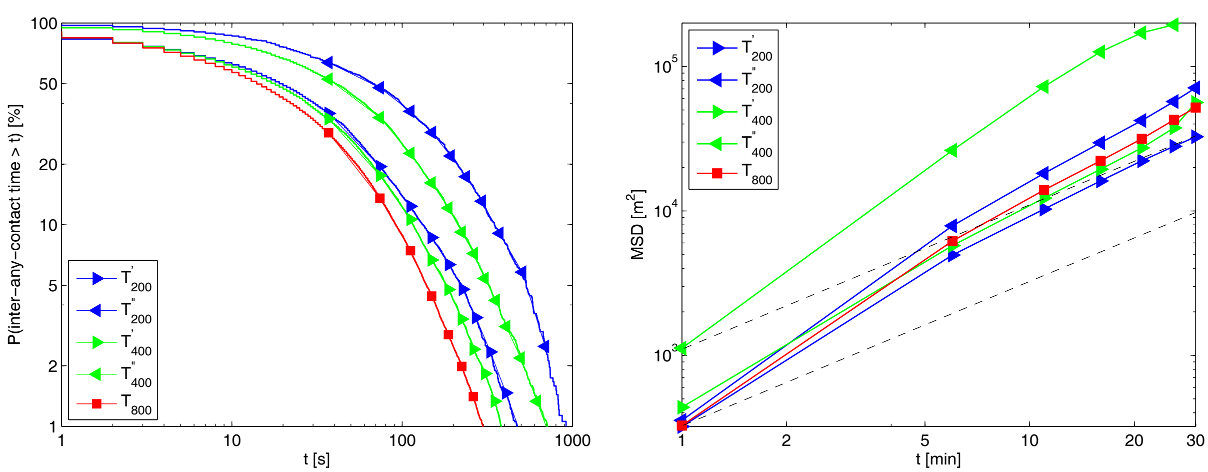

Figure 5. Left: CCDF of inter-any-contact times. Right: Mean square displacement (slope of the dashed lines is $\gamma = 1$).

Table 2. Number of neighbors and contacts.

T	T'_{200}	T'_{400}	T_{800}	T''_{400}	T''_{200}
# of neighbors	1.82	2.40	2.49	0.69	0.31
# of contacts [min^{-1}]	0.47	0.61	0.77	0.29	0.16
% of new contacts	85.4	86.8	88.0	90.7	89.7

exhibit superdiffusive behavior over an interval of ~10 minutes. This implies that spreading of the message injected in the network may quickly gain momentum. The figure shows that the MSD is larger in the afternoon (especially at T''_{400}) when visitors tend to move faster between the attractions to make the best use of the time before the park closes (it is not clear though why is MSD larger at T''_{400} than at T''_{200}). The larger MSD, however, did not result in faster message dissemination, as shown in Fig. 4. Higher mobility in the afternoon leads to wider dispersion of visitors and, therefore, fewer neighbors/contacts. This is obvious when comparing the average number of neighbors (devices within the range of 10 m) and contacts per minute at T'_{400} and T''_{400} (T'_{200} and T''_{200}) in Table 2. The table also shows that the percentage of new contacts is rather high. Hence, there are few repeated contact with the same devices within the 30-minute interval after T, which is consistent with the superdiffusive behavior observed in Fig. 5 (right).

The presented statistics describe encounters of individual nodes. In many practical scenarios, clustering of nodes (e.g. due to social grouping) and rate at which clusters split and merge also plays a significant role in content forwarding. A model that translates the split and merge rates to the stationary cluster size distribution is described in [19]. The distribution indicates to what extent a scenario provides partial multi-hop routes that can be used to complement opportunistic forwarding between clusters. It may have important implications for some of the theme park application scenarios. Epidemic broadcasting, however, leverages single-hop contact opportunities. Unfortunately, much of the social clustering information is lost in our GPS traces since, in case of groups, only one of the members was given a GPS device.

6. CONCLUSIONS

Intermittent connectivity could be useful for a number of theme park related applications if efficient routing/forwarding algorithms are designed. To be practical, the algorithms must target specific applications and mobility scenarios. We studied the mobility of park visitors based on a fairly large dataset of GPS traces. Using a broadcast application as an example, we showed the impact of hourly changes in the number of devices and their spatial distribution on the speed of content dissemination. We analyzed several contact-related statistics to interpret the observed performance. Our scenarios assume sparse deployment of infrastructure nodes to support the communication. Therefore, the density of mobile devices is crucial to reduce the delay of content delivery. Mobility models and simulations will be used to evaluate scenarios where the number of devices exceeds the number of available GPS traces. Our results suggest that generic mobility models are not sufficient. Targeted mobility models are needed in order to capture the non-stationarity in the number and spatial distribution of nodes. Therefore, we developed a tool to simulate the mobility of theme park visitors (see [20] for details). The tool can easily be adapted for scenarios where pedestrians exhibit similar mobility patters, such as trade shows, zoos, open-air museums, and multi-stage festivals.

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