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Analysis of Information Floating with a Fixed Source of Information Considering Behavior Changes of Mobile Nodes

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SUMMARY Information floating delivers information to mobile nodes in specific areas without meaningless spreading of information by permitting mobile nodes to directly transfer information to other nodes by wireless links in designated areas called transmittable areas. In this paper, we assume that mobile nodes change direction at intersections after receiving such information as warnings and local advertisements and that an information source remains in some place away from the transmittable area and continuously broadcasts information. We analyze performance of information floating under these assumptions to explore effects of the behavior changes of mobile nodes, decision deadline of the behavior change, and existence of a fixed source on information floating. We theoretically analyze the probability that a node cannot receive information and also derive the size of each transmittable area so that this probability is close to desired values.

key words: *information floating, epidemic transmission, change of behavior, fixed source, theoretical analysis, size of transmittable area*

1. Introduction

For multi-hop mobile communication, no backbone networks (including base stations) are necessary unlike cellular systems, and source and destination nodes communicate through a connected multi-hop path. Multi-hop paths are realized by direct communication among mobile nodes and relayed by mobile nodes. Multi-hop mobile communication, which appears in such networks as mobile ad hoc networks and wireless sensor networks [1]–[4], has been studied widely. During these studies, epidemic mobile communication is derived from multi-hop mobile communication [5].

Epidemic communication delivers information to destinations by direct wireless communication between adjacent nodes and the movement of nodes with information without a connected multi-hop path between source and destination nodes, unlike multi-hop mobile communication. These properties enable epidemic communication to deliver information to destinations even if the node density is so small that the construction of connected multi-hop paths is difficult. Although message delivery causes long delays because the speed of the message's dissemination depends on the mobility of the mobile nodes, some applications exist in which reachability without infrastructure precedes long delay times. Networks for such applications are called delay tolerant networks (DTNs) [6], [7]. Epidemic communication is applicable to the delivery of local information, local advertisements, accident information, and disaster information without infrastructure [5], [8]–[11].

Since epidemic communication spreads information among mobile nodes, information for a limited area may widely spread over service areas. This may cause many useless transmissions in non-target areas. Such useless transmissions waste node energy and increase futile network traffic. To prevent the unlimited diffusion of information, information floating (IF) has been proposed [12]–[16]. IF permits a node to transmit information only in an area called a transmittable area to prevent the meaningless spread of information. Each mobile node is assumed to know its position to realize an IF. The name information floating is derived from the fact that the information seems to float in the transmittable area.

In IF, only mobile nodes in the transmittable area transfer information to other nodes through wireless links. If the information is successively transferred to new mobile nodes, the IF continues. Conversely, if all the nodes with information leave the transmittable area, the IF ends. Hence, IF's lifetime, which is an important performance measure, has been studied theoretically and by computer simulation [12]–[16].

As studied in [13]–[16], theoretical analysis of IF is important to understand basic properties of IF for system design. In this paper, we theoretically analyze IF from a new viewpoint. The new viewpoint is to focus on three factors affecting IF. The first factor is the change of behavior of mobile nodes by information (including content). For example, warning information suggests that mobile nodes avoid accident sites. Local advertisements guide mobile nodes to a particular shop. We assume that as the behavior changes, mobile nodes may change direction at an intersection after receiving information by IF.

We suppose that for warnings, a mobile node changes direction at an intersection to avoid an accident site (Fig. 1), and for a shop's advertisement, a mobile node changes direction to visit that shop (Fig. 2). In Fig. 1, the vehicle A moves toward the direction of the dashed arrow and enters the transmittable area. Suppose that the vehicle A receives a warning for an accident from the vehicle B by IF in the transmittable area. Suppose that the accident site is in the direction of the dashed arrow. Then, the vehicle A changes its direction and moves toward the direction of the solid arrow to avoid the accident site. In Fig. 2, the vehicle A moves toward the direction of the dashed arrow and receives an advertisement

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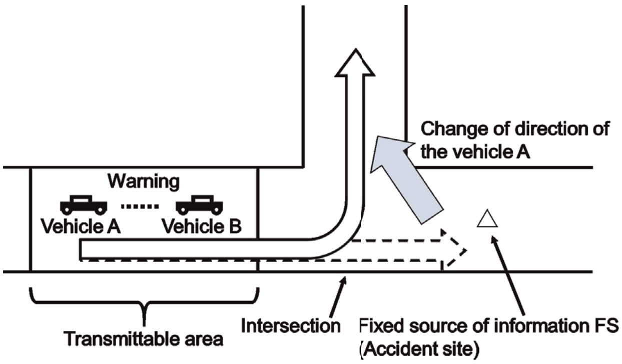


Fig. 1 Application of information floating to warnings.

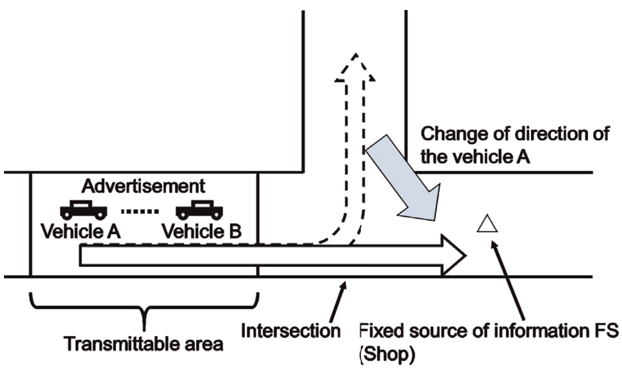


Fig. 2 Application of information floating to advertisements.

of a shop in the transmittable area from the vehicle B. Then, the vehicle A changes its direction and moves toward the direction of the solid arrow to approach the shop.

Such change of the behavior of mobile nodes will be caused by IF in actual situations, and at the same time, it affects performance of IF because the change of behavior of mobile nodes affects direct communication between mobile nodes. Hence, it is important to explore effects of the change of behavior on performance of IF; however, past performance analyses of IF never assumed the change of behavior of mobile nodes caused by IF [12]–[16].

Furthermore, in both of warnings and advertisements, mobile nodes have to decide to change directions before reaching the intersection. Hence, the decision to change has to be done within a certain deadline, and a transmittable area has to be in front of the intersection (Figs. 1 and 2). In the past researches of IF, however, effects of the decision deadline on IF have never been considered. Considering the decision deadline is the second factor of the new viewpoint of our analysis.

The models in Figs. 1 and 2 implicitly assume the existence of a fixed source of information (FS). Figure 1 assumes an accident site on the intersection's right and a transmittable area on the left. Of course, some mobile nodes coming from the right go straight and pass the accident site and the transmittable area. If the vehicle that caused the accident exists at the accident site, it might try to start an IF in the transmittable area as a warning. The vehicle can continuously send warning information directly to the vehicles approaching the accident site and make them carry information to the transmittable area. In this case, the vehicle that caused the accident can be an FS. Also, the accident site itself can be an FS because people passing by the accident site can notice the accident by themselves and notify other nodes about it. For advertisements, an FS can be an advertiser itself. For example, as an FS, a shop continuously sends advertisement information to nodes that pass the shop.

Mobile nodes that received information directly from an FS enter the transmittable area and can restart the IF that has ended. In both above cases, the FS remains in the same place, and continuously sends information to mobile nodes or notifies them information. Existence of an FS obviously affects performance of IF as mentioned above. Hence, it is important to evaluate IF considering that frequent restarts of IF are triggered by the nodes that received information directly from the FS. However, the past theoretical analyses never assumed existence of an FS [13]–[16]. The past theoretical analyses often assumed that only the source of information initiates the IF in a transmittable area, and also assumed that the IF never restarts after it ends [13]–[16]. Assuming existence of an FS is the third factor of the new viewpoint of our theoretical analysis.

As mentioned, this paper theoretically analyzes performance of IF considering the three factors explained above: change of node behavior, decision deadline, and FS existence, as a novel trial of performance analysis of IF. To do this, we use the model in Fig. 3. The model in Fig. 3 reflects the three factors. Although the model is quite simple, we can remove the excessive complexity in the analysis of the effects of various factors on IF due to this simplicity. Furthermore, the IF in such a model has never been analyzed, even though a model with the above three factors is a natural extension from a simple one-dimensional model in past researches [15], [16].

As a performance measure, since the lifetime cannot be used because IF frequently restarts, we analyze probability P_f that a node passing through the transmittable area cannot receive information before reaching the intersection. Furthermore, an FS can designate the size of each transmittable area in the transmission of information. Hence, a simple and quick way to choose an appropriate value for the size of each transmittable area is needed. As appropriate values for transmittable areas, we derive the size of each transmittable area so that P_f is close to the desired value.

The main contributions of this paper are as follows: We provide two approximate methods to theoretically analyze P_f considering the above three factors. One is a numerical method, and the other is in a closed form. Using these methods, we show how the three factors affect performance of IF. Also, we provide a closed form formula of the size of each transmittable area so that P_f is close to the desired value using the closed form formula of P_f. This simple formula helps us to understand the relation between the size of transmittable area and the desired value of P_f, which is necessary for design of IF systems. The rest of our paper is organized as follows. In Sect. 2, we describe our problem statement. In Sect. 3, we give a theoretical analysis of IF, as briefly outlined above. In Sect. 4, we give numerical results of analysis and discussions. Finally, we conclude this paper.

2. Problem Statement

In this paper, we consider an IF realized by mobile nodes moving along a road network shown in Fig. 3. Suppose that the mobile nodes are vehicles [15], [16]. Note that the theoretical analysis in the following section can be applied not only to the case of vehicles but also to that of pedestrians. In a road network, three road segments in three directions, E, W, and N, are connected at intersection O, and the road segments have FS, transmittable area TA1, and transmittable area TA2. Let ℓ_1, ℓ_2, and ℓ_3 be the distances from O to TA1, TA2, and FS, respectively. An FS continuously broadcasts information denoted by I_{IF}.

Mobile nodes move along six routes among the three directions (Fig. 4). Let M_{NE} be the set of mobile nodes moving from N toward E before receiving I_{IF} and changing direction. In the same manner, we define M_{EN}, M_{NW}, M_{WN}, M_{EW}, and M_{WE} as the sets of the mobile nodes. Let M_{NO} be the set of mobile nodes moving from N to O. M_{NO} is the union of M_{NE} and M_{NW}. In the same manner, we define M_{WO}, M_{EO}, M_{ON}, M_{OW}, and M_{OE}.

Mobile nodes of M_{EN} and M_{EW} pass the FS and receive I_{IF} to be floated in TA1 and TA2 directly from the FS by a wireless link. For accident sites, the mobile nodes sometimes notice the accident and generate I_{IF} by themselves. The nodes of M_{EW} and M_{EN} deliver I_{IF} to TA1 and TA2, respectively, and transfer the information to other mobile nodes to start an IF. The mobile nodes are permitted to transmit information only in TA1 and TA2. A mobile node can send information to another mobile node if the distance between them does not exceed constant r. Note that a sender has to be in a transmittable area (TA1 or TA2) to transmit information; however, a receiver can get the information even if it is outside of the transmittable area. For simplicity, assume that $\ell_1 > r$, $\ell_2 > r$, and $\ell_3 > r$. If all nodes with I_{IF} leave TA1, then the IF of TA1 ends; however, after a node that received I_{IF} from the FS or in TA2 enters TA1, the IF of TA1 restarts. The same is true for restarting in TA2.

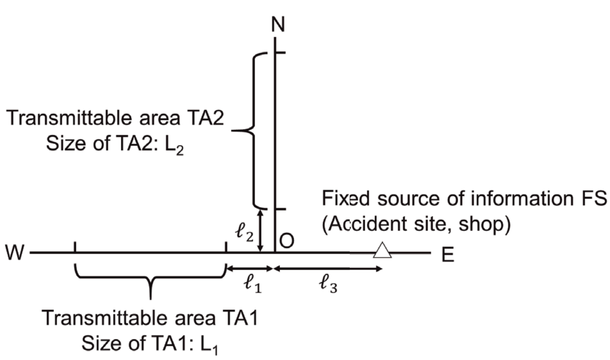


Fig. 3 Transmittable areas and source of information.

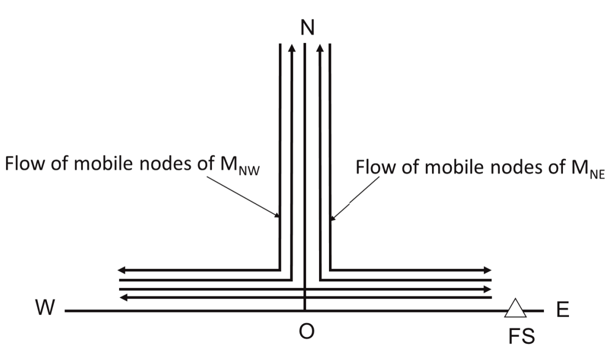


Fig. 4 Road network and flows of mobile nodes along road networks.

As seen from Figs. 3 and 4, the mobile nodes of M_{NE} can receive I_{IF} in TA2 before reaching the intersection if the IF is alive. Let p be the probability that a node changes its direction after receiving I_{IF} in TA1 or TA2. If I_{IF} is a warning that recommends avoiding the FS, a node of M_{NE} changes direction with probability p after receiving I_{IF} in TA2 and moves toward W. A node of M_{WE} also changes direction with probability p to move toward N after receiving I_{IF} in TA1. If I_{IF} is an advertisement that guides mobile nodes to visit the FS, a mobile node of M_{NW} changes direction with probability p after receiving I_{IF} and visit the FS. The same is true for the mobile nodes of M_{WN}. If a mobile node cannot receive I_{IF} before reaching the intersection, it does not change direction. Here, I_{IF} influences the mobile nodes approaching the intersection from N or W, and no nodes of M_{EN} or M_{EW} change direction.

Assume that every node moves at velocity v. Assume that the initial location of the mobile nodes of M_{EW} obeys a Poisson distribution with intensity λ_{EW}. Assume that each of the five other flows of the mobile nodes obeys a Poisson distribution. The intensities of the other flows are denoted by λ_{WE}, λ_{NE}, λ_{EN}, λ_{NW}, and λ_{WN}. Past research assumed a correlation between the density and the velocity of the nodes if the mobile nodes are vehicles [16]. However, correlation is not the main interest of this paper because it introduces unnecessary complexity; therefore, we do not assume it. In addition, we define the densities of the nodes of M_{EO}, M_{WO}, M_{NO}, M_{OE}, M_{OW}, and M_{ON} at the initial moment as λ_{EO}, λ_{WO}, λ_{NO}, λ_{OE}, λ_{OW}, and λ_{ON}, respectively. Then $\lambda_{EO} = \lambda_{EW} + \lambda_{EN}$, $\lambda_{WO} = \lambda_{WN} + \lambda_{WE}$, $\lambda_{NO} = \lambda_{NW} + \lambda_{NE}$, $\lambda_{OE} = \lambda_{WE} + \lambda_{NE}$, $\lambda_{OW} = \lambda_{NW} + \lambda_{EW}$, and $\lambda_{ON} = \lambda_{WN} + \lambda_{EN}$.

As mentioned in the preceding section, as a performance measure, we use probability P_f that a mobile node of M_{WO} and M_{NO} cannot receive I_{IF} in a transmittable area before reaching the intersection. An essential design issue in IF is to find the appropriate size for a transmittable area because we intuitively expect that P_f depends on the sizes of TA1 and TA2. Based on the theoretical analysis of P_f, we derive appropriate sizes of TA1 and TA2 so that P_f is close to the desired value while preventing futile spreading of I_{IF}.

3. Theoretical Analysis of P_f

In this section, we theoretically analyze P_f. Let $P_{f,1}$ be the probability that the mobile nodes of M_{WO} cannot receive I_{IF} in TA1. Let $P_{f,2}$ be the probability that the mobile nodes of M_{NO} cannot receive I_{IF} in TA2. Then

$$P_f = \frac{\lambda_{WO}}{\lambda_{WO} + \lambda_{NO}} P_{f,1} + \frac{\lambda_{NO}}{\lambda_{WO} + \lambda_{NO}} P_{f,2}. \quad (1)$$

Consider the IF of warnings. First, we consider an IF in TA1 to analyze $P_{f,1}$. Define that M_{NW}^c is the set of mobile nodes that are included in M_{NE}, change direction to avoid FS after receiving I_{IF} in TA2, and move to direction W. The following three flows contribute to keeping IF alive in TA1:

- All the nodes of M_{NW}^c
- All the nodes of M_{NW} and M_{WN}
- All the nodes of M_{EW} and M_{WE}

Note that all the nodes of M_{NW} and M_{WN} are included in this list because they do not move toward the FS from the beginning. We classify these nodes into two groups (Fig. 5). One group consists of nodes moving from W to O, which are white in Fig. 5, and the other group consists of those from O to W, which are black in Fig. 5. White nodes are the nodes of M_{WO}. Black nodes are the nodes of M_{NW}^c, M_{NW} and M_{EW}.

No white nodes have an I_{IF} before entering TA1. All the black nodes included in M_{EW} have I_{IF} before entering TA1 because these nodes pass the FS, and all the black nodes of M_{NW}^c have I_{IF} obviously; however, all the black nodes included in M_{NW} do not have I_{IF} before entering TA1 because mobile nodes receive I_{IF} in TA2 with probability $1 - P_{f,2}$.

We have to consider such black nodes that don't have I_{IF} before entering TA1 to precisely analyze $P_{f,1}$; however, this consideration is very complicated, although the black nodes that don't have I_{IF} are not a main factor affecting $P_{f,1}$ because $P_{f,2}$ should be as small as possible. For these reasons, we assume that $P_{f,2}$ is small and consider two kinds of approximations: Approximation 1 and Approximation 2. In Approximation 1, we ignore the black nodes that don't have an I_{IF} before entering TA1 and assume that only black nodes with I_{IF} before entering TA1 and white nodes contribute to the IF in TA1. In Approximation 2, we approximately assume all the nodes of M_{NW} receive an I_{IF} before entering TA1. Then in both Approximations 1 and 2, we can concentrate on the black nodes with I_{IF} in the analysis of P_f, while the density of the black nodes in Approximation 1 depends on $P_{f,2}$ for TA1 and $P_{f,1}$ for TA2.

Consider Fig. 5. Suppose that TA1 is $[a, a+L_1]$. White nodes w_1 to w_6 move from W to O, and black nodes b_1 to b_3 move from O to W. Consider w_5. As shown in Fig. 5, it follows w_4 and is followed by w_6. Suppose that w_5 does not receive I_{IF} before the situation in Fig. 5. Let X_i be the distance between w_i and w_{i+1} for integer i. Then the distance from w_5 to w_4 is X_4.

Suppose that $X_4 > r$, as shown in Fig. 5. If there is a black node with a direct link to w_5, and the black node is in TA1, then w_5 receives I_{IF} from the black node. Otherwise, w_5 cannot receive I_{IF} from any black nodes. In addition, w_5 cannot directly receive I_{IF} from w_4, and it is impossible for w_6 to receive it earlier than w_5 if both w_5 and w_6 receive I_{IF}. Consequently, w_5 has to wait until the distance from w_5 to a black node becomes r while the black node is in TA1 to receive I_{IF} for the first time if $X_4 > r$. In this case, w_5 cannot receive I_{IF} directly from any white nodes.

Next, suppose that $X_4 \le r$. In this case, w_5 may receive I_{IF} directly from w_4 earlier than the black nodes. Figure 6 is an example. At time $t = t_1$, w_3 receives I_{IF} from black node b_1. At $t = t_2$, as soon as w_3 enters TA1, w_3 sends I_{IF} to w_4. Note that since b_1 is no longer in TA1, it is not permitted to transmit I_{IF}. In the same manner, w_5 receives I_{IF} from w_4 at $t = t_3$, although w_5 has no opportunity to receive I_{IF} from the black nodes from t_1 to t_3. As seen from the example in Fig. 6, if $X_i \le r$, $X_{i+1} \le r$, $\cdots$, $X_{n-1} \le r$ and at least one among $w_i, w_{i+1}, \cdots, w_{n-1}$ receives I_{IF}, then w_n can receive it.

Consider a condition where white node w_N cannot receive I_{IF} in TA1. As mentioned above, both the black and white nodes potentially contribute to the delivery of I_{IF} to w_N. Consider a situation S_1 at $t = t_{pre}$, where w_N is at $x = a + L_1 + r$ at this moment. Figure 7 shows this situation, where w_N is w_3. Suppose that $X_0 > r$, $X_1 \le r$, $X_2 \le r$, ..., and $X_{N-1} \le r$. Define Z as $\sum_{i=1}^{N-1} X_i + 2r$. Define b_j as the nearest black node to $x = a + L_1$ in the black nodes on the left of $x = a + L_1$ at time $t = t_{pre}$. Let Y be the distance

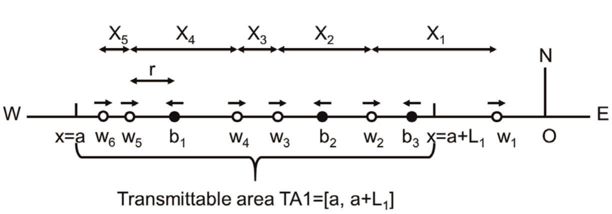


Fig. 5 Example of nodes moving around TA1.

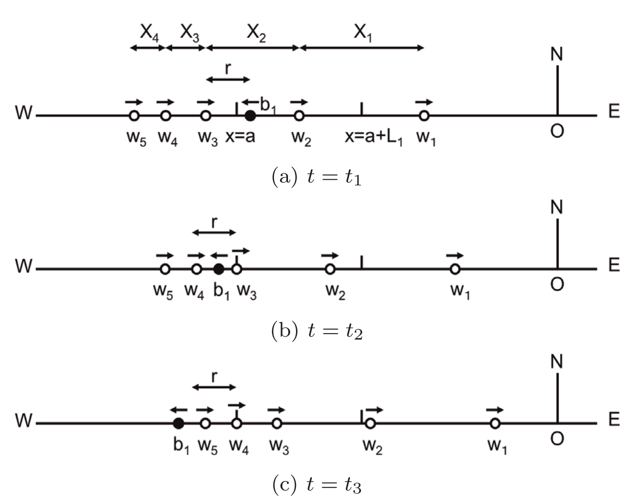


Fig. 6 Situation where w_5 receives information via w_3 and w_4.

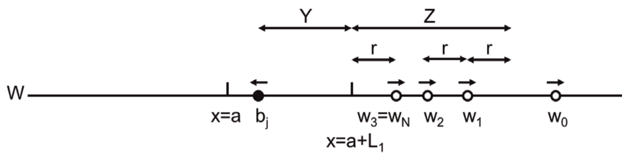


Fig. 7 Situation S_1 at $t = t_{pre}$, where $Y \leq Z$.

from $x = a + L_1$ to b_j.

In the above situation, we have the following condition: w_N cannot receive I_{IF} if and only if $Y > Z$ and $L_1 < \frac{Y-Z}{2}$. The proof is given in Appendix. From this condition,

$$\begin{aligned} P_{f,1} &= \Pr\left(Y > Z, L_1 < \frac{Y-Z}{2}\right) \\ &= \Pr(Y > Z)\Pr(Y > Z + 2L_1 | Y > Z). \end{aligned} \tag{2}$$

In Fig. 7, if we draw a segment of length r from each white node on the left of each node, then we have a long segment starting from $x = a+L_1$ and ending at w_1. This long segment is called a clump of length W. If the nodes comprising a clump are distributed according to a Poisson distribution with density λ_{WO}, the distribution function of W is as follows [17]:

$$\begin{aligned} \Pr(W < w) &= P_c(w, r, \lambda_{WO}) \\ &= 1 - \sum_{i=0}^{\lfloor \frac{w}{r} \rfloor} \frac{(-1)^i}{i!} e^{-i\lambda_{WO} r}\{\lambda_{WO}(w - ir)\}^{i-1} \\ &\quad \times \{\lambda_{WO}(w - ir) + i\}. \end{aligned} \tag{3}$$

Because $Z = W + r$, the distribution function of Z is

$$\begin{aligned} \Pr(Z < z) &= \Pr(W + r < z) = \Pr(W < z - r) \\ &= P_c(z - r, r, \lambda_{WO}). \end{aligned} \tag{4}$$

To compute the density function of Y, denoted by $f_Y(y)$, we have to consider the density of the nodes moving from O to W. Let Λ_{OW} be the density of nodes flowing from O to W and contributing to IF in TA1. Suppose that they include nodes that change direction after receiving I_{IF}, and that their distribution obeys a Poisson distribution of intensity Λ_{OW}. Then

$$f_Y(y) = \Lambda_{OW} e^{-\Lambda_{OW} y}. \tag{5}$$

We use different values for Λ_{OW} in Approximations 1 and 2 as in the following.

From Eqs. (4) and (5),

$$\begin{aligned} \Pr(Y > Z) &= \int_0^\infty \Pr(Z < y) f_Y(y) dy \\ &= \frac{(\Lambda_{OW} + \lambda_{WO}) e^{-\Lambda_{OW} r}}{\lambda_{WO} + \Lambda_{OW} e^{(\Lambda_{OW} + \lambda_{WO}) r}}, \end{aligned} \tag{6}$$

$$\begin{aligned} \Pr(Y > Z + 2L_1 | Y > Z) &= \frac{\Pr(Y > Z + 2L_1)}{\Pr(Y > Z)} \\ &= \frac{\int_0^\infty \int_{z+2L_1}^\infty f_Z(z) f_Y(y) dy dz}{\int_0^\infty \int_z^\infty f_Z(z) f_Y(y) dy dz} \\ &= \frac{\int_0^\infty \int_{z+2L_1}^\infty f_Z(z) \Lambda_{OW} e^{-\Lambda_{OW} y} dy dz}{\int_0^\infty \int_z^\infty f_Z(z) \Lambda_{OW} e^{-\Lambda_{OW} y} dy dz} \\ &= \frac{e^{-2\Lambda_{OW} L_1} \int_0^\infty \int_z^\infty f_Z(z) \Lambda_{OW} e^{-\Lambda_{OW} y} dy dz}{\int_0^\infty \int_z^\infty f_Z(z) \Lambda_{OW} e^{-\Lambda_{OW} y} dy dz} \\ &= e^{-2\Lambda_{OW} L_1}, \end{aligned} \tag{7}$$

where $f_Z(z)$ is the probability density function of Z; however, this function is eliminated in this equation. As a result, from Eqs. (2), (6), and (7),

$$P_{f,1} = \frac{(\Lambda_{OW} + \lambda_{WO}) e^{-\Lambda_{OW}(2L_1 + r)}}{\lambda_{WO} + \Lambda_{OW} e^{(\Lambda_{OW} + \lambda_{WO}) r}}. \tag{8}$$

By replacing λ_{WO}, Λ_{OW}, and L_1 with λ_{NO}, Λ_{ON}, and L_2, respectively,

$$P_{f,2} = \frac{(\Lambda_{ON} + \lambda_{NO}) e^{-\Lambda_{ON}(2L_2 + r)}}{\lambda_{NO} + \Lambda_{ON} e^{(\Lambda_{ON} + \lambda_{NO}) r}}. \tag{9}$$

In Approximation 1,

$$\Lambda_{OW} = \Lambda_{OW,1} = (1 - P_{f,2})(\lambda_{NW} + p\lambda_{NE}) + \lambda_{EW}, \tag{10}$$

$$\Lambda_{ON} = \Lambda_{ON,1} = (1 - P_{f,1})(\lambda_{WN} + p\lambda_{WE}) + \lambda_{EN}. \tag{11}$$

By numerically solving the equations after substituting them into Eqs. (8) and (9), we have $P_{f,1}$ and $P_{f,2}$ in Approximation 1.

In Approximation 2, we consider a situation where $P_{f,1}$ and $P_{f,2}$ are small and assume that all the nodes of M_{NW} and M_{WN} have I_f before entering TA1 and TA2, respectively. Then

$$\Lambda_{OW} = \Lambda_{OW,2} = \lambda_{NW} + p\lambda_{NE} + \lambda_{EW}, \tag{12}$$

$$\Lambda_{ON} = \Lambda_{ON,2} = \lambda_{WN} + p\lambda_{WE} + \lambda_{EN}. \tag{13}$$

Due to this assumption, the solution is successfully simplified. We have the following closed form in Approximation 2 because $\Lambda_{OW,2}$ and $\Lambda_{ON,2}$ are represented without $P_{f,1}$ and $P_{f,2}$:

$$P_{f,1} = \frac{(\Lambda_{OW,2} + \lambda_{WO}) e^{-\Lambda_{OW,2}(2L_1 + r)}}{\lambda_{WO} + \Lambda_{OW,2} e^{(\Lambda_{OW,2} + \lambda_{WO}) r}}, \tag{14}$$

$$P_{f,2} = \frac{(\Lambda_{ON,2} + \lambda_{NO}) e^{-\Lambda_{ON,2}(2L_2 + r)}}{\lambda_{NO} + \Lambda_{ON,2} e^{(\Lambda_{ON,2} + \lambda_{NO}) r}}. \tag{15}$$

Next, we decide the appropriate values of L_1 and L_2 so that P_f is close to desired value $P_{f,desired}$. Since we have a closed form solution of P_f in Approximation 2, we can simply compute the L_1 and L_2 values. By substituting $P_{f,desired}$ into $P_{f,1}$ in Eq. (14) and $P_{f,2}$ in Eq. (15) and solving them, we have

$$L_1 = -\frac{\log\left\{\frac{\lambda_{WO}+\Lambda_{OW,2}e^{(\Lambda_{OW,2}+\lambda_{WO})r}}{\Lambda_{OW,2}+\lambda_{WO}}P_{f,desired}\right\}}{2\Lambda_{OW,2}} - \frac{r}{2}, \tag{16}$$

$$L_2 = -\frac{\log\left\{\frac{\lambda_{NO}+\Lambda_{ON,2}e^{(\Lambda_{ON,2}+\lambda_{NO})r}}{\Lambda_{ON,2}+\lambda_{NO}}P_{f,desired}\right\}}{2\Lambda_{ON,2}} - \frac{r}{2}. \tag{17}$$

Note that if both of $P_{f,1}$ and $P_{f,2}$ are close to $P_{f,desired}$, then P_f is also close to $P_{f,desired}$ as can be seen from Eq. (1).

If I_{IF} is advertisement information that guides passengers to the FS, the following are the mobile nodes moving from O to W and carrying I_{IF}:

- Mobile nodes of M_{NW} that do not change directions after receiving I_{IF} in TA2
- Mobile nodes of M_{EW}

Then in Approximation 1,

$$\Lambda_{OW} = \Lambda_{OW,1} = (1 - P_{f,2})(1 - p)\lambda_{NW} + \lambda_{EW}, \tag{18}$$

$$\Lambda_{ON} = \Lambda_{ON,1} = (1 - P_{f,1})(1 - p)\lambda_{WN} + \lambda_{EN}. \tag{19}$$

In Approximation 2,

$$\Lambda_{OW} = \Lambda_{OW,2} = (1 - p)\lambda_{NW} + \lambda_{EW}, \tag{20}$$

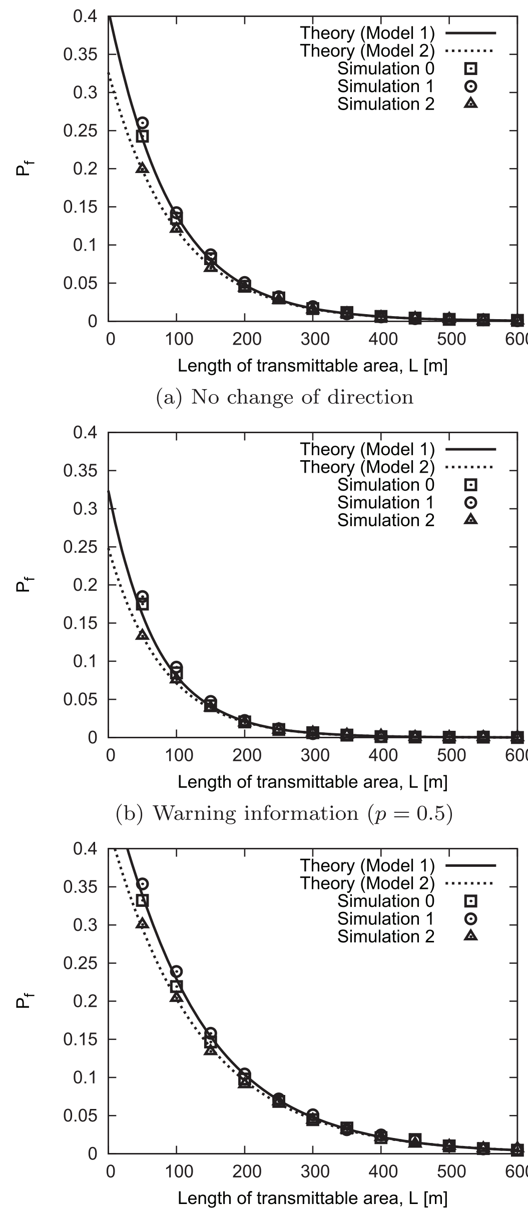
$$\Lambda_{ON} = \Lambda_{ON,2} = (1 - p)\lambda_{WN} + \lambda_{EN}. \tag{21}$$

By substituting Eqs. (18) and (19) into Eqs. (1), (8), and (9), we can numerically solve P_f in Approximation 1, and by substituting Eqs. (20) and (21) into Eqs. (1), (8), and (9), we have the closed form of P_f in Approximation 2.

4. Numerical Results

To confirm the validity of the approximate analyses in Approximations 1 and 2, we compare the numerical and simulation results. In Approximation 1, we assume that the mobile nodes of M_{NW} without I_{IF} before entering TA1 do not contribute to IF in TA1. The same is true for M_{WN} in TA2. In Approximation 2, we assume that all the nodes of M_{NW} and M_{WN} have I_{IF} before entering TA1 and TA2, respectively. In both Approximations 1 and 2, we assume that the distribution of the mobile nodes that changed directions at the intersection after receiving I_{IF} also obeys a Poisson distribution.

Figure 8 shows the numerical and simulation results for v = 10 m/sec = 36 km/h, r = 100 m, $\ell_1 = \ell_2 = \ell_3$ = 500 m, and $\lambda = \lambda_{NW} = \lambda_{WN} = \lambda_{NE} = \lambda_{EN} = \lambda_{WE} = \lambda_{EW}$ = 0.0025 m^{-1}. Here, the mobile nodes are vehicles. In Fig. 8, $L = L_1 = L_2$, and (a), (b), and (c) are different in the change of the behavior of mobile nodes. In Fig. 8(a), mobile nodes do not change direction after receiving I_{IF}. Namely, p = 0. In Fig. 8(b), they change direction to avoid the FS with probability p = 0.5. In Fig. 8(c), they change direction to approach the FS with probability p = 0.5. We plotted the numerical results of the theoretical analyses in Approximations 1 and 2. Simulation 0 means the results without approximation made for the analyses in Approximations 1 and 2. Simulations 1 and 2 mean the results with approximation made for the analyses in Approximations 1 and 2. In Simulation 1, we removed the nodes of M_{NW} and M_{WN} that don't have I_{IF} before passing O. We made the nodes of M_{NW} and M_{WN} that don't have I_{IF} before passing O have I_{IF} before entering a transmittable area in Simulation 2.



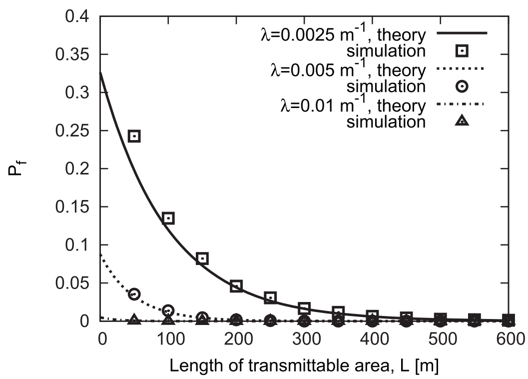
(a) No change of direction

(b) Warning information ($p = 0.5$)

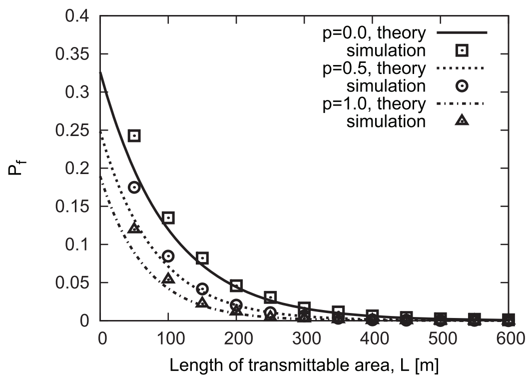
(c) Advertisement information ($p = 0.5$)

Fig. 8 Confirmation of validity of theoretical analysis.

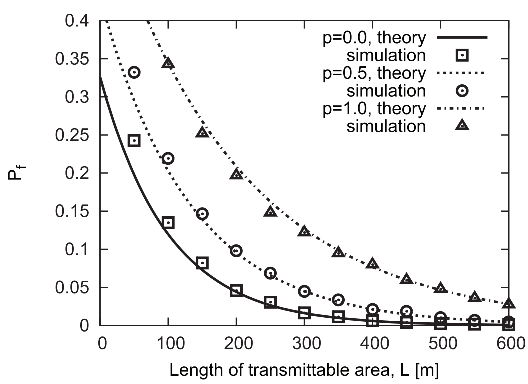
From these figures, we confirmed that the numerical results of Approximation 2 agree with the simulation results of Simulation 2 because the theoretical analysis for the former corresponds to the precise analysis of the latter. The numerical results of Approximation 1 also agree well with the simulation results of Simulation 1, although there is a small difference between them. The small difference was caused



(a) No change of direction

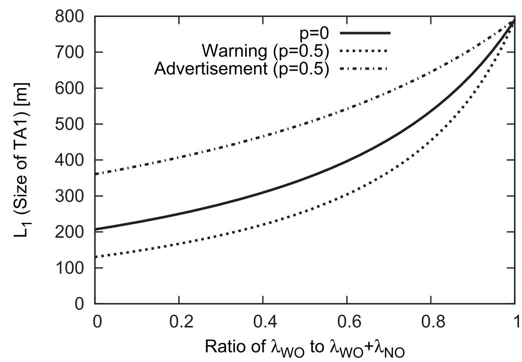


(b) Warning information ($\lambda = 0.0025\ \mathrm{m}^{-1}$)

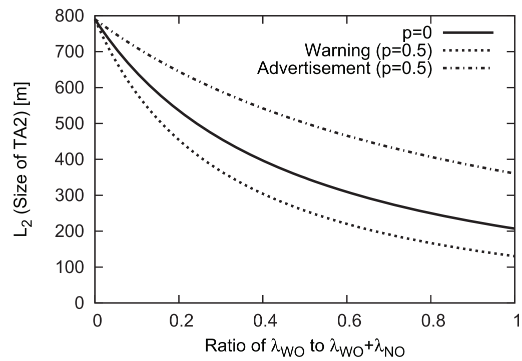


(c) Advertisement information ($\lambda = 0.0025\ \mathrm{m}^{-1}$)

Fig. 9 Basic tendency of P_f for case of uniform traffic.



(a) L_1 (Size of TA1)



(b) L_2 (Size of TA2)

Fig. 10 L_1 and L_2 to maintain $P_f = 0.01$.

by the approximation that the distribution of the nodes that changed directions at the intersection obeys a Poisson distribution.

The results of Simulations 0, 1, and 2 are also close to each other, especially for a large L, which realizes a small P_f. This indicates that we can use the theoretical results for both Approximations 1 and 2 to estimate the transmittable area needed for a sufficiently small P_f. Therefore we only show the numerical results of Approximation 2 and the simulation results of Simulation 0 in the following because the theoretical formula for Approximation 2 is simpler than Approximation 1 and is represented as a closed form equation.

Next, we show the basic tendency of P_f for uniform traffic where $\lambda_{NW} = \lambda_{WN} = \lambda_{NE} = \lambda_{EN} = \lambda_{WE} = \lambda_{EW} = \lambda$, in Fig. 9. In Fig. 9(a), mobile nodes do not change direction, and the P_f results are plotted for three node densities: $\lambda = 0.0025\ \mathrm{m}^{-1}$, $\lambda = 0.005\ \mathrm{m}^{-1}$, and $\lambda = 0.01\ \mathrm{m}^{-1}$. In this figure, P_f becomes larger as λ decreases. Hence, we have to make L larger to maintain a small P_f as λ becomes smaller. For example, to make P_f be close to 0, L should be 50 m, 200 m, and 500 m for $\lambda = 0.01$ m^{-1}, $\lambda = 0.005\ \mathrm{m}^{-1}$, and $\lambda = 0.0025\ \mathrm{m}^{-1}$, respectively.

In Fig. 9(b), the P_f results for the warning information are plotted for $p = 0$, $p = 0.5$, and $p = 1$, where $\lambda = 0.0025$ m^{-1}. P_f becomes closer to 0 as p becomes larger because the nodes of M^c_{NW} and M^c_{WN}, which contribute to IF in TA1 and TA2, respectively, increase as p increases. In contrast, for the advertisement, P_f becomes closer to 0 as p becomes smaller as shown in Fig. 9(c). For the advertisement, let M^{nc}_{NW} be the set of mobile nodes of M_{NW} that receive I_{IF} and do not change direction. In the same manner, M^{nc}_{WN} is defined. The nodes of M^{nc}_{NW} and M^{nc}_{WN} contribute to IF and increase if p decreases. Therefore, the tendency in Fig. 9(c) is obtained.

In Fig. 10, we show the theoretical values of L_1 and L_2 to maintain $P_{f,desired} = 0.01$. We obtain the simulation results of P_f using these L_1 and L_2 values. Figure 11 shows this result. L_1 and L_2 are generally different for nonuniform traffic. Here, we assume nonuniform traffic, and the horizontal axis in Figs. 10 and 11 represents the ratio of λ_{WO} to $\lambda_{WO} + \lambda_{NO}$, while $\lambda_{WO} + \lambda_{NO}$ is constant $0.01\ \mathrm{m}^{-1}$.

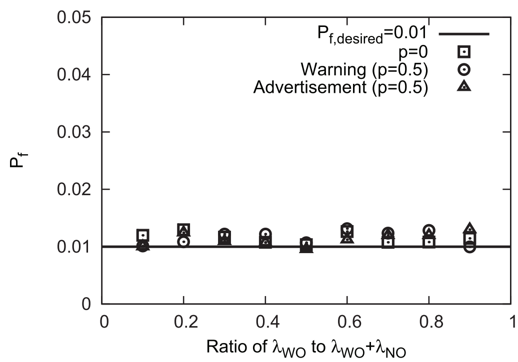
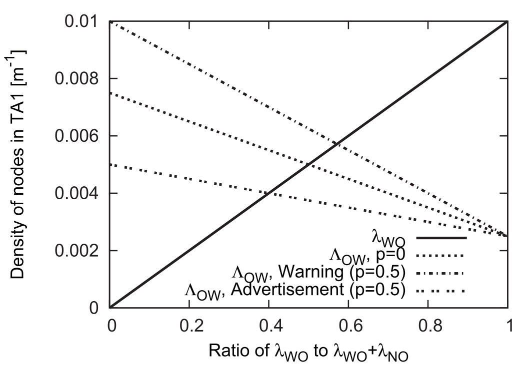
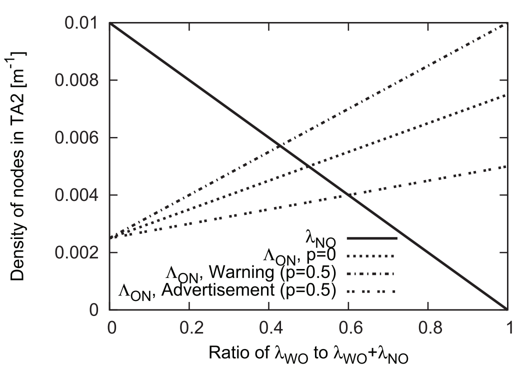


Fig. 11 Simulation results of P_f when L_1 and L_2 values in Fig. 10 are used.



(a) Density of nodes in TA1



(b) Density of nodes in TA2

Fig. 12 Densities of nodes contributing to IF in TA1 and TA2.

The other parameters are as follows: $\lambda_{WN} = \lambda_{WE} = \frac{\lambda_{WO}}{2}$, $\lambda_{NW} = \lambda_{NE} = \frac{\lambda_{NO}}{2}$, and $\lambda_{EW} = \lambda_{EN} = 0.0025\ \mathrm{m}^{-1}$.

From Fig. 10, L_1 can be smaller than L_2 if $\lambda_{WO} < \lambda_{NO}$, and L_2 can be smaller than L_1 otherwise. From Fig. 11, the obtained values of L_1 and L_2 successfully realize P_f close to $P_{f,desired}$.

To explain the tendency in Fig. 10, we show the values of λ_{WO} and Λ_{OW} in Fig. 12(a) and λ_{NO} and Λ_{ON} in Fig. 12(b) because λ_{WO} and Λ_{OW} are the densities of the nodes contributing to IF in TA1 and λ_{NO} and Λ_{ON} are those in TA2. From Fig. 12(a), Λ_{OW} decreases as λ_{WO} increases. Such a decrease of Λ_{OW} increases the required value of L_1 in Fig. 10(a). In contrast, from Fig. 12(b), Λ_{ON} increases as λ_{WO} increases, and such an increase of Λ_{ON} reduces the required value of L_2 in Fig. 10(b). From these tendencies, we can see the importance of Λ_{OW} and Λ_{ON} in TA1 and TA2, respectively. The closed form formula contributes to showing these tendencies by easily computing L_1 and L_2.

5. Conclusions

In this paper, we theoretically analyzed the information floating (IF) performance for warnings and local advertisements. We pointed out that IF analysis in these applications requires a new system model that simultaneously reflects three factors: behavior changes of mobile nodes due to the content of the information, decision deadlines for behavior changes, and the existence of a fixed source of information.

We analyzed P_f, which is the probability that a mobile node cannot receive information, in a simple road network based the above system model. We employed such a simple road network that only includes an intersection to understand the basic IF properties in our new system model as the first step. We obtained probability P_f by numerically solving simultaneous equations with an approximation and derived a closed form of P_f with another approximation. Using the closed form, we also derived the size of each transmittable area to make P_f close to the desired value. We showed the validity of the approximate analyses by comparing the numerical and simulation results and showed the properties of P_f and the size of each transmittable area based on the numerical results.

In this paper, we pay attention to an intersection on the left of a fixed source (FS); however, we implicitly assume a symmetric road network with transmittable areas on its right, and we can apply our theoretical method to such a symmetric road network. As a more general extension, the same problem in a lattice network should be considered.

The theoretical analysis in this paper is the first step of IF research in a new system model with the three factors, and various extensions of the theoretical analysis and other optimization problems are left as important future problems. The theoretical results of this paper showed some basic properties of IF including effects of the three factors. It is an important future problem to explore the difference between the theoretical results and actual behavior of IF in the real environment. To do this, we have to evaluate performance of IF by experiments in the real environment. To perform these experiments, we have to develop actual IF protocols in detail, and realize experimental systems. These are also important future issues.

Acknowledgments

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Appendix: Proof That w_N Cannot Receive I_{IF} if and Only if $Y > Z$ and $L_1 < \frac{Y-Z}{2}$

Let $c(n,t)$ be the coordinate of node n at time t. First we consider a situation S_1, where $Y \leq Z$, as represented in Fig. 7 and Fig. A·1. At $t = t_{past} = t_{pre} - \frac{Y}{v}$, nodes of S_1 are distributed as shown in Fig. A·1, where $c(b_j, t_{past}) = a + L_1$, $c(w_N, t_{past}) = a + L_1 + r - Y$ and $c(w_1, t_{past}) = a + L_1 - r - Y + Z$. If b_j is between w_1 and w_2, or between w_2 and w_3, or ..., or between w_{N-1} and w_N at $t = t_{past}$, then one among $w_1, w_2, \cdots, w_N$ can receive I_{IF} from b_j at $t = t_{past}$ because $X_1 \leq r, X_2 \leq r, \cdots, X_{N-1} \leq r$.

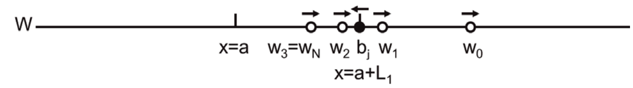
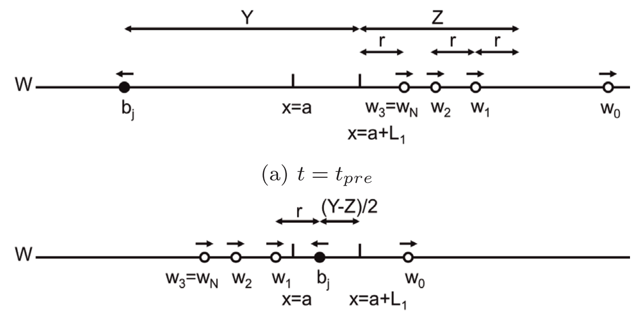


Fig. A·1 Situation S_1 at $t = t_{past} = t_{pre} - \frac{Y}{v}$.



(a) $t = t_{pre}$

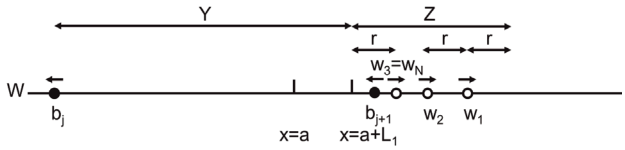
(b) $t = t_{past} = t_{pre} - \frac{Y}{v} + \frac{Y-Z}{2v}$

Fig. A·2 Situation S_2, where $Y > Z$ and $L_1 \geq \frac{Y-Z}{2}$.

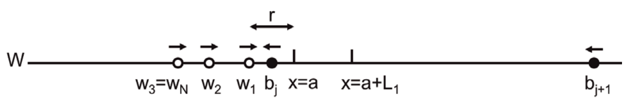
Namely, one among $w_1, w_2, \cdots, w_N$ can receive I_{IF} from b_j if b_j is in the interval $[c(w_N, t_{past}), c(w_1, t_{past})]$ at $t = t_{past}$. Also, if $c(w_N, t_{past}) - r \leq c(b_j, t_{past}) \leq c(w_N, t_{past})$, w_N can receive I_{IF} directly from b_j. If $c(w_1, t_{past}) \leq c(b_j, t_{past}) \leq c(w_1, t_{past}) + r$, w_1 can receive I_{IF} directly from b_j. If $Y \leq Z$, then $c(w_N, t_{past}) \leq c(b_j, t_{past}) + r$ and $c(w_1, t_{past}) \geq c(b_j, t_{past}) - r$. In other words, b_j is in the interval $[c(w_N, t_{past}) - r, c(w_1, t_{past}) + r]$ at $t = t_{past}$. Hence, at least one among $w_1, w_2, \cdots, w_N$ can receive I_{IF} from b_j at $t = t_{past}$ for the above reasons. Consequently, w_N can receive I_{IF} if $Y \leq Z$ because $X_1 \leq r, X_2 \leq r, \cdots, X_{N-1} \leq r$.

Next, suppose that $Y > Z$. First, we consider a situation S_2 in Fig. A·2 to prove that if $Y > Z$ and $L_1 \geq \frac{Y-Z}{2}$, then w_N can receive I_{IF}. Suppose that w_N is at $x = a + L_1 + r$ at $t = t_{pre}$, and $L_1 \geq \frac{Y-Z}{2}$ (Fig. A·2(a)). At $t = t_{past} = t_{pre} - \frac{Y}{v} + \frac{Y-Z}{2v}$, b_j is at $x = a + L_1 - \frac{Y-Z}{2}$ (Fig. A·2(b)). b_j is in TA1 at $t = t_{past}$ because $L_1 \geq \frac{Y-Z}{2}$. At the same time, the distance between b_j and w_1 is equal to r at $t = t_{past}$ because $c(w_1, t_{past}) = a + L_1 - \frac{Y-Z}{2} - r$. Then w_1 receives I_{IF} from b_j at $t = t_{past}$. Hence, w_N can receive I_{IF} via $w_1, w_2, \cdots, w_{N-1}$.

Next, we prove that w_N cannot receive I_{IF} if $Y > Z$ and $L_1 < \frac{Y-Z}{2}$. Suppose that $Y > Z$ and $L_1 < \frac{Y-Z}{2}$. Consider a situation S_3 in Fig. A·3. w_N is at $x = a + L_1 + r$ at $t = t_{pre}$ (Fig. A·3(a)). Suppose that w_1 is at $x = a - r$ at $t = t_{past} = t_{pre} - \frac{Z+L_1}{v}$ (Fig. A·3(b)). Hence, if there is no black node in TA1 during the time period from t_{past} to t_{pre}, $w_1, w_2, \cdots, w_N$ never receive I_{IF}. Because $c(b_j, t_{past}) = a + 2L_1 - Y + Z$ and $L_1 < \frac{Y-Z}{2}$, $c(b_j, t_{past}) < a$. From the definition, $c(b_{j+1}, t_{pre}) > a + L_1$. Also, $c(b_j, t_{pre}) < a$ and $c(b_{j+1}, t_{past}) > a + L_1$ because b_j and b_{j+1} move left. Hence, b_j remains on the left of $x = a$ and b_{j+1} remains on the right of $x = a + L_1$ from t_{past} to t_{pre}. Hence, w_N cannot receive I_{IF} if $Y > Z$ and $L_1 < \frac{Y-Z}{2}$.



(a) $t = t_{pre}$



(b) $t = t_{past} = t_{pre} - \frac{Z+L_1}{v}$

Fig. A·3 Situation S_3, where $Y > Z$ and $L_1 < \frac{Y-Z}{2}$.

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