Broadcasting in DTN as an Epidemic Dynamics

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Broadcasting in DTNs is an important problem with various applications in disaster relief, rural networks, vehicular networks. Significant work has been done in epidemiology that have addressed similar problems in a different setting. A natural question is to understand the applicability of these well understood theories in DTNs. This poster is an attempt towards making these connections. We study the effect of both omnidirectional and directional antenna in broadcasting. We derive an expression for the mean broadcasting time and study the information dissemination in the system using elements of classical epidemiology through rigorous simulations.

I. Introduction

Problem of broadcasting in a wireless delay-tolerant network (DTN) [1] can be appropriately mapped to disease spreading in classical epidemic model. Here, we study the broadcasting properties of a system of mobile agents equipped with short-range communication antennas. We have used specifically directional antenna and omnidirectional antenna and we refer them as "DA" and "OA" respectively in rest of this poster abstract. We consider, for simplicity, that there is only one message to broadcast. In analogy to classical epidemic modeling [2], agents can be in one of three possible states: *susceptible* (agent has not yet received the message), *infected* (agent has received the message and been broadcasting it for a given time), and *recovered* (agent is in idle mode after broadcasting). These three states are abbreviated as S, I and R respectively. The *recovered* agents after some time move back to *susceptible* state, following the classical SIRS dynamics of epidemiology. Due to limited battery power of the DTN nodes, instead of transmitting the message continuously (until battery drains out), the nodes become inactive or idle (recovered state) for some duration (denoted by τ_R). In order to model the store and forward concept of DTN, the message is forwarded for the entire infected period (denoted by τ_I)

We base our study in previous works on disease spreading on mobile agent systems [3–5]. We show that, information spreading dynamics of the systems with only OA agents can be described by simple mean-field theory. We also derive an expression for the average broadcasting time and compare the analytical findings with extensive agent-base stochastic simulations.

The study of epidemic broadcasting with DA is a novel approach and although there are some recent works on broadcast and DA [6, 7], to the best of our knowledge this is the *first* work which explores the impact DA produces through epidemic broadcasting. Interestingly DA with same power performs much better than OA. Precisely, this poster tries to solve the following pertinent problems:

- Understanding broadcasting in DTN using epidemic spreading models (specifically with mean-field approach).
- Estimation of broadcasting time in DTN analytically and experimentally.
- Examining the utility of DA in DTN and detailed comparative study of OA and DA with different conditions.

II. Agent-based model

II.A. Agent motion and antenna direction

We assume agents are self-propelled and move at constant speed in a two-dimensional box with periodic boundary condition, changing their direction of motion at Poissonian distributed times. The equation of motion of the i-th agent can be expressed as:

$$\dot{\mathbf{x}}_i(t) = v\left(\cos(\alpha_i)\check{x} + \sin(\alpha_i)\check{y}\right) \quad (1)$$

$$\theta_i(t) = F_\theta(t) \quad (2)$$

where $\mathbf{x}_i(t)$ represents the position of the i-th agent, $\theta_i(t)$ denotes the orientation of its antenna (a relevant variable for DA, but irrelevant for OA), v is the agent active velocity and α_i is the active direction of motion.

$F_\theta(t)$ is the dynamics of the antenna orientation which is determined by p_{rot}, the probability per time step of changing the antenna direction. Antenna changes its orientation randomly between 0 and 2π. Initially, the distribution of the antenna orientations are random.

II.B. Signal transmission - the agent antenna

Power of the signal captured by receiving agent i from transmitting agent j can be described by the Friis transmission formula as

$$P_r(\mathbf{x}_i, \theta_i, \mathbf{x}_j, \theta_j) = \frac{\lambda^2 P_t G_T(\theta_j, \mathbf{x}_j, \mathbf{x}_i) G_R(\theta_i, \mathbf{x}_i, \mathbf{x}_j)}{(4\pi)^2 \left|\mathbf{x}_i - \mathbf{x}_j\right|^2}$$

where λ is the signal frequency, G_T and G_R represent the gain of the agents in the direction to each other. The functional forms of G_T and G_R depend on the specific antenna and antenna beamwidth γ used by the egents. Agent i receive the message sent by j if P_r crosses a certain threshold δ. For more details regarding the Friis transmission formula and the possible functional forms of G_T and G_R we refer the reader to [8]. However, we have assumed that antennas are not ideal antennas. They exhibit a some small leakage of power as **side lobe** in DA . For more details see [9].

Notice that the system can have a mixture of OA and DA agents. Fig. 1 illustrated the six possible relative orientations of antennas.

III. Mean-field approach

When agent interactions are mainly binary and the system is well-mixed, we can represent the information dynamics by mean-field approach as

$$\dot{S} = \frac{R}{\tau_R} - (\rho\psi)\, IS \quad (3)$$

$$\dot{I} = (\rho\psi)\, IS - \frac{I}{\tau_I} \quad (4)$$

$$\dot{R} = \frac{I}{\tau_I} - \frac{R}{\tau_R} \quad (5)$$

where S, I and R are defined as $S = N_S/N$, $I = N_I/N$ and $R = N_R/N$, with N being the total number of agents in the system, and N_S, N_I, and N_R being the number of susceptible, infected and recovered agents, respectively. Here ρ stands for the agent density and ψ represents the (new) area an agent explores per time unit [5].

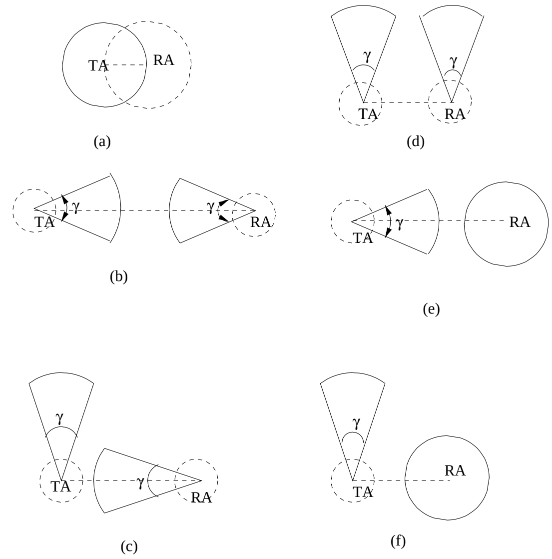

Figure 1: Relevant configurations between transmitting antenna (TA) and receiving antenna (RA), depending on the antenna type. Figure (a) corresponds to a pair of OAs. Figures (b), (c), and (d) illustrates the relevant configurations for a pair of DAs. The mixed case, i.e., the configurations corresponding to OA and DA are illustrated in figures (e) and (f). Notice that if the TA becomes RA and vice versa, the communication range remains the same.

III.A. Average broadcasting time

The fraction of informed agents at time t can be represented as

$$Y(t) = \left(\frac{1}{N} - 1\right) \exp\left[-(\psi\rho)\int_0^t dt' I(t')\right] + 1, \quad (6)$$

assuming that we know $I(t)$ and at $t = 0$ there is only one agent informed and transmitting the message.

According to Eq. (6) all agents receive the message, i.e. $Y(t) = 1$, at $t \to \infty$. No doubt that in a finite system, in simulations $Y(t)$ becomes 1 at a finite time t. To overcome these problems, we propose to use an alternative definition for broadcasting time. According to Eq.(6), $Y(t)$ experiences a crossover when:

$$\int_0^{T_b^*} dt' I(t') = \frac{1}{\psi\rho}, \quad (7)$$

where T_b^* is the new defined broadcasting time representing the time (t) where $Y(t) = 1 - \exp(-1)$.

IV. Results

We have mainly tried to compare the broadcasting behavior in systems with different ratio of OA and DA agents. Note that the power of DA is same as that of OA agents. First, we have shown the closeness of mean-field approach when all agents are equipped

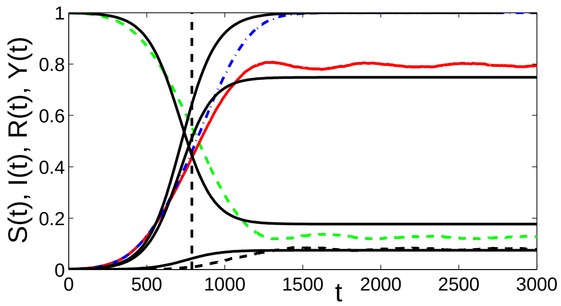

Figure 2: Time evolution of S (green dashed), I (red solid) , R (black dashed), and Y (blue dash-dotted) for a system with $N = 1000$ agents with OA at a density $\rho = 0.06$. Black solid curves correspond to the mean-field approach (Eqs. (3)-(5)) and (6). The vertical black dashed line corresponds to Eq. (7).

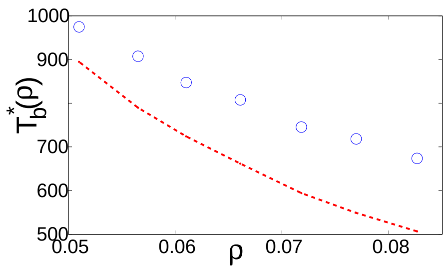

Figure 3: Average broadcasting time T_b^* as function of the agent density ρ. Simulations were performed using $N = 1000$ agents. Each circle corresponds to the average of 100 simulations.The red dashed curve indicates the theoretical prediction given by Eq. (7). Notice that there is no fitting parameter.

with OA. Then we incorporate the DA agents into the systems and observe various interesting results.

IV.A. Omnidirectional antenna

The simulation shown in Fig. 2, and the rest of the simulations of this poster, were performed with $N = 1000$ agents and the following parameters: $\tau_I = 500$, $\tau_R = 50$, and $v = 0.1$. In Fig. 2, agents are equipped with OA with a maximum interaction range $r = 1$, and the linear system size $L = 133$, i.e., $\rho = 0.056$.

Finally, we show that Eq. (7) can be used to predict T_b^* at different densities. Fig. 3 shows T_b^* as function of the agent density ρ. Each circle corresponds to an average over 100 simulations, while the dotted curve is the prediction given by Eq. (7). As it can be observed, the mean-field approach provides a reasonable description of the broadcasting dynamics of the system at intermediate densities without any fitting parameter.

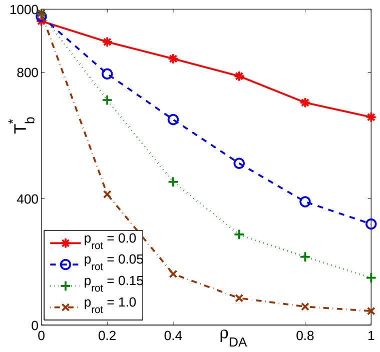

Figure 4: Average broadcasting time T_b^* vs. DA fraction ρ_{DA} for various rotation probability p_{rot}, agent density $\rho = 0.05$, beam width $\gamma = 60$.

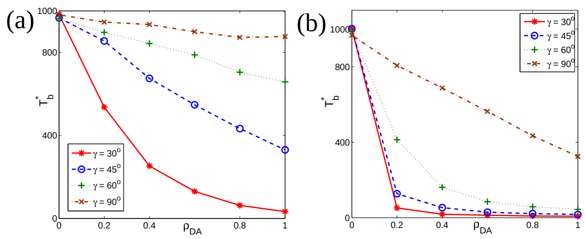

Figure 5: Average broadcasting time T_b^* vs. DA fraction ρ_{DA} for various values of antenna beam width γ with rotation probability $p_{rot} = 0$ (a) and $p_{rot} = 1$ (b) for an agent density $\rho = 0.05$.

IV.B. Omnidirectional vs. Directional antenna

In simulations, DA agents have the same values of P_t and δ as OA agents. Fig. 4 shows that the broadcasting time T_b^* decreases as the fraction of DA agents (ρ_{DA}) is increased. Notice that for $\rho_{DA} = 0$, i.e., for only OA agents, T_b^*, as expected, does not depend on p_{rot}.

Fig. 5 focuses on the two extreme cases, (a) $p_{rot} = 0$ and (b) $p_{rot} = 1$. When $p_{rot} = 0$, the evolution of message broadcasting depends exclusively on agent migration (Fig. 5 (a)). On the other hand, when $p_{rot} = 1$, the new area explored by the antenna per unit time is dominated by the turnings perform by the antenna direction. As it can be seen in Fig. 5 (b), these effects become more pronounced for smaller values of γ.

Fig. 6 shows the response of T_b^* as agent density ρ is changed. The simulation data indicates that DA performs better for all densities. Inset plot of Fig. 6 describes the comparative performance of system with all DA agents over the system with all OA agents. It shows that in higher density DA system performs better. This also highlights the benefits of the longer range transmission of DA agents in higher density where it broadcasts the message more quickly by reaching more number of distant agents.

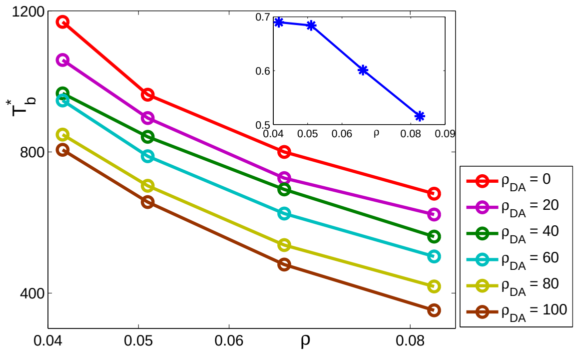

Figure 6: Average broadcasting time T_b^* vs. agent density ρ for various values of DA fraction ρ_{DA}, for $\gamma = 60$, $p_{rot} = 0$. Inset figure shows the Ratio of T_b^* of system with $\rho_{DA} = 100$ and $\rho_{DA} = 0$ for different agent density.

From the above stated detailed simulation results we can infer mainly three important observations:

1. System with DA agents with $p_{rot} = 1$ demonstrates lower broadcast time than the system of DA agents with $p_{rot} = 0$.

2. DA agents with smaller γ performs (in term of T_b^*) comparatively better than the agents with larger γ. This is true for all values of p_{rot}.

3. Independent of other parameters, system with DA agents always show better result compare to the system of only OA agents ($\rho_{DA} = 0$).

V. Conclusions

We have carried out experiments for various beam width, agent density, rotation probability as well as with various proportion of DA and OA. We have taken a deeper look into the dynamics to reason out the cause behind the superiority of DAs. A further more quantitative understanding regarding the effect of mixture of agents with different antenna beam width will facilitate the use of DA more effectively and will be main thrust of future work.

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