Energy Efficient Phone-to-Phone Communication Based on WiFi Hotspot in PSN

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***Abstract*—Pocket Switched Networks (PSN) utilize both human mobility and occasional connectivity to transfer messages between mobile humans' devices. Recently, a large number of mobile phones have come into our daily lives. Therefore, the PSN composed of human-carried mobile phones will be an ubiquitous network environment in the near future. In this paper, it is proposed that the WiFi hotspot mode of a mobile phone is applied in the PSN, in order to realize the phone-to-phone 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 switch between hotspot mode and client mode. Simulations based on the synthetic random-waypoint mobility pattern are conducted in ONE; the results show that EPCWH achieves the best performance in terms of message dissemination and energy consumption among different switch strategies.**

Keywords*—*PSN, Phone-to-phone, WiFi hotspot, Energy constraint, schedule.

I. INTRODUCTION

Delay-tolerant networks (DTN) [1] are challenged networks in which 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 result, the messages are routed in a store-carry-forward paradigm. DTN have been applied in interplanetary networks [2], disaster response networks [3], rural area networks [4], [5], wildlife tracking networks [6], and pocket switched networks [7].

Pocket Switched Networks (PSN) take advantage of both human mobility and occasional connectivity to transfer messages among human-carried mobile devices. The mobilities of devices make PSN different from WSN [8]. Routing protocols can utilize the devices' mobilities to transmit messages more rapidly. No doubt, designing forwarding algorithms [9] is the key point in PSN. However, the device used and the short-range communication protocol adopted are also crucial. The energy consumption of devices [10], [11] and the efficiency of communication protocol are often main concerns.

In recent years, there has been an obvious phenomenon in which a large number of smart phones has come into our daily lives. According to the reports of International Data Corporation (IDC) Worldwide Quarterly Mobile Phone Tracker [12], the usage of smart phones will reach 982 million by 2015. The report further reveals that PSN formed by smart phones will be a research focus in the near future. Therefore, the communication protocols among smart phones will play an important role for message dissemination and resource sharing. 3G, WiFi and Bluetooth are the three main communication protocols to be realized on smart phones. By contrast, Bluetooth is most unsuitable to PSN, for the reason that a short-distance communication leads to an enormous amount of communication opportunities missing, 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 [13], the coverage area of cellular networks is almost twice that of WiFi networks in the US. However, in consideration of the transmission rate and traffic cost, 90% of customers prefer WiFi over 3G, according to market research [14]. Even so, it is still impractical to directly use WiFi communication protocol in PSN, due to the lack of WiFi Access Points (APs).

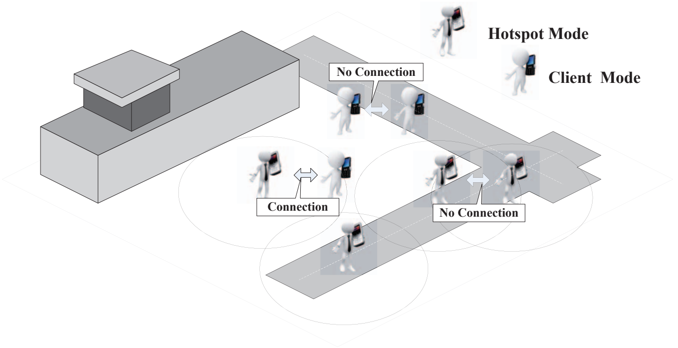


Fig. 1. An illustration of the phone-to-phone communication model based on WiFi hotspot.

Fortunately, recent studies [12], [15] have confirmed that the WiFi hotspot mode can be used to realize the phone-to-phone communications even in the network without WiFi APs. As illustrated in Fig.1, each human-carried phone could switch between hotspot mode and client mode. 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 is in the client mode. Two phones in the identical mode (whether hotspot or client) cannot communicate with each other. Through this method, a PSN where the communication occurs between two smart phones in different modes is formed.

However, a phone in hotspot mode could consume energy rapidly and shorten its battery lifetime significantly [16], especially 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. On the other hand, excessive phones in hotspot mode will not make a contribution to message dissemination, since two phones both in hotspot mode could not 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. 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.

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 switch within the limited energy constraint, in order to maximize the probability of establishing a connection between two randomly chosen phones.
- When a single (multiple copies) message exists in PSN at the same moment, we enhance the EPCWH to deal with the following two problems. (1) When the energy is enough to finish the optimal message dissemination, we question how to schedule the switch 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 switch within the limited energy constraint, in order to maximize the message dissemination scope.
- We conduct extensive simulations on the synthetic random-waypoint mobility. The results show that EPCWH achieves the best performance in terms of message dissemination and energy consumption among different switch strategies.

The remainder of the paper is organized as follows. Section II provides a brief overview of related work. The Energy efficient Phone-to-phone Communication method based on WiFi Hotspot (EPCWH) is presented in Section III. In Section IV, we evaluate the performance of EPCWH through extensive simulations. We conclude the paper in Section V.

II. RELATED WORK

A. Energy Constraint in DTN

Recently, an enormous amount of research work has been devoted to proposing optimal beaconing control strategies or routing protocols taking advantage of the limited energy in DTN (including PSN). For example, Altman *et al.* [10] 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. Li *et al.* [17] 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.* [3] 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.

Although the above research commendably solves the energy saving problems in DTN, they are still purely theoretical. In other words, both the communication device and the communication protocol are not mentioned. The model supposing 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 related to the efforts in terms of WiFi hotspot mode on mobile phones. For example, Sharma *et al.* [14] 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.* [18] 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.* [16] 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.* [19] present a cooperative approach to optimize the overall power consumption through choosing appropriate mobile hotspot nodes.

The above research achievements mainly focus on choosing adaptive nodes as WiFi hotspots to share the network service, in order to save energy consumption. However, they have no regard for 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 both WiFi AP and cellular service.

C. WiFi Hotspot in DTN

We argue that the following research finding is most relevant to this paper. Hu *et al.* [12] present 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 in the system for the reason that the vehicle can supply energy to mobile phones steadily. Therefore, the system is not appropriate for PSN, where the phone’s energy is extremely limited, especially when the phone switches to hotspot mode.

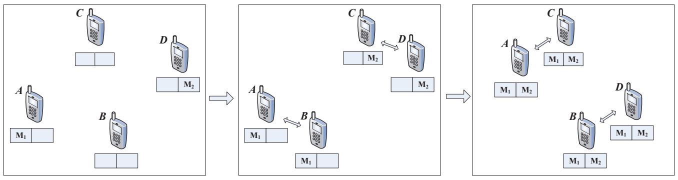


Fig. 2. An example of message dissemination process in PSN.

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

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). There are also 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. We respectively use random-waypoint and Epidemic [20] as a mobility pattern and routing protocol. In addition, as the phones move independently, the intermeeting times in random-waypoint tail off exponentially [21]. A phone can switch between hotspot mode and client mode, two 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. By comparison, the energy consumption of client mode could be negligible.

According to the above descriptions, we seek to utilize the WiFi connection between two phones in different modes to carry on message dissemination, in order to make as many people receive the message 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. Besides, a phone prefers to stay in client mode for saving energy. However, this approach misses a lot of communication opportunities, and leads to a bad performance of message dissemination. To sum up, there must be a scheduling strategy to switch between hotspot mode and client mode, in order to make a trade off between message dissemination and energy consumption. Main notations used throughout this paper are illustrated in Table I.

B. *System Description*

In PSN, the phones mainly 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: 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 [21], [22] 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. 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 $\lambda = \frac{1}{E(I)}$.

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 frequency of switching to hotspot mode for the phone holding the message at time t
$\beta(t)$	The frequency of switching to 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

Besides, 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 [12], 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.

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

First of all, consider the situation that multiple messages coexist in PSN at the same moment, the messages are periodically generated in stochastic phones. We turn the problem into finding a uniform switch strategy between hotspot mode and client mode to maximize the probability of establishing a connection between two randomly chosen phones taking advantage of the limited 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. (2) A in client mode and B in hotspot mode. 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: $\int_0^T \alpha(t)\mathrm{d}t \le \Omega$. Besides, since the encounter between two randomly chosen phones can occur at any time from 0 to T, the optimization objective actually 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.

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

As can be seen in Eq. 3, an ideal situation is assumed that maximizing $\int_0^T 2\alpha(t)(1-\alpha(t))\mathrm{d}t$ is equivalent to the following operation: maximizing $2\alpha(t)(1-\alpha(t))$, $\forall t \in [0, T]$. It is easy to find that, the maximum value of $2\alpha(t)(1-\alpha(t))$ is 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 not available for us due to the limited energy, we should find a switching strategy $\alpha(t)$ for each phone to solve the optimization problem. It is obvious that there are a myriad of different functional forms of $\alpha(t)$; which functional form to choose is a challenging problem.

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: $\int_0^T \alpha(t)\mathrm{d}t = \Omega$.

$Proof$: 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 $\forall t' \in [0, t]$, $\alpha'(t') \ge 1/2$, so $\Omega > \int_0^T \alpha'(t)\mathrm{d}t \ge \int_0^T \frac{1}{2}\mathrm{d}t$, 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 $0 \le \alpha'(t') \le 1/2$. We must be able to find another $\alpha''(t)$ satisfying Eq. 4, while $\int_0^T \alpha''(t)\mathrm{d}t \le \Omega$. 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: $\int_0^T \alpha(t)\mathrm{d}t = \Omega$.

$$\begin{cases} \alpha''(t) = \alpha'(t), & t \ne t' \\ 1/2 \ge \alpha''(t) > \alpha'(t), & t = t' \end{cases} \tag{4}$$

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.

$Proof$: 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. 5, 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.

$$\begin{aligned} \int_0^T 2\alpha(t)(1-\alpha(t))\mathrm{d}t &= \int_0^T 2(\gamma(t)+f)(1-\gamma(t)-f)\mathrm{d}t \\ &= -2\int_0^T \gamma^2(t)\mathrm{d}t + 2Tf^2 - 4\Omega f + 2\Omega \end{aligned} \tag{5}$$

To sum up, when multiple messages coexist in PSN at the same moment, we propose an energy efficient phone-to-phone communication method, which adopts a uniform frequency $\alpha(t)$ of switching to hotspot mode. The optimal solution $\alpha(t)$ is shown in Eq. 6.

$$\begin{cases} \alpha(t) = 1/2, & \Omega \ge T/2 \\ \alpha(t) = \Omega/T, & \Omega < T/2 \end{cases} \tag{6}$$

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

Next, consider the network environment with a single message. 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) When the energy is enough to finish the optimal message dissemination, how to schedule the switch between hotspot mode and client mode in order to minimize the total energy consumption. (2) When the energy is not enough to realize the ideal message dissemination, how to maximize message dissemination scope within the limited energy constraint.

As illustrated in Table I, 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. (2) A phone holding the message in client mode encounters another phone without the message in hotspot mode. Therefore, the derivative of $m(t)$ is expressed as Eq. 7.

$$\begin{aligned}\frac{\mathrm{d}m(t)}{\mathrm{d}t}&=\lambda[m(t)\alpha(t)n(t)(1-\beta(t))+m(t)(1-\alpha(t))n(t)\beta(t)]\\&=\lambda m(t)n(t)[\alpha(t)+\beta(t)-2\alpha(t)\beta(t)]\end{aligned}\tag{7}$$

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

$$P(t)=\alpha(t)+\beta(t)-2\alpha(t)\beta(t).\tag{8}$$

By combining Eqs. 7-8, we obtain the relationship between $m(t)$ and $P(t)$ as follows:

$$\frac{\frac{\mathrm{d}m(t)}{\mathrm{d}t}}{\lambda m(t)(N-m(t))}=P(t),\tag{9}$$

according to the Eq. 9 and $m(0)=1$, the message dissemination scope $m(T)$ can be calculated through Eq. 10. The problem changes to maximize $m(T)$ through controlling $\alpha(t)$ and $\beta(t)$.

$$m(T)=\frac{N}{(N-1)e^{-N\lambda\int_0^T P(t)\mathrm{d}t}+1}\tag{10}$$

Through the analyses [23] on Eq. 10, $m(T)$ increases with the increase of $\int_0^T P(t)\mathrm{d}t$. 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:

$$\begin{aligned}&Maximize \int_0^T \alpha(t)+\beta(t)-2\alpha(t)\beta(t)\mathrm{d}t\\&s.t.\quad\begin{cases}\int_0^T \alpha(t)\mathrm{d}t & \le\Omega\\ \int_0^T \beta(t)\mathrm{d}t & \le\Omega\end{cases}\end{aligned}\tag{11}$$

First of all, consider an ideal situation. When the energy is enough to finish the optimal message dissemination ($P(t)=1$), 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. 12 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. Besides, the total energy consumption in the network can be calculated through Eq. 13. Therefore, the purpose is to minimize the total energy consumption Ω_{sum}, while ensuring the optimal message dissemination ($P(t)=1$).

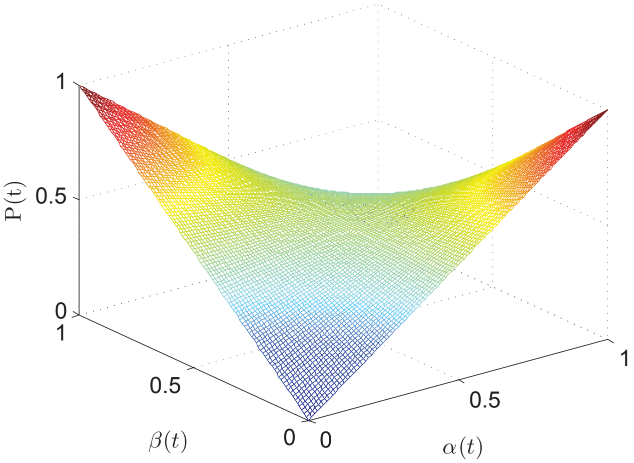


Fig. 3. $P(t)$ as a function of $\alpha(t)$ and $\beta(t)$.

$$P(t)=\alpha(t)+\beta(t)-2\alpha(t)\beta(t)=1\tag{12}$$

$$\Omega_{sum}=\int_0^T(m(t)\alpha(t)+n(t)\beta(t))\mathrm{d}t\tag{13}$$

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. 12 is satisfied if and only if $\alpha(t)=1$, $\beta(t)=0$ or $\alpha(t)=0$, $\beta(t)=1$. It is worth noticing 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 $t\le T'$: $\alpha(t)=1$, $\beta(t)=0$. If $t>T'$: $\alpha(t)=0$, $\beta(t)=1$. Combining the above analyses and Eq. 13, the optimization problem is actually to find an optimal T', in order to minimize $f(T')$, which is shown below:

$$\begin{aligned}f(T')&=\int_0^{T'}m(t)\mathrm{d}t+\int_{T'}^{T}n(t)\mathrm{d}t\\&=NT'+\frac{2\ln[(N-1)e^{-N\lambda T'}+1]}{\lambda},\end{aligned}\tag{14}$$

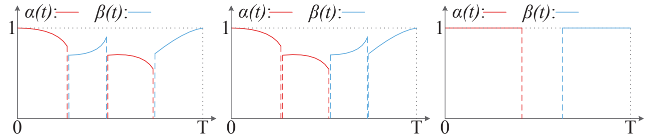
where $f(T')$ is gradually decreased, and then gradually rises with the increase of T'. Therefore, the solution (as shown in Eq. 15) to $\frac{\mathrm{d}f(T')}{\mathrm{d}T'}=0$ is the optimal T' to minimum $f(T')$.

$$T'=\frac{\ln(N-1)}{N\lambda}\tag{15}$$

We can obtain $m(T')=N/2$ by combining Eq. 10 and Eq. 15. It is comforting that the result really makes sense, since the

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 $T_2' = T - \Omega$



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

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

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', they reverse roles since the number 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. 16).

$$\Omega_{min}=\left(\frac{\ln(N-1)}{\lambda}-\frac{\ln N}{\lambda}+\frac{\ln 4}{\lambda}-\frac{\ln[(N-1)e^{-N\lambda T}+1]}{\lambda}\right) \quad (16)$$

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, $T_2' = T'$. In consideration of the constraint condition in Eq. 11, 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 also 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 strategy 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 $\Omega \geq T - \frac{\ln(N-1)}{N\lambda}$. It 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 is indicated that the maximum energy constraint to each phone is not enough for optimal message dissemination. 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. 11, however, the difference is $\Omega < T/2$. It is not difficult to find that 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). However, we still need to minimize the total energy consumption in the network; with this in mind, the following theorem is given.

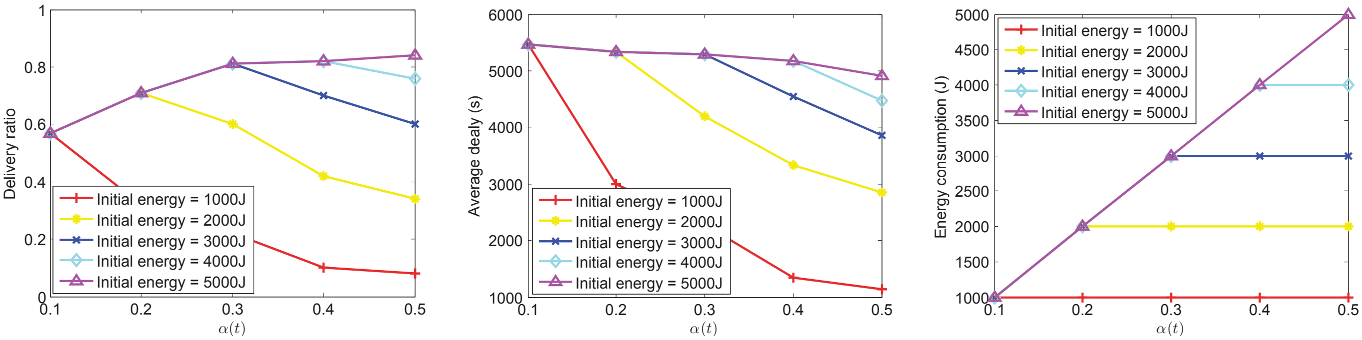
TABLE III. SIMULATION PARAMETERS

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

***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.

Proof : 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. 13. 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.

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. 6. Whereas, when a single message exists in the PSN, we enhanced EPCWH as shown in Table II.

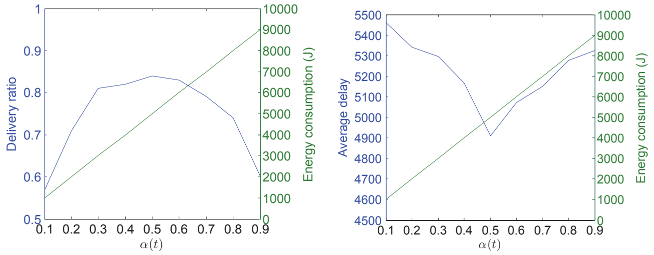


(a) Delivery ratio

(b) Average delay

(c) Energy consumption

Fig. 6. Delivery ratio, Average delay, and Energy consumption as a function of $\alpha(t)$.



(a) Delivery ratio

(b) Average delay

Fig. 5. Delivery ratio and Average delay as a function of $\alpha(t)$.

IV. PERFORMANCE EVALUATION

A. *Evaluation Settings*

To demonstrate the performance of the proposed EPCWH, an Opportunistic Network Environment (ONE) simulator [24] is employed in this paper. We carry out 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. Simulation parameters are given in Table III. 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 average elapsed time of the 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.

B. *Simulation on A PSN with Multiple Messages*

First of all, 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.

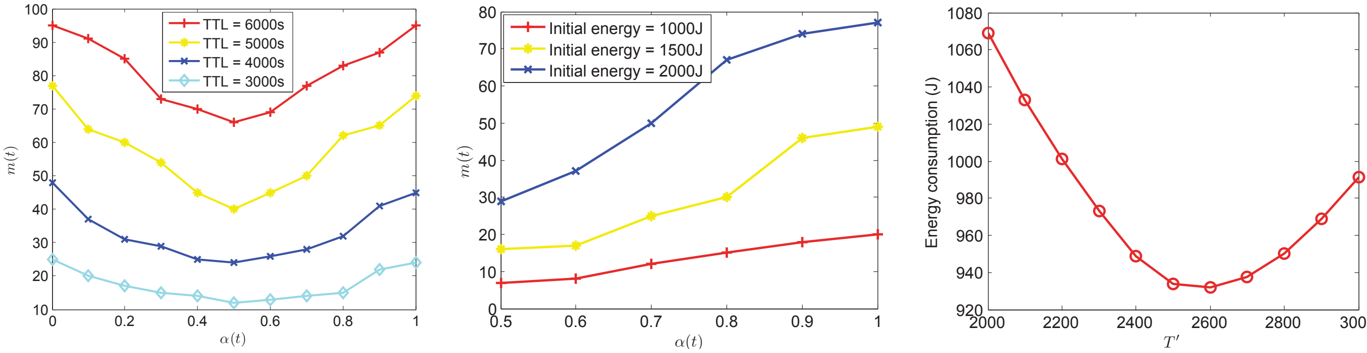
C. *Simulation on A PSN with A Single Message*

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 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. 15, 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. 15. As shown in Fig. 7-(c), EPCWH obtains the lowest energy consumption only when $T' = 2600$s.

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.



(a) Enough energy

(b) Not enough energy

(c) Energy consumption

Fig. 7. The relationships among Energy consumption, $m(t)$ and $\alpha(t)$.

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 the synthetic random-waypoint mobility pattern are conducted in ONE; the results show that EPCWH achieves the best performance in terms of message dissemination and energy consumption among the different switch strategies.

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REFERENCES

[1] K. Fall, "A delay-tolerant network architecture for challenged internets," in *Proc. of ACM SIGCOMM 2003*, pp. 27–34.

[2] I. Akyildiz, O. Akan, and C. Chen, "NetworksInterPlaNetary internet: state-of-the-art and research challenges," *Computer*, vol. 43, no. 2, pp. 75–112, 2003.

[3] M. Y. S. Uddin, H. Ahmadi, T. Abdelzaher, and R. Kravets, "Intercontact Routing for Energy Constrained Disaster Response Networks," *IEEE Transactions on Mobile Computing*, vol. 12, no. 10, pp. 1986–1998, 2013.

[4] A. Pentland, R. Fletcher, and A. Hasson, "Daknet: rethinking connectivity in developing nations," *IEEE Computer*, vol. 37, no. 1, pp. 78–83, 2004.

[5] X. Liu, K. Li, G. Min, Y. Shen, A. X. Liu, and W. Qu, "A Multiple Hashing Approach to Complete Identification of Missing RFID Tags," *IEEE Transactions on Communications*, vol. 62, no. 3, pp. 1046–1057, 2014.

[6] P. Juang, H. Oki, Y. Wang, M. Martonosi, L. Peh, and D. Rubenstein, "Energy-efficient computing for wildlife tracking: design tradeoffs and early experiences with zebranet," in *Proc. of ASPLOS 2002*, pp. 96–107.

[7] S. Yang, C. Yeo, and S. Lee, "Cooperative Duty Cycling For Energy-Efficient Contact Discovery in Pocket Switched Networks," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 4, pp. 1815–1826, 2013.

[8] J. Crowcroft, M. Segal, and L. Levin, "Improved structures for data collection in wireless sensor networks," in *Proc. of IEEE INFOCOM 2014*.

[9] M. Xiao, J. Wu, and L. Huang, "Community-Aware Opportunistic Routing in Mobile Social Networks [supplemental]," *IEEE Transactions on Computers*, vol. 63, no. 7, pp. 1682–1695, 2014.

[10] E. Altman and A. Azad, "Combined optimal control of activation and transmission in delay-tolerant networks," *IEEE/ACM Transactions on Networking*, vol. 21, no. 2, pp. 482–494, 2013.

[11] X. Liu, H. Qi, K. Li, I. Stojmenovic, A. X. Liu, Y. Shen, W. Qu, and W. Xue, "Sampling Bloom Filter-Based Detection of Unknown RFID Tags," *IEEE Transactions on Communications*, vol. 63, no. 4, pp. 1432–1442, 2015.

[12] S. Hu, H. Liu, L. Su, H. W. T. F. Abdelzaher, P. Hui, W. Zheng, Z. Xie, and J. A. Stankovic, "Towards automatic phone-to-phone communication for vehicular networking applications," in *Proc. of IEEE INFOCOM 2014*.

[13] A. Rahmati and L. Zhong, "Context-for-wireless: Context-sensitive energy-efficient wireless data transfer," in *Proc. of ACM Mobisys 2007*, pp. 165–178.

[14] "Chetan sharma consulting," http://www.chetansharma.com/.

[15] A. Sharma, V. Navda, R. Ramjee, V. N. Padmanabhan, and E. M. Belding, "Cool-tether: Energy efficient on-the-fly wifi hot-spots using mobile phones," in *Proc. of ACM CoNEXT 2010*.

[16] K.-H. Jung, Y. Qi, C. Yu, and Y.-J. Suh, "Energy efficient wifi tethering on a smartphone," in *Proc. of IEEE INFOCOM 2014*.

[17] Y. Li, Z. Wang, and D. Jin, "Optimal beaconing control for epidemic routing in delay-tolerant networks," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 1, pp. 311–320, 2012.

[18] K. Keshav, V. R. Indukuri, and P. Venkataram, "Energy efficient scheduling in 4g smart phones for mobile hotspot application," in *Proc. of IEEE NCC 2012*, pp. 1–5.

[19] J. Dong, Z. Ou, A. Ylä-Jääski, and Y. Cui, "Mobile hotspots cooperation towards better energy efficiency," in *Proc. of IEEE Globecom Workshops 2013*, pp. 760–765.

[20] A. Vahdat and D. Becker, "Epidemic Routing for Partially-Connected Ad Hoc Networks," Tech. Rep., Apirl 2000.

[21] G. Robin, N. Philippe, and K. Ger, "Message delay in manet," in *Proc. of ACM SIGMETRICS 2005*, pp. 412–413.

[22] E. Wang, Y. Yang, and J. Wu, "A Knapsack-based Message Scheduling and Drop Strategy for Delay-tolerant Networks," in *Proc. of EWSN 2015*, pp. 120–134.

[23] ——, "Dynamic beaconing control in energy-constrained delay tolerant networks," in *Proc. of IEEE ICC 2015*.

[24] A. Keränen, J. Ott, and T. Kärkkäinen, "The one simulator for dtn protocol evaluation," in *Proc. of ICST 2009*, p. 55.