Phone-to-phone Communication Utilizing WiFi Hotspot in Energy-Constrained Pocket Switched Networks

En Wang, Yongjian Yang†, Jie Wu, *Fellow, IEEE*, Wenbin Liu

***Abstract*—In Pocket Switched Networks (PSN), devices carried by humans form a network environment, which utilizes both human mobility and occasional connectivity to deliver messages among mobile devices. Mobile phones are widely used in our daily lives. Therefore, the PSN composed of human-carried mobile phones will soon become an ubiquitous network environment. In this paper, we propose a communication strategy, which applies the WiFi hotspot mode of a mobile phone in the PSN, in order to realize the device-to-device communications. However, due to the lack of energy supply, a phone in hotspot mode could rapidly consume energy and shorten its battery lifetime significantly. To maximize the message dissemination scope within the limited energy constraint of each phone in PSN, an Energy efficient Phone-to-phone Communication method based on WiFi Hotspot (EPCWH) is presented to schedule the phone's switching between hotspot mode and client mode. Simulations based on the synthetic random-waypoint mobility pattern and real traces are conducted in ONE; the results show that EPCWH achieves the best performance in terms of message dissemination and energy consumption among different switching strategies.**

***Index Terms*—PSN, Phone-to-phone, Hotspot mode, Client mode, Energy constraint, Schedule.**

I. Introduction

Delay-tolerant networks (DTN) are a kind of intermittently connected network environment [2], [3], where nodes are sparsely distributed and end-to-end connection is not guaranteed due to the node's uncertain mobility and the easy-interrupt connections. As a consequence, the messages are transmitted in a store-carry-forward paradigm. DTN have been proposed for use in the following network environments: interplanetary networks [4], disaster response networks [5], [6], vehicular delay tolerant networks [7], rural area networks [8], wildlife tracking networks [9], and pocket switched networks [10].

This paper will primarily focus on the Pocket Switched Networks (PSN) environments, which take advantage of both human mobility and occasional connectivity to deliver messages among mobile devices. The mobilities of devices make PSN different from the general WSN [11]. Therefore, routing protocols in PSN can utilize the devices' mobility to transmit messages more rapidly. While designing forwarding algorithms [12] is the most important in PSN, the devices used by humans and the short range communication protocol adopted in PSN are also crucial. Reducing the energy consumption of devices [13], [14] while maintaining efficient communication protocol is needed in order to effectively deliver messages.

Smart phones are enormously popular and are being used daily. According to reports from the International Data Corporation (IDC) Worldwide Quarterly Mobile Phone Tracker [15], smart phone usage will reach 982 million by 2015. Furthermore, this report reveals that PSN formed by smart phones will quickly become a worthwhile research opportunity. Therefore, communication protocols among smart phones will play an important role in message dissemination and resource sharing. The three main communication protocols utilized on smart phones are 3G, WiFi, and Bluetooth. However, Bluetooth is most unsuitable in PSN, because a short-distance communication results in missing an enormous amount of communication opportunities, especially when the phones' locations are scattered. 3G and WiFi are the main ways of surfing the Internet through smart phones. According to the work in [16], the coverage area of cellular networks is almost twice that of WiFi networks in the US. However, due to transmission rate and traffic cost, 90% of customers prefer WiFi over 3G, according to market research [17]. Even so, it is still impractical to directly use WiFi communication protocol in PSN, due to the lack of WiFi Access Points (APs).

Fortunately, recent studies [15], [18] have confirmed that the WiFi hotspot mode can be used to realize phone-to-phone communications even in the network without WiFi APs. It is worth noticing that the mentioned 'phone-to-phone' communication is not a voice communication, but device-to-device communication (WiFi communication). As illustrated in Fig. 1, each human-carried phone could switch between hotspot mode and client mode. Two phones within each other's communication range can establish a connection, if and only

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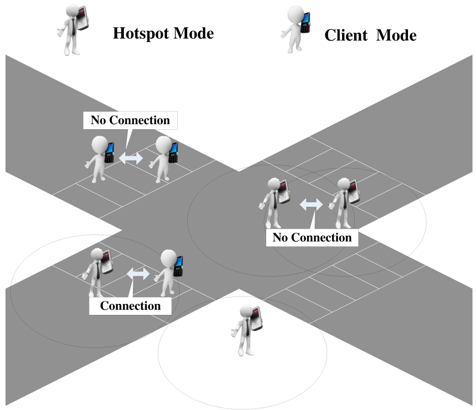


Fig. 1. An illustration of the phone-to-phone communication model based on WiFi hotspot. Two phones both in hotspot or client mode could not establish a connection. However, they can establish a connection in each other's communication range, if and only if, one of them is in the hotspot mode, and the other is in the client mode.

if, one of them is in hotspot mode while the other is in client mode. Two phones in the same mode (whether hotspot or client) cannot communicate with each other [15], [19]. When two smart phones are in different modes, their communication forms a pocket switched network.

However, hotspot mode becomes problematic because it consumes the phone's energy rapidly which significantly shortens its battery life. [20]. This is especially true in PSN where the phones' energy cannot be supplied in a timely manner. Therefore, energy conservation and communication efficiency are both important in PSN. There must be a trade off between the energy consumption and the message dissemination. The longer the phone is in hotspot mode, the faster the energy is consumed. Additionally, an excess of phones in hotspot mode will not make a contribution to message dissemination, because differing modes are needed to establish a connection. Reducing the time spent in hotspot mode is conducive to energy saving, however, it has no contribution to the message dissemination. In summary, there is still a lack of an energy efficient phone-to-phone communication based on WiFi hotspots in PSN. It is because of this that proposing a scheduling strategy to switch between hotspot mode and client modes is necessary, in order to maximize the message dissemination scope within the limited energy consumption. In this paper, we propose a phone-to-phone communication strategy utilizing WiFi hotspot in energy-constrained PSN, and conduct simulations both in random-waypoint mobility pattern and real traces (EPFL and PMTR). Simulation results show that EPCWH achieves the best performance in terms of message dissemination and energy consumption among different switching strategies.

The main contributions of this paper are briefly summarized, as follows:

- When multiple messages coexist in PSN at the same moment, we propose an Energy efficient Phone-to-phone Communication method based on WiFi Hotspot (EPCWH) to schedule the switching between hotspot mode and client mode, which minimizes energy consumption, therefore maximizing the probability of establishing a connection between two randomly chosen human-carried phones.
- When a single (multiple copies) message exists in PSN at the same moment, we enhance the EPCWH to deal with the following problems: (1) When the energy is enough to finish the optimal message dissemination, we question how to schedule the switching between hotspot mode and client mode, in order to minimize the total energy consumption. (2) When the energy is not enough to support the ideal message dissemination, we question how to schedule the switching within the limited energy constraint, in order to maximize the message dissemination scope. The above two problems are solved by using proposed EPCWH strategy.
- We conduct extensive simulations on both the synthetic random-waypoint mobility pattern and real traces (EPFL [21] and PMTR [22]). The results show that EPCWH achieves the best performance in terms of message dissemination and energy consumption among different switching strategies.

The remainder of the paper is organized as follows: We review the related work in Section II. In section III, we present the energy efficient phone-to-phone communication method based on WiFi Hotspot (EPCWH) is presented in Section III. In Section IV, the performance of EPCWH is evaluated through extensive simulations. We conclude the paper in Section V. All the proofs are presented in Appendix.

II. RELATED WORK

In this paper, we propose an energy efficient phone-to-phone communication method based on WiFi hotspot in PSN. Previous studies related to this paper are comprised of the following three sections: (1) Saving the energy consumption in PSN; (2) Utilizing the WiFi hotspot mode in smart phones to establish connections; (3) Maximizing the message dissemination scope through reasonably scheduling the switching between hotspot mode and client mode.

A. Energy Constraint in DTN

Recently, an enormous amount of research work has been devoted to proposing optimal beaconing control strategies or routing protocols to take advantage of the limited energy in DTN (including PSN). It is because of how problematic the excessive energy consumption of devices in DTN is, that this research is becoming increasingly popular. However, beaconing is necessary for devices to discover the available communication opportunities. Meanwhile, routing protocol is also crucial to reasonably utilize connections. However, both of these actions require energy expenditure. Therefore, saving energy consumption becomes the key issue of concern in DTN. For example, Altman $et\ al.$ [13] propose an optimal method to control the activation and transmission in DTN, in which energy is consumed not only in data transmission, but also during listening and several signaling activities. Furthermore, an optimal energy management strategy is derived to solve the following problems: what time a mobile phone should turn on to receive a message, and what the beaconing frequency is. Li *et al.* [23] present an optimal beaconing control for Epidemic routing in DTN. They utilize a continuous-time Markov model to formulate the optimization problem regarding beaconing control. Subsequently, the delivery ratio is maximized within an energy constraint. In order to minimize the energy expended on communication in DTN, Uddin *et al.* [5] present a novel multicopy routing protocol for disaster-response applications. They exploit naturally recurrent mobility and contact patterns formed by rescue workers, volunteers, and survivors to achieve an adequate delivery ratio within a low energy constraint. In [24], they propose an innovative hybrid approach, which is called Backpressure With Adaptive Redundancy (BWAR). The strategy is robust, distributed and also does not require any prior knowledge of network load conditions. They also present variants of BWAR that remove redundant packets via a timeout mechanism, and that improve the utilization of energy. Niyato *et al.* [25] present a framework to analyze optimization performance, which is based on a framework combining optimization and game-theoretic. They use the optimization model to obtain the message delivery policy of each individual mobile node. A novel game-theoretic model is then developed to analyze the cooperation strategies of multiple mobile nodes.

Although their research commendably solves the energy saving problems in DTN, they are still purely theoretical, where neither the communication device nor the communication protocol are mentioned. The model is based on the premise that two nodes in "on" status can establish a connection may be difficult to be achieved in practice.

B. WiFi Hotspot on Mobile Phone

Our work is also relevant to WiFi hotspot mode on mobile phones. Recently, some research has proposed utilizing WiFi hotspot or WiFi tethering technology on mobile phones to share 3G or 4G service, in order to save the energy of WiFi APs and WiFi Clients. For example, Sharma *et al.* [18] propose an architecture called Cool-Tether that takes advantage of the cellular radio links of nearby mobile smart phones, and then builds a WiFi hotspot on-the-fly to provide energy efficient connectivity. It is worth noticing that Cool-Tether uses a novel reverse-infrastructure mode for WiFi, where the client host serves as AP while the gateway serves as a client. Keshav *et al.* [19] propose using a 4G network to provide high speed data link; mobile phones take turns to act as WiFi APs to share 4G service with the nearby clients. They also make a trade-off between quality of network service and battery life of mobile phone. Jung *et al.* [20] bring in the sleep cycle, as in power save mode, to save energy of the tethering smart phone that acts as mobile AP. Satisfyingly, it requires no modification on the client side. Dong *et al.* [26] present a cooperative approach to optimize power consumption through choosing appropriate mobile hotspot nodes. In [27], they propose a new unified analytical model, which is referred as DTN-Meteo. DTN-Meteo maps an important class of DTN optimization problems over heterogeneous mobility models into a Markov chain traversal over the relevant solution space. So far, this is the first analytical work that accurately predicts performance for utility-based algorithms and heterogeneous node contact rates. In [28], they successfully balance the tradeoff between the amount of traffic being offloaded and the user's satisfaction, through proposing an incentive framework. Aiming to minimize the incentive cost focusing on a specific offloading target, users with high delay tolerance and large offloading potential should be prioritized for traffic offloading.

The forementioned research's achievements focus on choosing adaptive nodes as WiFi hotspots to share the network service, to save energy consumption. However, they disregard the importance of utilizing nodes' mobility and WiFi connection to disseminate messages. Meanwhile, the above works also leave out of consideration applying to a network environment (DTN, PSN *et al.*) without WiFi AP and cellular service.

C. WiFi Hotspot in DTN

Hu *et al.* [15] presents a practical mobile phone sensing system, which utilizes WiFi hotspot functionality on drivers' smart phones to realize the communications among vehicles through toggling the phone between the normal client and the hotspot modes. They also implement this system on off-the-shelf Google Galaxy Nexus and Nexus S phones.

However, the phone's energy consumption is not considered because the vehicle is constantly supplying enough energy for the mobile phone. Therefore, the system is not appropriate for PSN, because it doesn't solve the problem of how to successfully conserve the phone's limited energy.

III. ENERGY EFFICIENT PHONE-TO-PHONE COMMUNICATION BASED ON WIFI HOTSPOT

To deliver a well-defined problem formulation and gain useful strategy insights, we first introduce the assumptions related to this paper and present the energy efficient phone-to-phone communication problem to be addressed. Subsequently, a PSN with multiple messages is considered in this paper; we propose EPCWH to schedule the switching between hotspot mode and client mode, in order to maximize the probability of establishing a connection between two randomly chosen phones within the limited energy. Next, a PSN with a single message is further considered. EPCWH is enhanced to be a more efficient method to maximize the message dissemination scope within the limited energy constraint. In summary, an energy efficient phone-to-phone communication method based on WiFi hotspot in PSN is achieved.

A. Problem Formulation

Consider the following network environment: There is a PSN composed of N human-carried phones in the fixed area (each one holds a phone), with messages to be disseminated in the network. Each message has a given TTL, after which the message is no longer useful and should be dropped. We respectively use random-waypoint and Epidemic [29] as a mobility pattern and routing protocol. In addition, as the phones move independently, the intermeeting times in random-waypoint tail off exponentially [30]. A phone can switch between hotspot mode and client mode; additionally, two

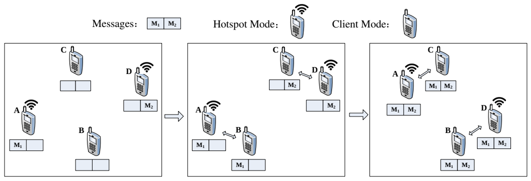


Fig. 2. An example of message dissemination process in PSN. Node A in hotspot mode encounters Node B in client mode, while Node D in hotspot mode encounters Node C in client mode. A and B establishes a connection, while C and D also connect with each other. They exchange messages with each other. Subsequently, the similar situation happens when A encounters C, and B encounters D.

phones in each other's communication range can establish a connection, if and only if, one of them is in hotspot mode and the other in client mode. Two phones with the identical mode (whether hotspot or client) cannot communicate with each other. Hotspot mode could significantly consume energy [18], [19]. However, the energy consumptions of client mode and switching between two modes are not considered in this paper, but will appear in future work.

According to the above descriptions, we seek to utilize the WiFi connection between two phones in different modes to carry on message dissemination, so that the message's audience is as large as possible (advertisement, coupon $et\ al.$). An example of the message dissemination process is illustrated in Fig. 2. However, it is well-known that the hotspot mode is in a status of high energy consumption. In the absence of energy supply, a phone cannot stay in hotspot mode for too long. On the other hand, since two phones both in hotspot mode cannot establish a connection, putting too many phones in hotspot mode will not contribute to message dissemination, nor will it conserve energy. However, this approach misses several communication opportunities, which leads to a bad performance of message dissemination. In summary, the scheduling strategy to switch between modes is crucial for a balanced trade of between message dissemination and energy consumption.

To achieve this, several challenging problems must be addressed: (1) How to estimate the message dissemination scope according to the uncertain mobility. (2) How schedule the switch between modes to maximize the delivery ratio within the limited energy when multiple messages coexist in PSN. (3) How to schedule the switch more accurately to maximize the message dissemination scope, when a single message exists in PSN at the same moment.

This paper proposes an energy efficient device-to-device communication method based on WiFi hotspot to solve the subsequent problems. When multiple messages coexist in PSN at the same moment, we propose a switching strategy between hotspot mode and client mode, to maximize the chances of establishing a connection between two randomly chosen phones within the limited energy constraint. When a single message exists in PSN at the same moment, this method estimates the message dissemination scope through predicting the dissemination process. Subsequently, an enhanced switching strategy between hotspot mode and client mode is presented to maximize the message dissemination scope within the limited energy constraint. Main notations used throughout this paper are illustrated in Table I.

TABLE I
MAIN NOTATION USED THROUGHOUT THE PAPER

Symbol	Meaning
N	The total number of phones in PSN
T	Initial time-to-live (TTL) for messages
T_1'	Optimal time for a phone holding the message to switch from hotspot mode to client mode
T_2'	Optimal time for a phone without the message to switch from client mode to hotspot mode
$\alpha(t)$	The probability to be in hotspot mode for the phone holding the message at time t
$\beta(t)$	The probability to be in hotspot mode for the phone without the message at time t
f	The time-invariant frequency of switching to hotspot mode
$m(t)$	Number of the phones holding the message at time t
$n(t)$	Number of the phones without the message at time t ($n(t) = N - m(t)$)
$P(t)$	Probability of establishing a connection between two randomly chosen phones at time t
$E(I)$	Mathematical expectation of intermeeting times
λ	Parameter in the exponential distribution of intermeeting times ($\lambda = 1/E(I)$)
C	Energy consumption rate of staying in hotspot mode (without loss of generality, $C = 1$ J/s)
Ω	Maximum energy constraint to each phone
Ω_{sum}	The total energy consumption in PSN
Ω_{min}	The minimum total energy consumption to satisfy the optimal message dissemination

B. System Description

In PSN, the phones primarily utilize occasional communication opportunities to transfer messages. Therefore, the intermeeting times will seriously influence the delivery ratio. We first define the intermeeting time as follows:

Definition 1: Intermeeting time I is the elapsed time from the end of the previous contact to the start of the next contact between a pair of phones.

According to the descriptions in Section III-A , the recent research [30], proves that intermeeting times tail off exponentially in many popular mobilities, such as random walk, random-waypoint, and random direction. Our simulations are based on the random-waypoint mobility pattern and two real traces (EPFL and PMTR). As a result, the intermeeting times approximately follow exponential distribution: $f(x) = \lambda e^{-\lambda x}$ $(x \geq 0)$. We assume that λ is the parameter for above exponential distribution, and $E(I)$ stands for the mathematical expectation of intermeeting times; then we have $\lambda = \frac{1}{E(I)}$.

This paper focuses the analyses on pairwise encounters between the human-carried phones, as opposed to optimizing general communications within the clusters of more than two phones. This is mainly according to the work in [15], where the researchers record all the vehicles' meeting events in the T-drive dataset containing 9,211 taxicabs. According to their simulations using Google smart phones equipped by vehicles, they find that pairwise encounters occupy about 80% of all meeting occurrences. In order to completely solve the communication congestion problem, we introduce spectrum access technology to avoid congestion which happens among the clusters of more than two phones. Dynamic spectrum allocation [31] is used to help improve the practicability of the communication model.

C. Energy Efficient Phone-to-phone Communication of Multiple Messages

In the scenario where multiple messages coexist in PSN at the same moment, they are periodically generated in randomly selected phones. The geographical locations and transmission scopes of the messages are unknown; Epidemic routing protocol is used in the network. When two mobile phones interact, the following becomes uncertain: (1) Which mode the mobile phone is utilizing. (2) How many messages do the mobile phones have. (3) How long will the mobile phones stay in the mutual communication area. In light of these factors, it becomes difficult to distinguish the phones, it is generally difficult to distinguish the phones. Therefore, when multiple messages coexist in PSN at the same moment, the phones are regarded as no difference. We further turn the problem into finding a uniform switching strategy between hotspot and client mode in order to maximize the likelihood of establishing a connection between two phones while conserving energy.

As illustrated in Table I, symbols $\alpha(t)$ and $\beta(t)$ respectively stand for the hotspot switching frequencies of the phone holding the message and the phone without the message. When multiple messages coexist in PSN at the same moment, we adopt a uniform switching strategy (as shown in Eq. (1)). All the phones in the network regard $\alpha(t)$ as the frequency of switching to hotspot mode.

$$\alpha(t) = \beta(t) \tag{1}$$

When two randomly chosen phones (A and B) encounter each other, they can establish a connection in two cases: (1) A in hotspot mode and B in client mode ($\alpha(t)(1-\alpha(t))$). (2) A in client mode and B in hotspot mode ($(1-\alpha(t))\alpha(t)$). As a result, the $P(t)$ (probability of establishing a connection between two randomly chosen phones at time t) can be formulated as Eq. (2).

$$P(t) = 2\alpha(t)(1-\alpha(t)) \tag{2}$$

Each phone has a maximum energy constraint (Ω in Table I), meanwhile, each message has an initial time-to-live (T in Table I). In order to schedule the switching strategy within the limited energy constraint, $\alpha(t)$ should satisfy: $\int_0^T \alpha(t)\mathrm{d}t \le \Omega$. In light of the fact that the encounter between two chosen phones can occur at any time from 0 to T, the optimization objective, then changes to maximize $\int_0^T 2\alpha(t)(1-\alpha(t))\mathrm{d}t$. In summary, an energy efficient phone-to-phone communication of multiple messages requires a scheduling strategy $\alpha(t)$ to satisfy the optimal equation as Eq. (3).

$$\begin{aligned} &Maximize \int_0^T 2\alpha(t)(1-\alpha(t))\mathrm{d}t \\ &s.t. \quad \int_0^T \alpha(t)\mathrm{d}t \le \Omega \end{aligned} \tag{3}$$

Eq. (3)demonstrates an ideal situation with the assumption that maximizing $\int_0^T 2\alpha(t)(1-\alpha(t))\mathrm{d}t$ is equivalent to the following operation: maximizing $2\alpha(t)(1-\alpha(t))$, $\forall t \in [0,T]$. The maximum value of $2\alpha(t)(1-\alpha(t))$ can easily be obtained, if and only if, $\alpha(t) = 1/2$. As a result, an optimal situation is $\alpha(t) = 1/2$, $\forall t \in [0,T]$. However, the optimal switching strategy requires the energy constraint of a phone to satisfy: $\Omega \ge T/2$. In other words, if $\Omega \ge \frac{T}{2}$, the optimal solution to Eq. (3) is $\alpha(t) = 1/2$, $\forall t \in [0,T]$ for all the phones in PSN.

However, if $\Omega < T/2$, the optimal solution to Eq. (3) is unavailable due to the limited energy, therefore, we should find a switching strategy $\alpha(t)$ for each phone to solve the optimization problem. Due to the wide variety of the functional forms of $\alpha(t)$, choosing a functional form becomes challenging.

Theorem 1: When $\Omega < T/2$, in order to maximize the $\int_0^T 2\alpha(t)(1-\alpha(t))\mathrm{d}t$, the optimal solution $\alpha(t)$ of Eq. (3) satisfies: $\int_0^T \alpha(t)\mathrm{d}t = \Omega$.

The proof of Theorem 1 is shown in Appendix A, where we could achieve that the optimal solution $\alpha(t)$ of Eq. (3) satisfies: $\int_0^T \alpha(t)\mathrm{d}t = \Omega$. The insight meaning of Theorem 1 is shown as follows. If we attempt to maximize the dissemination scope within the limited energy constraint, the optimal solution of each device is to use up the initial energy. However, even if we use up the given energy, the dissemination scope is not necessarily maximal.

Theorem 2: When $\Omega < T/2$, among the different functional forms of $\alpha(t)$, the constant function $\alpha(t) = f$ obtains the optimal solution to Eq. (3).

Proof for Theorem 2 is found in Appendix B. Theorem 2 provides a constant function of $\alpha(t)$ in order to obtain the optimal solution to Eq. (3), which has insightful meanings as follows. There are countless kinds function shapes for $\alpha(t)$ satisfying Eq. (3). Among them, we could prove that the constant function $\alpha(t) = f$ obtains the optimal solution.

To sum up, when multiple messages coexist in PSN at the same moment, we propose an energy efficient phone-to-phone communication method, which maximizes the probability of establishing a connection between two randomly chosen phones taking advantage of the limited energy. The communication method adopts a uniform frequency $\alpha(t)$ of switching to hotspot mode. The optimal solution $\alpha(t)$ is shown in Eq. (4).

$$\begin{cases} \alpha(t) = 1/2, & \Omega \ge T/2 \\ \alpha(t) = \Omega/T, & \Omega < T/2 \end{cases} \tag{4}$$

D. Energy Efficient Phone-to-phone Communication of A Single Message

Next, consider a network environment with a single message, and the humans holding mobile phones replicate the message with the help of random encounters. All the message copies in PSN are the same, they are the copies of the single original message. Similarly, a switching strategy between hotspot mode and client mode is necessary to maximize the message dissemination scope within the limited energy constraint. However, the network environment in this Section is significantly different from the one in Section III-C. The number of messages in a phone is only a value of 0 or 1; and the effective communication only occurs between a phone with the message and another one without the message. There is no need for two phones with the message to establish a connection, for the reason that they both have the single message. Similarly, it is also not necessary for two phones without the message to establish a connection, since they have nothing to exchange.

Based on the above analyses, the phones could be divided into two categories: holding the message, and without the message. We propose an energy efficient phone-to-phone communication method, which can deal with the following two problems: (1) How to schedule the switch between modes when the energy is enough to finish optimal message dissemination while minimizing energy consumption. (2) How to maximize message dissemination when the energy is not enough to realize the ideal [message dissemination.

Table I illustrates, symbols $m(t)$ and $n(t)$ respectively denote the number of phones holding the message and phones without the message at time t. The phone holding the message has a frequency $\alpha(t)$ of switching to hotspot mode, and the phone without the message has a frequency $\beta(t)$. Therefore, the following two cases can lead to the increase of $m(t)$. (1) A phone holding the message in hotspot mode encounters another phone without the message in client mode ($\lambda m(t)\alpha(t)n(t)(1-\beta(t))$). (2) A phone holding the message in client mode encounters another phone without the message in hotspot mode ($\lambda m(t)(1-\alpha(t))n(t)\beta(t)$). Therefore, the derivative of $m(t)$ is expressed as Eq. (5).

$$\begin{aligned}\frac{\mathrm{d}m(t)}{\mathrm{d}t}=&\lambda[m(t)\alpha(t)n(t)(1-\beta(t))+m(t)(1-\alpha(t))n(t)\beta(t)]\\=&\lambda m(t)n(t)[\alpha(t)+\beta(t)-2\alpha(t)\beta(t)]\end{aligned}\tag{5}$$

When a phone holding the message encounters another phone without the message, the probability of establishing a connection between them at time t is formulated as

$$P(t)=\alpha(t)+\beta(t)-2\alpha(t)\beta(t).\tag{6}$$

By combining Eqs. 5-6, we obtain the relationship between $m(t)$ and $P(t)$ as follows:

$$\frac{\frac{\mathrm{d}m(t)}{\mathrm{d}t}}{\lambda m(t)(N-m(t))}=P(t),\tag{7}$$

according to the Eq. (7) and $m(0)=1$, the message dissemination scope $m(T)$ can be calculated through Eq. (8). The problem changes to maximize $m(T)$ through controlling $\alpha(t)$ and $\beta(t)$.

$$m(T)=\frac{N}{(N-1)e^{-N\lambda\int_0^T P(t)\mathrm{d}t}+1}\tag{8}$$

Through the analyses on Eq. (8), $m(T)$ increases with the increase of $\int_0^T P(t)\mathrm{d}t$ [32]. Meanwhile, the maximum energy constraint to each phone is Ω, we seek to maximize the message dissemination scope within the energy constraint. Therefore, the optimization objective is shown as follows:

$$\begin{aligned}&Maximize\int_0^T \alpha(t)+\beta(t)-2\alpha(t)\beta(t)\mathrm{d}t\\&s.t.\quad\begin{cases}\int_0^T\alpha(t)\mathrm{d}t&\leq\Omega\\\int_0^T\beta(t)\mathrm{d}t&\leq\Omega\end{cases}\end{aligned}\tag{9}$$

Ideally, the energy is enough to finish the optimal message dissemination ($P(t)=1$), so the question is then, how to schedule $\alpha(t)$ and $\beta(t)$ to minimize the total energy consumption. Note that if we seek to capture optimal message dissemination, Eq. (10) must be satisfied. In other words, we are in dire need of designing a scheduling strategy of $\alpha(t)$ and $\beta(t)$, in order to utilize all the effective communication opportunities. Moreover, the total energy consumption in the network can be calculated through Eq. (11). Therefore, the purpose changes to minimize the total energy consumption Ω_{sum}, while ensuring the optimal message dissemination ($P(t)=1$).

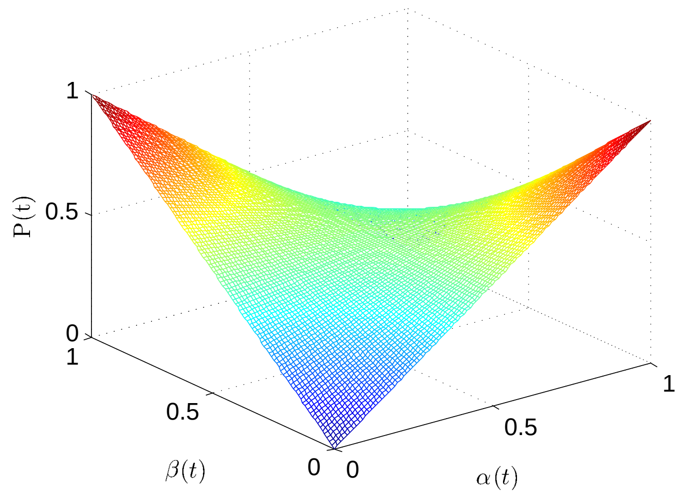


Fig. 3. $P(t)$ as a function of $\alpha(t)$ and $\beta(t)$.

$$P(t)=\alpha(t)+\beta(t)-2\alpha(t)\beta(t)=1\tag{10}$$

$$\Omega_{sum}=\int_0^T(m(t)\alpha(t)+n(t)\beta(t))\mathrm{d}t\tag{11}$$

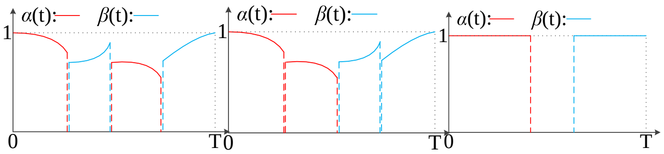
To discover the relationships among $\alpha(t)$, $\beta(t)$ and $P(t)$, Fig. 3 shows the change of $P(t)$ as a function of $\alpha(t)$ and $\beta(t)$. Eq. (10) is satisfied if and only if $\alpha(t)=1$, $\beta(t)=0$ or $\alpha(t)=0$, $\beta(t)=1$. It is significant that $m(t)$ increases with time t, while $n(t)$ decreases with time t. Therefore, to minimize the total energy consumption, there must be a T', which satisfies following conditions. If $t\leq T'$: $\alpha(t)=1$, $\beta(t)=0$. If $t>T'$: $\alpha(t)=0$, $\beta(t)=1$. Through the combination of this analyses and Eq. (11), the optimization problem becomes finding an optimal T', in order to minimize $f(T')$, which is shown below:

$$\begin{aligned}f(T')=&\int_0^{T'}m(t)\mathrm{d}t+\int_{T'}^{T}n(t)\mathrm{d}t\\=&NT'+\frac{2\ln[(N-1)e^{-N\lambda T'}+1]}{\lambda},\end{aligned}\tag{12}$$

where $f(T')$ is gradually decreased, and then gradually rises with the increase of T'. Therefore, the solution (as shown in Eq. (13)) to $\frac{\mathrm{d}f(T')}{\mathrm{d}T'}=0$ is the optimal T' to minimum $f(T')$.

$$T'=\frac{\ln(N-1)}{N\lambda}\tag{13}$$

We can obtain $m(T')=N/2$ by combining Eq. (8) and Eq. (13). The clarity of this result is obvious, since the optimal T' is just the time that the message disseminates half of the phones in the network. Before T', phones holding the message remain in hotspot mode since the number of phones holding the message is smaller than the number of phones without the message, while phones without the message remain in client mode. After T', the phones reverse roles since the number



(a) General scheduling (b) Better scheduling (c) Optimal scheduling

Fig. 4. Different scheduling strategies of $\alpha(t)$ and $\beta(t)$.

of phones holding the message is larger than the number of phones without the message. In conclusion, when the energy is enough to finish the optimal message dissemination, we propose a scheduling strategy of $\alpha(t)$ and $\beta(t)$ to get the minimum total energy consumption (as Eq. (14)).

$$\Omega_{min}=\left(\frac{\ln(N-1)}{\lambda}-\frac{\ln N}{\lambda}+\frac{\ln 4}{\lambda}-\frac{\ln[(N-1)e^{-N\lambda T}+1]}{\lambda}\right) \quad (14)$$

Therefore, when $t \leq T'$, $\alpha(t)=1$, whereas when $t > T'$, $\alpha(t)=0$. The optimal time T_1' (as denoted in Table I) for a phone holding the message to switch from hotspot mode to client mode is equal to T'. Similarly, $T_2'=T'$. Due to the constraint condition in Eq. (9), the scheduling strategy requires Ω to satisfy the following conditions: $\Omega \geq \frac{\ln(N-1)}{N\lambda}$ and $\Omega \geq T-\frac{\ln(N-1)}{N\lambda}$, $\Omega \geq T/2$ can be inferred. In other words, when $\Omega \geq T/2$, $\Omega \geq \frac{\ln(N-1)}{N\lambda}$ and $\Omega \geq T-\frac{\ln(N-1)}{N\lambda}$, the optimal scheduling is $T_1'=T_2'=\frac{\ln(N-1)}{N\lambda}$ (as shown in Table II).

Next, when $\Omega \geq T/2$, while $\Omega < \frac{\ln(N-1)}{N\lambda}$ and $\Omega \geq T-\frac{\ln(N-1)}{N\lambda}$. This means that the maximum energy constraint to each phone cannot satisfy the phone holding the message; with this in mind, we need to shift T_1' and T_2' (as denoted in Table I) to an earlier time. It is not difficult to find that when $T_1'=\Omega$, $\int_0^T \alpha(t)=\Omega \leq \Omega$; when $T_2'=\Omega$, then $\int_0^T \alpha(t)=T-\Omega \leq \Omega$ (since $\Omega \geq T/2$). Therefore, the optimal scheduling strategy is $T_1'=T_2'=\Omega$. Similarly, when $\Omega \geq \frac{\ln(N-1)}{N\lambda}$ and $\Omega < T-\frac{\ln(N-1)}{N\lambda}$, the optimal switching time is $T_1'=T_2'=T-\Omega$.

When $\Omega < T/2$, it indicates that the maximum energy constraint of each phone is not enough for optimal message dissemination. However, we still need to schedule the $\alpha(t)$ and $\beta(t)$, in order to maximize the message dissemination scope and minimize the energy consumption. The optimization objective is still shown in Eq. (9), however,while the difference is $\Omega < T/2$. Therefore, the maximum value of $\int_0^T \alpha(t)+\beta(t)-2\alpha(t)\beta(t)\mathrm{d}t$ is achieved only when $\int_0^T \alpha(t)\beta(t)=0$. As a result, a general scheduling strategy to maximize the message dissemination scope is shown in Fig. 4-(a). The following theorem is given to minimize the total energy consumption in the network:

Theorem 3: When $\Omega < T/2$, in order to maximize the $\int_0^T \alpha(t)+\beta(t)-2\alpha(t)\beta(t)\mathrm{d}t$ and minimize the total energy consumption, the scheduling strategy shown in Fig. 4-(c) captures the optimal solution.

The proof of Theorem 3 is shown in Appendix C, which illustrates that when a single message exists in the network, the best solution to schedule the switching between hotspot mode and client mode is shown in Fig. 4-(c). In other words, the best solution for minimizing energy consumption is to schedule the highest hotspot frequency for the phone holding the message in the earlier period of system time, and schedule the highest hotspot frequency for the phone without the message in the later.

According to Theorem 3, when $\Omega < T/2$, we omit derivation details for the remaining cases and collect the results for all cases in Table II. In summary, when multiple messages coexist in PSN at the same moment, we propose an Energy efficient Phone-to-phone Communication method based on WiFi Hotspot (EPCWH) as shown in Eq. (4). Whereas, when a single message exists in the PSN, we enhanced EPCWH as shown in Table II.

IV. PERFORMANCE EVALUATION

Having presented our system model and having elaborated on the energy efficient phone-to-phone communication method, in this section, we conduct simulations based on the synthetic random-waypoint mobility pattern and report our findings in the following two scenarios: a PSN with multiple messages and a PSN with a single message. To further prove the applicability of the proposed EPCWH, we conducted simulations on the real traces (EPFL and PMTR).

A. Evaluation Settings

To demonstrate the performance of the proposed EPCWH, an Opportunistic Network Environment (ONE) simulator [33] is employed in this paper. We perform experiments using the synthetic random-waypoint mobility, where each human-carried phone repeats its own behavior, selecting a destination randomly and walking along the shortest path to reach the destination. We configure the random-waypoint experiment environment as follows: there are 100 human-carried phones in the fixed area and some messages to be disseminated in the network. Each message has a given TTL, after which the message is no longer useful and should be dropped. Messages are routed under Epidemic protocol. Two scenarios are considered in the simulations: one is a PSN with multiple messages, while the other is a PSN with a single message. Simulation parameters are given in Table III. Furthermore, we also conduct simulations on two real traces (EPFL and PMTR) to further prove the feasibility of EPCWH, simulation parameters of real traces are given in Table IV.

While a range of data is gathered from the experiments, we take the following four main performance metrics into consideration:

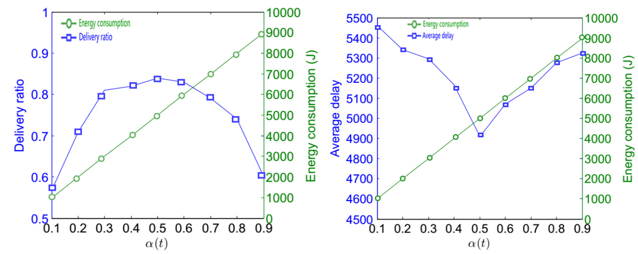
(1) Delivery ratio, which is the ratio between the number of messages successfully delivered to the destination versus the total number of messages generated in the network.
(2) Message dissemination scope $m(t)$, which is the number of phones holding the message at time t.
(3) Average delay, which is the total elapsed time of the successfully delivered messages versus the total number of successfully delivered messages.
(4) Energy consumption, which is the ratio of the total energy consumption for all the phones in the PSN to the number of human-carried phones.

TABLE II
OPTIMAL SCHEDULING STRATEGIES IN DIFFERENT CONSTRAINT CONDITIONS

Constraint Condition		Optimal Switching Time
$\Omega \geq \frac{T}{2}$	$\Omega \geq \frac{\ln(N-1)}{N\lambda}$ and $\Omega \geq T - \frac{\ln(N-1)}{N\lambda}$	$T_1' = T_2' = \frac{\ln(N-1)}{N\lambda}$
	$\Omega < \frac{\ln(N-1)}{N\lambda}$ and $\Omega \geq T - \frac{\ln(N-1)}{N\lambda}$	$T_1' = T_2' = \Omega$
	$\Omega \geq \frac{\ln(N-1)}{N\lambda}$ and $\Omega < T - \frac{\ln(N-1)}{N\lambda}$	$T_1' = T_2' = T - \Omega$
$\Omega < \frac{T}{2}$	$\Omega < \frac{\ln(N-1)}{N\lambda}$ and $\Omega < T - \frac{\ln(N-1)}{N\lambda}$	$T_1' = \Omega$ and $T_2' = T - \Omega$
	$\Omega < \frac{\ln(N-1)}{N\lambda}$ and $\Omega \geq T - \frac{\ln(N-1)}{N\lambda}$	$T_1' = \Omega$ and $T_2' = \frac{\ln(N-1)}{N\lambda}$
	$\Omega \geq \frac{\ln(N-1)}{N\lambda}$ and $\Omega < T - \frac{\ln(N-1)}{N\lambda}$	$T_1' = \frac{\ln(N-1)}{N\lambda}$ and $T_2' = T - \Omega$

TABLE III
SIMULATION PARAMETERS UNDER RANDOM-WAYPOINT MOBILITY PATTERN

Parameter	Value
Simulation time	10000s
Simulation area	4500m×3400m
Number of nodes	100
Transmission speed	250kBps
Transmission range	30m
Buffer size	500MB
TTL	10000s
Interval time of message generation	100s
Message size	500kB
Hotspot energy consumption rate	1J/s
$\alpha(t)$	0, 0.1, 0.2, $\cdots$, 0.9, 1
Energy constraint	1000J, 2000J, $\cdots$, 5000J



(a) Delivery ratio (b) Average delay

Fig. 5. Delivery ratio and Average delay as a function of $\alpha(t)$ under the random-waypoint mobility pattern.

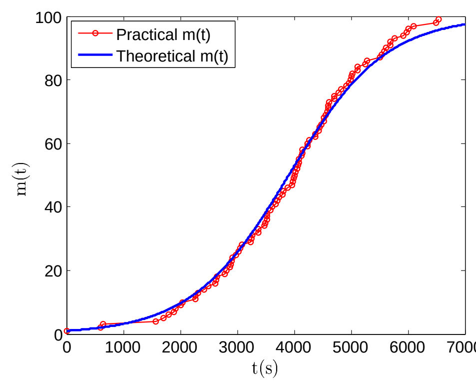


Fig. 8. The theoretical value and practical value of $m(t)$.

B. Simulation results under random-waypoint mobility pattern

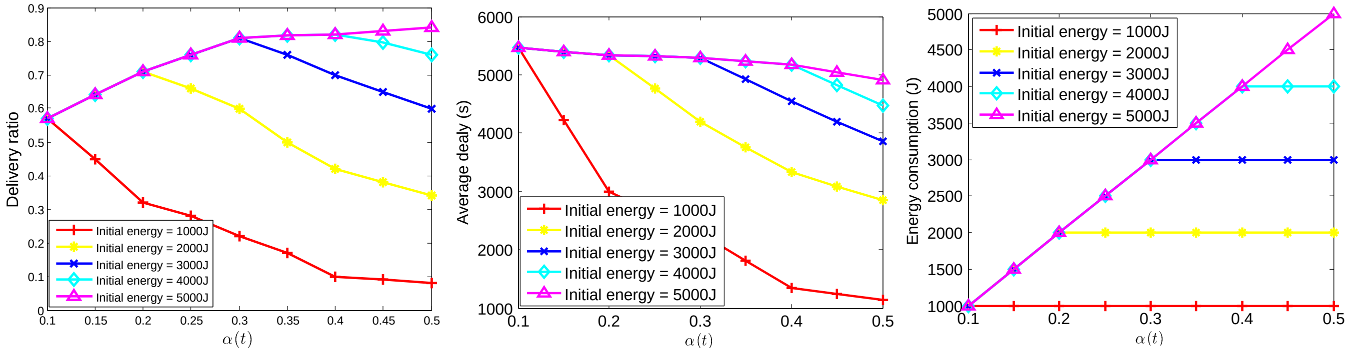
1) Simulation on A PSN with Multiple Messages: In the first part of the simulations, we use delivery ratio to measure the message dissemination scope. Delivery ratio, average delay, and energy consumption as a function of the frequency $\alpha(t)$ of switching to hotspot mode are tested in the two situations: (1) energy is enough to finish optimal message dissemination; (2) energy is not enough to realize optimal message dissemination.

First, when the simulation time is 10,000s, and the initial energy Ω is larger than 10,000J, each human-carried phone has enough energy to stay in hotspot mode. Fig. 5 describes the variation trend of delivery ratio, average delay, and energy consumption as a function of switching frequency $\alpha(t)$. According to the conclusion in Section III-C, when initial energy $\Omega \geq T/2$, the optimal solution is $\alpha(t) = 1/2$. It closely matches the simulation results. As shown in Fig. 5, compared with other switching frequencies, EPCWH ($\alpha(t) = 1/2$) achieves the best performance in terms of delivery ratio and average delay.

Secondly, when the initial energy $\Omega < 5000$J, each human-carried phone does not have enough energy to be in hotspot mode. The Ω is set to 1,000−5,000J respectively, Fig. 6 displays the variation of delivery ratio, average delay, and energy consumption along with the growth of switching frequency $\alpha(t)$. According to the conclusion in Section III-C, when initial energy $\Omega < T/2$, the optimal solution is $\alpha(t) = \Omega/T$. Therefore, the best solutions of $\alpha(t)$ corresponding to $\Omega = 1000, 2000, \cdots, 5000$J are $0.1, 0.2, \cdots, 0.5$. As shown in Fig. 6, the simulation results precisely satisfy the theoretical results.

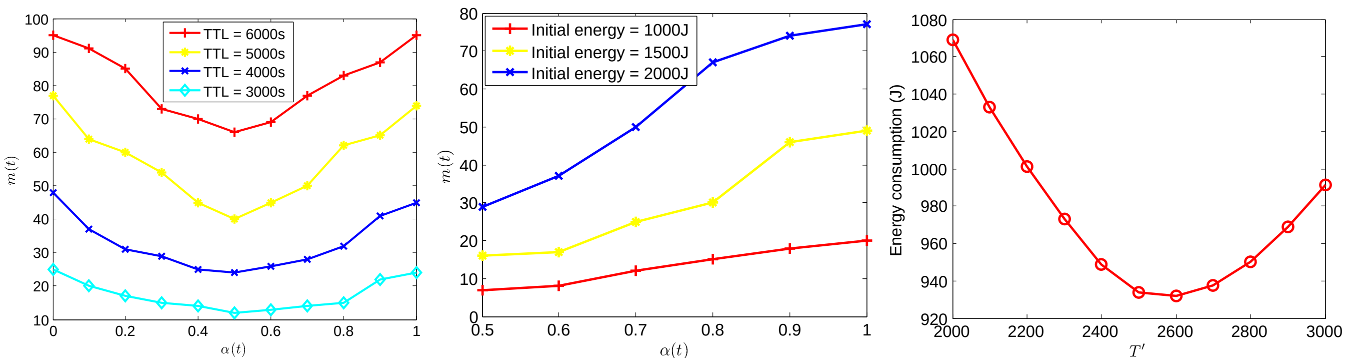
2) Simulation on A PSN with A Single Message: In the second part of the simulations, at the initial time of the system, a single message is generated in a random source. The message dissemination scope is measured through the number of phones holding the message at time t (i.e., $m(t)$). We also consider the following two conditions: energy enough situation, and energy not enough situation.

To verify the accuracy of $m(t)$ predicated by Eq. (8), we draw the figure of $m(t)$ under the random-waypoint scenario and compare it with the predicted results of Eq. (8). Fig. 8 shows that the theoretical results of $m(t)$ can closely match the practical results. It indicates that Eq. (8) can be used to calculate $m(t)$ precisely. When the energy is enough to realize the optimal message dissemination, Fig. 7-(a) depicts how the message dissemination scope $m(t)$ varies along with the increasing switching frequency $\alpha(t)$, on the premise that $\alpha(t) + \beta(t) = 1$. As can be seen in Fig. 7-(a), the following two conditions achieve the best performances in terms of message dissemination scope: (1) $\alpha(t) = 1, \beta(t) = 0$. (2) $\alpha(t) = 0, \beta(t) = 1$, which proves the correctness of theoretical results. We also vary the TTL of the message to further validate the applicability of EPCWH. When the energy is not enough to support the optimal dissemination, we simulate the



(a) Delivery ratio (b) Average delay (c) Energy consumption

Fig. 6. Delivery ratio, Average delay, and Energy consumption as a function of $\alpha(t)$ under the random-waypoint mobility pattern.



(a) Enough energy (b) Not enough energy (c) Energy consumption

Fig. 7. The relationships among Energy consumption, $m(t)$ and $\alpha(t)$ under the random-waypoint mobility pattern.

change trend of $m(t)$. Fig. 7-(b) provides some important data corresponding to the different initial energy. With the growth of switching frequency $\alpha(t)$, $m(t)$ monotonically increases. The optimal solution is achieved when $\alpha(t) = 1$ and $\beta(t) = 0$.

Secondly, to verify the correctness of Eq. (13), we vary the optimal time (T') for a phone holding the message to switch from hotspot mode to client mode, and observe the variation trend of energy consumption. Due to the number of phones $N = 100$, and $\lambda = 1/26500$, the optimal $T' \approx 2600$s according to Eq. (13). As shown in Fig. 7-(c), EPCWH obtains the lowest energy consumption only when $T' = 2600$s. In conclusion, the simulation results show that EPCWH achieves the best performance in terms of message dissemination and energy consumption among different switching strategies under the synthetic random-waypoint mobility pattern.

C. Simulation results under real traces

In order to further confirm the applicability of the proposed EPCWH strategy in PSN, we conduct simulations under the real traces (EPFL [21] and PMTR [22]). The simulation results show that no matter under the random-waypoint mobility pattern or the real traces, EPCWH still achieves the best performance in terms of message dissemination and energy consumption among different switching strategies.

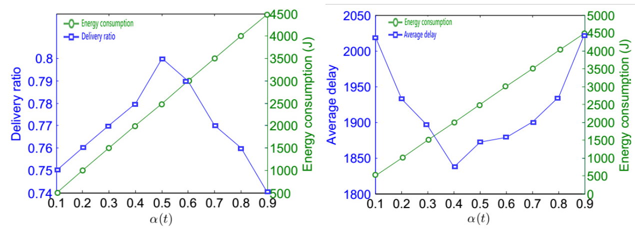
1) Simulation on EPFL real trace: EPFL dataset contains mobility traces of taxi cabs in San Francisco, USA. It contains GPS coordinates of approximately 500 taxis collected over 30 days in the San Francisco Bay Area. Without loss of generality; we use the data of the first 200 taxis in this paper. We plugged the epfl dataset into ONE to simulate taxi mobility over the first 5000s.

TABLE IV
SIMULATION PARAMETERS UNDER REAL TRACES

Parameter	Value	
	EPFL	**PMTR**
Simulation Time	5000s	1000000s
Number of Nodes	200	44
Transmission Speed	250Kbps	
Buffer Size	500MB	
Message Size	500kB	
TTL	5000s	1000000s
Energy consumption rate	1J/s	
$\alpha(t)$	0.1, 0.2, $\cdots$, 0.9	
Limited energy constraint	500J, 1000J, $\cdots$, 2500J	100000J, 200000J, $\cdots$, 500000J
Enough energy	$>$ 5000J	$>$ 1000000J

Focusing on the real trace EPFL, we use delivery ratio to measure the message dissemination scope. In order to eliminate the interference of limited buffer space, we set an enough buffer size: 500MB. Delivery ratio, average delay, and energy consumption as a function of the frequency $\alpha(t)$ of switching to hotspot mode are tested when the energy is enough to finish the optimal message dissemination.

First, when the simulation time is 5000s, and the initial energy Ω is larger than 5000J, each taxi-carried phone has enough energy to stay in hotspot mode. The variation tenden-



(a) Delivery ratio (b) Average delay

Fig. 9. Delivery ratio and Average delay as a function of $\alpha(t)$ under the EPFL trace.

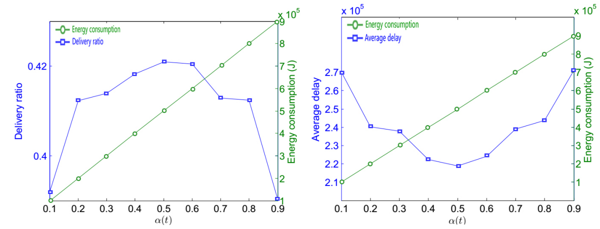
cies of delivery ratio, average delay, and energy consumption as a function of initial number of copies are shown from Fig. 9-(a) through Fig. 9-(b). The curves' shapes are similar with that of Fig. 5, which further proves that the conclusion in Section III-C is still useful under the real trace: when initial energy $\Omega \geq T/2$, the optimal solution is $\alpha(t) = 1/2$. It closely matches the simulation results. As shown in Fig. 9, compared with other switching frequencies, EPCWH ($\alpha(t) = 1/2$) achieves the best performance in terms of delivery ratio and average delay.

Second, when the initial energy $\Omega < 5000$J, each taxi-carried phone does not have enough energy to be in hotspot mode all the time. The Ω is set to 500J, 1000J, $\cdots$, 2500J, respectively, Fig. 10 displays the variation of delivery ratio, average delay, and energy consumption along with the growth of switching frequency $\alpha(t)$. According to the conclusion in Section III-C, when initial energy $\Omega < T/2$, the optimal solution is $\alpha(t) = \Omega/T$. Therefore, in EPFL real trace, the best solutions of $\alpha(t)$ corresponding to $\Omega = 500, 1000, \cdots, 2500$J should be $0.1, 0.2, \cdots, 0.5$, respectively. As shown in Fig. 10-(a), the simulation results precisely satisfy the theoretical results.

In addition, Fig. 10-(b) describes the variation trend of average delay as a function of switching frequency $\alpha(t)$. It then becomes apparent that there is an downtrend of average delay along with the growth of switching frequency $\alpha(t)$ under the real trace EPFL, which matches our understanding and makes sense for the reason that higher switching frequency leads to higher delivery delay. Furthermore, higher initial energy results in shorter delivery delay. In analysis, this is due to the way higher initial energy prolongs the device's survival time, which further increases the message's average delay. Moreover, Fig. 10-(c) provides some important data regarding energy consumption performance.

2) Simulation on PMTR real trace: PMTR dataset contains mobility traces from 44 mobile devices at University of Milano. The data was collected in November 2008. We plugged the trace of 40 devices in PMTR dataset into ONE to simulate taxi mobility over the first 1000000s.

Taking the real trace PMTR into consideration, we also use delivery ratio to measure the message dissemination scope. Similar with the setting in EPFL real trace, we set an enough buffer size to eliminate the buffer overflowing interference. Delivery ratio, average delay, and energy consumption as a function of the frequency $\alpha(t)$ of switching to hotspot mode are tested when the energy is enough to finish optimal message dissemination.



(a) Delivery ratio (b) Average delay

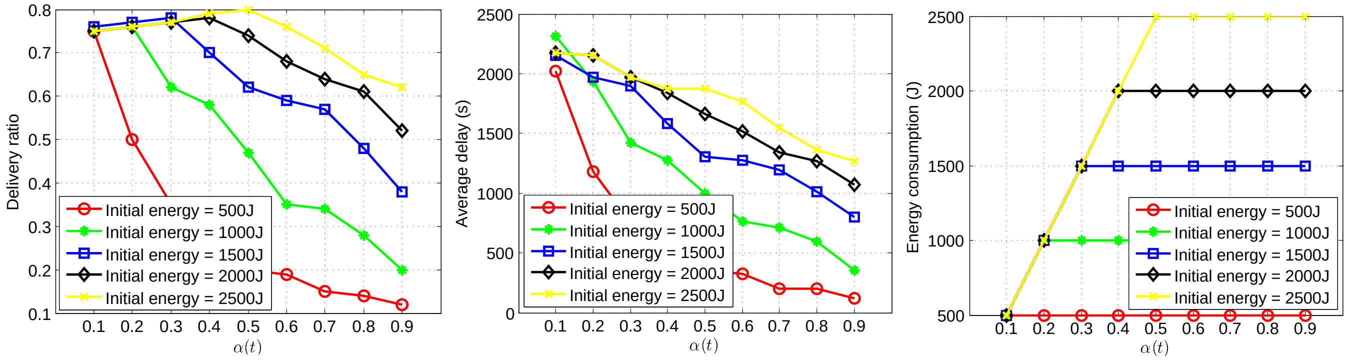
Fig. 11. Delivery ratio and Average delay as a function of $\alpha(t)$ under the PMTR trace.

First of all, when the simulation time is 1000000s, and the initial energy Ω is larger than 1000000J, each human-carried phone has enough energy to stay in hotspot mode. The variation tendencies of delivery ratio, average delay, and energy consumption as a function of initial number of copies are shown from Fig. 11-(a) through Fig. 11-(b). The curves' shapes are also similar with that of Fig. 5 and Fig. 9, which further proves that the conclusion in Section III-C is still useful under the real trace PMTR: when initial energy $\Omega \geq T/2$, the optimal solution is $\alpha(t) = 1/2$. As shown in Fig. 11, compared with other switching frequencies, EPCWH ($\alpha(t) = 1/2$) achieves the best performance in terms of delivery ratio and average delay.

Secondly, when the initial energy $\Omega < 1000000$J, each human-carried phone does not have enough energy to be in hotspot mode all the time. The Ω is set to 100000J, 200000J, $\cdots$, 500000J, respectively, Fig. 12 displays the variation of delivery ratio, average delay, and energy consumption along with the growth of switching frequency $\alpha(t)$. According to the conclusion in Section III-C, when initial energy $\Omega < T/2$, the optimal solution is $\alpha(t) = \Omega/T$. Therefore, in EPFL real trace, the best solutions of $\alpha(t)$ corresponding to $\Omega = 100000, 200000, \cdots, 500000$J should still be $0.1, 0.2, \cdots, 0.5$, respectively. As shown in Fig. 12-(a), the simulation results precisely satisfy the theoretical results. We omit detailed description of Fig. 12-(b) and Fig. 12-(c) for the reason that they are similar with Fig. 10-(b) and Fig. 10-(c).

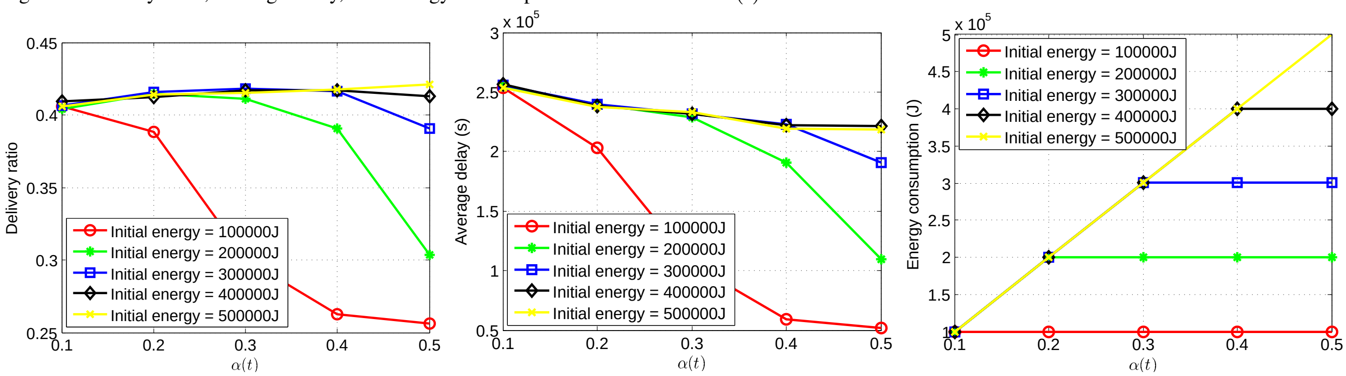
V. CONCLUSION

In this paper, we propose an Energy efficient Phone-to-phone Communication method based on WiFi Hotspot (EPCWH) in PSN. EPCWH applies WiFi hotspot mode on the mobile phone to realize the phone-to-phone communication. Two phones in each other's communication range can establish a connection if and only if one of them is in the hotspot mode and the other in the client mode. However, in the absence of energy supply, the energy consumption caused by staying in hotspot mode will shorten the phone's battery lifetime notably. To maximize the message dissemination scope utilizing the limited energy constraint in PSN, we present the scheduling strategies to switch the phone between hotspot mode and client mode in the following two scenarios: a PSN with multiple messages and a PSN with a single message. Simulations based on both the synthetic random-waypoint mobility pattern and the real traces (EPFL and PMTR) are conducted in ONE; the results show that EPCWH achieves the best performance



(a) Delivery ratio (b) Average delay (c) Energy consumption

Fig. 10. Delivery ratio, Average delay, and Energy consumption as a function of $\alpha(t)$ under the EPFL trace.



(a) Delivery ratio (b) Average delay (c) Energy consumption

Fig. 12. Delivery ratio, Average delay, and Energy consumption as a function of $\alpha(t)$ under the PMTR trace.

in terms of message dissemination and energy consumption among the different switching strategies.

Acknowledgement

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APPENDIX

A. Proof of Theorem 1

To prove the Theorem 1, we adopt the reduction to absurdity. Suppose that there exists a $\alpha'(t)$ satisfying: $\int_0^T \alpha'(t)\mathrm{d}t = \Omega' < \Omega$, and $\alpha'(t)$ can also maximize the optimization objective: $\int_0^T 2\alpha'(t)(1-\alpha'(t))\mathrm{d}t$. It is not difficult to find that there must exist t', which satisfies following expression: $\alpha'(t') < 1/2$. Otherwise, for $\forall t' \in [0,t]$, $\alpha'(t') \geq 1/2$, so $\Omega > \int_0^T \alpha'(t)\mathrm{d}t \geq \int_0^T \frac{1}{2}\mathrm{d}t$, which goes against the assumption: $\Omega < \int_0^T \frac{1}{2}\mathrm{d}t$. Therefore, there exists t' satisfying: $\alpha'(t') < 1/2$. Meanwhile, $2\alpha'(t)(1-\alpha'(t))$ is an increasing function when $0 \leq \alpha'(t') \leq 1/2$. We must be able to find another $\alpha''(t)$ satisfying Eq. (15), while $\int_0^T \alpha''(t)\mathrm{d}t \leq \Omega$. However, it is not difficult to find that $\int_0^T 2\alpha''(t)(1-\alpha''(t))\mathrm{d}t > \int_0^T 2\alpha'(t)(1-\alpha'(t))\mathrm{d}t$, which proves that $\alpha'(t)$ is not the best solution to Eq. (3). In conclusion, there is not a $\alpha'(t)$ satisfying: $\int_0^T \alpha'(t)\mathrm{d}t < \Omega$, which can also maximize $\int_0^T 2\alpha'(t)(1-\alpha'(t))\mathrm{d}t$. Above analyses prove that the optimal solution $\alpha(t)$ to Eq. (3) satisfies: $\int_0^T \alpha(t)\mathrm{d}t = \Omega$.

$$\begin{cases} \alpha''(t) = \alpha'(t), & t \neq t' \\ 1/2 \geq \alpha''(t) > \alpha'(t), & t = t' \end{cases} \tag{15}$$

B. Proof of Theorem 2

There are a myriad of different functional forms of $\alpha(t)$. Any functional form of $\alpha(t)$ can be expressed as $\alpha(t) = \gamma(t) + f$. According to Theorem 1, $\alpha(t)$ satisfies: $\int_0^T \alpha(t)\mathrm{d}t = \Omega$, then $\int_0^T \gamma(t) + f\mathrm{d}t = \Omega$. $\int_0^T \gamma(t)\mathrm{d}t = \Omega - fT$ can also be inferred. The optimization objective $\int_0^T 2\alpha(t)(1-\alpha(t))\mathrm{d}t$ can be unfolded as Eq. (16), where we seek to find the minimum value of $\int_0^T \gamma^2(t)\mathrm{d}t$. The perfect solution is easy to find out: $f = \Omega/T$ and $\gamma(t) = 0$. Therefore, the constant function $\alpha(t) = f$ obtains the optimal solution to Eq. (3); Theorem 2 is also proved.

$$\begin{aligned} \int_0^T 2\alpha(t)(1-\alpha(t))\mathrm{d}t &= \int_0^T 2(\gamma(t)+f)(1-\gamma(t)-f)\mathrm{d}t \\ &= -2\int_0^T \gamma^2(t)\mathrm{d}t + 2Tf^2 - 4\Omega f + 2\Omega \end{aligned} \tag{16}$$

C. Proof of Theorem 3

To maximize $\int_0^T \alpha(t)+\beta(t)-2\alpha(t)\beta(t)\mathrm{d}t$, the following two conditions must be satisfied: (1) $\int_0^T \alpha(t)\mathrm{d}t = \int_0^T \beta(t)\mathrm{d}t = \Omega$. (2) $\int_0^T \alpha(t)\beta(t)\mathrm{d}t = 0$. There is a general scheduling strategy as shown in Fig. 4-(a). However, the strategy cannot minimize the total energy consumption, which is shown in Eq. (11). Considering that $m(t)$ is an increase function with t, $n(t)$ is a decrease function with t. Therefore, the strategy shown in Fig. 4-(b) can get lower energy consumption than that of Fig. 4-(a). Furthermore, the strategy shown in Fig. 4-(c) obviously achieves the lowest energy consumption.

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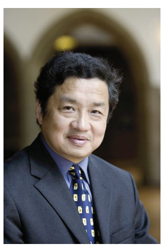

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