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Content synchronization using device-to-device communication in smart cities

Wenzhong Li[a,*], Xiao Chen[b], Sanglu Lu[a]

[a] State Key Laboratory for Novel Software Technology, Nanjing University, Nanjing, China
[b] Department of Computer Science, Texas State University, San Marcos, USA

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ABSTRACT

With the acceleration of high data demand from mobile users and urbanization, Device-to-Device (D2D) communication networks have emerged as a new paradigm to alleviate the traffic load on the cellular networks. Due to high mobility of devices, establishing and ensuring the success of D2D transmission in an intermittently connected network is a major challenge. In this paper, we consider the challenging problem of synchronizing the content of a subset of nodes in D2D networks. We adopt the City Section mobility model to mimic node movement in a city area, and produce theoretical analysis to the properties of the model. Based on this model, we propose two content synchronization strategies called *direct contact synchronization* and *relay-assisted synchronization*. We provide theoretical analysis to the performance of the two strategies, which derives the theoretical upper bound of their synchronization delay. We further conduct simulations to compare the proposed algorithms, which confirms the theoretical conclusion that relay-assisted synchronization substantially outperforms direct contact synchronization in terms of success rate and delay with a slight increase in the cost.

1. Introduction

According to the traffic forecasting report of CISCO [1], annual global IP traffic will reach 2.3 ZB per year by 2020 and nearly two-thirds of the Internet traffic will be carried over Content Delivery Networks (CDNs) by 2019, especially the traffic of video streaming, video gaming, video conferences and multimedia over mobile devices (nodes) like tablets, smart phones and machine-to-machine (M2M) modules.

Currently, mobile users rely on cellular technologies such as 3G or 4G to download contents from the Internet anywhere anytime. At the same time, urbanization is accelerating its pace, in 2015, the urban areas of the United States contain 81.6% of the population [2]. The increasing content requirements from these people over the Internet place new and intense pressure on the existing cellular infrastructure which is struggling to accommodate users' booming data demand [3]. In a city, delivering these contents to mobile users in a timely manner is critical to making the city "smart" by enhancing its efficiency, comfort, and sustainability. Therefore, researchers are seeking new paradigms to assist the traditional cellular communication infrastructure.

One promising solution is to offload cellular traffic via the use of Device-to-Device (D2D) communication [4,5]. D2D communication is defined as the direct communication between two mobile devices capable of short range communication [6,7] without traversing the core network like the cellular. In other words, if a mobile device makes an update or gets an updated content from some sources, it can directly distribute this latest version to other devices interested in the content when they move into a close distance without going through the cellular network. The process to distribute the new content to all the interested devices is called *content synchronization* among these devices. However, due to the high mobility of devices, there does not guarantee a path between the devices at all times, hence there has been an increasing interest to operate D2D over cellular using multi-hop transmissions (henceforth referred to as *multi-hop D2D*) [3,8,9]. The D2D communication we mention in this paper is multi-hop and intermittent. Then how to establish and ensure the message delivery using multi-hop D2D transmission in an intermittently connected network is a major challenge.

Let us take the vehicular network as an example. Consider in a city area, a set of vehicles move in the streets and employ vehicle-to-vehicle communication for information exchange. Each vehicle is equipped with wireless devices which are capable of short range communication [6,7]. Each device may store a number of files according to user interests, like city maps, news from a web site,

* Corresponding author.
E-mail address: lwz@nju.edu.cn (W. Li).

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music and video clips. Assume a file is copied to a set of mobile devices and it is updated over time. When two devices move into their communication range, they will synchronize the shared file to the latest versions. When a file is updated, it is challenging to synchronize the content of a set of interested devices in the intermittently connected environment.

Previous researches put forward a lot of data consistency strategies in wireless networks [10,11]. Barbara et. al.[10] proposed three cache invalidation schemes, namely, Broadcasting Timestamps (TS), Amnestic Terminals (AT), and Signature (SIG), which are suitable for wireless mobile networks such as cellular networks. Cao et al. [12] extended the idea to multi-hop wireless networks, and proposed a relay peer-based data consistency scheme to maintain content consistency between source hosts and cache hosts using both push-based and pull-based strategies. Li et al. [13] proposed algorithms to synchronize frequently offline devices in a wireless ad hoc network with probabilistic consistency. Tran et al. [14] further proposed a data synchronization method for delay-tolerant sensor network using air vehicle to carry update information. However, the existing works either rely on network infrastructure to broadcast update information or are based on continuous end-to-end multi-hop communications, which cannot be applied to D2D networks. There are very few articles discussing D2D content synchronization strategies and their latencies, which are important to verify the usefulness of D2D communication to alleviate the traffic load in the cellular networks. Therefore, in this paper, we investigate the problem of content synchronization for D2D communication in the context of a smart city. More specifically, we aim to answer the following questions: Consider a D2D network formed by mobile devices in a smart city, when the content of a device is updated, how can the identical content in other devices be synchronized to the latest version? How long does it take for the synchronization process to finish?

Answers to the above questions heavily rely on the mobility patterns and content update strategies. Since mobility provides communication opportunities in D2D networks, mobility pattern greatly affects the performance of content delivery. A lot of mobility models have been proposed in the past [15–19]. In this paper, we adopt the *City Section Mobility Model* [20] to mimic vehicles moving in a city street network. We will analyze the theoretical properties of the City Section mobility model, which has not been explored in the past.

To deliver the updated content to a set of destinations, we adopt the similar idea of data forwarding in Delay Tolerant Networks (DTNs) which also needs to address the issue of intermittent connectivity. In DTNs, numerous data forwarding strategies have been proposed, which include epidemic routing [21], probabilistic forwarding [22,23], history-based and utility-based routing [24], etc. Enlightened by these routing schemes in DTNs, we propose two content synchronization strategies for D2D networks: the *direct contact synchronization* strategy which spreads updates to every encountered node with shared files, and the *relay-assisted synchronization strategy* which uses a constant number of relays to help distribute the updated content. We provide theoretical analysis to derive the bounds of synchronization delay of the two strategies.

The major contributions of this paper are summarized as follows.

- We provide theoretical analysis to the properties of the City Section mobility model. Our analysis shows the upper and lower bounds of the expected pair encounter probability and the expected traveling path length in a City Section mobility model (see Theorem 1).
- We propose two content synchronization strategies for D2D networks. The performance of the two strategies is analyzed theoretically, and the bounds of their expected synchronization delay are derived (see Theorems 2 and 3).
- We conduct simulations to compare the performance of the direct contact and relay-assisted synchronization algorithms. Simulation results show that relay-assisted synchronization substantially outperforms direct contact synchronization in terms of success rate and delay with a little extra cost.

The rest of the paper is organized as follows. Section 2 surveys the related works. Section 3 introduces the system model. Section 4 proposes two synchronization strategies. Section 5 conducts the theoretical analysis of the synchronization strategies. Section 6 presents simulations conducted to compare the proposed algorithms. And the paper is concluded in Section 7.

2. Related works

In this section, we survey the existing works on D2D communication, mobility models, routing strategies, and theoretical analysis of propagation delay in various wireless mobile networks.

2.1. D2D communication

Despite significant research on cellular D2D [25–27], there are very few works which consider the cellular multi-hop D2D case. One of the earliest related works is [28] in which the relay selection problem for cellular D2D was studied. The works in [29] and [30] investigate the maximum ergodic capacity and outage probability of cooperative relaying in relay-assisted D2D communication. The results show that multi-hop D2D lowers the outage probability and improves cell edge throughput capacity by reducing the effect of interference from the cellular users. The authors in [31] propose a cooperative D2D communication framework which introduces the cooperative relay technique to conventional underlay/overlay D2D communications. Adaptive mode selection and spectrum allocation schemes are also presented to ensure better performance for both cellular and D2D users. However, none of these works factors in the impact of mobility of devices on the system performance and on the successful delivery of time-sensitive contents in particular.

2.2. Mobility models

Node mobility models are essential in performance analysis and simulation in wireless mobile networks. There have been a lot of works in the literature that study the mobility models. The Random Walk mobility model was described mathematically by Einstein in [15], which was developed to mimic entities in nature moving in extremely unpredictable ways. In this model, a node moves from its current location to a new location by randomly choosing a direction and speed. Differently, the Random Waypoint model [17] includes pause times between changes in direction and speed. In [19], a group mobility model called *Reference Point Group Mobility (RPGM)* is proposed, where nodes move as in groups and each group has a leader to determine the movement direction. There is also some research to model the small-world property in movement, like the *SWIM* [32] and *SLAW* [33] mobility models. Some mobility models have geographic restrictions, such as the *affinity based mobility model* [34,35], where mobile nodes tend to remain confined to a given area or have more affinity towards a certain region over other.

The theoretical properties of the movement models like Random Walk and Random Waypoint were extensively studied in the past. However, little attention has been paid to the theoretical aspects of the City Section mobility model [20], which is addressed in this paper.

2.3. Routing strategies

The intermittent connectivity and dynamic changing topology in D2D networks are typical for delay-tolerant communications. In the following, we survey the routing strategies that were proposed for DTNs. Basically there are two categories: the *single-copy* schemes and the *multi-copy* schemes.

Direct transmission [36] is the simplest single-copy approach which let the source or a moving relay node (*DataMule*) deliver the message to the destination directly. However, the delay may be very long. Spyropoulos et al. [37] studied several "smart" single-copy based routing strategies by using utility-based forwarding. They evaluated the performance theoretically and experimentally. Yuan et al. [38] presented a single-copy based routing protocol *PER* in the DTN networks where the nodes follow a predictable semi-deterministic trajectory.

Epidemic routing [21] is the most straightforward multi-copy approach. It floods the message throughout the network to guarantee the shortest transmission path, which is simple to implement but is extremely wasteful of network resources. A number of approaches have been proposed to reduce the overhead of epidemic routing [22–24,39–41]. Liu and Wu [23] put forward a hop-count-limited forwarding scheme, in which every message has the maximum number of hops that it can be forwarded. The history-based and utility-based routing are studied in [24]. In order to achieve both low delay and transmission, Spyropoulos et al. [41] presented two multiple-copy based routing protocols: *Spray and Wait* and *Spray and Focus*. Later the performance of Spray and Wait was enhanced by a message scheduling and dropping strategy put forward by Wang et al. in [42]. Lin et al. [39] proposed a routing protocol based on network coding to reduce the number of bytes transmitted. Xiao et al. [43] put forward dealine-sensitive utility-based single- and multi-copy routing schemes to guarantee that messages are delivered to their destinations before the deadlines. Sakai et al. [44] designed an abstract onion-based anonymous routing protocol and then extended it to multi-copy forwarding. Also a performance and security analysis of the routing protocol was conducted. Routing schemes taking advantage of the social properties of nodes were discussed in [45–47].

2.4. Delay analysis for wireless mobile networks

The delay of information propagation has been studied in [48–52]. Sharma et al. [48] showed that for an ad hoc network formed by n mobile nodes, the message delay scales as $O(log^2 n/\delta^2(n))$ under the Brownian mobility model, and $\Theta(1/r(n)v(n))$ under the Random Waypoint mobility model. Under the assumption that the distribution of the inter-contact times between mobile nodes is independent and exponential, the authors in [49] presented an explicit expression of the expected delay in *multiple-copy routing* in mobile ad hoc networks. The expected delay is a function of the number of nodes and the mean of the exponential distribution. In [50] and [51], a framework based on ordinary differential equations (ODEs) was proposed to study the performance of epidemic routing and its variations. Under the framework, closed-form formulas of different performance metrics can be derived, such as delay, throughput and buffer dynamics. Jacquet et al. [52] proved that in a DTN where the density of nodes is ν and the speed is υ, the information propagation speed is bounded by $(1+O(\nu^2))$ in the random waypoint model, and the speed is bounded by $O(\sqrt{\nu\upsilon}\upsilon)$ in other mobility models (random walk, Brownian motion).

However, most existing analytical results are based on free movement models without considering the obstacles and traffic regulations. Different from the existing works, our analysis to the delay of content synchronization is based on the restricted movement (City Section mobility) model which mimics the vehicle movement in a city street network.

3. System models

We consider a set of mobile nodes (i.e. vehicles) moving on the city streets to form a D2D network. The mobility of nodes, which is restricted to city streets, follows the City Section mobility model. When two nodes move into each other's communication range, they synchronize their content with each other. When the content in a node is updated, it is interesting to know how fast the other nodes are synchronized with the new version only relying on device-to-device communication. Next we proceed to describe the system model in detail.

3.1. Problem formulation

This paper addresses the problem of content synchronization via D2D communication in mobile environments. Specifically, we study the efficiency of different synchronization strategies in terms of synchronization delay. We make the formal definition of the problem as follows.

We consider a set of mobile nodes $\mathcal{N}$ (e.g. vehicles) moving on the city streets to form a D2D network, where two nodes can communicate only when they move into each other's communication range. The movement of the nodes are assumed to follow a mobility model Ψ, i.e., the trajectory of the nodes can be described by the model with some system parameters. Consider a piece of content that are interested by a set of nodes $\mathcal{M}$ ($\mathcal{M} \subseteq \mathcal{N}$), i.e., the same content is stored in each node in $\mathcal{M}$. If one node τ in $\mathcal{M}$ makes changes to the content, the content in the rest of nodes in $\mathcal{M} - \{\tau\}$ should be synchronized to the newest version. And we use ξ to denote the strategy that is used to synchronize the content in the D2D network.

We further define a function $\delta_{[\xi,\Psi]}(\mathcal{N}, \mathcal{M}, \kappa)$ $(1 \le \kappa \le |\mathcal{M}|)$ to represent the time when κ nodes in $\mathcal{M}$ are updated. Therefore $\delta_{[\xi,\Psi]}(\mathcal{N}, \mathcal{M}, 1)$ represents the time that an update is initiated by one node, and $\delta_{[\xi,\Psi]}(\mathcal{N}, \mathcal{M}, |\mathcal{M}|)$ represents the time that all nodes in $\mathcal{M}$ are synchronized. The synchronization delay can be calculated by $T_\xi = \delta_{[\xi,\Psi]}(\mathcal{N}, \mathcal{M}, |\mathcal{M}|) - \delta_{[\xi,\Psi]}(\mathcal{N}, \mathcal{M}, 1)$.

In our paper, we focus on a specific well-known mobility model called City Section Mobility [20]. In the rest of the paper, Ψ refers to the City Section mobility unless it is explicitly indicated. We study the performance of different synchronization strategies under Ψ. The problem can be formulated as: given $\Psi =$ *City Section Mobility*, derive the analytical expression of the mathematical expectation of T_ξ under different synchronization strategies ξ.

3.2. Mobility model

Most previous research on wireless mobile networks assumes that mobile nodes move freely in a given area, i.e. the Random Walk [15,16] and Random Waypoint [17] mobility models. However, in the real world, node mobility is restricted by obstacles and rules. For example, vehicles in a city always move along the streets. Davies et al. introduced the City Section mobility model in [20] to simulate node mobility in a street network in a city area. This model was also widely adopted to evaluate the performance of wireless ad hoc and vehicular networks [18].

In the City Section mobility model, the street network of a city is mapped to a grid road topology (also known as a *grid graph*), and the node movement is constrained to the grid. All edges in the grid graph are considered bi-directional, double-lane roads with speed limits. Initially mobile nodes (i.e. vehicles) are randomly

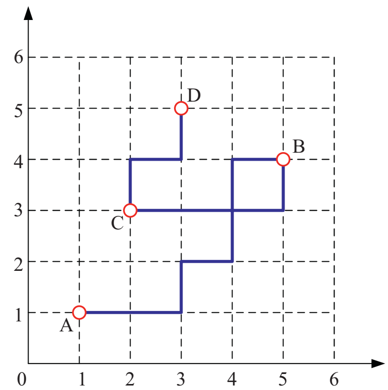


Fig. 1. The movement trace of a node in City Section mobility model.

deployed in the street intersections. Then each mobile node randomly selects an intersection in the grid graph as its destination and moves towards it. We assume the movement from the current position to the destination adopts the shortest path between the two points, which is known as the Manhattan distance. Upon reaching the destination, the mobile node pauses for a specified time and then randomly chooses another destination and repeats the process.

Fig. 1 shows an example of the movement of a node in the City Section mobility model. The city street network is a 6×6 grid. The node starts from point $A(1, 1)$, moving to its destination $B(5, 4)$. There are many shortest paths from A to B and the node picks a path at random. The process is, in each intersection, the node either approaches B vertically or horizontally. The direction is randomly selected, until the node finally reaches the destination. Fig. 1 shows a possible trajectory from A to B. After arriving at B, the node chooses a random destination C and moves to it, and then to the next destination D.

The City Section mobility model can simulate the realistic movement of mobile nodes in a city section environment. In this model, the traveling behavior of mobile nodes is severely restricted to the grid graph, since in the real world, mobile nodes do not have the ability to roam freely without regard to obstacles and traffic regulations.

3.3. Network model

We consider a D2D network of N nodes randomly deployed on a grid graph of size $L \times L$. All nodes move according to the City Section mobility model. Each node has a communication range of distance R ($R \geq 0$). Two nodes "encounter" if they are in each other's communication range R. We assume links are bi-directional, and nodes can communicate with each other only when they encounter.

Like [41], we assume that the communication range R is very small compared to the length of the city street. Thus two nodes can communicate only when they encounter.

4. Content synchronization strategies

In a D2D network, each mobile node stores a set of files. Some files may be copied by a set of nodes, i.e., many drivers use electronic city map for route guidance. Assume for a specific file, there are M nodes having a copy of the file. We refer to them as the nodes interested in the content of the file. Each node is able to make changes to the file, therefore a synchronization strategy is needed to update the file in other interested nodes via D2D communications.

In D2D networks, synchronization happens only when two nodes having the same files encounter, and the process works as follows. The two nodes communicate with each other and exchange file IDs and version numbers they hold. If different file versions are detected, they update their files to the new version. To accomplish synchronization, we introduce the following strategies.

4.1. Direct contact synchronization strategy

The idea of direct contact synchronization is similar to that of epidemic routing [21] and the detailed algorithm is in Fig. 2. If a file in a node is updated to the latest version, it becomes the

Algorithm Direct Contact Synchronization

Require: The source node s that has the new content and the node set interested in the content $I = \{i_1, i_2, \cdots, i_{M-1}\}$; s is the initial updated node x

while not all of the interested nodes are updated **do**
  On contact between an updated node x and node y (when their distance is less than communication range R):
  if $y \in I$ and is not updated **then**
    /* Reached an interested node */
    y is updated and will follow the same process as x;
  else
    Do nothing
  end if
end while

Fig. 2. Direct contact synchronization algorithm.

Algorithm Relay-assisted Synchronization

Require: The source node s that has the new content and the node set interested in the content $I = \{i_1, i_2, \cdots, i_{M-1}\}$; s is the initial content holder x; the number of relay nodes allowed is K

while not all of the interested nodes receive the new content **do**
  On contact between an updated node x and a node y (when their distance is less than communication range R):
  if $y \in I$ and is not updated **then**
    /* Reached an interested node */
    y is updated and will follow the same process as x;
  else if $y \notin I$ and $K > 0$ **then**
    /* Reached a relay candidate */
    $K = K - 1$;
    y gets the content and becomes a relay node and will follow the same process as x;
  else
    Do nothing
  end if
end while

Fig. 3. Relay-assisted synchronization algorithm.

source and the initial updated node. It will spread the update (by synchronization) directly to every interested node it encounters. Once an interested node is updated, it will follow the same procedure to keep "infecting" other interested nodes until all of the interested nodes are synchronized to the new version.

This process is like epidemic routing, but there are two differences. On one hand, epidemic routing transmits a message to every encountered node, but in the synchronization process, only the interested encountered nodes will synchronize with each other. On the other hand, in epidemic routing, there is only one destination and the flooding will stop when it receives the message. However, the synchronization process will not stop until all of the interested nodes are updated to the new version.

4.2. Relay-assisted synchronization strategy

In the direct contact synchronization strategy, if the network is sparse and only a few nodes have the same content, then the synchronization chance will be rare. As a result, it will take a long time to synchronize their content. Intuitively, using a number of relays to distribute the content will decrease the synchronization delay. The basic idea of relay-assisted synchronization is to introduce a number of relay nodes to help distribute the updated content.

Assume in a network with N nodes, M of them have a copy of a file (thus they are interested in the file content). When one node gets the latest version of the file, there are $M-1$ nodes, which are called *non-updated nodes*, that need to be synchronized. The $N-M$ nodes without the file, which are called *candidates*, can serve as relays. Assume only K relay nodes are used. The strategy can be described as follows and the detailed algorithm is in Fig. 3.

- If an updated node encounters a non-updated interested node, they synchronize their content.
- If an updated node encounters a candidate and the relay number is less than K, it copies the updated file to the candidate and makes it a relay.
- An updated or a relay node will act exactly the same as the updated node.

The performance of these strategies will be analyzed in Section 5.

5. Theoretical analysis

In this section, we analyze the performance of the proposed synchronization strategies. We first give the assumptions and preliminary, then present lower bounds and upper bounds on pair encounter probability and pair path length, and then provide the theoretical analysis to prove the correctness of the bounds.

5.1. Assumptions

Throughout this paper, the following assumptions will be made.

- We assume the city street network is a regular grid of size $L \times L$, as introduced in [18]. In the real world, the street network may not be a square. However, our analysis to the regular grid provides a lower bound and an upper bound of system performance, which also holds for non-regular grid environments.

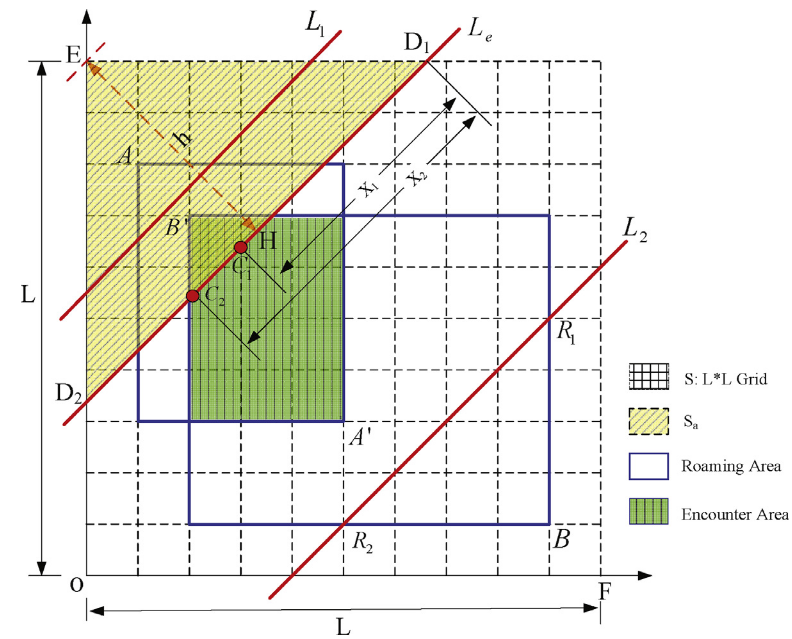


Fig. 4. The movement of two random nodes.

- Our analysis focuses on the delay-tolerant networks (DTNs) where mobile nodes are sparsly deployed and intermittently connected. Similar to [52], we assume information transmission occurs much faster than node movement. The data transmission delay is ignored so that we can study the synchronization delay of D2D based solely on the network mobility and topology. Since the mobile nodes are sparsely deployed in the city area, it is rare that multiple nodes encounter and communicate at the same time, therefore wireless interference is also neglectable in the analysis.
- We assume content synchronization between two nodes can be finished during one encounter. We also assume relay nodes have enough space to carry updated content for the other nodes.

5.2. Preliminary

Before proposing the analytical results, we introduce some definitions.

Consider a grid graph with size $L \times L$, a set of N mobile nodes are randomly deployed in the intersections of the grid, moving according to the City Section mobility model. Assume n_1 and n_2 are two randomly chosen mobile nodes, as illustrated in Fig. 4. Node n_1 is in position $A(x_1, y_1)$ (x_1 and y_1 are the coordinates of the point) and is moving to its destination $A'(x_1', y_1')$ with speed $v_1(t)$; at the same time, node n_2 is moving from $B(x_2, y_2)$ to $B'(x_2', y_2')$ with speed $v_2(t)$; where $v_1(t)$ and $v_2(t)$ are instantaneous movement speed as a function of time t.

Shortest path: It is easy to see that the length of the shortest path from A to A' is $|x_1' - x_1| + |y_1' - y_1|$. There are many shortest paths from A to A'. The node only chooses a random path to move. So in each intersection of the grid, node n_1 will randomly decide approaching to the destination horizontally or vertically. Similar movement decision is made by node n_2 from B to B'.

Roaming area: As shown in Fig. 4, we denote the rectangle area decided by point A and A' as $S_{AA'}$. It contains all of the shortest paths from A to A' and the movement of node n_1 is restricted to this area, which is called the roaming area of n_1. Similarly, the roaming area of n_2 is the rectangle area decided by point B and B', which is denoted as $S_{BB'}$.

Common area: We denote the overlapping of the roaming areas of two nodes $S_{AA'}$ and $S_{BB'}$ as their common area $S_{B'A'}$. If two nodes encounter with each other, they must meet inside their common area.

Roaming lines: Roaming lines are a set of parallel lines satisfying the condition that each intersection in the roaming line has equal shortest path length to the starting point. As illustrated in Fig. 4, L_1 is a roaming line of n_1, and L_2 is a roaming line of n_2. After moving some distance, the node should be in some point of the roaming line. For example, the roaming lines of node n_2 can be expressed as an equation with parameter t, $L_2(t) : (x_2' - x_2) + (y_2 - y_2') = \int_0^t v_2(t)dt$, where $v_2(t)$ is the movement speed and t is the moving time. The meaning behind this equation is that at time t, a node travels to each intersection on $L_2(t)$ the same distance $\int_0^t v_2(t)dt$ from the starting point B. In other words, after a period of time t, node n_2 must be in one of the intersections of $L_2(t)$ on the grid. For example, in Fig. 4, when n_2 moves 4 unit length from point B, its roaming line is L_2, and it must be at some point on the segment R_1R_2 in L_2.

Encounter line: We define the encounter line L_e as the common roaming line of two nodes. If two nodes move towards each other, their roaming lines will encounter eventually. For example, in Fig. 4, L_e is an encounter line of n_1 and n_2. We define the *height* of L_e as the distance from a corner of the grid to the encounter line. For example, the height of L_e in Fig. 4 is $EH = h$. The *length* of L_e is defined as the length of the segment that L_e intersects with the grid. For example, the length of L_e in Fig. 4 is D_1D_2, which equals $2h$ due to the property of equilateral triangle.

5.3. Analysis of encounter opportunities

In this section, we study the encounter probability, traveling distance and the expected encounter time of two nodes in the City Section mobility model.

The following theorem gives the theoretical bounds of pair-wise encounter probability and expected path length of two nodes moving in opposite directions.

Theorem 1. *In a city of size L*L, assume n_1 and n_2 are two random mobile nodes and R is their communication range, where $R \ll L$. If* *the two nodes move according to City Section mobility model towards each other in opposite directions, the following results hold.*

(I) Let P_e be the pair encounter probability of n_1 and n_2. The expectation of P_e is $E(P_e)$. The encounter probability is bounded by

$$\frac{7\sqrt{2}}{30}\frac{R}{L} - \frac{3}{16}\frac{R^2}{L^2} \le E(P_e) \le \frac{1}{6}. \tag{1}$$

(II) Let l be the path length between a pair of nodes in the grid graph. The expectation of l can be estimated by

$$E(l) \approx \frac{2L}{3}. \tag{2}$$

Proof. We proof (I) and (II) separatively .

Proof of (I):

As illustrated in Fig. 4, nodes n_1 and n_2 start from two random points A and B, and move toward their destinations A' and B'. Note that before n_1 and n_2 encounter, they may travel through a series of points (such as the movement trajectory shown in Fig. 1), in which case we only consider the last two points of each node as the starting point and the destination.

According to the City Section mobility model, their movements are restricted to the roaming areas of the rectangles $S_{AA'}$ and $S_{BB'}$. If n_1 and n_2 encounter, they must meet at some point in the overlapped common area $S_{B'A'}$. Note that even if their roaming areas do not overlap, there still exists the possibility that the two nodes encounter. For example, the destinations A' and B' may be close enough for the two nodes to communicate directly even if their roaming area is not overlapping. However, as stated in the theorem, $R \ll L$, it assumes that the communication range R is significantly small compared to the city area length L. This assumption is mostly true in real situations: for example, the communication range of WiFi devices is about 20 m while the length of a street block is normally larger than 1000 m in most cities. Therefore, the assumption $R \ll L$ implies that the possibility of two nodes without overlapping area can communicate directly with each other is tiny and neglectable. In our later analysis, if S_1 and S_2 are non-overlap, the encounter probability of n_1 and n_2 is approximately 0.

The movement of a node is characterized by its roaming lines. If two nodes encounter, their roaming lines move towards each other and eventually coincide, that is, they have an encounter line L_e. Since the meeting point is within the area of $S_{B'A'}$, L_e must cross $S_{B'A'}$. If L_e has no intersection with $S_{B'A'}$, it either means n_1 moves too fast that it reaches its destination before n_2 enters the common area $S_{B'A'}$, or n_1 moves too slow that it doesn't enter $S_{B'A'}$ before n_2 reaches its destination; in neither case will they encounter.

Therefore a necessary condition is that two mobile nodes encounter only when L_e intersects $S_{B'A'}$. Note that this is not a sufficient condition. Even if L_e intersects $S_{B'A'}$, there is still no guarantee that n_1 and n_2 encounter. For example, in Fig. 4, L_e crosses $S_{B'A'}$, but it is possible that n_1 is at point C_1 and n_2 is at point C_2 and the distance $|C_1C_2|$ is larger than their communication range R, which makes them unable to communicate.

Let P_a be the probability that L_e intersects $S_{B'A'}$. It is obvious that $P_e \le P_a$. Thus P_a is an upper bound of the pair encounter probability.

As illustrated in Fig. 4, consider a pair of nodes n_1 and n_2 in the $L \times L$ grid area S. The relative positions of n_1 and n_2 have the following possible situations:

(1) n_1 is on the upper side or lower side of n_2;

(2) n_1 is on the left side or right side of n_2.

There are 4 combinations of the situations, and each will happen at the same odds. We only consider the case that n_1 is on the upper left side of n_2, as shown in Fig. 4. Due to symmetry, the other cases will yield the same conclusion.

As shown in Fig. 4, the encounter line of n_1 and n_2 is L_e and it cuts the grid area S into two parts: S_a and $S_b = S - S_a$, where S_a is the upper left area above L_e (the triangle ED_1D_2) and S_b is the area below L_e. Considering the locations of the destination points A' and B', we have the following cases:

Case 1: both A' and B' are in S_a;

Case 2: both A' and B' are in S_b;

Case 3: A' is in S_a and B' is in S_b;

Case 4: A' is in S_b and B' is in S_a;

Among all the cases, only in case 4 that L_e intersects $S_{B'A'}$. In the other three cases, L_e and $S_{B'A'}$ have no intersection, thus the encounter probability is 0. So P_a equals the probability that case 4 occurs.

Since A' and B' are random points uniformly distributed in S, the probability of A' in S_b equals $\frac{S_b}{S}$, and the probability of B' in S_a equals $\frac{S_a}{S}$. So,

$$\begin{aligned} P_a &= Pr\{Case\ 4:\ A' \ in\ S_b\ and\ B'\ in\ S_a\} \\ &= \frac{S_b}{S}\cdot\frac{S_a}{S} = \frac{S_a(S-S_a)}{S^2} \end{aligned}$$

It is easy to see that $S = L^2$. The size of the area S_a depends on the location of L_e. Denoted by h the height of L_e, as indicated in Fig. 4, the probability P_a can be written as a function of h:

$$P_a(h) = \begin{cases} \dfrac{h^2(L^2-h^2)}{L^4}, & 0 \le h \le \dfrac{\sqrt{2}L}{2}; \\ \dfrac{(L^2-(\sqrt{2}L-h)^2)(\sqrt{2}L-h)^2}{L^4}, & \dfrac{\sqrt{2}L}{2} < h \le \sqrt{2}L. \end{cases}$$

The height of L_e is a random variable. For a random starting point A, the probability that it has an encounter line with height $H \le h$ equals the probability that point A lies in S_a, which is given by

$$\begin{aligned} F_H(h) &= Pr\{H \le h\} = \frac{S_a}{S} \\ &= \begin{cases} \dfrac{h^2}{L^2}, & 0 \le h \le \dfrac{\sqrt{2}L}{2}; \\ \dfrac{L^2-(\sqrt{2}L-h)^2}{L^2}, & \dfrac{\sqrt{2}L}{2} < h \le \sqrt{2}L. \end{cases} \end{aligned}$$

Thus the probability distribution function (PDF) the height of L_e is

$$P_H(h) = F'_H(h).$$

The expectation of P_a can be calculated as

$$\begin{aligned} E(P_a) &= \int_{h=0}^{\sqrt{2}L} P_a(h)P_H(h)dh \\ &= 2\int_{h=0}^{\frac{\sqrt{2}L}{2}} \frac{h^2(L^2-h^2)}{L^4}\frac{2h}{L^2}dh \\ &= \frac{1}{6} \end{aligned} \tag{3}$$

Since the expectation of the possibility that L_e crosses $S_{B'A'}$ is an upper bound of the pair encounter probability, we have

$$E(P_e) \le E(P_a) = \frac{1}{6}. \tag{4}$$

Next, we derive a lower bound of the expectation of P_e. As it has been mentioned, even if L_e crosses the common area $S_{B'A'}$, the two nodes may still not encounter if their distance is larger than their communication range R. As illustrated in Fig. 4, assume n_1 and n_2 are located at point C_1 and C_2 in L_e. Let X_1 and X_2 be the distance from C_1 and C_2 to one of the end point of L_e (i.e., point D_1 in Fig. 4). The two nodes encounter only when $|X_1 - X_2| \le R$.

For an encounter line L_e with height h, X_1 and X_2 are two random variables in the range [0, 2h]. In the analysis, we assume that X_1 and X_2 are uniformly distributed random variables in [0, 2h]. In the real situation, X_1 and X_2 are not evenly distributed and they

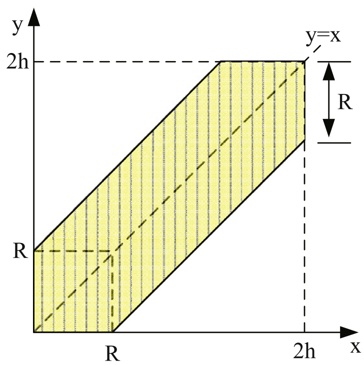


Fig. 5. The range of $|x - y| < R$.

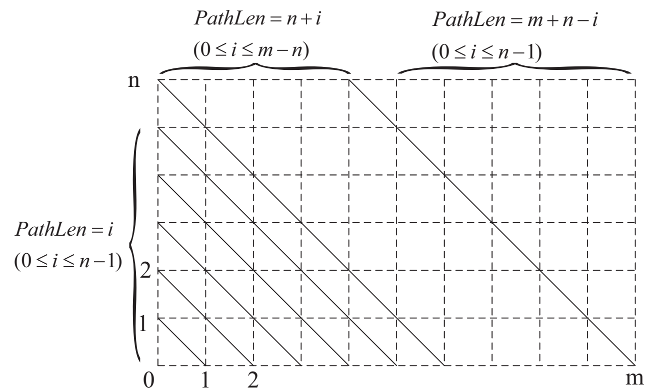


Fig. 6. Path length in a $m \times n$ grid.

appear more in the center of L_e, which causes higher encounter probability of the two nodes than the uniform distribution. Thus the analysis of the uniform distribution case can provide a lower bound to the expectation P_e.

Due to the property of the uniform distribution, given the height h of L_e, the conditional probability hold as follows:

$$Pr\{X_1 = x|h\} = \frac{1}{2h} \quad (0 \le x \le 2h), \tag{5}$$

and

$$Pr\{X_2 = y|h\} = \frac{1}{2h} \quad (0 \le y \le 2h). \tag{6}$$

Given h, the probability of encounter equals $Pr\{|x-y| \le R|h\}$. If $R > 2h$, it is clear that the probability equals 1 for all x and y in $[0, 2h]$. When $R \le 2h$, Fig. 5 shows the range of y for a given x. As shown in the figure, to guarantee $|x-y| \le R$, y should be within $\pm R$ of the line $y = x$. The probability equals the ratio of the shadow area to the square $2h*2h$, which is $\frac{1-\frac{1}{2}(2h-R)(2h-R)*2}{2h*2h} = \frac{4hR-R^2}{4h^2}$. So,

$$Pr\{|x-y| \le R|h\} = \begin{cases} 1, & h < \frac{R}{2}; \\ \frac{4hR-R^2}{4h^2}, & h \ge \frac{R}{2}. \end{cases} \tag{7}$$

Now the encounter probability can be estimated by

$$P_e(h) = P_a(h)Pr\{|x-y| \le R|h\}. \tag{8}$$

According to Eq. (7), $Pr\{|x-y| \le R|h\} \ge \frac{4hR-R^2}{4h^2}$ holds for all h. Similar to Eq. (3), a lower bound of the expectation of encounter probability can be derived by

$$\begin{aligned} E(P_e) &= \int_{h=0}^{\sqrt{2}L} P_a(h)Pr\{|x-y| \le R|h\}P_H(h)dh \\ &\ge 2\int_{h=0}^{\frac{\sqrt{2}L}{2}} \frac{h^2(L^2-h^2)}{L^4}\frac{4hR-R^2}{4h^2}\frac{2h}{L^2}dh \\ &= \frac{7\sqrt{2}}{30}\frac{R}{L} - \frac{3}{16}\frac{R^2}{L^2}. \end{aligned} \tag{9}$$

Combining Eqs. (9) and (4), part (I) of the theorem is proved.

Proof of (II):

According to the City Section mobility model, a pair of nodes n_1 and n_2 are randomly distributed in a $L \times L$ grid. In order to calculate the expectation of path length between the two nodes, we first look into the following simple case.

Consider a grid of size $m \times n$ $(m > n > 0)$ as shown in Fig. 6. Assume a node n_1 is deployed in a fixed location at the lower left corner of the grid, and the other node n_2 is randomly deployed in the grid. There are $(m+1)(n+1)$ possible positions for n_2. Consider the path length between the two nodes:

The path length is 0: there is only one position (0, 0);

The path length is 1: there are two possible positions (0, 1) and (1, 0);

The path length is 2: there are three possible positions (0, 2), (1, 1) and (2, 0);

...Inductively, if $0 \le i \le n$, there are $i+1$ positions whose path length is i, as illustrated in Fig. 6. By symmetry, there are also $i+1$ positions whose path length is $m+n-i$ $(0 \le i \le n-1)$. Besides, there are $n+1$ positions whose path length is $n+i$ for $0 \le i \le m-n$. So, the total path length can be calculated as:

$$\begin{aligned} &\sum_{i=0}^{n-1} i(i+1) + \sum_{i=0}^{n-1}(m+n-i)(i+1) + \sum_{i=0}^{m-n}(n+1)(n+i) \\ &= \frac{(m+n)(m+1)(n+1)}{2} \end{aligned} \tag{10}$$

Now we consider the situation that in a $L \times L$ grid, n_1 is deployed at point (i, j), and n_2 is randomly deployed. Point (i, j) divides the grid into 4 subgrids with sizes $i \times j$, $i \times (L-j)$, $(L-i) \times j$ and $(L-i) \times (L-j)$, respectively. According to equation (10), the total path length of each subgrid is:

$$\begin{aligned} w_1(i,j) &= \frac{(i+j)(i+1)(j+1)}{2} \\ w_2(i,j) &= \frac{(i+L-j)(i+1)(L-j+1)}{2} \\ w_3(i,j) &= \frac{(L-i+j)(L-i+1)(j+1)}{2} \\ w_4(i,j) &= \frac{(2L-i-j)(L-i+1)(L-j+1)}{2} \end{aligned}$$

Let $w(i, j)$ denote the total path length when n_1 is deployed at point (i, j), thus $w(i,j) = w_1(i,j) + w_2(i,j) + w_3(i,j) + w_4(i,j)$. The total path length when (i, j) enumerates all nodes in the grid is

$$w = \sum_{i=0}^{L}\sum_{j=0}^{L} w(i,j). \tag{11}$$

Define a function $\phi(u, v) = \frac{(u+v)uv}{2}$ for $u, v \in I$. It is obvious that

$$\begin{aligned} \phi(i,j) < w_1(i,j) < \phi(i+1, j+1) \\ \phi(i, L-j) < w_2(i,j) < \phi(i+1, L-j+1) \\ \phi(L-i, j) < w_3(i,j) < \phi(L-i+1, j+1) \\ \phi(L-i, L-j) < w_4(i,j) < \phi(L-i+1, L-j+1) \end{aligned}$$

We derive the lower bound of w as follows.

$$\begin{aligned} w(i,j) &= w_1(i,j)+w_2(i,j)+w_3(i,j)+w_4(i,j) \\ &> \phi(i,j)+\phi(i,L-j)+\phi(L-i,j) \\ &\quad +\phi(L-i,L-j) \\ &= \frac{L}{2}(i^2+j^2+(L-i)^2+(L-j)^2). \end{aligned} \tag{12}$$

Thus

$$\begin{aligned} w &= \sum_{i=0}^{L}\sum_{j=0}^{L} w(i,j) \\ &> \frac{L}{2}\sum_{i=0}^{L}\sum_{j=0}^{L}(i^2+j^2+(L-i)^2+(L-j)^2) \\ &= \frac{L}{2}4(L+1)\sum_{i=0}^{L}\sum_{j=0}^{L} i^2 \\ &= \frac{1}{3}L^2(L+1)^2(2L+1). \end{aligned} \tag{13}$$

Since n_1 and n_2 are randomly deployed in the grid, each of them has $(L+1)\times(L+1)$ possible positions. So the average path length is

$$E(l) = \frac{w}{(L+1)^4} > \frac{1}{3}\frac{L^2(L+1)^2(2L+1)}{(L+1)^4}. \tag{14}$$

When L is sufficiently large, $\frac{L^2(L+1)^2}{(L+1)^4}\approx 1$, which yields a lower bound:

$$E(l) > \frac{2L+1}{3}. \tag{15}$$

Similarly, we can derive an upper bound,

$$\begin{aligned} w &= \sum_{i=0}^{L}\sum_{j=0}^{L} w(i,j) \\ &< \frac{L+2}{2}4(L+1)\sum_{i=0}^{L}\sum_{j=0}^{L}(i+1)^2 \\ &= \frac{1}{3}(L+1)^2(L+2)^2(2L+3), \end{aligned} \tag{16}$$

and

$$E(l) = \frac{w}{(L+1)^4} < \frac{(L+1)^2(L+2)^2(2L+3)}{3(L+1)^4} \approx \frac{2L+3}{3}. \tag{17}$$

Combining Eqs. (14) and (17), when L is sufficiently large, the constant component can be ignored and the expected path length between a pair of nodes in the grid can be estimated by $E(l)\approx\frac{2L}{3}$. Part (II) of the theorem is proved. □

With the above theorem, we further provide several discussions.

Discussion 1: expected encounter time

Let T_e be the expected time that n_1 and n_2 meet on their encounter line (when they move to one of the intersections in the encounter line). Let $v(t)$ be the relative movement speed of n_1 and n_2, i.e., $v(t)=v_1(t)+v_2(t)$, where $v_1(t)$ and $v_2(t)$ are the movement speeds of n_1 and n_2 as a function of time t. The value of T_e can be obtained by solving the following equation

$$\int_{t=0}^{T_e} v(t)dt = \frac{2L}{3}. \tag{18}$$

As a special case, when $v_1(t)$ and $v_2(t)$ move in constant speeds $v_1(t)=\bar{v}_1$ and $v_2(t)=\bar{v}_2$, T_e can be estimated by

$$T_e \approx \frac{2L}{3(\bar{v}_1+\bar{v}_2)}. \tag{19}$$

According to the analysis, if two nodes move in opposite directions and encounter, their expected traveling time is T_e, which will be used to estimate the delay of the content synchronization strategies.

Discussion 2: other encounter opportunities

Except moving in opposite directions, there are other opportunities that two nodes encounter each other. These include (1) moving in the same direction: the two nodes move in the same direction with different speeds, and one node catches up the other from behind; (2) moving in orthogonal directions: the two nodes move in orthogonal directions towards each other, and they encounter at some intersection in the city roads.

However, in practice, the probability for two random mobile nodes catching up in the same direction or meeting orthogonally in a crossroad is much less compared to the possibility of encountering from moving in opposite directions. Therefore, moving from opposite directions contributes to the most of the encounter opportunities in city section mobility. The analysis of the encounter probability in Theorem 1 provides a good approximation for the communication opportunities of two random nodes in the D2D communications system.

Next, we will analyze the performance of the proposed synchronization strategies. Following the notations in the problem formulation, we use $\mathcal{N}$ to denote the set of mobile nodes, whose size is $|\mathcal{N}|=N$, and $\mathcal{M}$ to denote the set of interested mobile nodes, whose size is $|\mathcal{M}|=M$.

5.4. Analysis of the direct contact synchronization strategy

In the direct contact synchronization strategy, two nodes with the same file will synchronize with each other when they encounter. Assume a mobile node gets an update of its file, when it meets another node with the same file, they will synchronize their content and then the other node will update its file to the new version. After that, during movement, the updated nodes will continue synchronizing their content with the interested nodes they encounter. This process continues until the update is spread to all of the interested nodes in the network.

We define the *synchronization delay* as the amount of time it takes for all of the interested nodes to synchronize to the new version after an update is made.

The following theorem calculates the expected synchronization delay for the direct contact synchronization strategy.

Theorem 2. *Assume a file f is stored in M interested nodes in the D2D network under the City Section mobility model. Let T_d be the expected delay for synchronizing the content of the M nodes to the new version using direct contact synchronization strategy. T_d can be calculated by*

$$T_d = \frac{2T_e}{MP_e}H_{M-1}, \tag{20}$$

where $H_k=\sum_{q=1}^{k}\frac{1}{q}$ is the kth *Harmonic Number [53].*

Proof. Let $T(i)(1\le i\le M)$ be the expected remaining synchronization delay after i copies have been updated. According to the problem formulation in Section 3.1, $T(i)=\delta_{[\xi,\Psi]}(\mathcal{N},\mathcal{M},M)-\delta_{[\xi,\Psi]}(\mathcal{N},\mathcal{M},i)$. Clearly $T(M)=0$, and

$$T_d = T_\xi = T(1)-T(M) = T(1), \tag{21}$$

which represents the synchronization delay starting from an updated node.

Consider at a moment, there are i nodes being updated. Like [41], we assume the time a pair of nodes meeting their encounter line is independent. According to Theorem 1, T_e is the expected time that any pair of nodes meeting their encounter line. For a random node pair, there are three situations: they are both updated nodes; they are both non-updated nodes; or one is updated and the other is non-updated. Only in the last case that a non-updated node can synchronize its content to the new version. The possibility that one node is drawn from the i updated nodes and the other is drawn from the $M-i$ nodes is $\frac{1}{i(M-i)}$. Therefore, the expected time that an updated node has an encounter line with a non-updated node is $\frac{T_e}{i(M-i)}$.

According to the analysis in the previous section, when a pair of nodes have an encounter line, their encounter probability is P_e. That is, with probability P_e, the number of updated nodes becomes $i+1$, and with probability $1-P_e$ the number of updated nodes remains i. So

$$T(i) = \frac{T_e}{i(M-i)} + P_e T(i+1) + (1-P_e)T(i).$$

That is,

$$T(i) - T(i+1) = \frac{T_e}{i(M-i)P_e}$$

Solving the equation inductively, we have

$$\begin{aligned} T_d &= T(1) = \frac{T_e}{P_e}\sum_{i=1}^{M-1}\frac{1}{i(M-i)} \\ &= \frac{2T_e}{MP_e}\sum_{i=1}^{M-1}\frac{1}{i} = \frac{2T_e}{MP_e}H_{M-1}. \end{aligned}$$

The theorem is proved. □

5.5. Analysis of the relay-assisted synchronization strategy

The relay-assisted synchronization strategy uses K relays that are not interested in the content to help content distribution. When an update is made, the updated file can be sent to the relay nodes. Then the relay nodes will spread the content to the interested nodes. With the assistance of the relay nodes, the synchronization delay is supposed to be reduced. The following theorem provides an upper bound of this strategy.

Theorem 3. *Assume a file f is stored in M mobile nodes in the D2D network under the City Section mobility model. Let T_r be the expected delay for synchronizing the content of the M nodes to the new version using the relay-assisted synchronization strategy with K relay nodes. The following upper bound holds for T_r:*

$$T_r \le \frac{2T_e H_{N-M}}{(N-M+1)P_e} + \frac{T_e(H_{M-1} + H_{K+M-1} - H_{K+1})}{(K+M)P_e}. \tag{22}$$

Proof. In the relay-assisted synchronization strategy, K relays are used to help distribute the updated content. The analysis of its synchronization process is a little more complicated than that of the direct contact synchronization strategy, since when an updated node encounters another node, it may update the content of the other node or make it a relay. In order to simplify the analysis, we assume that the synchronization process goes through the following two phases:

Phase 1: Spread the updated content to K relays;

Phase 2: Distribute the update to all non-updated interested nodes.

We assume phase 2 occurs after phase 1 has finished. That is, only after K relays obtain the updated content, the $M-1$ non-updated nodes will be synchronized. In real situation, phase 1 and 2 occur concurrently, so the sum of the expected delays of the two phases will give an upper bound for T_r. The expected delay of phase 1 and 2 are denoted by T_1 and T_2 respectively.

We now analyze the expected delay in phase 1. According to the synchronization strategy, the first K candidate nodes met by the updated nodes will become relays. Similar to the proof of Theorem 2, let $T(i) (0 \le i \le K)$ be the expected remaining time of phase 1 when i relays are found. In this case, the expected time that any of the $i+1$ updated nodes having an encounter line with any of the $(N-M-i)$ candidates is $\frac{T_e}{(i+1)(N-M-i)}$. Consider the encounter probability P_e, we have

$$T(i) = \frac{T_e}{(i+1)(N-M-i)} + P_e T(i+1) + (1-P_e)T(i).$$

Solving the equation, we obtain

$$T_1 = T(1) = \frac{2T_e}{(N-M+1)P_e}H_{N-M}.$$

In phase 2, starting from the $K+1$ updated nodes, we study the expected delay when the $M-1$ non-updated nodes are synchronized. Let $T'(i) (1 \le i \le M)$ be the expected remaining time of phase 2 after i non-updated nodes are synchronized. In this case, the expected time that any of the $K+i$ updated nodes meeting its encounter line with any of the $(M-i)$ non-updated nodes is $\frac{T_e}{(K+i)(M-i)}$. Consider the encounter probability P_e, we have

$$T'(i) = \frac{T_e}{(K+i)(M-i)} + P_e T'(i+1) + (1-P_e)T'(i).$$

Solving the equation,

$$T_2 = T'(1) = \frac{T_e}{(K+M)P_e}(H_{M-1} + H_{K+M-1} - H_{K+1}).$$

Combining the results of T_1 and T_2, we obtain the following upper bound:

$$\begin{aligned} T_r \le T_1 + T_2 &= \frac{2T_e H_{N-M}}{(N-M+1)P_e} \\ &\quad + \frac{T_e(H_{M-1} + H_{K+M-1} - H_{K+1})}{(K+M)P_e}. \end{aligned}$$

The theorem is proved. □

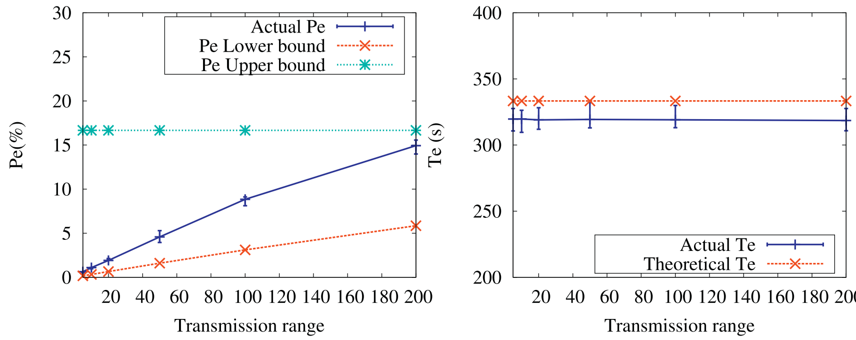
Comparing Eqs. (20) and (22), if M is much smaller than K, the upper bound of T_r is smaller than T_d. This implies that when the number of copies is small, using a number of relays can reduce the synchronization delay. Especially when $M \ll K$, the relay-assisted strategy will perform much better than the direct contact strategy.

6. Numerical results

In this section, we describe the simulations we conducted to evaluate the theoretical analysis and compare the proposed Direct Contact Synchronization, Relay-assisted Synchronization, and the benchmark epidemic Strategies using a custom simulator written in Matlab.

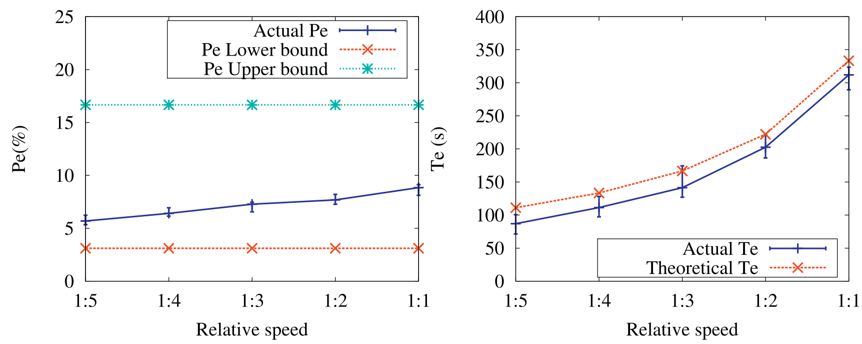
6.1. Verification of $\mathrm{P_e}$ *and* $\mathrm{T_e}$

In this part, we conduct simulations to compare the actual meeting probability and the delay for two nodes to meet in the intersection rectangle S in Fig. 4 with the theoretical values of P_e and T_e derived in the theorem. We set the grid size $L \times L$ to be 1000 m × 1000 m and randomly generated the initial locations of two nodes and let them move according to the City Section mobility model. They encountered each other when they moved into each other's communication range. We tried 500,000 pairs of such nodes and the actual encounter probability and delay for all of the node pairs were averaged and shown with their 95% confidence intervals in the figures.



(a) Pe (b) Te

Fig. 7. Comparison of actual and theoretical P_e and T_e with the same node speed (the curves show the 95% confidence interval).



(a) Pe (b) Te

Fig. 8. Comparison of actual and theoretical P_e and T_e with variable node speeds (the curves show the 95% confidence interval).

In the first experiment, we let two nodes travel with the same average speed of 10 meters/second (simplified to 10 m/s) according to the City Section mobility model. We varied the communication range R from 5 to 200. The results are shown in Figs. 7(a) and (b), respectively. As shown in the figure, when R is small, the encounter probability is very close to the lower bound. When R increases, the encounter probability increases and approaches to the upper bound. In all the cases, the actual value of the encounter probability falls between the theoretical lower and upper bounds, which proves the correctness of the bounds in Theorem 1(I). In addition, with the increase of the communication range, the actual P_e increases and approaches to the upper bound. This is because two nodes are more likely to meet if the communication range is larger. For T_e, the actual encounter delay is very close to the theoretical value calculated from Theorem 1, which verifies the accuracy of the theoretical estimation.

In the second experiment, we set the transmission range R to be 100 and let two nodes travel with different average speeds. We obtained the P_e and T_e values when their relative speeds change from 1: 1 to 1: 5 as shown in Figs. 8 (a) and (b). For P_e, the actual value still falls between the theoretical lower and upper bounds. Also, when the speed difference is larger as one node travels faster than the other, the value of P_e is lower, which means it is more difficult for them to meet. The curve of the actual delay T_e is right below the theoretical curve in Fig. 8 (b). They go up when the speed difference becomes larger.

6.2. Performance comparison of the proposed algorithms

In this section, we compare the following algorithms.

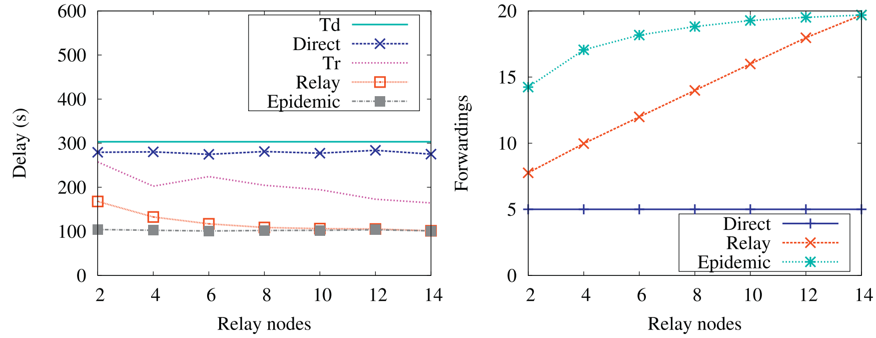
- The Direct Contact Synchronization Strategy (Abbreviated to *Direct*) where the content is spread by the source node directly to all of the interested nodes as described in Algorithm 2.
- The Relay-assisted Synchronization Strategy (Abbreviated to *Relay*) where the content is spread with the help of some relay nodes to all of the interested nodes as described in Algorithm 3.
- The Epidemic Strategy (Abbreviated to *Epidemic*) where the message is spread epidemically throughout the network to all of the interested nodes, which is the baseline for comparison.

6.2.1. Metrics and process

We use the following important metrics to evaluate the performance of the proposed algorithms. We define a *successful synchronization* as the one that successfully synchronizes the content in all of the interested mobile nodes.

- *Delay*: The total time length in seconds to finish a successful synchronization process.
- *Number of forwardings* (abbreviated to *forwardings*): The number of content copies forwarded to a node without a copy in a successful synchronization process. This metric is adopted from [54] and represents the overhead in the network in terms of how many times a content must be forwarded in order to reach all the interested nodes. The number of forwardings in the simulation measures the number of contents forwarded, which does not include the metadata exchange.

In the following experiments, we randomly generated 20 mobile nodes in a 1000 m × 1000 m grid and let them move according to the City Section mobility model. The nodes can randomly choose from three different speeds: 10 m/s (slow), 20 m/s (medium), and 30 m/s (fast). We randomly picked one node as the source node that had the latest content, a number of other nodes interested in the content, and some relay nodes to help forward the content in the Relay algorithm. We set different values to the parameters and ran the proposed algorithms with each parameter



(a) Delay (b) Forwardings

Fig. 9. Comparison of the Direct, Relay, Epidemic algorithms, and theoretical values with various relay nodes when the communication range is 5.

setting 1,000 times and averaged the results for delay and forwardings.

6.2.2. Experiment 1

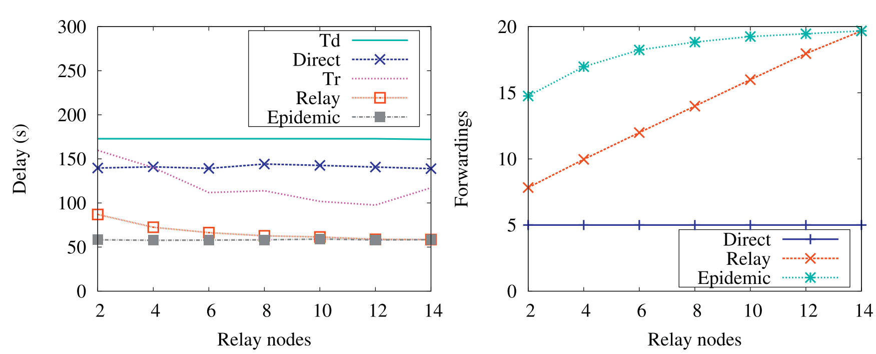
In this experiment, we fixed the number of interested nodes to 4 in the Direct, Relay, and Epidemic algorithms and set the communication range to 5 to compare the delay and forwardings of these algorithms. The synchronization process starts from the source node that has the latest content. Two nodes could directly synchronize the content if they were within each other's communication range. In the Direct algorithm, there are no relay nodes. In the Relay algorithm, the maximum number of relay nodes should not exceed the total number of mobile nodes minus the number of interested nodes minus the number of source node. In this setting, it is $= 20 - 4 - 1 = 15$. We set the number of relay nodes to even numbers from 2 to 14 in a step of 2. In the Epidemic algorithm, every newly met node will become a relay node. The simulation results are shown in Fig. 9.

In Fig. 9(a), we compare the delay of Direct, its theoretical value T_d, Relay, its theoretical value T_r, and Epidemic. We can see that theoretical T_d and T_r provide good upper bounds for the actual delays of Direct and Relay, respectively. The Epidemic algorithm has the lowest delay because it spreads the content to whatever node it encounters and Direct has the highest delay because it does not get the help from the relay nodes. Since Epidemic and Direct do not rely on the relay nodes, their theoretical and actual delays are basically flat with the increase of the relay nodes. The actual delay of the Relay algorithm is very close to that of the Epidemic algorithm, especially when the number of relay nodes increases.

In Fig. 9(b), we compare the number of forwardings of the Direct, Relay, and Epidemic. The number of forwardings of the Direct algorithm is equal to the number of interested nodes plus one because eventually all of the interested nodes plus the source will be synchronized to the new version. Since there are 4 interested nodes, the total number of forwardings of the Direct algorithm is fixed at 5. The number of forwardings of the Relay algorithm is increased with the increase of the relay nodes because up to K relay nodes will get a copy of the content during the synchronization process. The number of forwardings of the Epidemic algorithm is the highest due to the fact that every newly met node will receive a copy of the content.

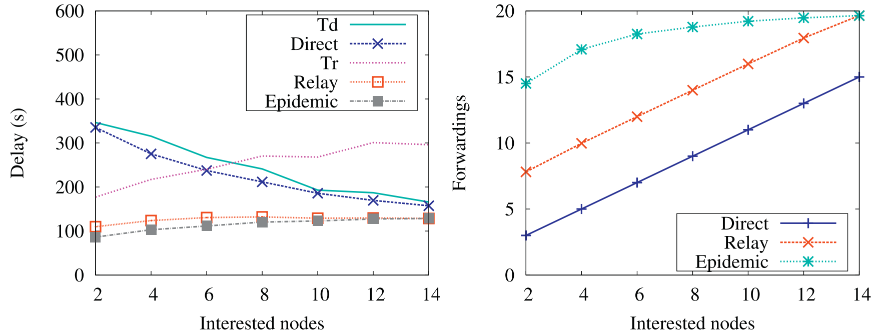
6.2.3. Experiment 2

In this experiment, we assigned the same values as those in Experiment 1 to the parameters except that we enlarged the communication range from 5 to 10. In Fig. 10(a), we compare delay of the Direct, its theoretical value T_d, Relay, its theoretical value T_r, and Epidemic. Again, theoretical T_d and T_r provide good upper bounds for the actual delays of Direct and Relay, respectively. The actual delay of the Epidemic algorithm is the lowest and the actual delay of Relay is very close to that, especially when the number of relay nodes increases. The actual delay of Direct is the highest. Since Epidemic and Direct do not use relay nodes, their theoretical and actual delays are basically flat as the number of relay nodes increases. Also, because of the increase of the communication range, the actual delays of the three algorithms in this experiment are lower than those in Experiment 1. The comparison of the number of forwardings of the Direct, Relay, and Epidemic algorithms is shown in Fig. 10(b). The forwardings of these algorithms are about the same as those in Experiment 1 as the increase of the communication range from 5 to 10 has no obvious effect on the number of copies generated in the synchronization process.



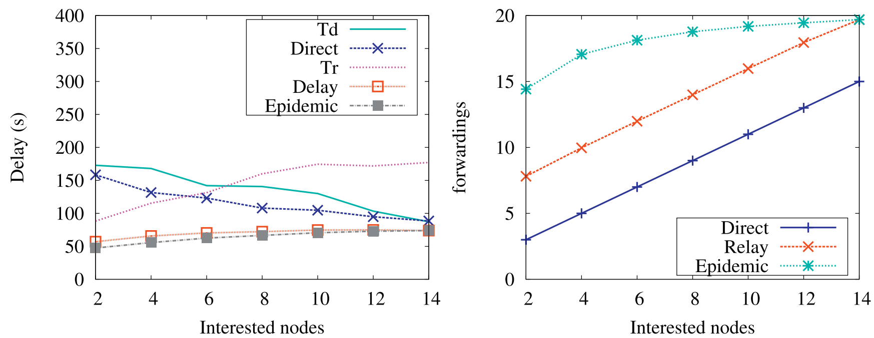
(a) Delay (b) Forwardings

Fig. 10. Comparison of the Direct, Relay, Epidemic algorithms, and theoretical values with various relay nodes when the communication range is 10.



(a) Delay (b) Forwardings

Fig. 11. Comparison of the Direct, Relay, Epidemic algorithms, and theoretical values with various interested nodes when the communication range is 5.



(a) Delay (b) Forwardings

Fig. 12. Comparison of the Direct, Relay, Epidemic algorithms, and theoretical values with various interested nodes when the communication range is 10.

6.2.4. *Experiment 3*

In this experiment, we fixed the number of relay nodes to 5 in the Relay algorithm and set the communication range to 5 to compare the delays and forwardings of the Direct, Relay, and Epidemic algorithms. As before, in the Relay algorithm, the maximum number of interested nodes is the total number of mobile nodes minus the number of relay nodes minus the number of source node. In this setting, it is $= 20 - 5 - 1 = 14$. So we set the number of interested nodes to even numbers from 2 to 14 in a step of 2. The simulation results are shown in Fig. 11.

In Fig. 11(a), we compare the delay of Direct, its theoretical value T_d, Relay, its theoretical value T_r, and Epidemic. For the direct contact algorithm, both T_d and the actual delay decrease with the increasing number of interested nodes. The reason is that when an interested node receives an updated copy, it can help forward the update to other interested nodes it encounters. So when there are more interested nodes in the system, the encounter opportunities between updated and non-updated nodes are increased, thus the overall synchronization delay will be decreased. Again, the results confirm that theoretical T_d and T_r provide good upper bounds for the actual delays of Direct and Relay, respectively. The actual delay of Relay is very close to that of the benchmark Epidemic algorithm and the delay of Direct is higher than that of Relay.

In Fig. 11(b), we compare the forwardings of the Direct, Relay, and Epidemic algorithms. We can see that the number of forwardings of the Direct algorithm is equal to the number of interested nodes plus one because eventually all of the interested nodes plus the source will be synchronized to the new version. The number of forwardings of the Relay algorithm is about 4–5 copies higher than that of the Direct algorithm because of the extra copies spreading to up to 5 relay nodes. The number of forwardings of the Epidemic algorithm is the highest since a copy is forwarded to any newly-met node.

6.2.5. *Experiment 4*

In this experiment, we assigned the same values as those in Experiment 3 to the parameters except that we enlarged the communication range from 5 to 10. In Fig. 12(a), we compare the delay of Direct, its theoretical value T_d, Relay, its theoretical value T_r, and Epidemic. Again, the delays follow the same relationship as those in the previous experiments. Because of the increase of the communication range, the delay of the various algorithms in this experiment is lower than that in Experiment 3. The comparison of the forwardings of the Direct, Relay, and Epidemic algorithms are shown in Fig. 12(b). The forwardings of these algorithms do not have an obvious change from those in experiment 3 with the communication range increased from 5 to 10.

In summary, from the above experiments, we can conclude that the Relay algorithm outperforms Direct by having a delay which is very close to the benchmark epidemic algorithm and with a slight increase in the number of forwardings. The theoretical delays T_d and T_r provide good upper bounds for the actual delays of the Direct and the Relay algorithms, respectively.

7. Conclusion

In order to alleviate the intense pressure on the cellular infrastructure due to users' high data demand and make the cities more smart, D2D communication networks have become a promising paradigm. In the context of D2D communication, networks are intermittently connected due to node mobility. In such an environment, information exchange relies on D2D communication when two nodes encounter. In this paper, we have investigated the problem of content synchronization for a set of mobile devices moving in a city area using D2D communication.

We have used the City Section mobility model to mimic node movement in a city street network, and produced theoretical analysis to the encounter characteristics of the model. We have derived the upper and lower bounds of the expected encounter probability and the expected traveling path length of mobile node pairs. Based on the mobility model, we have proposed two content synchronization strategies. The direct contact synchronization strategy spreads an update to a set of interested nodes in an epidemic way. The relay-assisted strategy introduces a constant number of relay nodes to help distribute the updated content. Theoretical analysis of the two strategies has been conducted and the theoretical bounds of the content synchronization delay of the two strategies have been given. The performance of the proposed strategies has been evaluated by simulations, which confirms the tightness of the theoretical delay bounds and that the relay-assisted synchronization strategy substantially outperforms the direct contact synchronization strategy in terms of delay with a slight increase in the cost. In the future, we will enhance the theoretical bounds of the proposed strategies, and explore more efficient synchronization algorithms in D2D networks and compare their performance both theoretically and experimentally.

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Wenzhong Li receives his B.S. and Ph.D degree from Nanjing University, China, both in computer science. He is now an associate professor in the Department of Computer Science, Nanjing University. During 2011–2013 he was an Alexander von Humboldt scholar in University of Göttingen, Germany. Dr. Li's research interests include wireless networks, pervasive computing, mobile cloud computing, and social networks. He has published over 50 peer-review papers at international conferences and journals, which include INFOCOM, ICDCS, PERCOM, SECON, ICPP, IEEE/ACM Transactions on Networking, IEEE Transactions on Parallel and Distributed Systems, IEEE Transactions on Wireless Communications etc. He served as Program Co-chair of MobiArch 2013 and Registration Chair of ICNP 2013. He was the TPC member of several international conferences and the reviewer of many journals. He is the principle investigator of two funding from NSFC, and the co-principle investigator of a China-Europe international research staff exchange program. Dr. Li is a member of IEEE, ACM, and China Computer Federation (CCF). He was also the winner of the Best Paper Award of ICC 2009.

Xiao Chen is an Associate Professor of computer science with Texas State University, San Marcos, TX, USA. She received her Ph.D. degree in Computer Engineering from Florida Atlantic University. Her research interests include delay-tolerant networks, sensor networks, and ad hoc wireless networks. She has served as an associate editor, program committee member, session chair, and reviewer for numerous international journals and conferences.

Sanglu Lu received her B.S., M.S., and Ph.D. degrees from Nanjing University in 1992, 1995, and 1997, respectively, all in computer science. She is currently a professor in the Department of Computer Science and Technology and the deputy director of State Key Laboratory for Novel Software Technology. Her research interests include distributed computing, pervasive computing, and wireless networks. She is a member of IEEE and ACM.