

A Mobility Model for Pedestrian Content Distribution

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ABSTRACT

Mobile communication devices may be used for spreading multimedia data without support of an infrastructure. Such a scheme, where the data is carried by people walking around and relayed from device to device by means of short range radio, could potentially form a public content distribution system that spans vast urban areas. The transport mechanism is the flow of people and it can be studied but not engineered. The question addressed in this paper is how well pedestrian content distribution may work. We answer this question by modeling the mobility of people moving around in a city, constrained by a given topology. Our contributions are both the queuing analytic model that captures the flow of people and the results on the feasibility of pedestrian content distribution. Furthermore, we discuss possible extensions to the mobility model to capture speed-distance relations that emerge in dense crowds.

Categories and Subject Descriptors

C.2.1 [Network Architecture and Design]: Distributed networks, Network communications, Store and forward networks, Wireless communication. C.2.2 [Network Protocols]: Applications, Protocol architecture.

General Terms

Algorithms, Performance, Design, Experimentation.

Keywords

Delay-tolerant networks, broadcast, multicast, content distribution, queuing analysis, mobility modeling.

1. INTRODUCTION

Ubiquitous wireless coverage has often been promoted for providing continuous connectivity in mobile communications. Such coverage is alas hard, or at least uneconomical, to provide in reality. The work presented in this paper is based on the premise that continuous connectivity is not universally needed and that intermittent communication is useful for applications

characterized by a low degree of interactivity, e.g., broadcasting, paging, messaging, and data collection. We explore the performance of a communication mode that relies on mobile nodes which communicate with one another when they are within radio range and which carry the data onwards through their own movements. Hence, the mobility patterns of nodes affect the speed, throughput and reliability of the data forwarding. The application area addressed herein is the distribution of multimedia contents and we are primarily concerned with pedestrian mobility.

The setup is as follows. The mobile nodes may communicate over short-range radio, such as Bluetooth or WiFi. We assume a simple model of the physical layer in which nodes connect if they are within a transmission range Δ of one another. Interference, fading, power control and other data-link functions are not considered. The mobile nodes—which could be devices such as mobile phones, media players and cameras—may cache contents both for their users and for other mobile nodes. When two or more nodes get within transmission range, they will connect according to the hand-shaking protocol of the data link and will then start to exchange data. We assume that the contents are brought in by some of the mobile nodes, or that nodes receive the data when passing by an access point, depending on the case of study. Furthermore, the contents are provided in atomic units—mp3 files, still images, video clips, news items—that are meaningful to the application independently of one another. We assume that the storage in the mobile nodes does not restrict the performance and we do not consider the issue of power efficiency of the system. Our concern is with the performance of the content distribution: the spread of the contents, as well as the rate and length distribution of contacts. We have developed a detailed queuing-analytic model for people moving on a street and use it to study how well contents are distributed there. The model shows explicitly how the mobility and system parameters affect the performance. The model for a single street may be used to build a network of streets to model larger areas. This is shown in principle and with an example. The analytic results are compared to simulation results with good agreement. Both the model and the simulations capture topological restrictions of the mobility as well as the stochastic number of nodes in a region of interest.

The structure of the paper is as follows. We review related work in the next section and discuss similarities and differences of our contributions with those reported in the literature. The street model is introduced in Section 3 and the performance results for a single street are discussed in Section 4. The content distribution in a street and in a city area is addressed in Section 5. In Section 6 we discuss possible extensions to the street model. We conclude our findings in Section 7.

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2. RELATED WORK

We position our work with related works in two respects: the wireless content distribution, and mobility modeling.

2.1 Content distribution

There has been substantial work on peer-to-peer content distribution systems for the Internet. BitTorrent is a successful instance of such systems that post-facto has gained interest by the research community; see for instance [1]. It is based on a general family of gossip protocols [2]. Our system belongs to the general field of delay-tolerant networking [3]. The application of gossiping protocols to mobile communication has been proposed in, for instance, [4] – [7]. Multicast for delay-tolerant networks has been proposed in [8]. Our work assumes open user groups. The type of mobile content distribution system that we analyze is described in [9], [10].

2.2 Mobility modeling

Mobility has most frequently been studied by simulation where a fixed number of nodes move on a convex area, often a square or a circle [11]. The random waypoint model is notable owing to its popularity; its stationary distribution of nodes is provided in closed form in [12]. The random-trip model is a general mobility model that allows perfect simulation and general topologies [13]. Mobility-assisted routing for mobility in two-dimensions has been studied in [5], [14], [15].

There is precedence for using queuing models for mobility: The Markovian highway PALM model is used for dimensioning cellular telephony for cars on a highway [16]. The one-dimensional topology is also considered for ad hoc networks in [17]. This model assumes a fixed number of nodes moving on a finite line with reflections at the end. A more general one-dimensional model is presented in [18]. It allows the selection of destination, speed and pause times to be correlated. Our work is based on the mobile infostation model in [19]. We extend it by considering the boundary effects for finite street segments, the generalization to a grid of streets, and a wider set of performance issues.

The mobility parameters of our model may be obtained from measurements in urban areas. However, we have not found a suitable datasets for this in the extensive CRAWDAD and MobiLib databases [20], [21]. The time and/or space granularity of the measurements is too coarse for our scenarios; we study extreme cases of intermittency, where contacts on the order of few tens of seconds are used to exchange data chunks. Available traces are obtained in experiments where measuring nodes (PDAs/iMotes distributed to students or conference participants) typically search for contacts every two minutes. Traces with finer time resolution are available from experiments in infrastructure based WLANs, where measuring nodes record the IDs of reachable APs [22]. It is however impossible to extract accurate locations of nodes (and estimate contact rates and durations) from these traces. Most of measurement-based studies in the area of data forwarding in DTNs are focused on (mobility-assisted) unicast routing. Performance measures typically used in these works are inter-contact times for particular pairs of nodes and periods of re-appearance of a node at a particular location [23] – [26]. Due to the granularity problem, rough approximations had to be introduced to estimate these (e.g., to assume that two nodes are in contact if they are connected to the same AP). Besides, these are metrics for which useful statistics can be obtained even from

small-scale experiments with only few tens of mobile nodes. We are interested in the rate of contacts that a node establishes with *any* node interested in spreading the content, which largely depends on the *density* of nodes in the studied area. Available traces are however related to very specific scenarios and their validity is difficult to generalize. Some other works, which are more similar to ours in the sense that they consider single-hop content sharing, are focused only on “long-enough” contacts [27] when granularity of measurements is not a critical issue. In [28], authors propose a method to generate mobility simulation scenarios based on measured densities of pedestrians on streets. The method aims at capturing flow intensities at street endpoints rather than contact rates and durations.

3. THE STREET MODEL

We consider a scenario where nodes move on a two-way street segment and exchange data with other nodes in proximity. The street segment is such that the node arrivals and departures occur only at its endpoints, i.e. it is a segment of an actual street between two intersections. Nodes arrive at both endpoints, according to Poisson processes with parameters λ and λ' . The rationale for this assumption is that we consider people arriving independently from a large population. Besides, temporal correlation among the arrivals tends to improve the performance of the system, as we have shown in [29]. Since we are primarily concerned with the *achievable* performance, we consider Poisson arrivals to be representative scenario for our study.

The speed of the nodes are i.i.d. random variables with a probability density function $f_v(v)$ with the support $[V_{min}, V_{max}]$; $0 < V_{min} \leq V_{max} \leq \infty$. We assume that node encounters do not incur delay, i.e. nodes are bypassing each other freely, without lining up behind a node that moves slowly. The described scenario resembles the arrival and movement of pedestrians on a sidewalk that is wide enough to prevent collisions, but not wider than the transmission range of their mobile devices. We believe that this is realistic for low arrival rates of pedestrians to the street. From the viewpoint of the achievable performance, the continuous flow of people is the critical case since congestion/congregation points would incur longer contact times and thus facilitate the spread of the content. We describe a model that allows us to study the basic performance measures of a distribution system in this environment, such as:

- *Contact rate*: the number of contacts per second that the node makes while being in the street segment.
- *Contact duration*: the life-time of the contacts that the node makes.

In order to obtain a tractable model, we impose the following assumptions and limitations:

- Contacts with nodes in other street segments are not possible, meaning that all connections break at the endpoints.
- Nodes do not change speed or direction while in a street segment, but they may do so upon entering a new segment.

Suppose that an observer node moves in the street segment at a speed v_o (Fig. 1). Let $L \geq 2\Delta$ be the street length and Δ the transmission range of a node. We distinguish between three types of contacts that the observer node may make: with slow nodes ($v < v_o$) that it overtakes, with fast nodes ($v > v_o$) that are overtaking, and with counter-directed nodes that are bypassing the observer node. Since node arrivals to the street are Poisson, it is

easy to show that, for the each type, the number of contacts over an arbitrary time interval is also Poisson distributed, but with a time-dependent mean. Therefore, we model the observer node as an $M/G/\infty$ queue with three types of arrivals. The mean arrival rate to this observer queue is $\mu(v_o, t) = \mu_f(v_o, t) + \mu_s(v_o, t) + \mu_c(v_o, t)$, where μ_f , μ_s and μ_c are mean arrival rates for the fast, slow, and counter-directed nodes, respectively. If the speed distribution of nodes entering the street is uniform on $[V_{min}, V_{max}]$, it can be shown that the mean arrival rates are given by the expressions in Table 1.

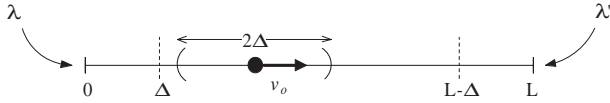


Fig. 1. An observer node with the transmission range Δ travels along a street segment of length L at speed v_o .

Let $N(t)$ denote the total number of nodes in the observer queue at time t and $N_f(t)$, $N_s(t)$ and $N_c(t)$ the numbers of fast, slow, and counter-directed nodes, respectively:

$$\Pr\{N(t) = n\} = \Pr\{N_f(t) + N_s(t) + N_c(t) = n\} \quad (1)$$

Note that $\Pr\{N(0) = 0\} \neq 0$ because all nodes within the first Δ meters of the street will be within the transmission range of the observer node at the moment when it enters the street. We assume that $N(0) = 0$ to simplify the presentation; *the complete model includes the non-zero initial state of the observer queue.*

When the observer travels at speed v_o , the probability of having i fast nodes within its transmission range can be written as:

$$\Pr\{N_f(v_o, t) = i\} = \sum_{j=i}^{\infty} \Pr\{N_f(\cdot) = i \mid A_f(v_o, t) = j\} \Pr\{A_f(\cdot) = j\} \quad (2)$$

where $A_f(v_o, t)$ is the arrival-counting process for fast nodes. Since the fast node arrivals constitute a non-homogeneous Poisson process with parameter $\mu_f(v_o, t)$, $A_f(v_o, t)$ is given by:

$$\Pr\{A_f(v_o, t) = j\} = \frac{m_f(v_o, t)^j}{j!} e^{-m_f(v_o, t)} \quad (3)$$

where $m_f(v_o, t) = \int_0^t \mu_f(v_o, \tau) d\tau$. The conditional probability for $N_f(v_o, t)$ given that $A_f(v_o, t) = j$ can be obtained as:

$$\Pr\{N_f(v_o, t) = i \mid A_f(v_o, t) = j\} = \binom{j}{i} q_f(v_o, t)^i (1 - q_f(v_o, t))^{j-i} \quad (4)$$

where $q_f(v_o, t)$ is the probability that a fast node, which has arrived at some time $0 \leq \tau \leq t$, is still in service (within the transmission range) at time t . This probability depends on the service time, which we denote by $s_f(v_o, v, \tau)$, as:

$$q_f(v_o, t) = \int_0^t \Pr\{s_f(v_o, v, \tau) > t - \tau \mid \text{fast node arrival at } \tau\} \times \Pr\{\text{fast node arrival at } \tau\} d\tau \quad (5)$$

Since the arrivals are Poisson, (5) becomes

$$q_f(v_o, t) = \frac{1}{m_f(v_o, t)} \int_0^t \Pr\{s_f(v_o, v, \tau) > t - \tau \mid v > v_o\} \mu_f(v_o, \tau) d\tau \quad (6)$$

On an infinitely long street (the highway model [19]) the service time would be $2\Delta/|v - v_o|$. However, on a finite street segment, the service time can be truncated because

- the observer node has just entered the street ($0 < \tau < \Delta/v_o$),
- the observer node is just about to exit the street ($(L - \Delta)/v_o < \tau < L/v_o$), or
- the node or the observer node exit the street before $t = \tau + 2\Delta/|v - v_o|$

Therefore, on a finite street, the service time $s_f(v_o, v, \tau)$ of a node depends on its speed v and the time τ when the contact had been established. It can be obtained by considering all possible ways in which a contact may end.

Probability $q_f(v_o, t)$ in (6) can be obtained from $s_f(v_o, v, \tau)$ and the conditional speed distribution of fast nodes that arrive to the observer queue $f_v(v \mid V > v_o)$. In the case of the uniform speed distribution, it is given by:

$$f_v(v \mid V > v_o) = \frac{1 - \frac{v_o}{v}}{V_{max} - v_o \left(1 + \ln \frac{V_{max}}{v_o}\right)}, \quad (7)$$

for $v_o < v \leq V_{max}$. Finally, from (2), (3), and (4):

$$\Pr\{N_f(v_o, t) = i\} = \frac{(m_f(v_o, t) q_f(v_o, t))^i}{i!} e^{-m_f(v_o, t) q_f(v_o, t)} \quad (8)$$

Hence, the number of fast nodes connected to the observer node is Poisson distributed with time-dependent mean $m_f(v_o, t) q_f(v_o, t)$. It is easy to show that the numbers of connections with slow and counter-directed nodes are also Poisson distributed with means

Table 1. Mean arrival rates at the observer queue for fast, slow, and counter-directed nodes (\leftarrow means “same as in the previous column”).

$\mu \backslash t$	$0 < t \leq \frac{\Delta}{v_o}$	$\frac{\Delta}{v_o} \leq t < \frac{L - \Delta}{v_o}$	$\frac{L - \Delta}{v_o} \leq t < \frac{L}{v_o}$
$\mu_f(v_o, t)$	$\frac{\lambda}{V_{max} - V_{min}} (V_{max} - v_o)$	$\frac{\lambda}{V_{max} - V_{min}} \left(V_{max} - v_o \left(\ln \frac{V_{max}}{v_o} + 1 \right) \right)$	\leftarrow
$\mu_s(v_o, t)$	$\frac{\lambda}{V_{max} - V_{min}} v_o \ln \frac{v_o}{V_{min}}$	$\frac{\lambda}{V_{max} - V_{min}} \left(V_{min} + v_o \left(\ln \frac{v_o}{V_{min}} - 1 \right) \right)$	0
$\mu_c(v_o, t)$	$\frac{\lambda'}{V_{max} - V_{min}} \left(V_{max} - V_{min} + v_o \ln \frac{V_{max}}{V_{min}} \right)$	\leftarrow	\leftarrow

$m_s(v_o, t)q_s(v_o, t)$ and $m_c(v_o, t)q_c(v_o, t)$, respectively. Therefore,

$$\Pr\{N(v_o, t) = n\} = \frac{\rho(v_o, t)^n}{n!} e^{-\rho(v_o, t)}, \quad (9)$$

where $\rho(v_o, t) = m_f q_f + m_s q_s + m_c q_c$. The probability that the observer node is connected (to at least one node) at time t is given by:

$$\Pr\{N(v_o, t) \neq 0\} = 1 - e^{-\rho(v_o, t)} \quad (10)$$

Average contact rate can be obtained from the node arrival rates given in Table 1:

$$\frac{1}{(V_{\max} - V_{\min})} \frac{1}{L} \int_{V_{\min}}^{V_{\max}} \int_0^{L/v_o} \mu(v_o, t) dt dv_o \quad (13)$$

The tail distribution of the contact durations, $\bar{F}_T(t) = P(T > t)$, is also of interest because it gives us the percentage of useful contact (we omit the derivation for brevity).

4. PERFORMANCE RESULTS

In this section, we show performance results from the street model and compare them with results from the simulator described next.

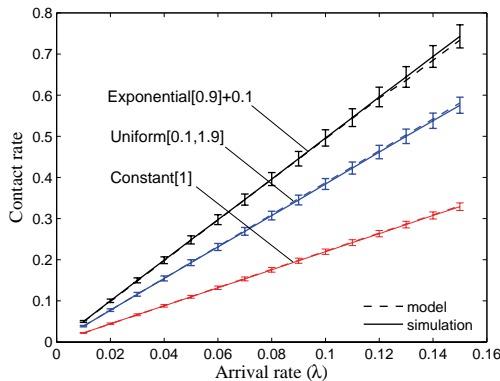
4.1 Simulations

We have built a simulation model of pedestrian content distribution using the Omnet++ [30] discrete event simulator. In the simulator, we attach a node generator to the street endpoints. Each generated node independently selects a random speed from an arbitrary but known probability distribution. The node then traverses the street at the constant speed. Whenever the distance between two nodes is less than or equal to the transmission range Δ they are connected and can communicate with each other. For each node, we record the contact rate and the contact duration. We introduce a warm-up period in our simulation runs to minimize the effect of the initial transient. We conduct 10 runs where in each run we collect statistics from 1000 nodes.

4.2 Street model

We present performance results from the analytical and simulation models for a street of length $L = 100$ m, transmission range $\Delta = 10$ m and symmetric Poisson arrival rates $\lambda = \lambda'$.

Fig. 2 (left) shows the effect of the speed distribution on the



contact rate. Results obtained both from the model and from the simulations are shown. We consider three different speed distributions, all with the same mean of 1 m/s but with different variance: a constant speed, a uniform distribution with the support $[0.1, 0.9]$ m/s, and an exponential distribution with mean 0.9 m/s that is shifted by 0.1 to have the same lower bound and mean as for the Uniform $[0.1, 1.9]$ distribution. We see that the contact rate increases with the arrival rate and with the variance of the speed distribution. The increase with the arrival rate is linear ($\mu(v_o, t)$ in (13) is a linear function of $\lambda = \lambda'$).

The contact duration is a random variable T whose tail distribution $\bar{F}_T(t_{\min}) = P(T > t_{\min})$ is plotted in Fig. 2 (right) for two different speed distributions. Here t_{\min} is the minimum required contact duration, e.g. the connection setup time. Contacts that are shorter than t_{\min} are considered useless for content distribution. The setup time is one of a few parameters that can be engineered in the system and it is therefore a key performance issue to minimize t_{\min} . The shape of the tail distribution for constant speed is due to the fact that contacts in the forward direction last for the whole length of the street, while those in the opposite direction last for Δ/v s, when the node speed is v .

5. CONTENT DISTRIBUTION

In this section, we show how the street model can be used to study content distribution in a street segment and how the results can be extended to a topology represented by a grid of streets, which is typical for an urban area.

5.1 Content distribution in a street segment

We consider a simple scenario where content (e.g. a short text message) spreads epidemically among nodes. We assume that every contact longer than t_{\min} results in successful spreading of the content. Let p_0 and q_L be the percentages of nodes that bring contents when they arrive to the near and far ends of a street segment of length L (Fig. 3). Our objective is to determine the spatial distribution of the content $p(x)$ in the forward and $q(x)$ in the opposite direction, and particularly the percentages p_L and q_0 of nodes that will possess the content when they exit the street segment. In a grid of streets, which can be built by concatenating multiple street segments, inputs (p_0, q_L) and outputs (p_L, q_0) of a street segment become outputs, respectively, inputs of neighboring segments. This allows us to study the content distributions in a city area using a simple recursive algorithm.

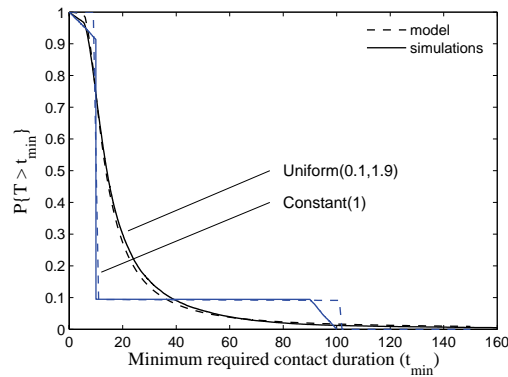


Fig. 2. Average contact rate (left) for various speed distributions as a function of the arrival rate of nodes. Tail distribution of contact durations (right) for Constant[1] and Uniform[0.1,1.9] speed distributions.

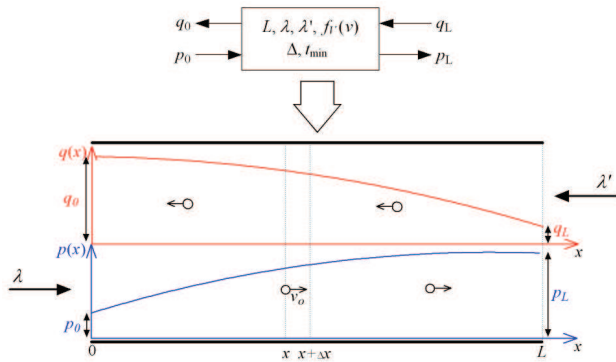


Fig. 3. Content distribution on a street segment. The pedestrians enter with average rates λ and λ' .

We again use the notion of an observer node to find the content possession probabilities $p(x)$ and $q(x)$. The probability that a random observer, which moves in the forward direction, possesses the content at $x + \Delta x$ is

$$p(x + \Delta x) = p(x) + (1 - p(x))\theta(x), \quad (14)$$

where $\theta(x)$ is the probability that it meets and connects to a node with the content on $[x, x + \Delta x]$. Since the arrivals of fast, slow, and counter-directed nodes to the observer node are Poisson distributed with means μ_f , μ_s , and μ_c , respectively, probability of meeting at least one of the nodes with the content and establishing a contact that will last for at least $T > t_{\min}$ seconds is given by:

$$\theta(v_o, x) = 1 - e^{-\left(\mu_f(v_o, x/v_o)\bar{F}_{T_f}(t_{\min})p(x) + \mu_s(v_o, x/v_o)\bar{F}_{T_s}(t_{\min})p(x) + \mu_c(v_o, x/v_o)\bar{F}_{T_c}(t_{\min})q(x)\right)\frac{\Delta x}{v_o}} \times e^{-\left(\mu_c(v_o, x/v_o)\bar{F}_{T_c}(t_{\min})q(x)\right)\frac{\Delta x}{v_o}}, \quad (15)$$

given that the observer node moves with the speed v_o . Since $1 - e^{-\varepsilon} \approx \varepsilon$ for $\varepsilon \ll 1$:

$$\theta(v_o, x) = \left(\mu_f(v_o, x/v_o)\bar{F}_{T_f}(t_{\min})p(x) + \mu_s(v_o, x/v_o)\bar{F}_{T_s}(t_{\min})p(x) + \mu_c(v_o, x/v_o)\bar{F}_{T_c}(t_{\min})q(x)\right)\frac{\Delta x}{v_o}. \quad (16)$$

Probability $\theta(x)$ is obtained by averaging (16) over the speed of the observer node v_o and it can be written:

$$\theta(x) = (p(x)a(x) + q(x)b(x))\Delta x, \quad (17)$$

where:

$$a(x) = \frac{1}{V_{\max} - V_{\min}} \int_{V_{\min}}^{V_{\max}} \frac{1}{v_o} (\mu_f(v_o, x/v_o)\bar{F}_{T_f}(t_{\min}) + \mu_s(v_o, x/v_o)\bar{F}_{T_s}(t_{\min})) dv_o$$

$$b(x) = \frac{1}{V_{\max} - V_{\min}} \int_{V_{\min}}^{V_{\max}} \frac{1}{v_o} \mu_c(v_o, x/v_o)\bar{F}_{T_c}(t_{\min}) dv_o \quad (18)$$

assuming that v_o is uniformly distributed on $[V_{\min}, V_{\max}]$. After substituting (17) in (14) and letting $\Delta x \rightarrow 0$, the following differential equation is obtained:

$$p'(x) = (1 - p(x))(p(x)a(x) + q(x)b(x)), \quad (19)$$

where $p'(x)$ denotes the derivative of $p(x)$ with respect to x . Similarly for $q(x)$:

$$q'(x) = -(1 - q(x))(p(x)c(x) + q(x)d(x)), \quad (20)$$

where $c(x) = b(x)$ and $d(x) = a(x)$ if $\lambda = \lambda'$. When $L \gg \Delta$, μ_f , μ_s , μ_c become independent of x (they are given by the middle column of Table 1. in that case) and therefore $a(x)$, $b(x)$, $c(x)$, and $d(x)$ become constants. Then the system of differential equations given by (19)-(20) can be easily solved with the initial conditions $p(0) = p_0$ and $q(L) = q_L$. This assumption is not essential, but it greatly simplifies the solution to (19)-(20). It slightly overestimates the possession probabilities $p(x)$ and $q(x)$ by ignoring the boundary effects in the first and the last Δ meters of the street.

We show the content dispersion in the forward direction $p(x)$ for various speed distributions and minimum required contact durations in Fig. 4 (left). Due to the symmetry, content dispersion in the opposite direction is simply $q(x) = p(L - x)$ and it is not shown in the figure. Our scenario assumes the following values of the street parameters: $\Delta = 10$ m, $\lambda = \lambda' = 0.02$, and $p_0 = q_L = 5\%$. It can be observed from Fig. 4 (left) that the content spreads more efficiently when the variance of the nodal speed distribution increases. As shown in Section IV, the larger speed variance results in a larger number of contacts and longer contact durations, which facilitate the content distribution. In the case of minimum contact duration $t_{\min} = 10$ s, the content spreads very efficiently in spite of the very low arrival rate (one arrival per 50 s on average) and low percentages of nodes bringing the content to the street ends ($p_0 = q_L = 5\%$). However, the content distribution can be hampered by the requirements on the minimum contact duration, as in the case when $t_{\min} = 15$ s, which is also shown in Fig. 4 (left). It is therefore important to minimize the connection setup time in order to reduce the required contact duration.

In Fig. 4 (right), we vary the percentage p_0 of forward nodes that arrive with the content. We assume that nodes traveling in the opposite direction do not bring the content to the street ($q_L = 0$). The scenario assumes the following street parameters: $\Delta = 10$ m, $t_{\min} = 10$ s, and $V \sim \text{Uniform}[0.5, 1.5]$. We may notice that, if the arrival rates of nodes are sufficiently large ($\lambda = \lambda' = 0.02$), the content dispersion depends very little on the arrival rate of the nodes with the content. The reason is that the content becomes resident in the street as long as there are new nodes to which the content can be passed before a node disappears from the street. For $\lambda = 0.02$ and $p_0 = 1\%$, the content arrives to the street every 83 minutes on average, yet every node that passes through this street will obtain the content with the probability of 85%. Remark that the 83 minutes widely exceeds the sojourn time of the nodes in the street. Even though this analytic model does not provide the means to analyze non-recurrent content arrivals, such as when a single node injects the content to the street, these results indicate that the content will be still present in the street long after the node departs, even in that case. This effect becomes more pronounced as the length of the street segment increases. When the arrival rates decrease, the content dispersion becomes less efficient and the ability of the street to act as a virtual storage disappears, which is illustrated in Fig. 4 (right) for the case when $\lambda = \lambda' = 0.01$. The critical arrival rate, for which the

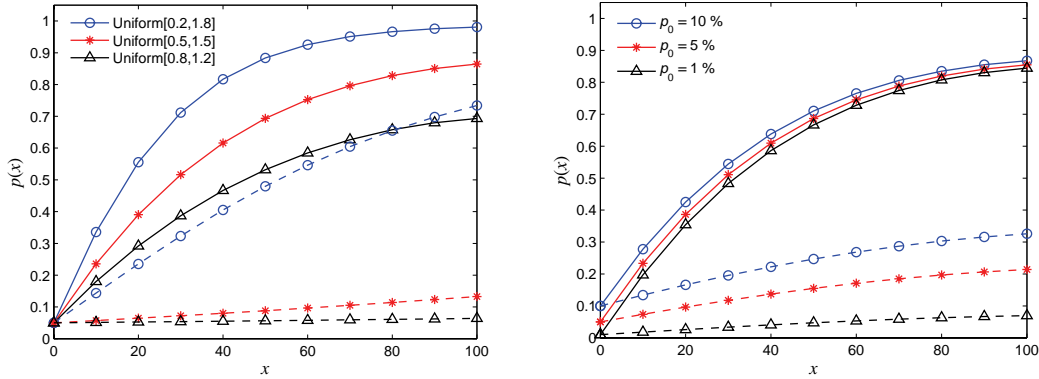


Fig. 4. Left: content dispersion for $t_{\min} = 10$ s (solid) and $t_{\min} = 15$ s (dashed) for various speed distributions and $\lambda = \lambda' = 0.02$ s⁻¹. Right: content dispersion for $\lambda = \lambda' = 0.02$ s⁻¹ (solid) and $\lambda = \lambda' = 0.01$ s⁻¹ (dashed) for various percentages p_0 of forward nodes that arrive with the content and uniform speed distribution on [0.5, 1.5].

dispersion performance becomes significantly affected by p_0 , depends on the variance of the nodal speed distribution.

5.2 Content distribution in an urban area

Based on the street model described in the previous section, we evaluate the efficiency of mobility-assisted content distribution on a topology shown in Fig. 5 (left). The equivalent grid consists of 29 street segments whose lengths vary between 20 m and 200 m. There are 12 passages that connect this area to the outside world: we assume that the arrival rates to the passages are $\lambda_i = \lambda$, $i = 1, \dots, 12$. Upon arriving at an intersection, nodes continue to move on the same street (if possible) with probability 0.5 or turn to other adjoining streets with equal probabilities (the alternative of choosing among all the routes with equal probability extends the sojourn times of the nodes in the area and hence shows better performance; it does not otherwise affect the results). Nodes with the content constitute p_{in} percents of the nodes that arrive to the first street (hence, the content arrival rate is λp_{in}); it is marked in Fig. 5 (middle). The source of the content could be, for example, an access point located close to the first street segment. The performance metric of interest is *dispersion*, which represents the percentage of nodes in the area that possess the content in the steady state.

To illustrate the spatial spreading of the content, we assume the following parameters in our model: uniformly distributed nodal

speeds in [0.5, 1.5], $\Delta = 10$ m, $t_{\min} = 20$ s, $\lambda = 0.05$, and $p_{in} = 5\%$. The dispersion for this case is 77.5 %; the spatial distribution of the content is shown in Fig. 5 (middle). The content distribution is fairly efficient: there are no indications that the percentage of users with the content depends on the distance from the source of the content.

Besides the variance of the speed distribution, the minimum required contact duration t_{\min} has the largest impact on the system performance. Its effect on the content dispersion for various arrival rates is shown in Fig. 5 (right). It confirms that critical cases are when the arrival rate is very low. The tail distribution of the contact duration $\bar{F}_T(t_{\min})$ affects the dispersion through the coefficients of differential equations (18) and (19), and it is a function of Δ/t_{\min} . Since extending the range of mobile devices Δ is coupled with many problems, such as the increased interference and power consumption, minimum required contact duration t_{\min} is the system parameter that is most likely to be engineered to improve the performance. In that respect, several issues can be addressed, including the segmentation of the contents into atomic units of optimal size and, as mentioned before, the time-efficiency of service discovery.

We also conducted a set of simulations, which indicate that the model gives a fairly good estimate of the content dispersion. These results are reported in [29].

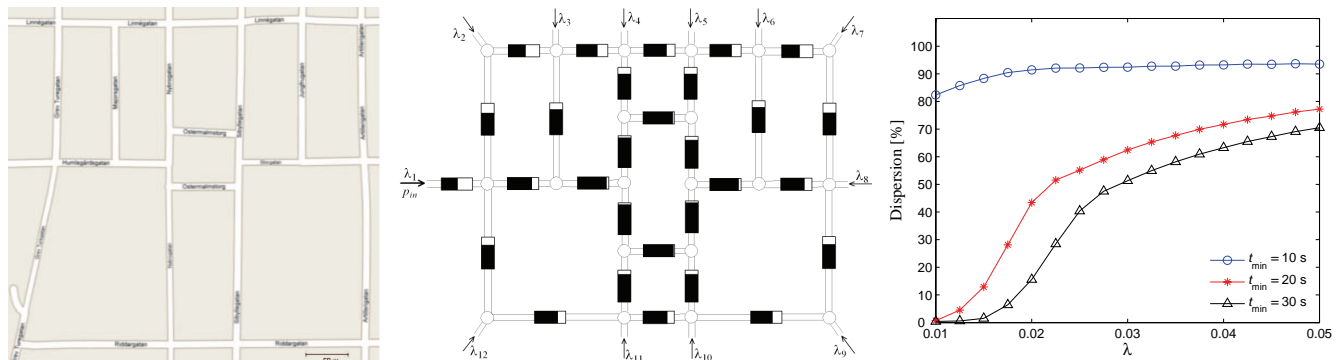


Fig. 5. A part of Stockholm's downtown area (left) and the spatial distribution of the content in a corresponding network of street segments (middle). Darkened areas denote the percentages of nodes with the content in the steady state. Right: Effect of t_{\min} on content dispersion for various arrival rates ($p_{in} = 5\%$, $V \sim U[0.5, 1.5]$, $\lambda = 0.02$ s⁻¹, $\Delta = 10$ m, $t_{\min} = 20$ s).

6. PEDESTRIAN INTERACTION

In the envisioned network, pedestrians carry the data onwards through their own movements and therefore their mobility patterns affect the speed, throughput and reliability of the data forwarding. Realistic mobility modeling is vital for the evaluation of such networks. So far we assumed that moving nodes do not interact with surrounding nodes. Walking behavior of a person is however very dependent on the actions of its immediate neighbors. For instance, a person slowing down in front is likely to cause others to slow down or to change direction. This type of interaction among pedestrians will affect the rate and the duration of contact opportunities.

Although the street model presented in Section 3 does not provide a faithful representation of pedestrian mobility, it gives a valuable insight into various system parameters and how they affect the content distribution. The assumption that pedestrians do not interact and choose their speeds independently of one another is somewhat justified for low arrival rates, which were in the focus of our study. However, the obtained results are optimistic in the assumption that all pedestrians in the observed area are participating in content delivery. The actual densities of pedestrians that are needed to facilitate the spreading depend on the penetration level of the service, the popularity of the content, soliciting, caching, and relaying protocols, etc. It is likely that needed densities are such that the assumption of uncorrelated speeds does not hold. Therefore, we are seeking to extend the mobility model to include the interaction between pedestrians. Our objective is to obtain a model that faithfully captures contact rates and contact length distributions for some common-case scenarios of urban mobility. The following sections contain an outlook of possible future work.

6.1 Extensions to the street model: social forces

The interaction between pedestrians may be attributed to social forces described by Helbing et al. [31]. The social forces reflect the intentions of a pedestrian not to collide with other people and obstacles. In response to these forces pedestrians accelerate or decelerate as if they were subjects to external forces. The following forces are defined in the model:

(i) If his motion is not disturbed, pedestrian i will walk with a certain preferred velocity \bar{v}_i^0 . The deviation of the actual velocity \bar{v}_i from his preferred velocity would create the driving force $\vec{f}_d(i) = (\bar{v}_i^0 - \bar{v}_i) / \tau_i$, where τ_i is the “acceleration time”. The driving force creates a tendency to approach \bar{v}_i^0 .

(ii) A pedestrian tends to keep a certain distance from other pedestrians. Approaching another person too closely results in social repulsion. The repulsive force is a monotonic decreasing function of the distance between two pedestrians $d_{i,j}$, which may take the following form: $\vec{f}_r(i,j) = A e^{-d_{i,j}/B} \bar{n}_{i,j}$, where A and B are constants and $\bar{n}_{i,j}$ is a unit vector pointing from node i to node j .

An expression similar to the previous one holds for a force between a pedestrian and a wall or other type of a static obstacle. Additional forces can be defined, such as attraction forces that drive a pedestrian towards points of interest. These forces are responsible for the formation of pedestrian groups.

Assume for the moment a one-directional street segment of length L . Let $x_i(t)$ and $v_i(t)$ denote the position and the speed of node i at time t . Headway distance for node $i \geq 1$ is $s_i(t) = x_{i-1}(t) - x_i(t)$.

The velocity change for node i can be described as

$$\frac{dv_i}{dt} = \frac{v_o - v_i}{\tau} + f_r(s_i) + \xi_i(t)$$

where v_o is the preferred velocity in this street, τ is the “acceleration time”, $f_r(s_i)$ is the repulsive interaction between nodes i and $i-1$, and ξ_i is Gaussian white noise. Interaction potential $U(s_i)$ is defined as $f_r(s_i) = -U'(s_i)$. The equation of motion can be reformulated in terms of a Fokker-Planck equation that describes the time evolution of the joint probability density function $P(v_1, \dots, v_n, s_1, \dots, s_n)$. If we assume that the headway distances and velocities are uncorrelated $\langle s_i(t) v_j(t) \rangle = 0$ for all i and j , then $P(\cdot)$ has the stationary solution

$$P(v_1, \dots, v_n, s_1, \dots, s_n) = \prod_{i=1}^n g(s_i) h(v_i),$$

where $g(s)$ and $h(v)$ are probability density distributions of headway distances and velocities, respectively [32]. The repulsive interaction force $f_r(s)$ can be determined from the observed distance distribution $g(s)$ and the speed variance. It has been shown in [32] that, in the case of no interaction among pedestrians ($U(s) = 0$), the headway distances are exponentially distributed $g(s) \propto A e^{-Bs}$ as in the case of Poisson arrivals to the street. Hence, the classical queuing theory can be used to analyze the system, which is the approach that we followed in [29]. Certain analogies with the queuing systems can also be drawn for $U(s) \neq 0$.

Non-trivial extensions are needed to adapt the model to pedestrian content distribution scenarios. The model assumes that nodes are ordered on a street according to their indexes and not allowed to overtake each other. Therefore, it is better suited to describe the movement of vehicles on a single-lane street than pedestrians on a sidewalk. We wish to consider bi-directional flow of people on a sidewalk that contains a number of virtual lanes. The number of lanes depends on the width of the sidewalk and the personal space requirements of pedestrians. A lane can be allocated to the traffic in either direction depending on flow intensities. These assumptions are based on the observations that people tend to create lanes when they walk in a constrained space. In an extended model, the interaction potential and the probability of overtake would depend on the occupancy of neighboring lanes. Our plan is to use the model to study the content distribution in more complex topologies, e.g. in a grid of streets. In addition to the walking model, appropriate route choice models need to be defined to describe how people navigate intersections. We intend to verify our models with the help of state-of-the-art pedestrian mobility simulators used in traffic engineering and urban planning.

7. CONCLUSION

We have considered mobility-assisted content dissemination to an arbitrarily large group of pedestrian nodes with short-range radio connectivity. The service provides content distribution even if ubiquitous coverage is not feasible, and it offers a new ad hoc distribution mode for contents that originate from the mobile nodes. We developed a detailed analytical model to study the connectivity properties of street mobility at low arrival rates of pedestrian, which is the critical case for the system. The analytic results are compared to simulation results with good agreement. The model is extended to a network of streets to model larger

areas. We focus on areas characterized by low user density, where people usually do not congregate or swarm. The reported results give an insight into various system parameters and how they affect the content distribution. We have found that the content spreads with high efficiency in a large number of common-case scenarios. We will hence continue to evaluate the system by considering speed-distance relations that emerge when people try not to collide with each other in a busy street. These relations directly affect the contact rate and the contact length distribution, and therefore, the efficiency of contact dissemination.

8. REFERENCES

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