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Performance evaluation of information floating considering behavior changes of mobile nodes

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Abstract: Epidemic wireless communication delivers information to destination by spreading information by direct wireless communication between mobile nodes and movement of mobile nodes. To prevent disorderly diffusion of information for a specific local area in epidemic wireless communication, information floating (IF), which restricts mobile nodes to transmit the information only in the transmittable area, has been considered. In this paper, we consider IF for delivery of such information as accident warning and advertisement of a shop. We assume that mobile nodes change direction after receiving the information to avoid the accident site or to approach the shop. We also assume that mobile nodes that pass a fixed source of information (the accident site or the shop) carry the information to the transmittable area. Under these assumptions, we analyze the probability that a node cannot receive information in a transmittable area in the road network where the fixed source of information is surrounded by intersections. We also derive the size of each transmittable area so that this probability is close to desired value.

Keywords— **information floating, epidemic transmission, change of behavior, fixed source, theoretical analysis, size of transmittable area**

1. Introduction

Epidemic wireless communication delivers information to destination by spreading information by direct wireless communication between mobile nodes and movement of mobile nodes [1]. Although message delivery causes long delays because the speed of the message's dissemination depends on mobility of mobile nodes, some applications exist in which reachability without infrastructure precedes long delay times. Networks for such applications are called delay tolerant networks (DTNs) [2], [3]. Epidemic wireless communication is applicable to some applications in which reachability without infrastructure precedes long delay times, such as the delivery of local information, local advertisements, accident information, disaster information without infrastructure and so on.

To prevent disorderly diffusion of information for a specific local area in epidemic wireless communication, information floating (IF) has been proposed [4], [5], [6], [7], [8]. IF permits a node to transmit information only in an area called a transmittable area. To realize IF, it is assumed that each node knows its position and that a transmittable area is informed together with the information to be floated. In [4], [5], [6], [7], [8], the lifetime of IF is analyzed theoretically and by computer simulation as a performance measure of IF because they assume that only one mobile node can be a source of IF and that the IF never restarts if the IF ends.

However, if we consider IF for delivery of such information as accident warning and advertisement of a shop, multiple nodes that receive information directly from the accident site or the shop can carry information into a transmittable area. In other words, IF can restart in such a case. In addition, mobile nodes may change direction after receiving the information to avoid the accident site or to approach the shop. Hence, we analyzed IF assuming the restart of IF and the direction change of mobile nodes [9]. For this analysis, we considered a new network model consisting of three roads connected to an intersection, and assumed that a fixed source of information (FS; the accident site or the shop) exists on one of the roads, and a transmittable area exists on each of the other two roads. We analyzed the probability that mobile nodes cannot receive information before reaching the intersection and the size of each transmittable area to make the probability close to the desired value in the network model as a novel trial of performance analysis of IF; however, the analysis considered only one side of the FS although the FS is normally surrounded by multiple intersections, and analyses considering both side of the FS have been left as future works [9]. In this paper, therefore, we analyze the probability that mobile nodes cannot receive information in transmittable areas in an extended network model where the FS is surrounded by intersections. We also derive the size of each transmittable area so that this probability is close to desired value.

2. Definitions and Assumptions

We consider the road network model shown in Fig. 1. There are two intersections O1 and O2, and an FS is located between O1 and O2. There are four transmittable areas TA1, TA2, TA3, and TA4 on road segments O1-W, O1-N1, O2-E, and O2-N2, respectively. Lengths of TA1, TA2, TA3, and TA4 are L_W, L_{N1}, L_E, and L_{N2}, respectively. Distances from O1 to TA1, from O1 to TA2, and from O1 to FS are ℓ_1, ℓ_2, and $\ell_{FS,1}$, respectively. Distances from O2 to TA3, from O2 to TA4, and from O2 to FS are ℓ_3, ℓ_4, and $\ell_{FS,2}$, respectively.

Mobile nodes enter the network from directions W, N1, E, and N2, and these four types of mobile nodes obey a Poisson process with intensities λ_W, λ_{N1}, λ_E, and λ_{N2}, respectively, at the initial moment. All mobile nodes move at constant velocity v. Mobile nodes from W move toward N1 after passing O1 with probability q_{WN1} before receiving information. Denote the set of these nodes by M_{WN1}. In the same manner, we define probabilities q_{WO2}, q_{N1W}, q_{N1O2}, q_{EN2}, q_{EO1}, q_{N2E}, q_{N2O1}, q_{O2W}, q_{O2N1}, q_{O1E}, and q_{O1N2} and sets of nodes M_{WO2}, M_{N1W}, M_{N1O2}, M_{EN2}, M_{EO1}, M_{N2E}, M_{N2O1},

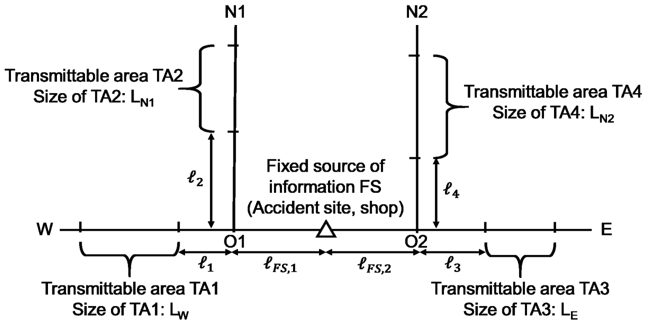


Figure 1. Road network model.

M_{O2W}, M_{O2N1}, M_{O1E}, and M_{O1N2}.

An FS continuously broadcasts information denoted by I_{IF}. Mobile nodes passing the FS receive I_{IF} directly from the FS by a wireless link. The mobile nodes are permitted to transmit information only in a transmittable area. A mobile node can send information to another mobile node if the distance between them does not exceed constant r. For simplifying analysis, we assume that $\ell_1 > r$, $\ell_2 > r$, $\ell_3 > r$, $\ell_4 > r$, $\ell_{FS,1} > r$, and $\ell_{FS,2} > r$ in the same manner as [9].

Let p be the probability that a node changes its direction after receiving I_{IF}. For example, if I_{IF} is a warning that recommends avoiding the FS, a node of M_{WO2} changes direction with probability p after receiving I_{IF} in TA1 and moves toward N1. As another example, if I_{IF} is an advertisement that guides mobile nodes to visit the FS, a node of M_{N2E} changes direction with probability p after receiving I_{IF} in TA4 and visits the FS. If a mobile node cannot receive I_{IF} before reaching the intersection, it does not change direction.

3. Performance Analysis of IF

First, we theoretically analyze the probability that a node cannot receive information in a transmittable area, denoted by P_f. Let $P_{f,W}$, $P_{f,N1}$, $P_{f,E}$, and $P_{f,N2}$ be the probabilities that the mobile nodes from W, N1, E, and N2 cannot receive I_{IF} in TA1, TA2, TA3, and TA4, respectively. P_f can be represented as

$$P_f = \frac{\lambda_W P_{f,W} + \lambda_{N1} P_{f,N1} + \lambda_E P_{f,E} + \lambda_{N2} P_{f,N2}}{\lambda_W + \lambda_{N1} + \lambda_E + \lambda_{N2}}. \quad (1)$$

First, we consider a case of warnings and analyze $P_{f,W}$, $P_{f,N1}$, $P_{f,E}$, and $P_{f,N2}$ in this case. In [9], the following probability $P_{f,1}$ is theoretically analyzed.

- $P_{f,1}$: Probability that a node of M_1 cannot receive I_{IF} until passing a transmittable area, where
  - M_1 and M_2 are the sets of mobile nodes,
  - Nodes of M_1 move toward the same direction, and nodes of M_2 move toward the direction opposite to that of M_1,
  - Nodes of M_1 do not have I_{IF} at an initial moment, and nodes of M_2 have I_{IF} at an initial moment,
  - Densities of nodes of M_1 and M_2 are λ_1 and λ_2, respectively,
  - Length of the transmittable area is L.

From [9], $P_{f,1}$ can be computed as

$$P_{f,1} = \frac{(\lambda_2 + \lambda_1)e^{-\lambda_2(2L+r)}}{\lambda_1 + \lambda_2 e^{(\lambda_2+\lambda_1)r}}. \quad (2)$$

By substituting $\lambda_1 = \lambda_W$, $\lambda_2 = \Lambda_W$, and $L = L_W$ into Eq. (2), we can compute $P_{f,W}$ as

$$P_{f,W} = \frac{(\Lambda_W + \lambda_W)e^{-\Lambda_W(2L_W+r)}}{\lambda_W + \Lambda_W e^{(\Lambda_W+\lambda_W)r}}, \quad (3)$$

where Λ_W is the density of nodes moving from O1 toward W and having I_{IF}.

In the same manner, if we define Λ_{N1} as the density of nodes moving from O1 toward N1 and having I_{IF}, Λ_E as the density of nodes moving from O2 toward E and having I_{IF}, and Λ_{N2} as the density of nodes moving from O2 toward N2 and having I_{IF}, we can compute $P_{f,N1}$, $P_{f,E}$, and $P_{f,N2}$ as

$$P_{f,N1} = \frac{(\Lambda_{N1} + \lambda_{N1})e^{-\Lambda_{N1}(2L_{N1}+r)}}{\lambda_{N1} + \Lambda_{N1} e^{(\Lambda_{N1}+\lambda_{N1})r}}, \quad (4)$$

$$P_{f,E} = \frac{(\Lambda_E + \lambda_E)e^{-\Lambda_E(2L_E+r)}}{\lambda_E + \Lambda_E e^{(\Lambda_E+\lambda_E)r}}, \quad (5)$$

$$P_{f,N2} = \frac{(\Lambda_{N2} + \lambda_{N2})e^{-\Lambda_{N2}(2L_{N2}+r)}}{\lambda_{N2} + \Lambda_{N2} e^{(\Lambda_{N2}+\lambda_{N2})r}}. \quad (6)$$

Λ_W generally depends on $P_{f,N1}$, $P_{f,E}$, and $P_{f,N2}$; however, because our aim is to make $P_{f,N1}$, $P_{f,E}$, and $P_{f,N2}$ sufficiently small, we approximately assume that $P_{f,N1} = 0$, $P_{f,E} = 0$, and $P_{f,N2} = 0$ in the analysis of Λ_W for simplicity. In [9], the same approximation is used, and the validity of this approximation is shown by comparing the numerical and simulation results. From this approximation, we can represent Λ_W as the sum of the densities of the following three types of nodes:

- Nodes of M_{N1W}
- Nodes of M_{N1O2} that change directions to avoid FS after receiving I_{IF} in TA2
- Nodes of M_{O2W} that do not change directions after receiving I_{IF} in TA3 or TA4

Therefore, we can compute Λ_W as

$$\begin{aligned}\Lambda_W = {} & \lambda_{N1} q_{N1W} + \lambda_{N1} q_{N1O2} \cdot p \\ & + (\lambda_E q_{EO1} q_{O2W} + \lambda_{N2} q_{N2O1} q_{O2W}) \cdot (1-p). \quad (7)\end{aligned}$$

In the same manner, we can compute Λ_{N1}, Λ_E, and Λ_{N2} as

$$\begin{aligned}\Lambda_{N1} = {} & \lambda_W q_{WN1} + \lambda_W q_{WO2} \cdot p \\ & + (\lambda_E q_{EO1} q_{O2N1} + \lambda_{N2} q_{N2O1} q_{O2N1}) \cdot (1-p), \quad (8)\\ \Lambda_E = {} & \lambda_{N2} q_{N2E} + \lambda_W q_{N2O1} \cdot p \\ & + (\lambda_W q_{WO2} q_{O1E} + \lambda_{N1} q_{N1O2} q_{O1E}) \cdot (1-p), \quad (9)\\ \Lambda_{N2} = {} & \lambda_E q_{EN2} + \lambda_W q_{EO1} \cdot p \\ & + (\lambda_W q_{WO2} q_{O1N2} + \lambda_{N1} q_{N1O2} q_{O1N2}) \cdot (1-p). \quad (10)\end{aligned}$$

In a case of advertisements, we can also use Eq. (1) and Eqs. (3) to (6) to compute P_f; however, we have to use the formulas of Λ_W, Λ_{N1}, Λ_E, and Λ_{N2} different from the above formulas for a case of warnings. In a case of advertisements, Λ_W can be represented as the sum of the densities of the following four types of nodes:

- Nodes of M_{N1W} that do not change directions after receiving I_{IF} in TA2
- Nodes of M_{O2W}
- Nodes of M_{EN2} that change directions to approach FS after receiving I_{IF} in TA3 and move toward W after passing O1
- Nodes of M_{N2E} that change directions to approach FS after receiving I_{IF} in TA4 and move toward W after passing O1

Therefore, we can compute Λ_W for advertisements as

$$\begin{aligned}\Lambda_W = {} & \lambda_{N1} q_{N1W} \cdot (1-p) \\ & +(\lambda_E q_{EO1} q_{O2W} + \lambda_{N2} q_{N2O1} q_{O2W}) \\ & +\lambda_E q_{EN2} q_{O2W} \cdot p + \lambda_{N2} q_{N2E} q_{O2W} \cdot p. \end{aligned} \tag{11}$$

In the same manner, we can compute Λ_{N1}, Λ_E, and Λ_{N2} for advertisements as

$$\begin{aligned}\Lambda_{N1} = {} & \lambda_W q_{WN1} \cdot (1-p) \\ & +(\lambda_E q_{EO1} q_{O2N1} + \lambda_{N2} q_{N2O1} q_{O2N1}) \\ & +\lambda_E q_{EN2} q_{O2N1} \cdot p + \lambda_{N2} q_{N2E} q_{O2N1} \cdot p, \end{aligned} \tag{12}$$

$$\begin{aligned}\Lambda_E = {} & \lambda_{N2} q_{N2E} \cdot (1-p) \\ & +(\lambda_W q_{WO2} q_{O1E} + \lambda_{N1} q_{N1O2} q_{O1E}) \\ & +\lambda_W q_{WN1} q_{O1E} \cdot p + \lambda_{N1} q_{N1W} q_{O1E} \cdot p, \end{aligned} \tag{13}$$

$$\begin{aligned}\Lambda_{N2} = {} & \lambda_E q_{EN2} \cdot (1-p) \\ & +(\lambda_W q_{WO2} q_{O1N2} + \lambda_{N1} q_{N1O2} q_{O1N2}) \\ & +\lambda_W q_{WN1} q_{O1N2} \cdot p + \lambda_{N1} q_{N1W} q_{O1N2} \cdot p. \end{aligned} \tag{14}$$

Next, we derive the appropriate values of L_W, L_{N1}, L_E, and L_{N2} so that P_f is close to desired value $P_{f,desired}$. By solving equations $P_{f,W} = P_{f,desired}$, $P_{f,N1} = P_{f,desired}$, $P_{f,E} = P_{f,desired}$, and $P_{f,N2} = P_{f,desired}$ from the above formulas, we have

$$L_W = -\frac{\log\left\{\frac{\lambda_W + \Lambda_W e^{(\Lambda_W+\lambda_W)r}}{\Lambda_W+\lambda_W} P_{f,desired}\right\}}{2\Lambda_W} - \frac{r}{2}, \tag{15}$$

$$L_{N1} = -\frac{\log\left\{\frac{\lambda_{N1} + \Lambda_{N1} e^{(\Lambda_{N1}+\lambda_{N1})r}}{\Lambda_{N1}+\lambda_{N1}} P_{f,desired}\right\}}{2\Lambda_{N1}} - \frac{r}{2}, \tag{16}$$

$$L_E = -\frac{\log\left\{\frac{\lambda_E + \Lambda_E e^{(\Lambda_E+\lambda_E)r}}{\Lambda_E+\lambda_E} P_{f,desired}\right\}}{2\Lambda_E} - \frac{r}{2}, \tag{17}$$

$$L_{N2} = -\frac{\log\left\{\frac{\lambda_{N2} + \Lambda_{N2} e^{(\Lambda_{N2}+\lambda_{N2})r}}{\Lambda_{N2}+\lambda_{N2}} P_{f,desired}\right\}}{2\Lambda_{N2}} - \frac{r}{2}. \tag{18}$$

4. Numerical Results

4.1 Results of P_f

To confirm the validity of our analysis, we show the numerical and simulation results of P_f in Fig. 2. For reference, Fig. 2 also shows the results of $P_{f,W}$, $P_{f,N1}$, $P_{f,E}$, and $P_{f,N2}$. We use the following values for the parameters: $v = 10$ m/sec $= 36$ km/h, $r = 100$ m, $\ell_1 = \ell_2 = \ell_3 = \ell_4 = \ell_{FS,1} = \ell_{FS,2} = 500$ m, $\lambda_W = \lambda_{N1} = 0.005$ m^{-1}, $\lambda_E = \lambda_{N2} = 0.01$ m^{-1}, $q_{WN1} = q_{WO2} = q_{N1W} = q_{N1O2} = q_{EN2} = q_{EO1} = q_{N2E} = q_{N2O1} = q_{O1E} = q_{O1N2} = q_{O2W} = q_{O2N1} = \frac{1}{2}$. The sizes of all transmittable ares are the same (i.e., $L_W = L_{N1} = L_E = L_{N2} = L$), and the horizontal axis represents the size L. Figure 2(a) shows the results for a case where nodes never change directions even if they receive I_{IF} (i.e., $p = 0$, no change of direction), Fig. 2(b) shows the results for a case where nodes change directions to avoid FS with probability $p = 0.5$ after receiving I_{IF} (warning), and Fig. 2(c) shows the results for a case where nodes change directions to approach FS with probability $p = 0.5$ after receiving I_{IF} (advertisement). From these figures, we can confirm that the numerical results agree well with the simulations results. The main reason for a difference between the numerical and simulation results is the approximations $P_{f,N1} = 0$, $P_{f,E} = 0$, and $P_{f,N2} = 0$ in the analysis of Λ_W. We can also see how P_f decreases with an increase of L.

As mentioned, our aim is to send information to as many nodes as possible while preventing futile spreading of information. In such a region (i.e., the region of large L and small P_f), the numerical and simulation results especially agree well with each other. This tendency indicates that Eqs. (15) to (18) compute L_W, L_{N1}, L_E, and L_{N2} to make P_f close to $P_{f,desired}$ more accurately if $P_{f,desired}$ is sufficiently small. The specific results of L_W, L_{N1}, L_E, and L_{N2} are shown in the succeeding subsection.

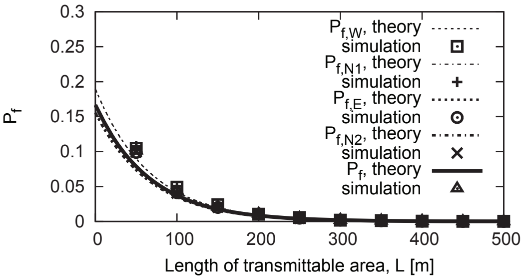
4.2 Results of Size of Each Transmittable Area so that P_f is Close to Desired Value

Figure 3 shows the numerical results of L_W, L_{N1}, L_E, and L_{N2} to maintain $P_f = 0.01$. In this figure, $\lambda_W = \lambda_{N1} = 0.005$ m^{-1} and $\lambda_E = \lambda_{N2} = 0.002$ m^{-1}, and the values of other parameters are the same as those for Fig. 2. From this figure, the required values of L_W and L_{N1} for warnings are smaller than those for a case of no change of direction (i.e., $p = 0$). In contrast, the required values of L_E and L_{N2} for warnings are larger than those for a case of no change of direction. This is because the nodes from W and N1, which are much more than those from E and N2, change direction to avoid the FS, and as as result, nodes from O1 to W or N1 increase and those from O2 to E or N2 decrease. The results for advertisements show the tendency opposite to the above results for warnings.

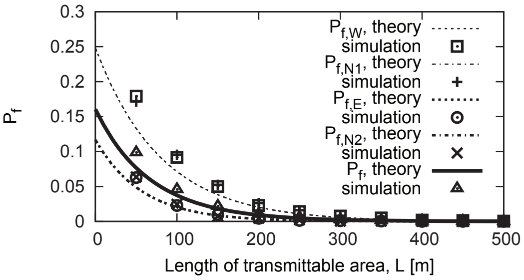
These results indicate that it is important to decide the size of each transmittable area considering the whole network structure surrounding the FS.

5. Conclusions

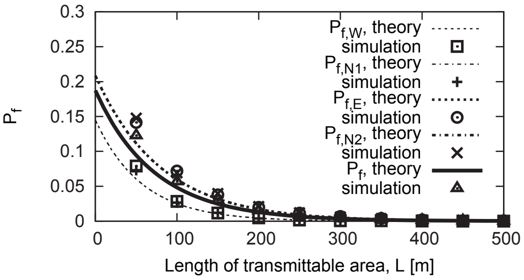
In this paper, we considered information floating (IF) of warnings and advertisements, and extended the analysis in [9], which theoretically derived the probability that a node cannot receive information in a transmittable area (P_f) and the size of each transmittable area so that P_f is close to desired value.



(a) No change of direction ($p = 0$)



(b) Warning ($p = 0.5$)



(c) Advertisement ($p = 0.5$)

Figure 2. Results of P_f.

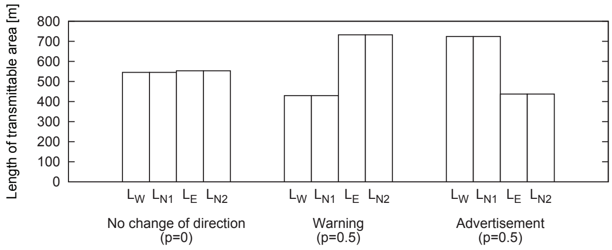


Figure 3. Sizes of transmittable areas to maintain $P_f = 0.01$.

While [9] considered only one side of the fixed source (FS) including one intersection, this paper considered both sides of the FS including two intersections, and theoretically analyzed P_f and the size of each transmittable area so that P_f is close to desired value in the road network model. From the numerical results, we showed the importance to decide the size of each transmittable area considering the whole network structure surrounding the FS in the case where nodes can change directions after receiving information.

Future works include extensions of the analysis of IF to other road structures (e.g., lattice structure), other patterns of behavior changes of mobile nodes and so on. This work is partially supported by JSPS KAKENHI Grant Numbers 80269547, 16K06344.

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