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RESEARCH ARTICLE

Modeling epidemic data diffusion for wireless mobile networks

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ABSTRACT

Data/content dissemination among the mobile devices is the fundamental building block for all the applications in wireless mobile collaborative computing, known as mobile peer-to-peer. Different parameters such as node density, scheduling among neighboring nodes, mobility pattern, and node speed have a tremendous impact on data diffusion in a mobile peer-to-peer environment. In this paper, we develop analytical models for object diffusion time/delay in a wireless mobile network to apprehend the complex interrelationship among these different parameters. In the analysis, we calculate the probabilities of transmitting a single object from one node to multiple nodes using the epidemic model of spread of disease. We also incorporate the impact of node mobility, radio range, and node density in the networks into the analysis. Utilizing these transition probabilities, we estimate the expected delay for diffusing an object to the entire network both for single object and multiple object scenarios. We then calculate the transmission probabilities of multiple objects among the nodes in the wireless mobile network considering network dynamics. Through extensive simulations, we demonstrate that the proposed scheme is efficient for data diffusion in the wireless mobile network. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS
mobile P2P; data dissemination; wireless data diffusion

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1. INTRODUCTION

The multifaceted utilization of mobile computing devices, including smart phones, personal digital assistants, tablet computers with increasing functionalities, and the advances in wireless technologies, has fueled the utilization of collaborative computing (P2P, peer-to-peer) technique in mobile environment. Cheap and ubiquitous platforms of networked mobile devices will be the key to real-time delivery of large volumes of useful information and would support a variety of applications. Mobile collaborative computing, known as mobile peer-to-peer (MP2P), can provide an economic way of data access among users of diversified applications in our daily life (exchanging traffic condition in a busy high way, sharing price-sensitive financial information, getting the most-recent news), in national security (exchanging information and collaborating to uproot a terror network, communicating in a hostile battle field), and in natural catastrophe (seamless rescue operation in a collapsed and disaster torn area).

Wireless mobile devices often form on-demand or opportunistic networks to disseminate or exchange data among themselves. The opportunistic network has characteristics of prolonged disconnection and unpredictable and unstable topologies. Therefore, the continuous multihop connection between two end point devices is a fairy tale in most of the cases. The network and application protocol should exploit the proximity of mobile devices to bridge partitions of end point devices.

The great success of P2P networks in wired environments inspires the evolution of MP2P networks. MP2P has been proposed to share the network resources among the peers in mobile network [1]. In a MP2P network, a set of moving peers (throughout the paper, the term peer, mobile device, user, and node are used interchangeably) collaborate with each other to exchange information without using any central coordination or fixed infrastructure in a mobile environment [2–4]. In this paradigm, peer devices are those in transmission range, directly connected with each other in a pairwise basis. To communicate with peers who are outside of transmission range of a node, messages are propagated through multiple hops. MP2P can be implemented in many kinds of network connectivity and mobility conditions.

In many applications, it is necessary to disseminate information to the entire network, that is, to all the participating peers, as fast as possible, because of the temporal nature of the information. Because the transmission in a wireless network is broadcasting in general, we devise analytical models for data diffusion using the broadcast property of the wireless nodes. When multiple nodes try to broadcast data simultaneously, there will be contention among the nodes. In many cases, nodes in contending radio range maintains a scheduling for distributing data. In our models, we also incorporate the interleaving data transmission among the contending nodes. Mobility is a key factor for data dissemination in a mobile network. To address the mobility effect on data diffusion, we consider the speed of nodes and their pattern of movement. Hence, we develop generalized analytical models for epidemic data diffusion in a mobile network, both for single object and multiple objects diffusion. To the best our knowledge, these are the first analytical models in epidemic data diffusion for mobile network.

The remainder of the paper is organized as follows. In Section 2, we give a brief description of existing research works in analytical modeling on data dissemination. In Section 3.1, we describe the system model, and in Section 3, we describe our analytical model for data dissemination based on epidemiology and probability, respectively. Extensive simulations are performed to verify our model in Section 4. We finalize our discussion in Section 5.

2. BACKGROUND AND RELATED WORK

Researchers have been actively investigating data dissemination method for mobile networks, especially mobile *ad hoc* networks [5–9]. As a result, several data dissemination techniques have been proposed in the literature. Most of the technique relies on the simulation results for the verification of their system. A few of the works provide the analytical model for the data dissemination.

Epidemic model for disease dissemination is an important research topic in biostatistics and physiology. The spreading of epidemics is analogous to data diffusion process in many scenarios of communication network. The communication researcher has recently utilized the epidemic model of disease spreading in the field data dissemination for *ad hoc* network. The mathematical field of epidemic modeling has a long history where both the stochastic and deterministic models are used to study for infectious disease [10,11].

Reed-Frost [12] model is the most referenced work in the field of mathematical analysis of epidemiology. However, this model lacks of generalization for generating function. Later, Deitz *et al.* provided a modified model of En'ko, which eliminates the generalization problem of Reed-Frost model [10].

Maria *et al.*, propose seven degrees of separation system for information exchange between mobile and stationary nodes in P2P fashion [13]. This system exploits the host mobility and spatial locality of information. The authors utilize stochastic epidemic model to analytically determine the delay for data spreading to all devices in a network. Their model is a pure birth process that is simple continuous time Markov chain (CTMC). Because only a small number of nodes are considered in this analysis, there is a need of rigorous experiment with many nodes to validate the system. A similar work is presented by Helgason *et al.* [14]. The authors suggest cooperative wireless content distribution using CTMC. The cooperation among the nodes is categorized in three basic types: no cooperation at all, cooperative sharing, and generous sharing. In cooperative sharing, a node shares only the contents that they are interested, whereas in generous sharing, a node relays the content of other nodes. They also extend their model to capture energy and storage limitation of mobile devices. They calculated the absorption state of CTMC numerically. Their numerical results showed that generous cooperation model diffuses data quicker than any other model. However, an analytical study of the Markov chain model is quite complex even for simple epidemic model of data diffusion. Moreover, numerical solutions of such a model become impractical when the number of nodes is enormous. On the other hand, we are interested in modeling data dissemination in large-scale networks.

Recently, modeling based on ordinary differential equation (ODE) for epidemic style data dissemination is gaining popularity in the literature [15,16]. The ODE models appear as fluid limits of Markovian models with appropriate scaling when the number of nodes under consideration is large. The major disadvantage of ODE models over the Markovian model is that they provide the moments of the various performance metrics of interest whereas a numerical solution of Markov chain models can provide complete information about coverage and replication of data.

Khelil *et al.* develop an epidemic-based diffusion algorithm using simulation results [17]. The simulation result has revealed the impact of node density on information diffusion in a mobile network. The observation has guided the authors to lay out an ODE to model the data diffusion pattern. Our analytical model is different from this model because our model is extended to incorporate the other network dynamics for information diffusion.

In [18], Mundinger *et al.* present a data dissemination solution for nodes with different download and upload capacity. The solution based on differential download and upload capacity provides the lower bound for data dissemination among nodes in mobile network. In this paper, the authors has utilized simulation data to measure both the upload and download capacities. Therefore, this analytical solution is heavily dependent on the simulation data instead of real life scenario.

Recently, Özkasap *et al.* have presented the exact performance analysis of the data dissemination in P2P network using anti-entropy algorithm [19,20]. Their data distribution policy is almost similar to epidemic format of data distribution. They describe three different ways of data distribution: *push, pull, and hybrid*. In push approach, the sender proactively asks and delivers objects to the receiver. In pull method, the receiver queries the required objects from the sender and acquires the objects. The hybrid system is a simple combination of both push and pull approaches. The paper claims the exact performance measure in P2P epidemic information diffusion. This epidemic style information dissemination protocol cannot be applicable in MP2P because this protocol does not consider the churn out of peers, which is a common phenomena in MP2P network. Our proposed scheme considers the mobility and uncertainty in mobile P2P network that stand out our scheme from this push, pull, and hybrid data dissemination.

Gossip style data exchange is an important area of research for data dissemination in large-scale data distribution. Rena *et al.* have presented a probabilistic analysis of push/pull approach of a gossip-based protocol [21]. The gossip style data dissemination protocol has been devised from the analytical model using the transition probabilities of the nodes inside a network. The nodes change their state by acquiring, keeping, and releasing objects during data dissemination operation. They have investigated the replication and coverage of an object in a large-scale distributed system. This investigation helps to formulate the expression of approximate time and amount or replication of an object in terms of the number of nodes in a system. The optimal buffer size for each node to maximize the performance of data dissemination in gossip style is one of the contributions of this work. Our proposed scheme differs with this data dissemination protocol in terms of application domain because it is most suitable for wireless mobile network.

3. MODELING AND ANALYSIS OF EPIDEMIC DATA DIFFUSION

In this section, we first describe the system model for the problem domain. Subsequently, we identify and model analytically the data diffusion process in wireless mobile network using MP2P. We separately analyze two different scenarios. First, we consider a situation, where a single object needs to be distributed to all the interested nodes in wireless mobile network. Second, we consider every node in the network holds multiple objects, and these objects will be distributed to every other nodes in network. In other words, there are multiple objects prevail in the network, and a node is interested in all the objects. Eventually, each node will acquire all the objects present in the network. We discuss two analytical models, one for each scenario, in the Sections 3.2 and 3.3, respectively.

3.1. System model

In our system model, we consider a network of mobile nodes, interested in exchanging information. We assume that these nodes can form a network on-the-fly using an *ad hoc* networking technology to establish communication between them. Although search for hardware technologies to engineer *ad hoc* networks is still an active area of research, several of them have already been implemented in wireless local area network [22] and are intended to be implemented in future cellular networks [23–25]. In our model, each node participates in forming a P2P network. We assume that the network is equipped with a low-level (lower than application level) single-hop broadcast service. We consider that all nodes communicate in half-duplex mode. While a node is active in the network, it can discover all other nodes within its radio range and exchange information with them. In the rest of the paper, we emphasize reliable communication at the application level, without considering lower level details. Figure 1 shows an example of the considered network. In the figure, the circles outside the wireless gateway and the mobile devices show the radio range of the gateways and devices. The overlapping circles denote the connection between the devices. The arrows in different direction attached with the users represent direction of movement of the users. These mobile nodes receive information or data as object from either public or private networks and from user inputs. We consider that each mobile node is equipped with (primary, secondary, or both kinds of) memory, as large as to store all the objects. We consider all objects to be diffused to the entire network. Each of the nodes can transmit a complete object with single transmission. This is also true for reception of data. The transmission and reception operations are considered as atomic and error free.

3.2. Single object diffusion

Let the number of peers in the P2P network be N and the peers be designated as $n_1, n_2, \ldots, n_N$. These nodes are moving in a closed area of size A with random direction mobility (RDM) model [26]. The transmission range of each node is r. Let, at any moment t, the total number of nodes infected with a specified content/object be C_t. There are $N - C_t$ susceptible nodes in the network, and all of them are interested to have the particular object. Let S_t be the number of susceptible nodes in a tth period. Formally, the relation of the infective, susceptible, and total nodes can be expressed as

$$C_t + S_t = N, \quad \forall t \tag{1}$$

Therefore, this system can be categorized as a demand-based system [27]. In epidemic modeling, a healthy person

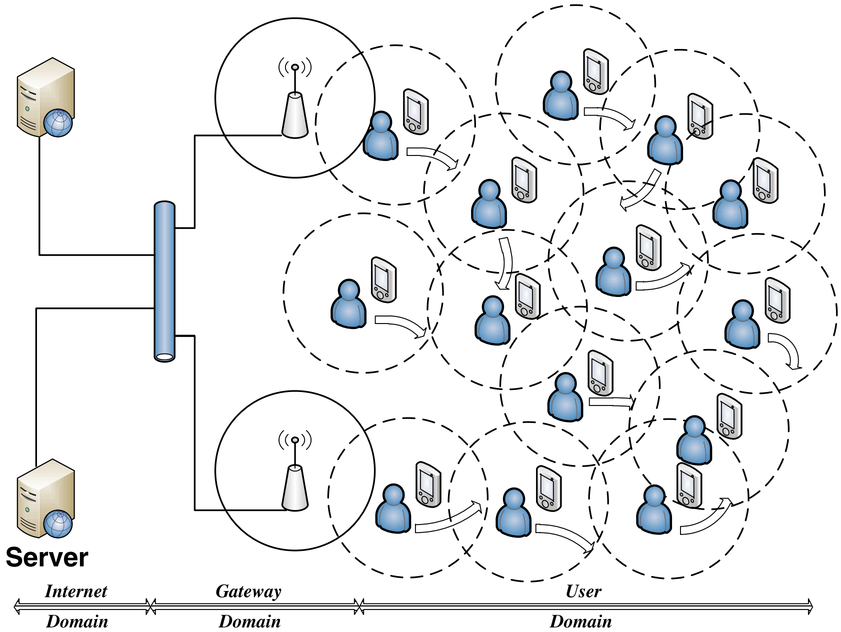

Figure 1. Schematic diagram of the network model.

becomes infected by the transportable disease when he meets an infected individual. Even multiple persons can be infected at the same time. To resemble the real-life scenario of broadcast, we consider that an infected node can transmit data to multiple susceptible nodes in a single transmission.

Consider that the total number of new infected nodes in the $t+1$th time is C'_{t+1}. Therefore, the total infected nodes in the $t+1$th time is

$$C_{t+1} = C_t + C'_{t+1} \tag{2}$$

If an infected node has k neighbors, the probability that any of the neighbors is susceptible can be derived as

$$\alpha = \frac{S_t}{N-1} \tag{3}$$

We also consider two facts of wireless mobile network: mobility and transmission error due to contention. In a mobile network, the nodes are not stationary. Instead, they are moving in a different direction. Therefore, we need to identify the meeting probability between nodes in a network. Additionally, in the wireless network, multiple nodes are able to transmit concurrently. When a node obtains data from multiple nodes simultaneously in a wireless environment, none of the data is correct because of reception error. Therefore, it is not guaranteed that the contact between an infected and susceptible nodes generates a successful event of content transmission. Let β be the meeting probability of two nodes in a network and γ be the probability of successful exchange of data between interested peer in a wireless mobile network. Therefore, a susceptible will be converted to an infective with the probability

$$p = \alpha \times \beta \times \gamma \tag{4}$$

The nodes in the mobile network infected with objects independently. The independence of the infection events motivates us to model the demand-based data diffusion in the wireless mobile network with chain-binomial model. In the chain-binomial model, the number of susceptible node that will be infected in the next time cycle follows the binomial distribution with parameter S_t, p. Thus, the one-step transition probability of the entire system is

$$\begin{aligned} P_{ij}[C_{t+1} = j+i \mid C_t = i] &= \binom{S_t}{j} (p)^j (1-p)^{S_t - j} \\ &= \binom{N-i}{j} (p)^j (1-p)^{N-i-j} \end{aligned} \tag{5}$$

In (5), the state i denotes that the total number of infected node is i, and the state j denotes that the total number new infected nodes is j. Because the state j is completely dependent on the current state i, we can model the entire process as a *Markov process*. Figure 2 shows the transition probability graph for Markov process. Figure 2 shows all possible transitions from state i to another state. Here, the state number inside the circle actually represents the total number of infected node in the current state.

Consider that an infected node has an average of k number of neighbors in a state i. Therefore, the maximum number of newly infected nodes in the next state is

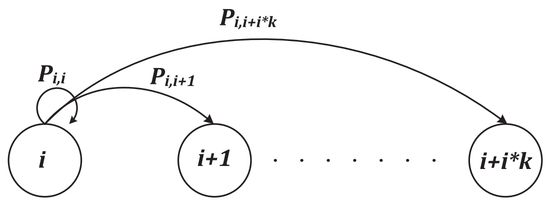

Figure 2. Transition probabilities from *i*th state to next states for Markov chain.

the minimum between the total susceptible nodes and the total number of susceptible neighbors of currently infected nodes. Formally,

$$\max(j) = \min(S_t, \alpha \times i \times k) \tag{6}$$

Therefore, the expected number of new infected nodes in the next step is

$$E[C_{t+1} = j+i | C_t = i] = \sum_{l=0}^{\max(j)} \binom{S_t}{l} (p)^l (1-p)^{S_t - l} \times l \tag{7}$$

There is a critical parameter k that is the average number of neighbors of an infected node at each stage. In this analytical model, we assume that the nodes are uniformly distributed in the whole network area. Therefore, node's radio range plays an important role for identifying the number of neighboring nodes. A good approximation is to find the ratio of the covered region of the infected node to the total area of the entire region. This ratio can be used to estimate the number of neighbors of an infected node.

3.2.1. Area under the coverage.

Finding the area under the coverage of the multiple infected nodes' radio range is a challenging task, because in a small area, compared with the number of infected nodes and their radio range, there are multiple overlapping of the covered area. Therefore, simple addition of the geometric covered area would not give the actual area covered by multiple nodes. We assume that the wireless coverage of a node is represented by a circle where the radius of the circle is equivalent to the radio range. We will use the term "circle as" the coverage area of nodes radio throughout the section. To obtain the good approximation, we analytically estimate the area under the coverage in the following.

Consider there are n equal circles in a unit area where the radius of each circle is r. The area of ith circle is designated as a_i. We can find the actual area under coverage

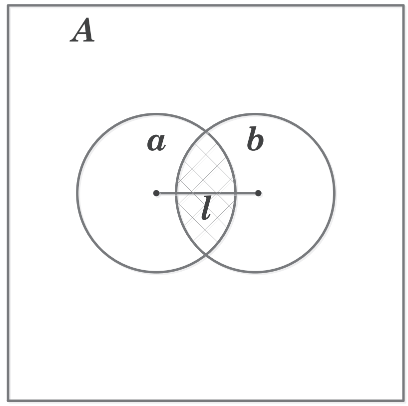

Figure 3. Intersection of two circles.

with n circles ϕ_n using the inclusion-exclusion principle

$$\begin{aligned}\phi_n &= \left|\bigcup_{i=1}^{n} a_i\right| \\ &= \sum_{i=1}^{n} |a_i| - \sum_{1 \le i < j \le n} \left|a_i \bigcap a_j\right| \\ &\quad + \sum_{1 \le i < j < k \le n} \left|a_i \bigcap a_j \bigcap a_k\right| \\ &\quad - \cdots + (-1)^{n-1} \left|a_i \bigcap \ldots \bigcap a_n\right| \\ &= n|a_1| - \binom{n}{2} \left|a_1 \bigcap a_2\right| + \binom{n}{3} \left|a_1 \bigcap a_2 \bigcap a_3\right| \\ &\quad - \cdots + (-1)^{n-1} \left|a_i \bigcap \ldots \bigcap a_n\right| \end{aligned} \tag{8}$$

In (8), the unknown terms to find the actual coverage area is the intersection area of multiple $(2, 3, \ldots, n)$ circles. The intersection areas are calculated in the following.

Case 1: When there is only one infected node, the area under the radio range of the node is the coverage area of the infected node.

Case 2: When there are two infected nodes in an area A, there is a possibility that the coverage area of this two nodes will overlap. Figure 3 illustrates one of the possible scenarios. In this figure, the circle a and the circle b are intersected with each other. The distance of their centers is ℓ. We can find the coverage area for both circle in the unit square A using the following theorem.

Theorem 1. *The expected area of intersection of two equal circles in a unit square is* $\int_0^{2r} 2\ell(\ell^2 - 4\ell + \pi) \times \left(2r^2 \cos^{-1}(\ell/2r) - (\ell/2)\sqrt{4r^2 - \ell^2}\right) d\ell$ *where* r *is the radius of each circle and* ℓ *is the*

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distance between the centers of the circles and $0 \le \ell \le 2r$.

Proof. Consider that the radius of the circles is much smaller than each side of the unit square. Two circles intersect with each other if and only if $0 \le \ell \le 2r$. Therefore, the probability that two arbitrary circles in a unit square intersect is equivalent to the probability of the distance between the centers of the circles is less than $2r$. The probability $p(\ell)$ of the distance between the centers of the circles, ℓ, is [28]

$$p(\ell) = 2\ell(\ell^2 - 4\ell + \pi) \tag{9}$$

The intersection area of two circles is dependent on the radius of each circle, r, and the distance between the centers of the circle. The intersection area ϕ_2 is given by

$$\phi_2 = 2r^2 \cos^{-1}\left(\frac{\ell}{2r}\right) - \frac{\ell}{2}\sqrt{4r^2 - \ell^2} \tag{10}$$

In both (9) and (10), the only variable is ℓ. The value of ℓ can be varied from 0 to $2r$. Therefore, the expected intersection area $E[\phi_2]$ between two arbitrary circle in a unit square is

$$\begin{aligned} E[\phi_2] &= \int_0^{2r} p(\ell) \times \phi_2 \, d\ell \\ &= \int_0^{2r} 2\ell(\ell^2 - 4\ell + \pi) \\ &\quad \times \left(2r^2 \cos^{-1}\left(\frac{\ell}{2r}\right) - \frac{\ell}{2}\sqrt{4r^2 - \ell^2}\right) d\ell \end{aligned} \tag{11}$$

□

Case 3: Three circles can intersect in three ways. Because (11) utilizes only the intersection of three circles, we are interested in the common intersection area ϕ_3 of circles a, b, and c in Figure 4. The following theorem states the intersection area of three circles in a unit square.

Theorem 2. *Consider three arbitrary circles a, b, and c with radius r in a unit square. The probability of mutual intersection of these three arbitrary circles in a unit square is* $\left(2\ell(\ell^2 - 4\ell + \pi)\right) \times \left(4r^2 \cos^{-1}(\ell/4r) - (\ell/2)\sqrt{16r^2 - \ell^2}\right)$ *where*

- ℓ *is the distance between the centers of any two circles* `a` *and* `b` *and* $0 \le \ell \le 2r$
- d *is the maximum distance from the center of the circle* `c` *to the center of any circle* `a,b` *and also* $0 \le d \le 2r$

Proof. We prove this theorem in two parts. From Theorem 1, the probability of intersection between two circles in a unit square is $2\ell(\ell^2 - 4\ell + \pi)$ where the distance between the center of the circle is ℓ. Because the probability states the intersection of two circle, for example, the circle `a,b`, we need to find out the probability of the intersection of the another circle, `c`, to both the circles `a,b`. The condition of intersection of any circle with circle `c` is that the distance between the centers of the circle and circle `c` must be less than $2r$. In Figure 5, a_0 and b_0 denote the center of circles `a,b`, respectively. We just draw two circles with radius $2r$ concentric to a_0 and b_0, respectively. Both of the circles are shown by dashed line in Figure 5. Because the center c_0 of the circle `c` must be with the range of $2r$ from both a_0 and b_0, c_0 must lie inside the intersecting area of the two outer circles with radius $2r$. The enclosed area by the arc pqr and psr is the intersection area of the two outer circles.

The area of the square A is equivalent to a unit square. Therefore, the area enclosed by the arc pqr and psr is equivalent to the probability of

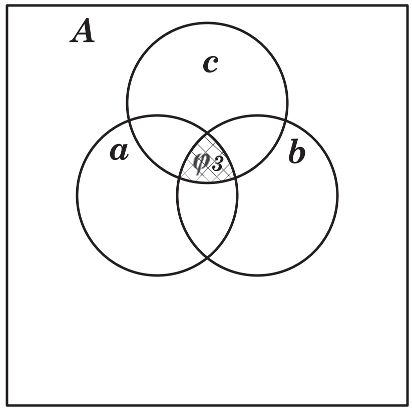

Figure 4. Intersection of three circles.

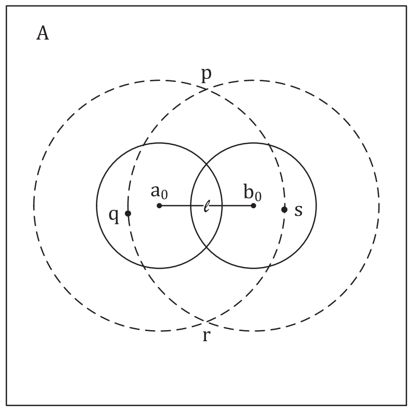

Figure 5. Possibility of third circle for intersection.

having the center of an arbitrary circle. The distance between the centers of the outer circle is ℓ. Therefore, the enclosed area is

$$\varphi = 4r^2 \cos^{-1}\left(\frac{\ell}{4r}\right) - \frac{\ell}{2}\sqrt{16r^2 - \ell^2} \quad (12)$$

The probability of mutual intersection of three circles is

$$\wp = \left(2\ell(\ell^2 - 4\ell + \pi)\right) \times \left(4r^2 \cos^{-1}\left(\frac{\ell}{4r}\right) - \frac{\ell}{2}\sqrt{16r^2 - \ell^2}\right) \quad (13)$$

□

Corollary 1. *The expected mutual intersecting area of three circles is*

$$\omega = \int_0^{2r}\int_0^{2r} \wp \times p(s) \times \phi_3 \,\mathrm{d}\ell\, \mathrm{d}s \quad (14)$$

where $p(s)$ denotes the probability density for distance s between the center c_0 and any of the centers a_0 and b_0 [29]

$$p(s) = \left[\frac{2s}{r^2}\left(\frac{2}{\pi}\cos^{-1}\left(\frac{s}{2r}\right) - \frac{s}{\pi r}\sqrt{1 - \frac{s^2}{4r^2}}\right)\right] \quad (15)$$

and ϕ_3 denotes the intersection area of three circles [30].

Case 4: Calculation of intersecting area geometrically for more than three circles is (almost) unsolvable because exponential number of combinations in the arrangement of four or more circles exhibits the complexity for finding a closed-form equation to calculate the intersection area. Moreover, the intersecting area for two and three circles dominate results than intersection of more circles with small number of circles compared with large area. Therefore, we restrain to find the closed-form equation of finding the expected area of intersection for more than three circles.

In [31], Librino *et al.* devise an trellis-based iterative algorithmic solution to compute the intersection area for more than three circles. The expected mutual intersection area can be calculated using this algorithm with the intersection probability for more than three circles. We find combination in the arrangement of different number of circles in an area experimentally and generate the probability of intersecting more than three circles in an area from this combination.

In the aforementioned description, we have perceived the way of calculating the mutual intersection area for different number of circles. This values can be inscribed in (8) to calculate the actual coverage area by different number of overlapping circles in an area. Consider the total area covered by the infected nodes C_t is A_1. Then the value of number of neighbors, k, is

$$k = \frac{A_1}{A} \times \frac{N}{C_t} \quad (16)$$

3.2.2. Mobility parameter.

In (4), the meeting probability β among the nodes is a pivotal parameter. Because we consider a mobile network, the nodes' movement pattern influences the meeting probability. If the transmission range r is small compare with the area size A, it has been shown that the exponential inter-contact time is a good approximation for both random way point and RDM model [32]. In [32], Jindal *et al.* presented a meeting rate between any two nodes in an area where all nodes follow the random direction model. Let $\bar{L}$ be the epoch length, $\bar{v}$ the average node speed, $\bar{T}_{\text{stop}}$ the average pause time after an epoch, and $\bar{T}$ the expected epoch duration. Let node x move according to the RDM from its stationary distribution at time 0. Let y be a static node uniformly chosen from the total nodes N. The expected hitting time ET_{rd} of node x and node y for the random direction model is given by

$$ET_{\text{rd}} = \left(\frac{A}{2r\bar{L}}\right)\left(\frac{\bar{L}}{\bar{v}} + \bar{T}_{\text{stop}}\right) \quad (17)$$

If node y is also moving according to the RDM, then the probability distribution of the meeting time EM_{rd} for the RDM has an approximately exponential distribution and the expected value

$$EM_{\text{rd}} = \frac{ET_{\text{rd}}}{p_m \hat{v}_{\text{rd}} + 2(1 - p_m)} \quad (18)$$

where $\hat{v}_{\text{rd}}$ is the normalized relative speed for RDM and $p_m = \bar{T}/(\bar{T} + \bar{T}_{\text{stop}})$ is the probability that a node is moving at any time. The normalized relative speed for this RDM model is $\hat{v}_{\text{rd}} = 1.27$ [32].

The expected time for any node x to reach any other node in the network is

$$\tau = \frac{EM_{\text{rd}}}{N - 1} \quad (19)$$

Therefore, the rate of contact between any of two nodes in a network with N nodes that are moving according to RDM model is

$$\lambda = \frac{1}{\tau} = \frac{N - 1}{EM_{\text{rd}}} \quad (20)$$

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Because the intercontact times among the nodes are exponentially distributed, we can calculate the value β of (2) as

$$\beta = 1 - e^{-\lambda} \tag{21}$$

3.2.3. Scheduling parameter.

The contact between an infected and susceptible is not always guaranteeing a successful transmission of an object. There are three folds of contention that may occur for the event of transmission in a wireless network. These are *finite bandwidth, scheduling, and interference*. In this paper, we only consider the scheduling issue for the transmission. We have also utilized the transmission probability due to scheduling presented by Jindal *et al.* [32]. Let E_{sch} represent the event that a scheduling mechanism allows nodes x and y to exchange a object in a time unit. The scheduling mechanism prohibits any other transmission within one hop from the transmitter and receiver in the same time unit. The probability of this event $P(E_{\text{sch}})$ is dependent on the interested transmitter–receiver pair that contending with the x–y. Because we consider only the scheduling issue in the wireless network, it is obvious that

$$\gamma = P(E_{\text{sch}}) \tag{22}$$

Consider that there are a nodes within the one hop of the transmitter and receiver pair and that there are c number of nodes within two hopes but not in one hop of the x–y pair. Event E_a denotes the existence of a nodes, and E_c denotes the existence of c nodes. Let $t(a, c)$ denote the expected number of possible transmission within the range of x–y pair. By symmetry, all contending pairs are equally likely to capture the time slot and start transmission. Therefore,

$$P(E_{\text{sch}}|E_a, E_c) = \frac{1}{t(a, c)} \tag{23}$$

where $t(a, c)$ can be calculated using (23).

$$t(a, c) = \left(1 + p_a p_{ex}\left(\left(\begin{array}{c} a \\ 2 \end{array}\right) - 1\right)\right) + \frac{a c p_c p_{ex}}{2} \tag{24}$$

where

$$p_a = \frac{1}{16} + \frac{A}{4\pi r^2} \tag{25}$$

$$p_c = \frac{3}{20} - \frac{A}{5\pi r^2} \tag{26}$$

$$\begin{aligned} A = \int_r^{2r} \frac{x}{2r^2} \Bigg(& r^2 \cos^{-1}\left(\frac{x^2 - 3r^2}{2rx}\right) \\ & + 4r^2 \cos^{-1}\left(\frac{x^2 + 3r^2}{4rx}\right) \\ & - \frac{1}{2}\sqrt{(x^2 - r^2)(9r^2 - x^2)}\Bigg)\, dx \end{aligned} \tag{27}$$

The only unknown value of (23) is p_{ex}. The value of p_{ex} can be calculated using (24)

$$\begin{aligned} p_{ex} = & \sum_{m=1}^{N-1} \frac{2m(N-m)}{N(N-1)} \sum_{i=m}^{N-1} \frac{1}{N-1} \frac{1}{m(N-m)} \\ & \times \frac{1}{\sum_{j=1}^{i} \frac{1}{j(N-j)}} \end{aligned} \tag{28}$$

3.2.4. Getting the final result.

The values of α, β, and γ are derived analytically and can be substituted in (2). Using these values, we can calculate the expected number of new infected nodes from (4). In the next section, we will present the rigorous simulation result and compare the result with analytically derived values of infected nodes in each time unit.

3.3. Multiple objects diffusion

Consider a system where multiple objects will be disseminated in a network. Assume that there are m number of objects to be distributed in a network of N nodes where $N \geq m$. Initially, each of the m objects will be held by a single node. Therefore, the probability for a node to hold any object is m/N. Consider that a node n_0 has O_t objects at any instant t. The initial and terminal conditions of O_t can be described as

$$O_0 = \frac{m}{N} \tag{29}$$

$$O_\infty = m \tag{30}$$

Each node has k average neighboring nodes. Without loss of generality, we can consider that each of the neighbors has also O_t number of objects at the time instant t. Consider that a node n_0 and the neighboring nodes of n_0 have w different objects than the node n_0. Consider that V_k denotes the set of unique objects among k nodes where each of the k nodes contains $O_t^1, \ldots, O_t^k$ objects, respectively. O_t^0 denotes the set of objects in node n_0. Formally,

$$\begin{aligned} V_k &\subseteq O_t^1 \cup \ldots \cup O_t^k \\ w &\subseteq V_k \setminus O_t^0 \end{aligned} \tag{31}$$

We will show the derivation for calculating the value of w.

The k neighbors of node n_0 hold total $k \times O_t$ elements on average at any time t. We consider two aspects for calculating the object difference between the node n_0 and the rest of the k neighbors. The aspects are as follows:

(1) All the objects that are held by k neighbors may not be unique.
(2) There could be overlap of objects between the node n_0 and the k neighbors.

To compute the first aspect, we must find the probability of unique objects among two nodes. The following theorem gives the probability of unique objects in k nodes in a network.

Theorem 3. *The total expected number of unique objects held by k nodes in a network is*

$$V_k = V_{k-1} + \sum_{l=0}^{O_t} \frac{\binom{O_t}{l}\binom{m - O_t}{V_{k-1} - O_t + l}}{\binom{m}{V_{k-1}}} \times l \quad (32)$$

where there total number of objects prevail in a network is m and each node holds O_t number of objects at time instant t.

Proof. To proof the theorem, we need to establish the base case when the number of node is 0 and 1.

Case k=0: When the number of node is 0, for example, $k = 0$, then

$$V_0 = 0 \quad (33)$$

Case k=1: If we consider only one node, then total number of objects held by this node represents the total number of unique objects. Here, each node contains O_t number of objects at any time instant t. Therefore,

$$V_1 = O_t \quad (34)$$

Case k≥2: Consider, two nodes n_a and n_b in a network where each of them holds O_t^a and O_t^b objects at any time instant t among the total m objects in network. There are g objects that are in common between O_t^a and O_t^b. The n_b node contain z number exclusive objects than the node n_a. Figure 6 shows the object allocation between the nodes n_a and n_b, the common objects g, and the exclusive objects z in the node n_b. Formally,

$$\begin{aligned} g &\subseteq O_t^a \cup O_t^b \\ z &\subseteq O_t^b \setminus O_t^a \end{aligned} \quad (35)$$

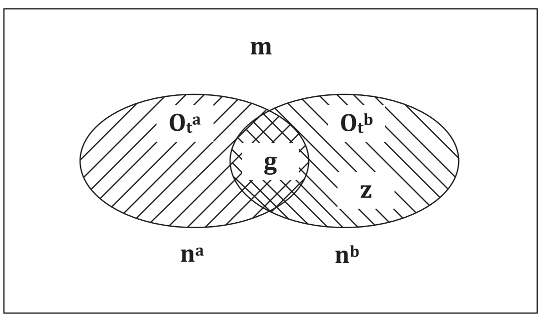

Figure 6. Set representation of object allocation between node n_a and n_b.

The probability of z exclusive objects in n_b than n_a is

$$p(z) = \frac{\binom{O_t^b}{z}\binom{m - O_t^b}{O_t^a - O_t^b + z}}{\binom{m}{O_t^a}}, \quad \text{where} \quad O_t^a \geq O_t^b \quad (36)$$

The expected number of exclusive objects held by the node n_b is

$$E[z] = \sum_{l=0}^{O_t^b} \frac{\binom{O_t^b}{l}\binom{m - O_t^b}{O_t^a - O_t^b + l}}{\binom{m}{O_t^a}} \times l \quad (37)$$

Therefore, the total number of unique objects held by these two nodes is

$$\begin{aligned} V_2 &= O_t^a + \textit{Total number of exclusive objects held by node b} \\ &= O_t^a + E[z] \\ &= O_t^a + \sum_{l=0}^{O_t^b} \frac{\binom{O_t^b}{l}\binom{m - O_t^b}{O_t^a - O_t^b + l}}{\binom{m}{O_t^a}} \times l \end{aligned} \quad (38)$$

Consider that both nodes n_a and n_b contain the average number of objects, O_t. Therefore, $O_t^a = O_t^b = O_t$. Because $O_t^a = O_t$, the O_t^a can be replaced by V_1. (38) can be expressed with respect to (34) as

$$\begin{aligned} V_2 &= V_1 + \sum_{l=0}^{O_t^b} \frac{\binom{O_t^b}{l}\binom{m - O_t^b}{V_1 - O_t^b + l}}{\binom{m}{V_1}} \times l \\ &= V_1 + \sum_{l=0}^{O_t} \frac{\binom{O_t}{l}\binom{m - O_t}{V_1 - O_t + l}}{\binom{m}{V_1}} \times l \left[\because \; O_t^b = O_t\right] \end{aligned} \quad (39)$$

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Thus, we can write a general equation for total unique objects held by k nodes in a network in a recursive fashion of (39),

$$V_k = V_{k-1} + \sum_{l=0}^{O_t} \frac{\binom{O_t}{l}\binom{m - O_t}{V_{k-1} - O_t + l}}{\binom{m}{V_{k-1}}} \times l \tag{40}$$

□

Next, we calculate the second aspect where node n_0 has some objects that are also held by the k neighbors. Because V_k denotes the total number of unique objects held by the k neighboring nodes of n_0 and O_t represents the total objects in n_0, we should find the number of common objects in between O_t and V_k. It is inevitable that $V_k \geq O_t$ where $k \geq 1$. The probability that there are g number of common objects in V_k and O_t is

$$p(g) = \frac{\binom{O_t}{g}\binom{m - O_t}{V_k - g}}{\binom{m}{V_k}} \tag{41}$$

The expected number of common objects held by the two nodes is

$$E[g] = \sum_{l=0}^{O_t} \frac{\binom{O_t}{l}\binom{m - O_t}{V_k - l}}{\binom{m}{V_k}} \times l \tag{42}$$

Thus, the total number of objects in V_k that are not in the node n_0 is

$$w = V_k - E[g] \tag{43}$$

In the system model, consider that every node posses enough bandwidth to send all the objects it holds and receive all the objects it obtains from its neighbors in a single transmission. Thus, in an ideal condition, the node n_0 will receive all the w objects in the next round (t + 1). However, in wireless mobile network, the mobility and transmission error play crucial role for data dissemination. The meeting probability β between nodes in a mobile network is given in (21). Equation (22) provides the successful transmission probability γ of objects in wireless network where multiple nodes can transmit simultaneously. Thus, the expected number of objects that the node n_0 will get in the $t + 1$ round is

$$\begin{aligned} O_{t+1}^{exp} &= w \times \beta \times \gamma \\ &= (V_k - E[g]) \times \beta \times \gamma \\ &= \left(V_k - \sum_{l=0}^{O_t} \frac{\binom{O_t}{l}\binom{m - O_t}{V_k - l}}{\binom{m}{V_k}} \times l \right) \times \beta \times \gamma \end{aligned} \tag{44}$$

In (44), the variable V_k is dependent on the value of O_t. The O_t is a time-varying variable that denotes the average number of objects in a node in the network at time t. The m is constant for particular network. The values of β and γ are dependent on the network parameter that has been shown in the previous section. Therefore, (44) gives the near perfect approximation of acquiring objects by a node in a network of epidemic dissemination for multiple objects.

4. SIMULATION RESULTS

To verify the analytical model of epidemic diffusion of data, we developed a discrete event simulator in C++. In simulation, we mimic the real-time scenario for mobile network. We consider that peers use a distributed maximal independent set algorithm [33,34] to find non-interfering nodes in a network. Members of an independent set can transmit simultaneously without network interference. Note that maximal independent set of a wireless mobile network changes because of mobility of nodes. Consider that L is the number of maximum independent sets during the cycle t and $S_i(t)$ is the ith independent set. Then the following equality holds:

$$N = \sum_{1 \leq i \leq L} |S_i(t)| \tag{45}$$

The distribution cycle is divided into the L number of slots; that is, the total number of slots in a cycle is equivalent to the number of maximum independent sets. A peer $p \in S_i(t)$ transmits only during the ith slot.

In simulation, we focus on a wireless network with different node densities on a square area of 500 m^2. The total number of nodes varies in the areas from 100 to 200 nodes. Initially, these nodes are randomly distributed throughout the simulation area. We assume that nodes mobility pattern follows RDM model with a mean speed of 1–5 m/s and mean pause time before changing direction of movement is 0 s. We consider this setting that will represent the customers mobility within a mall to a slow moving vehicle in a city. We assume nodes to be equipped with a standard IEEE 802.11 interface. We experiment with different radio transmission ranges from 20 to 60 m.

We simulate both single object and multiple objects scenarios separately and compare the simulation results with our analytical results. For single object diffusion, a node is chosen randomly and given an object. This object is diffused in the entire network. In multiple object diffusion, each node holds a unique object. The simulation terminates when all nodes get all the objects presented in the network.

4.1. Single object diffusion

This section discusses the validity of the presented analytical model for single object data diffusion through simulation. For the simulation, an object is given to a randomly chosen node in the network. This node broadcasts this object to its neighbors. This process continues until all the nodes in the network obtain that object.

Figure 7 shows the comparison of the analytical results with the simulation results. In this figure, the number of infected nodes is plotted with the passage of time. The result shows that both the analytical results and the simulation result match with close proximity. The analytical result indicates little slower infection rate than the simulation result in the beginning. Later, the analytical result coincides with the simulation result. This behavior is expected because all the neighbors of the infected node in simulation effected immediately and so on. On the contrary, every step in the analytical result, the number of neighbors is calculated on the average of the entire area.

In the epidemic data dissemination, the number of nodes and their speed of moving are key factors. We consider different number of nodes moving in a 500 m × 500 m area where each node has a radio range of 30 m. In Figure 8, we can observe that the time for object diffusion among all the nodes decreases with the increase of nodes. However, the enormous increase of nodes in terms of data distribution area may not follow the same result. This fact can also be observed from the same figure. The rate of decrease for data diffusion time declines with the increase of the number nodes. The similar argument also holds for the speed of the nodes. The data diffusion rate increases (alternatively, data dissemination time decreases) with changing the node speed of the mobile modes from 1 to 2 m/s. Nevertheless, data diffusion rate increases when the nodes move with 3 m/s. However, the rate of increase is sufficiently lower than the previous step. Our proposed analytical model is able to anticipate all the aforementioned scenarios as expected. In our analytical model, we consider the number of nodes, the scheduling among the nodes for data broadcasting, and the speed of the nodes. Figure 8 shows that our analytical result gives the almost accurate result.

Figure 9 shows the impact of radio range and the speed of nodes for object dissemination. With larger radio range, a node can communicate with more number of nodes at a time. Thus, a node can transmit and receive object to and from many nodes than the nodes with smaller radio range. However, the larger radio range does not only bring benefit. Instead, it has some drawbacks in scheduling-based broadcasting. In scheduling-based broadcasting, whereas a node gets the opportunity to broadcast its objects, none of its neighbors is able transmit object. With larger radio range, a node has many neighbors. Thus, a node has to wait long time to get its turn to broadcast. In addition, larger radio range increases the chance of collision of transmitted objects. Therefore, the data dissemination does not increase linearly with the increase of radio range. In the previous paragraph, we have already discussed the impact of mobility on data dissemination. Figure 9 also shows the analytical and simulation results of data dissemination among 100 nodes with different radio ranges and the node speeds. The difference of data diffusion time between the analytical and the simulation ones is less than 10% in all cases. Therefore, the result reveals that our proposed analytical model provides an optimistic prediction about data diffusion pattern and delay for entire network. The main reason of near perfect prediction is that this model also considers the average number of neighbors of infected nodes at each step of progression.

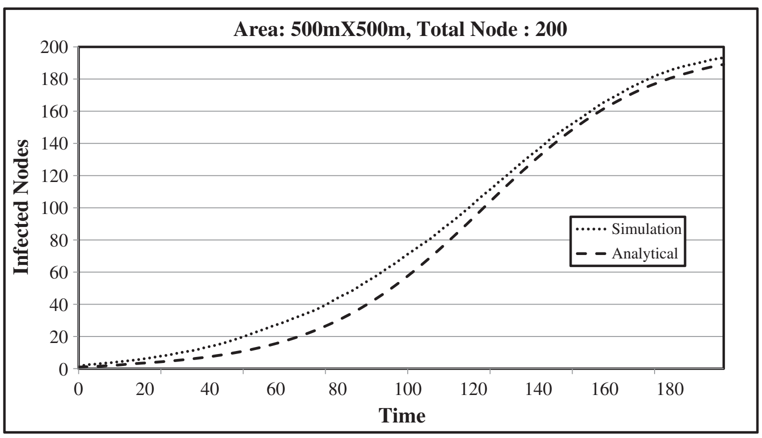

Figure 7. Comparison of analytical and simulation model for radio range 20 m.

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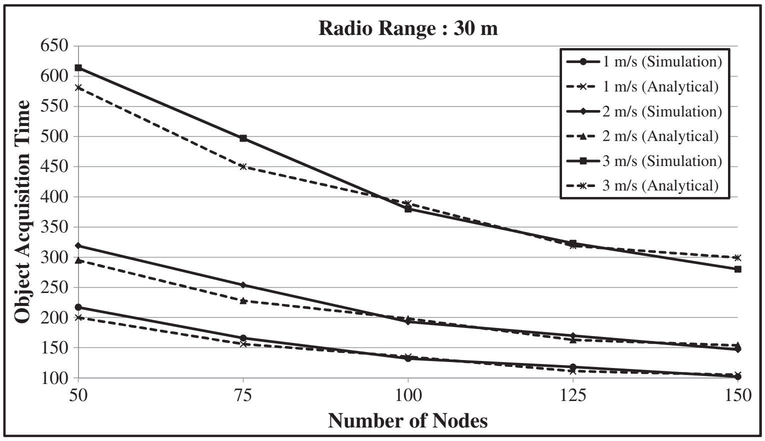

Figure 8. Comparison of analytical and simulation model for different number of nodes.

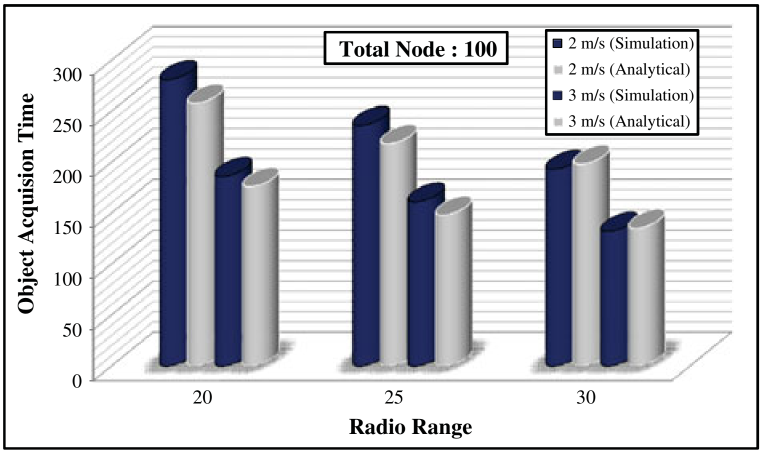

Figure 9. Comparison of analytical model and simulation result with the impact of mobility.

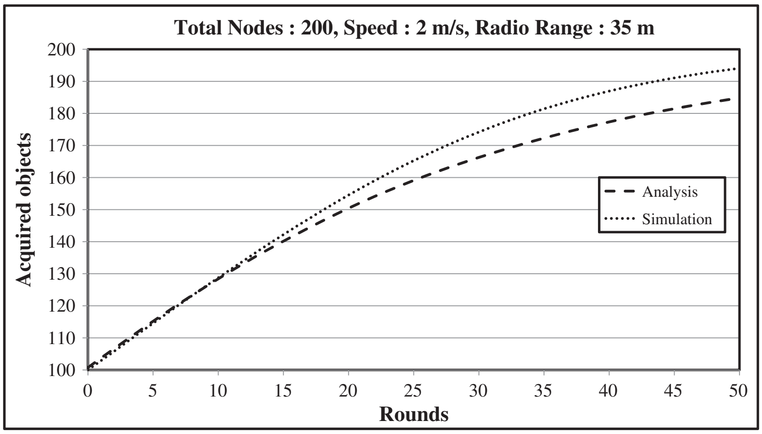

Figure 10. Comparison of analytical model and simulation of data dissemination.

4.2. Multiple object diffusion

In the multiple object diffusion simulation, a node exchanges all the objects it has in the meeting with other nodes. The simulation terminates when all the nodes in the network acquired all the objects prevail in the network.

Figure 10 shows the analytical results and simulation results for object dissemination pattern in the network for

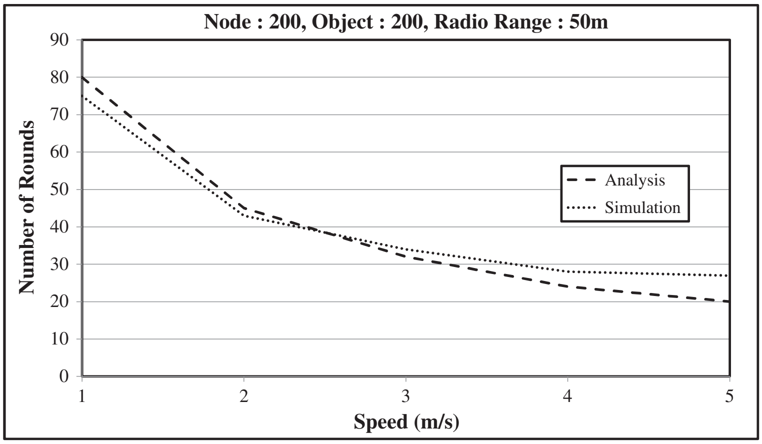

Figure 11. Comparison of analytical model and simulation with the impact of mobility.

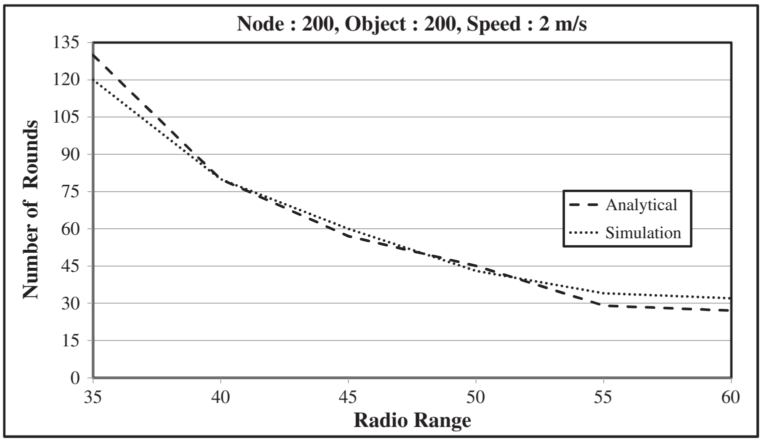

Figure 12. Comparison of analytical model and simulation with the impact of radio range.

200 nodes. The speed of each node is 2 m/s, and the radio range of each node is 35 m. A node will get 200 objects at the data diffusion process. The figure displays the result for required rounds for a node to acquire last 100 objects among 200 objects. The initial round for achieving first 100 objects for a node in the simulation is considered as the stability phase. Figure 10 depicts that the progression of data dissemination among the nodes according to the analytical result almost coincides with simulation result.

Different from other related works in the literature, our analytical model considers the mobility and speed of the nodes for data dissemination. Figure 11 shows the impact of nodes' speed in data dissemination. In simulation, the nodes' speed is varied from 1 to 5 m/s. With the increasing speed, the dissemination of data among the nodes is faster. Because the radio range is 50 m in this experiment, the increased speed up to 5 m/s also increases the number of new neighbors per round. Therefore, the exchange of objects between the nodes increases. The analytical result also reveals the similar results as shown in the Figure 11.

The counter impact of radio ranges for multiple object dissemination is shown in Figure 12. With the larger radio range, the number of neighbors of node increases. Therefore, a node distribute objects to more nodes in a single broadcast. Besides, a node also receives more object from its neighbor with larger radio range. However, the larger radio range has also negative impact on data dissemination. Nevertheless, the large radio range increases the collision of data in simultaneous broadcast. Moreover, the scheduling probability γ for a node also decreases with larger radio range. The simulation result clearly reveals this scenario in Figure 12. The total number of rounds to acquired all the objects does not decline in a straight line with the increase of radio range. The analytical results also follows same trend with the simulation results.

We have simulated the impact of data dissemination on node densities. The number of nodes is varied from 100 to 200. At the beginning of the simulation, each node carries a unique object. For, example, when the number of nodes is 150, the total number of objects in the system is also

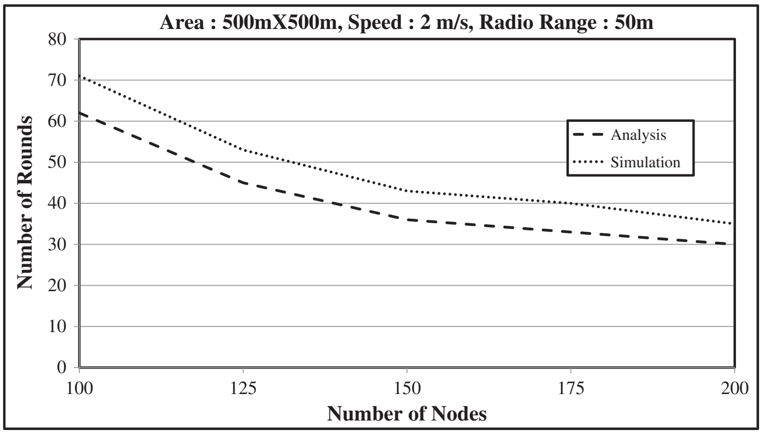

Figure 13. Comparison of analytical model and simulation with different node densities.

150. Figure 13 shows the data dissemination pattern with the varying number of nodes. It considers the total round required for acquiring 80% of total objects. When the node density increases, the data exchange rate among the nodes also increases. As a result, the total number of rounds for acquiring objects is also decreased. However, the rate of decrease from 100 nodes to 125 is not equivalent to the decrease of total rounds from 175 to 200 nodes because too many nodes in a small area also increases the collision of data broadcast. In Figure 13, the analytical result also follows the same pattern for decreased number of rounds with the increased of node densities. However, there is a difference between the analytical and simulation results. We have utilized data from simulation for calculating the average number of neighbors for a node. This average number of neighbors is fixed in the analytical results. However, in simulation, the average number of nodes is different at each step of the simulation. Moreover, the meeting and scheduling probabilities among the nodes in the analytical results are determined according to the number of nodes, their radio range, mobility pattern, and the speed of the node. This probability values remain the same in the stepwise calculation in analysis. The differences between the analytical and simulation results in initial stage are propagated to the later stages.

5. CONCLUSION

We have presented analytical models for contagion data dissemination in wireless mobile network. We have considered both the single and multiple object diffusion processes in mobile network and propose the appropriate analytical model for each of them. Our analytical models can be used to estimate the expected time/delay of object diffusion among the mobile nodes. The models and observations reveal the suitability of the epidemic process using spatial demand-based algorithm for information diffusion. Because the number of nodes in the system is fixed and the next state of the system is completely dependent on the current state, we have modeled the epidemic based data diffusion system as a Markov process and analyzed the behavior of the system. The analysis reveals the complex inter-relationship of node speed, wireless radio range, scheduling among the nodes for data broadcast, and node densities on object diffusion rate. In addition, for multiple object data diffusion, we have developed a progressive analytical model for objects exchanging pattern for a node. Simulation results show that our analytical model is accurately apprehended the dynamics (the number of nodes, their radio ranges, and the speed of the nodes) of data dissemination in wireless mobile network. The results imply that the object propagation rate experiences a phase transition as a function of node densities, radio range, and node speed in a mobile network, both single and multiple objects.

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