Floating information with stationary nodes

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***Abstract*—In the Floating Content application, mobile nodes collectively store and disseminate messages relevant to a certain area by using the principles of opportunistic networking. The system operates in best effort fashion relying solely on the nodes located in the area of interest, which is referred to as the *anchor zone* of the message. Past work has focused on mobility models, where the nodes are constantly moving and the messages are exchanged "on-the-fly". In this paper, we consider the case, where messages can be exchanged only when two nodes are stationary within each others' transmission range. Our objective is to characterize when the information *floats*, that is, when it is likely to remain available for long periods of time. We find that there exists a certain threshold for the mean node degree, which we refer to as the *permanence threshold*, above which the expected lifetime of the information increases very rapidly (in a finite system) or the information becomes permanent (in an infinite system). This threshold is about 1.3 for the basic case (a single stop per visit), which is clearly below the percolation threshold of about 4.5. Additional stops within the zone improve the situation further.**

I. Introduction

Several interesting spatial stochastic phenomena can be identified in the context of (mobile) wireless networks. One can study, e.g., the capacity of the network [1], [2], different aspects of connectivity [3], [4], channel assignment [5], spatial reuse [6], routing [7], [8], [9], [10], and a spatial distribution of mobile nodes under different mobility patterns [11], [12].

Percolation theory offers one powerful tool to this end. Basically, it states that once the node density is sufficiently high, a gigantic component (a connected component of the network) emerges almost surely, which spans across the given area. The numerical value for the percolation threshold of disks is about $\phi_c \approx 0.6763$ [13], [14], which corresponds to the average node degree of about 4.5 (assuming the Boolean connectivity model). Above this threshold, connectivity increases rapidly and a larger network forms. Conversely, under this threshold a network comprises only small isolated islands, and, e.g., mobility is required to deliver messages in DTN fashion.

In this paper, instead of end-to-end communication, we are interested in *storing* some information in a given area relying solely on the cooperation between mobile nodes, which arrive and depart dynamically. This leads to another quantity, referred to as the criticality threshold for the permanence of information (or the *permanence threshold* for short), above which the expected lifetime of the information increases very rapidly in a finite system. In an infinite system, the information is preserved indefinitely long.

The motivation for studying the permanence of information in this setting comes from the Floating Content application, which was introduced in [15]. In the Floating Content, mobile nodes collectively store a message at a certain area, e.g., a park or a square, which is referred to as the *anchor zone*. More specifically, whenever node A meets another node B within an anchor zone of some message that only A has, it transmits the message to B. Outside the anchor zone the nodes (are free to) delete the message. Therefore, the information is bound to eventually disappear due to the stochastic fluctuations. In practice, each message also has some expiration time. This type of information dissemination scheme can be motivated as follows: i) it is robust as it does not rely on any fixed infrastructure, ii) it has favorable privacy properties (anonymity), iii) spam is restricted as the content distribution is bounded to a given anchor zone. For more details on Floating Content, we refer to [15], [16], [17]. Other similar concepts have also been proposed, see, e.g., Digital Graffiti [18], Hovering Information [19], and Ad hoc Podcasting [20].

Past work [17], [16], [21] has focused on models, where the nodes are constantly moving and the exchange of messages occurs "on-the-fly". Here we consider the other extreme, where messages are exchanged only when two nodes are stationary and within each other's transmission range. In this case, the system's capability to store information depends solely on one dimensionless quantity, the mean node degree which should be above the permanence threshold. First we give analytical approximations for this. Then, by means of extensive simulations, we find that the numerical value for the permanence threshold is approximately 1.3, which is clearly below the percolation threshold of about 4.5.

The paper is organized as follows. In Section II, we introduce the model. Analytical results are given in Section III, and Section IV contains the numerical experiments. Section V concludes the paper.

II. Model

We consider a situation where nodes arrive to anchor zone $\mathcal{A}$ according to a Poisson process with rate λ. The initial location is uniformly and independently distributed on $\mathcal{A}$. The neighborhood is defined by a fixed transmission range d, i.e., a node can communicate (directly) only with those nodes that are within a distance of d from it (i.e., the so-called Boolean or Gilbert model [22]). Each node having the information transmits it to nodes not having it within their transmission range (cf. epidemic spreading).

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Each node remains still for a random duration of T_1. After that, a node leaves the area with probability $(1-p)$, and otherwise, with probability p, it moves *instantly* to a new randomly chosen location. Information is preserved during a move within the anchor zone. A node remains stationary in the new location again for a random time duration of T_2. This repeats until a node departs. The time durations T_i, referred to as the *stopping times*, are assumed to be i.i.d., $T_i \sim T$. Letting k denote the mean number of stationary periods, $k = 1/(1-p)$, the mean duration of a visit is simply

$$\mathrm{E}[T^*] = k\,\mathrm{E}[T] = \frac{\mathrm{E}[T]}{1-p}.$$

We further assume sufficiently long T_i that contact durations can be neglected (i.e., instant transmissions).

Consequently, at a random time instant, we have a *random geometric graph* [23] (or a random plane graph [22]) located in the anchor zone $\mathcal{A}$. However, instead of the static properties such as connectivity, we are interested in gaining insight to the transient behavior of the information carrying nodes in an anchor zone. As our objective is to characterize when information can be sustained, we assume that initially all nodes in the anchor zone are tagged, i.e., they carry the information. Alternatively, one could also study the probability that a system, e.g., with a single information carrying node survives a given time duration.

III. Analysis

The mean number of stationary nodes is [24],

$$\mathrm{E}[N] = \lambda \cdot \frac{\mathrm{E}[T]}{1-p},$$

which corresponds to the average node density of $n = \mathrm{E}[N]/|\mathcal{A}|$. If $n\,\pi\,d^2 \gg 1$, then nodes cover a considerable part of $\mathcal{A}$ (cf. percolation). Similarly, if transmission range d is so large that every node in the anchor zone $\mathcal{A}$ hears each other, the spatial dimension vanishes and one ends up with an M/G/∞ system. We are interested in scenarios where the information barely *floats*. In particular, we assume that d is small compared to anchor zone, the mean population is large $\mathrm{E}[N] \gg 1$, and our objective is to find for which node density n the information remains available for long periods of time.

The assumptions of instant mobility and instant transmissions mean that at any time instant, each node in the anchor zone belongs to some cluster (connected-component), all members of which either have or do not have the information. If the node density is high and the network *percolates* within the anchor zone, i.e., a large portion of nodes belong to the same component, then it is likely that this component has the information and the floating occurs.

A. Heuristic approximations for the permanence threshold

Here we consider the process in the special case $p = 0$, i.e., each node exits the anchor zone immediately after the stopping time. For simplicity, we further assume exponentially distributed stopping times, $T \sim \mathrm{Exp}(\mu)$ and that $\mathcal{A}$ is an r-disk. The objective is to derive simple approximations for the criticality threshold of the system. Possible boundary effects are neglected. We first consider the lower bound.

Instead of considering the original system, let us consider a system where clusters possessing the information are immediately divided to isolated nodes. In particular, we move the corresponding nodes to such locations that the distance to the nearest neighbor is at least $2d$. The modified system can be expected to have a better chances of upholding the information available as it maximizes the "information covered area" at each step. Thus its criticality threshold serves as a heuristic lower bound for the actual system. Suppose that there are m information carrying isolated nodes in $\mathcal{A}$ (on average). The birth-rate of new information carrying nodes

$$m \cdot \lambda \frac{\pi d^2}{\pi r^2} = m \cdot \lambda (d/r)^2.$$

At the same time, the number of information carrying nodes decreases at death-rate $m \cdot \mu$. In order to avoid extinction,

$$\lambda (d/r)^2 \geq \mu \quad \Rightarrow \quad n\,\pi\,d^2 \geq 1, \tag{1}$$

where the left-hand side quantity is equal to $\mathrm{E}[\nu]$, i.e., the condition says that the mean number of neighbors $\mathrm{E}[\nu]$ should be higher than one. Eq. (1) can be seen as a necessary criticality condition for the special case $p = 0$. In the derivation, we have neglected the fact that nodes having the information may overlap. Hence, the condition (1) is a lower bound for the permanence threshold.

The effect of the overlapping can be taken into account approximately as follows. The above assumed that the total area where new contacts are possible is the sum of m complete circles with radius d, i.e., the nodes are alone. Instead, let us assume that at the criticality all nodes that have the information are paired with another node. The total mean area B that two connected nodes cover (i.e., the mean area covered by a given node with one randomly located neighbor inside the transmission radius d) can be easily derived and gives $B = d^2(\pi + 3\sqrt{3}/4)$. There are $m/2$ such connected pairs inside the area, and by similar reasoning as above, the criticality condition reads

$$\lambda \frac{m}{2} \frac{B}{\pi r^2} \geq m\mu \quad \Rightarrow \quad n\,\pi\,d^2 \geq \frac{8\pi}{4\pi + 3\sqrt{3}} \approx 1.41. \tag{2}$$

The above can be expected to be a conservative estimate for the criticality threshold as in the actual system the total area covered by the information carrying nodes also contains nodes that are alone, as well as those that are pairs (and even higher order connected components, but with decreasing probability).

The approach can be developed further. Let m_1 and m_2 denote the number of isolated and paired nodes possessing the information, respectively. Neglecting the higher size clusters, and assuming stationarity,[1] one can write

$$\lambda \frac{\pi\,d^2}{\pi\,r^2} \cdot m_1 \approx \mu \cdot m_2,$$

which gives $m_2 \approx n\,\pi\,d^2 \cdot m_1$. The left-hand side is the birth-rate of size 2 clusters, and the right-hand side the

[1] In reality, a finite system is in transient towards extinction.

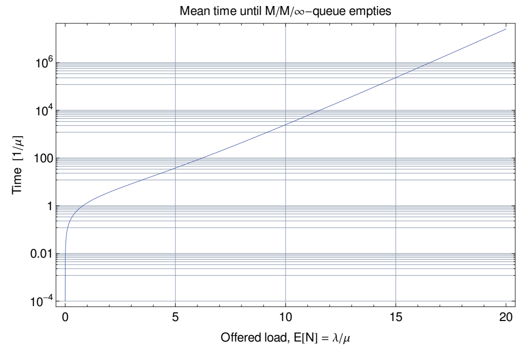

Fig. 1. Mean time until an M/M/∞ system becomes empty when initially in stationarity.

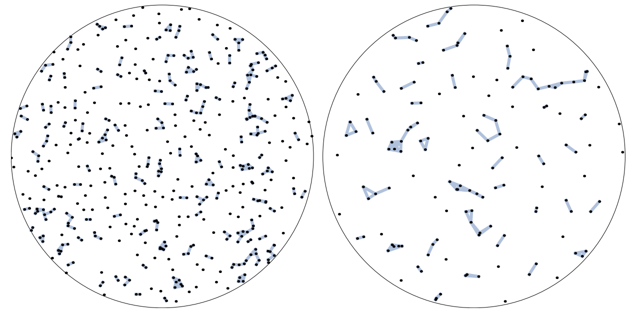

Fig. 2. Sample realizations from a stationary distribution: (left) $d = 0.05$ and 500 nodes on unit disk, (right) $d = 0.10$ and 150 nodes on unit disk. Active links are illustrated with gray lines.

corresponding death-rate. The birth-rate of the total population would be

$$\lambda(m_1 \cdot (d/r)^2 + m_2 \cdot (1 + 3\sqrt{3}/(4\pi))(d/r)^2) = \left(n\,\pi\, d^2 + \left(\frac{4\pi + 3\sqrt{3}}{8\pi}\right) (n\,\pi\, d^2)^2 \right) \cdot m_1 \mu,$$

and the death-rate similarly, $(m_1 + m_2)\mu = (1 + n\,\pi\, d^2) \cdot m_1\mu$. Combining these two then gives

$$n\,\pi\, d^2 \geq 2\sqrt{\frac{2\pi}{4\pi + 3\sqrt{3}}} \approx 1.19. \qquad (3)$$

For $n\,\pi\, d^2 = 1$, a node belongs to a cluster of size 3 or more with a probability of about 0.39, while for $n\,\pi\, d^2 = 1.3$ the same probability is about 0.52. In other words, the fraction of larger clusters is not negligible and it is not clear how accurate these, somewhat crude, estimates actually are. However, in the numerical section, we show that the latter two, albeit heuristic, indeed predict the criticality threshold of the fluid limit surprisingly accurately.

B. Asymptotic results for $p = 0$

For the basic model with $p = 0$, two straightforward limits are readily available. Suppose first that $d = 0$, i.e., a situation where information *is not exchanged*. In this case, the survival until time t depends solely on the sojourn time of the initial N nodes. If at time $t = 0$, all existing nodes have the information, then $N \sim \mathrm{Poisson}(\lambda/\mu)$, and the CDF of the lifetime is

$$\mathrm{P}\{T_{\mathrm{life}} < t\} = \sum_{i=0}^{\infty} \frac{a}{i!}\, e^{-a} \cdot (1 - e^{-\mu t})^i = e^{-a e^{-\mu t}},$$

where $a{=}\lambda/\mu$. For the median, $\mathrm{P}\{T_{\mathrm{life}} < t\} = 1/2$, we obtain

$$\mathrm{E}[N] = \lambda/\mu = \ln 2 \cdot e^{\mu t}.$$

For example, $\mu = 1$ and $t = 10$ gives $\lambda \approx 15268$. This means that for any fixed t, there exists a finite arrival rate $\lambda_{\min}$ that achieves the median lifetime of t, and thus $n\pi d^2$ converges to zero when d tends 0 as $n \leq (\lambda_{\min}/\mu)/(\pi r^2)$. This is illustrated later in Figure 5 of the numerical examples.

Alternatively, when d is sufficiently large so that all nodes are within each others' transmission range, the system reduces to a classical M/M/∞ queue. With the same initialization (at time $t = 0$, all existing nodes obtain the information), the lifetime is equivalent to the time from a random time instant until the M/M/∞ system becomes empty. Hence, the mean lifetime $\mathrm{E}[T_{\mathrm{life}}]$ is,

$$\mathrm{E}[T_{\mathrm{life}}] = (1 - e^{-\lambda/\mu}) \cdot \mathrm{E}[R^*],$$

where $(1 - e^{-\lambda/\mu})$ is the probability that system has at least one customer, and $\mathrm{E}[R^*]$ denotes the mean residual duration of the busy period on condition that the system is not empty (as seen by a random observer). The memoryless property of Markov process facilitates an efficient recursive computation of $\mathrm{E}[R^*]$. Figure 1 illustrates the mean lifetime for systems with a sufficiently large d as a function of $\mathrm{E}[N] = \lambda/\mu$ on logarithmic scale. We observe that even with a modest mean population sizes, the resulting performance in terms of mean lifetime is very good, as expected.

IV. Numerical Experiments

A. Unit disk

Parameters in the first numerical examples are the following:

- Anchor zone is a unit disk with radius $r = 1$.
- Poisson arrivals with rate λ.
- Exponentially distributed stopping times with mean $1/\mu$.
- Initially, $N_0 \sim \mathrm{Poisson}(\lambda/\mu)$ nodes are uniformly distributed in $\mathcal{A}$, who all carry the information. Their remaining stopping times obey the same exponential distribution with mean $1/\mu$ (i.e., the stationary distribution).

1) First look: In the first experiments, we use fixed transmission ranges: $d = 0.05, 0.1$. Two sample realizations of the nodes and the corresponding active links are illustrated in Figure 2. In the left figure, $d = 0.05$ and there are 500 nodes so that $n\,\pi\, d^2 = 1.25$, while on the right figure the transmission range is $d = 0.1$ and the number of nodes is 150, yielding $n\,\pi\, d^2 = 1.5$. We can observe that both networks are indeed rather sparse and multi-hop communication is not feasible.

Figure 3 depicts the simulation results with the transmission range of $d = 0.1$. On x-axis is the arrival rate λ, and the y-axis corresponds to the lifetime (time until extinction). The three curves correspond to 25%, 50% and 75% quartiles. Mobility parameters (μ, p) are varied, $(\mu, p) \in$

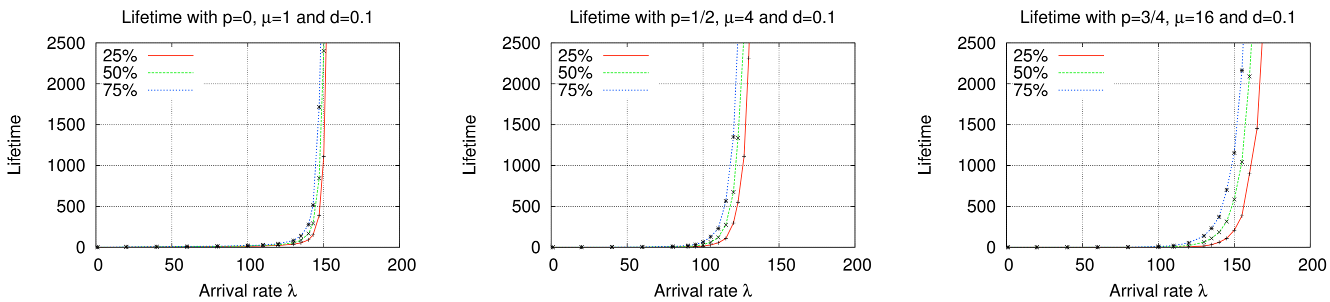

Fig. 3. Quartiles, $\mathrm{P}\{T_{\text{life}} < t\} = x$ for $x = 0.25$, 0.5 and 0.75 on unit disk with transmission range $d = 0.1$.

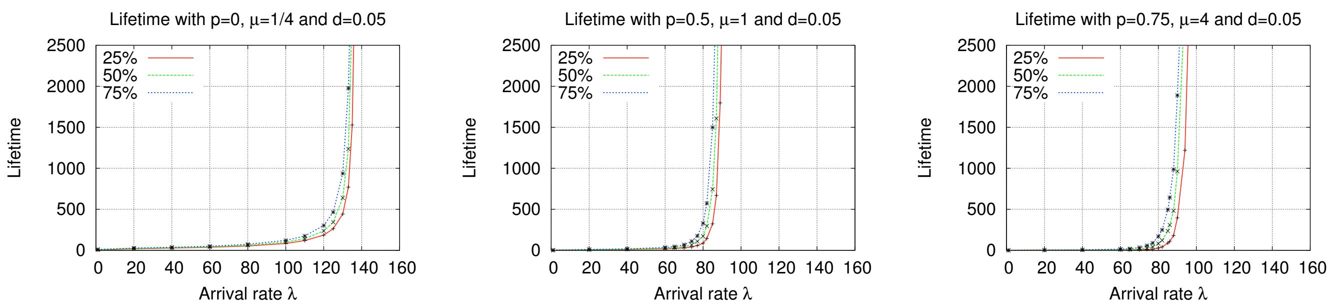

Fig. 4. Quartiles, $\mathrm{P}\{T_{\text{life}} < t\} = x$ for $x = 0.25$, 0.5 and 0.75 on unit disk with transmission range $d = 0.05$.

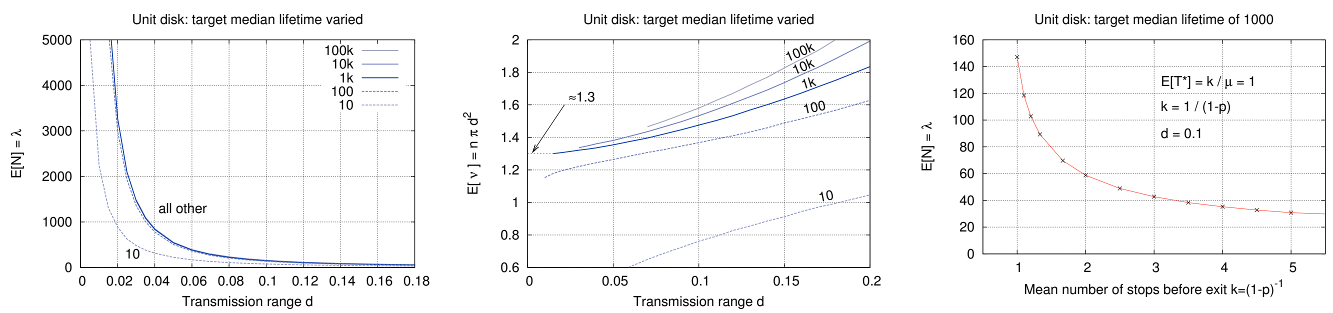

Fig. 5. Sufficient mean population (left) and node degree (middle) as a function of transmission range d in unit disk for $p = 0$. The cases $t \geq 1000$ are indistinguishable in left figure, but not in the middle. Right figure illustrates the sufficient mean population as a function of the mean number of stops $k = 1/(1-p)$ for unit disk with target lifetime of 1000, transmission range of $d = 0.1$ and $\mathrm{E}[T^*] = k/\mu = 1$.

$\{(1,0),(4,1/2),(16,3/4)\}$, so that the mean sojourn time $\mathrm{E}[T^*]$ decreases, $\mathrm{E}[T^*] = 1, 1/2, 1/4$. Recall also that the mean population is $\mathrm{E}[N] = \lambda\,\mathrm{E}[T^*]$. Next we consider the two times shorter transmission range of $d = 0.05$. In order to compensate for the smaller range, the mean stop times are quadrupled, and the mobility parameters are $(\mu, p) \in \{(1/4,0),(1,1/2),(4,3/4)\}$, so that the mean sojourn times are $\mathrm{E}[T^*] = 4, 2, 1$. The numerical results are depicted in Figure 4. General observation is that in all six cases there seems to be a certain threshold above which the (expected) lifetime skyrockets.

2) Criticality condition: Figure 5 (left) illustrates the mean number of nodes needed to achieve a median lifetime of 10, 100, 1k, 10k and 100k for $p = 0$. As $d \to 0$, the required mean population increases very rapidly. The three cases, 1k, 10k and 100k, are indistinguishable in this scale.

In Figure 5 (middle), on the y-axis is the mean node degree $\mathrm{E}[\gamma] = n\,\pi\,d^2$ (cf. Eqs. (1)–(3)). The five curves correspond to the same target median lifetimes. Based on curves with $t \geq 1\mathrm{k}$, there appears to be some value at the fluid limit when $d \to 0$ above which the target lifetime t can be arbitrary. This critical mean node degree is *the criticality threshold for the permanence of information*, and it appears to be about 1.3. When the mean node degree is above this threshold, the (expected) lifetime of a large system tends to infinity.

From Figure 5 (middle) one can also observe what happens when the target lifetime is small, e.g., $t = 10$. As discussed earlier, all curves with a fixed t eventually converge to 0, which is clearly visible here. We, however, are interested in what happens when both $t \to \infty$ and $d \to 0$.

3) Several stops: Figure 5 (right) illustrates how the several stops per visit with $p > 0$ improve the performance. Target

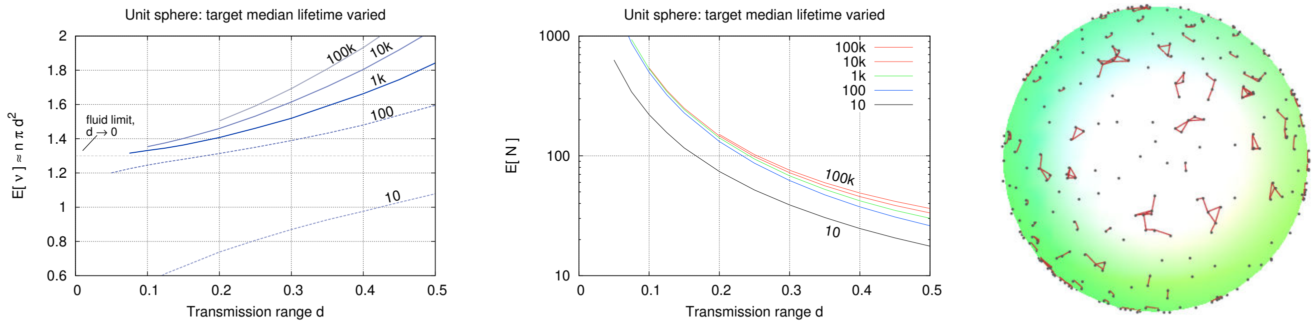

Fig. 6. Results in unit sphere for $p = 0$ are similar to the results with unit disk. The distances (i.e., transmission range d) are measured along the surface. Right figure illustrates a sample realization with $d = 0.1$ and 500 nodes.

median lifetime is 1000, mean visit time is $k/\mu = 1$ and transmission range is $d = 0.1$. Note that when k (or d) tends to ∞, the spatial dimension disappears and one obtains an M/G/∞ queue.

B. Unit Sphere

Let us next illustrate the same process on unit sphere, i.e., the nodes arrive according to a Poisson process with rate λ and the sojourn time at each location is exponentially distributed with mean $1/\mu$. The locations are uniformly and independently distributed on the unit sphere. The distances are measured along the surface of the sphere, which affects the coverage of a given transmission range d,

$$A(d) = 2\pi r^2(1 - \cos\frac{d}{r}),$$

which for $d = \pi r$ gives the full coverage $A(\pi r) = 4\pi r^2$. For a small d/r, $A(d) \approx \pi d^2$. The average node degree is

$$\mathrm{E}[\nu] = n\,A(d) = \frac{\lambda k}{\mu} \cdot \frac{1 - \cos(d/r)}{2r^2},$$

and for small d/r we have

$$\mathrm{E}[\nu] \approx \frac{\lambda k}{\mu} \cdot \frac{d^2}{4r^2} = n\,\pi\,d^2.$$

The motivation for sphere topology is the fact that there are no borders and thus it allows one to identify possible border effects (which we neglected in the analysis of the unit disk). When d is small, the situation is no different from the internal points of unit disk.

Figure 6 illustrates the simulation results for target median lifetimes of $t = 10$, 100, 1k, 10k, and 100k. Again, we can see that for $t \gg 1$, the criticality threshold appears to converge to some value about $n\,\pi\,d^2 \approx 1.3$. In general, the results are very similar to those of the unit disk. Note, however, that here the surface area is four times larger and thus the same transmission range d covers a smaller proportion of the total area than in the previous case.

Figure 7 illustrates how several stops with $p > 0$ improve the situation. Here we have chosen $p = 1/2$ and $p = 2/3$, which correspond to the average stops of $k = 2$ and $k = 3$, respectively. The mean stop time $1/\mu$ was adjusted accordingly so that $k/\mu = 1$. We observe a significant drop in the required average node degree between $k = 1$ and $k = 2$, whereas the change from $k = 2$ to $k = 3$ is smaller. Point $d = \pi$ on the right graph corresponds to the transmission range that covers the whole sphere and the system reduces to an M/G/∞ queue, as mentioned earlier.

C. Comparison with a direct mobility model

In [17], we have considered an elementary mobility model where each node moves directly with a constant speed to a random direction in an infinite plane. The anchor zone is again assumed to be a disk with radius r. By using a fluid approximation that is valid when $d \ll r$, we obtained for the criticality condition

$$n\,d\,r > 0.407. \tag{4}$$

The above model has some fundamental differences to the stationary model considered in this paper. In particular, here we explicitly assume that nodes are capable of transmission only when they are still at some location. In contrast, in [17], all transmissions occur on-the-fly. Moreover, for the direct mobility model of [17], one also obtains a conditional probability distribution for a node observed at $\mathbf{r}$ and moving in direction θ having the information. For example, for nodes entering the anchor zone this probability is zero.

Consequently, also the criticality conditions (cf. (1)–(3) vs. (4)) *have different forms*. In particular, the transmission range is a more critical parameter for stationary nodes than when nodes move directly across the anchor zone. On the other hand, the lack of mobility in the stationary model with $p = 0$ means that either the information remains available "everywhere", or nowhere, i.e., extending the anchor zone beyond some reasonable size has only a marginal effect to the (expected) lifetime. Obviously, in reality, a larger anchor zone is likely to correlate with parameter p of the stationary model.

V. Conclusions

We have analyzed under what circumstances a message (e.g., a file or photo image) does not become extinct (*sink*) in the Floating Content application when nodes are assumed to be operational only when they are not moving. This led us to analyze a variant of the Poisson point process, where each

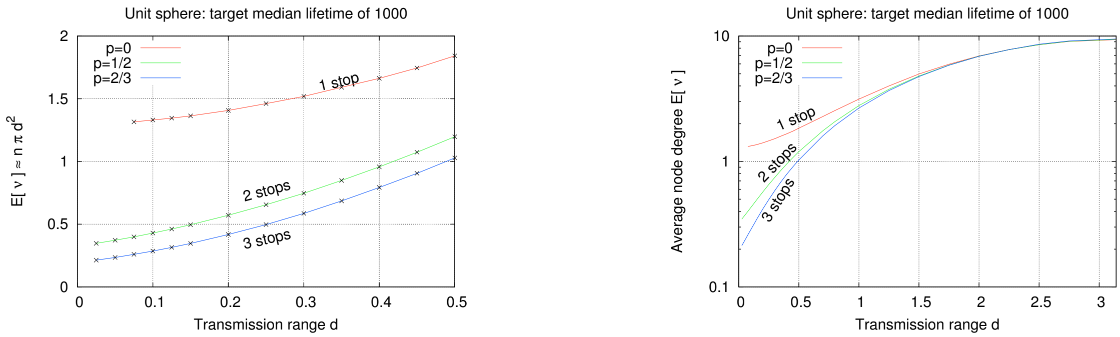

Fig. 7. Sufficient average node degree as a function of the transmission range d in unit sphere when each visits consists of $k = 1$, $k = 2$ and $k = 3$ stops on average. Target median lifetime is 1000 longer than an average visit. Right figure covers the whole range for the transmission range d with the average node degree $\mathrm{E}[\nu]$ on logarithmic scale on y-axis.

node is either active (has the information) or passive (does not have the information). In this setting, we are interested in understanding when and how long information remains available in the region (transient behavior).

We found that as soon as the mean node degree, i.e., the average number of neighbors, is higher than some threshold, which we refer to as the criticality threshold for the permanence of information (*permanence threshold*), the expected lifetime of the information starts to increase very rapidly. In an infinite system, the information is preserved indefinitely long. The permanence threshold for the basic case (single stop) at the fluid limit when transmission range d is very small is about 1.3. In practice, in most situations the threshold appears to be somewhere below 2, depending on the parameters of the scenario. These values are clearly below the percolation threshold, which corresponds to the mean node degree of about 4.5. Our future work includes a more detailed analysis of the permanence threshold, the value of which we would like to know more accurately also.

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