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Article *in* Wireless Communication over ZigBee for Automotive Inclination Measurement. China Communications · June 2013

DOI: 10.1109/CC.2013.6549257

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Offloading Mobile Data from Cellular Networks Through Peer-to-Peer WiFi Communication: A Subscribe-and-Send Architecture

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Abstract: Currently cellular networks do not have sufficient capacity to accommodate the exponential growth of mobile data requirements. Data can be delivered between mobile terminals through peer-to-peer WiFi communications (e.g. WiFi direct), but contacts between mobile terminals are frequently disrupted because of the user mobility. In this paper, we propose a Subscribe-and-Send architecture and an opportunistic forwarding protocol for it called HPRO. Under Subscribe-and-Send, a user subscribes contents on the Content Service Provider (CSP) but does not download the subscribed contents. Some users who have these contents deliver them to the subscribers through WiFi opportunistic peer-to-peer communications. Numerical simulations provide a robust evaluation of the forwarding performance and the traffic offloading performance of Subscribe-and-Send and HPRO.

Key words: mobile Internet; cellular networks offload; opportunistic routing; delay tolerant networks; peer-to-peer WiFi

I. INTRODUCTION

With the proliferation of Smart Mobile Terminals (SMTs) such as smartphones, laptops, pads and so forth, people use these devices to access Internet more and more frequently. According to global mobile data traffic report [1], global mobile data traffic grew 70 percent in 2012. Currently, a large percentage of mobile Internet data traffic is generated from the SMTs and mobile broadband-based PCs. Cisco forecasts that mobile data traffic will grow at a Compound Annual Growth Rate (CAGR) of 66 percent from 2012 to 2017. Current cellular networks do not have enough capacity to accommodate such an exponential growth of data. Cellular networks operators are able to increase bandwidth to meet the increasing bandwidth requirement. However, increasing the infrastructure capacity is costly and the infrastructure capacity cannot increase unlimitedly.

People find that many applications such as email or file transfer can afford to delay data transfers without significantly hurting user experience. Researchers began to use Delay Tolerant Networking (DTN) technologies to transfer bulk data instead of cellular network [2-9]. Delay tolerant networks are infrastructure-less wireless networks in which a continuous end-to-end path between a source-destination pair is not guaranteed [10-12]. As SMT users keep moving, the wireless links between SMTs are highly prone to disruption. Hence, SMT-based networks constitute a subclass of DTNs.

With the increasing of mobile Internet data

Received: 2013-02-23
Revised: 2013-04-29
Editor: ZHANG Ping

Many applications can afford the delay in data transfer without significantly hurting user experience. This paper provides a Subscribe-and-Send architecture, which utilizes opportunistic routing to transfer bulk data between mobile devices through free WiFi communication to save the cellular network bandwidth. Simulation results show that the architecture can increase the delivery ratio and decreease the delivery latency simultaneously and offload the cellular network data traffic effectively.

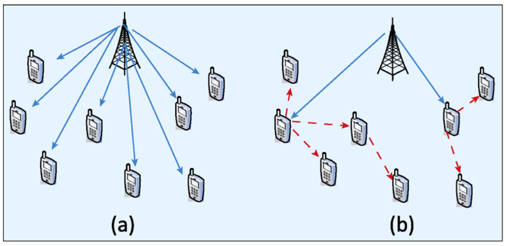

Fig.1 (a) *The infrastructure-only mode;* **(b)** *the DTN approach, where opportunistic WiFi communication is preferred whenever possible*

downloading and uploading requirements from SMTs, opportunistic routing between SMTs begins to play a more and more important role in saving the cellular network infrastructure bandwidth. Lots of SMT users are interested in a common content, so if each user downloads the content through the cellular network infrastructure like Figure 1 (a), the load of the cellular network infrastructure is high. Instead of the infrastructure-only mode, a SMT user can download the content through the cellular network infrastructure, and then send it to other users opportunistically through WiFi peer-to-peer communication as Figure 1 (b) shows.

Offloading the mobile Internet data traffic load to WiFi network is a promising solution to partially solving the cellular network bandwidth problem, because there is no monetary cost for it. One particular advantage of this type of networks is the possibility of exploiting them for the purpose of transferring data in the absence of cellular network coverage and Internet.

In this paper, we study the way to offload cellular network traffic through WiFi opportunistic peer-to-peer communications. We made the following contributions:

1) This paper proposes a Subscribe-and-Send architecture. The Subscribe-and-Send architecture composes of an application and an opportunistic routing protocol. The application deals with the subscribing and delivery, and the opportunistic routing protocol deals with selecting the relays. Under Subscribe-and-Send, a mobile user downloads some contents through the cellular network infrastructure and routes the contents to subscribers.

2) Secondly, this paper proposes a novel opportunistic routing protocol for Subscribe-and-Send. As opposed to the existing protocols, this newly proposed protocol has the objective of enabling nodes to disseminate messages to a large number of receivers while minimizing the number of re-transmissions.

II. Related Work

In this section, we discuss the general solutions for cellular traffic offloading and opportunistic forwarding protocols.

2.1 Cellular traffic offloading to WiFi networks

There are already several cellular traffic offloading solutions and applications proposed in both academic and industrial circles.

Balasubramanian et al. [4] designed a system, called Wiffler, to augment mobile 3G capacity. Instead of transmitting data immediately, Wiffler waits for WiFi network to become available. By using a simple method to predict future WiFi throughput, it waits only if 3G savings are expected within the application's delay tolerance. For applications that are extremely sensitive to delay or loss (e.g., VoIP), Wiffler quickly switches to 3G if WiFi is unable to successfully transmit the packet within a small time window. Balasubramanian studied how to switch interface between WiFi and 3G smoothly. In our study, both 3G and WiFi interfaces are in work mode. Only the content subscribed will be transferred through WiFi peer-to-peer.

HAN et al. [5] proposed to intentionally delay the delivery of information and offload it to the free opportunistic communications with the goal of reducing cellular data traffic. They investigated how to choose the initial set with only k users to minimize the amount of cellular data traffic. They proposed three algorithms called Greedy, Heuristic, and Random for the target-set selection problem. In our study, every user can download data through cellular network infrastructures.

Haddadi et al. [6] proposed a scalable, location-aware, personalized and private advertising system for mobile platforms, called MobiAd. Its key benefit of using mobile phones is to take advantage of the vast amount of information on the phones and the locations of interest to the user in order to provide personalized ads. MobiAd would perform a range of data mining tasks in order to maintain an interest profile on the user's phone, and use the infrastructure network to download and display relevant ads and report the clicks via a DTN protocol.

Dimatteo et al. [7] proposed an integrated architecture exploiting the opportunistic networking paradigm to migrate data traffic from cellular networks to metropolitan WiFi Access Points (APs). To quantify the benefits of deploying such architecture, they considered the case of bulk file transfer and video streaming. Their study shows that even with a sparse WiFi network the delivery performance can be significantly improved. The WiFi connections in our study are peer-to-peer WiFi connections that do not need the WiFi infrastructures (APs). However, we think the WiFi infrastructures could be in favour of the traffic offloading of our architecture as well.

Whitbeck et al. [8] proposed push-and-track, a content dissemination framework that harnesses ad hoc communication opportunities to minimize the load on the wireless infrastructure while guaranteeing tight delivery delays. Push-and-track achieves this through a control loop that collects user-sent acknowledgements to determine if new copies need to be re-injected into the network through the 3G interface. Push-and-track can be applied to two scenarios, periodic message flooding and floating data. In our study, the number of copies of a file is not determined by the architecture, but determined by the network condition.

WU Hongyi et al. [9] proposed an integrated cellular and ad hoc relaying system, iCAR. The basic idea of iCAR is to place a number of Ad hoc Relaying Stations (ARSs) at strategic locations, which can be used to relay signals between Mobile Hosts (MHs) and Base Transceiver Stations (BTSs). The iCAR system can efficiently balance traffic loads between cells by using ARS. The objective of iCAR system is to divert traffic from one (possibly congested) cell to another (non-congested) cell, which is different from the objective of our study. Our study is to reduce the traffic load on cellular network, not divert traffic from one cell to another cell.

2.2 Opportunistic routing

In the past few years, numerous opportunistic routing protocols for different DTN scenarios were developed.

Epidemic Routing (ER) was an early forwarding protocol for DTN. Many studies have shown that the delivery delay of ER is minimum and the delivery ratio is maximum when no resource constraints exist; however, it performs poorly when the buffer size and power are limited.

Probabilistic Routing Protocol using History of Encounters and Transitivity (PRoPHET) [13] uses the history of encounters to calculate the transitivity of a message to its destination. PRoPHET uses an algorithm that attempts to exploit the non-randomness of real-world encounters by maintaining a set of probabilities for successful delivery to known destinations in the DTN (delivery predictabilities) and replicating messages during opportunistic encounters only if the node that does not have the message appears to have a better chance of delivering it to the destination.

Spray-and-Wait [14] is a routing protocol that attempts to gain the delivery benefits of replication-based routing as well as the low resource utilization benefits of forwarding-based routing. When a node that has message copies (source or relay) encounters another node that has no copies of a message, the source or relay hands over half of its copies to the encountering node. When a node has only one copy of a message, it sends its message to the destination directly. Spray-and-Wait restricts the number of copies of a message; hence, it is more suitable for resource-constrained applications.

MaxProp [15] replicates only those messages that are not held by the encountered node. When a contact is discovered, all messages not held by the encountering node will be replicated and transferred to the encountering node. As the connection between two mobile relays cannot hold for a long time, it may break while a message is transferring. Then, the probability of the previous messages to be received successfully is higher than the latter messages. The computational complexity of MaxProp is high.

The BUBBLE Rap [16] is a social network-based DTN forwarding scheme. It reduces the number of copies of a message by replicating the messages to the encounters with higher social activity and locality. The shortcoming of the social-based routing protocols is that the social information which is employed to make the relay decision provided by the encountering nodes is the user's privacy sometimes.

We proposed an n-epidemic routing protocol that is an energy-efficient routing protocol for energy constraint DTNs [17]. We think it is better to transmit only when the number of neighbours reaches a certain threshold. The threshold of the number of neighbours in n-epidemic is fixed. Later, we find that fixed threshold cannot suit different scenarios. And the objective of the new study is not to save energy.

Some routing protocols select nodes as the message ferries with desirable mobility patterns [18-19]. But, node mobility patterns are hard to control or predict in realistic world.

III. Subscribe-and-Send Architecture

In this section, we introduce the Subscribe-and-Send architecture and how it offloads the mobile Internet data traffic from cellular networks through WiFi opportunistic peer-to-peer communications.

3.1 Premise: transmission model

We are concerned with the issue of distributing content to a variable set of SMTs. The SMTs are equipped with wireless broadband connectivity (e.g., 3G) and also able to communicate in WiFi. Both the wireless broadband connectivity and WiFi interface are in working mode. A software is installed on the SMT to subscribe contents on CSP and to send files to encountering nodes. The software can get a file through both the wireless broadband connectivity and the WiFi connectivity. We suppose the SMTs are WiFi direct devices. WiFi direct devices have a new capability that allows the creation of peer-to-peer connections between WiFi client devices without requiring the presence of a traditional WiFi infrastructure network (i.e., AP or router) [20].

3.2 Overview of Subscribe-and-Send architecture

There are two stages in Subscribe-and-Send: subscribe and send.

1) In the subscribe stage, a user accesses the CSP and subscribes some interesting contents on it by the software. The subscription composes of the name of subscribed content, the user's ID and the deadline of the subscription. Before the deadline of the subscription, the software does not download the subscribed content through the cellular network. It prefers to receive the content sending by others through WiFi connection.

2) Some users would like to download the interesting contents through the cellular network. These users can be called source nodes. Source nodes could be the members of a CSP, or the one who would like to pay for downloading contents through 3G. A node accesses the CSP and checks whether someone subscribes the content it has. If the content that a node has is subscribed by others, it starts the sending process and delivers the content to the subscriber through opportunistic WiFi connections. When two nodes meet, they exchange their respective subscription tables. If a node has the content subscribed by the encountering node, it sends the content to the node. Otherwise, the opportunistic routing protocol working in the routing layer determines how a node delivers its files. Different opportunistic forwarding protocols can be employed in the routing layer.

For example, node_1 contacts the CSP and downloads movie_1 through 3G, and node_7 subscribes movie_1 on the CSP as Figure 2 shows. Node_1 accesses the CSP and knows that node_7 subscribes movie_1. Then node_1 begins to send movie_1 to node_7 through opportunistic WiFi connections. As the WiFi connection cannot always be created, a relay has to carry the content and waits for the future WiFi connections. In Figure 2, the solid line means the connection created by 3G interface and the dot line means peer-to-peer WiFi communication. After node_3 gets movie_1 from node_1, as it has no other WiFi connections, node_3 has to carry movie_1 all the time. When node_3 meets node_7 at some place, it sends movie_1 to node_7.

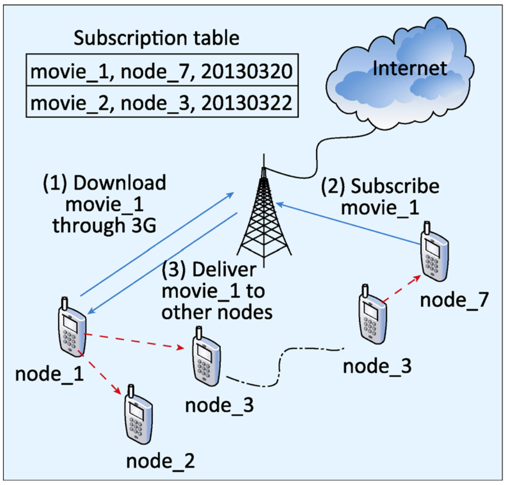

Fig.2 *Subscribe-and-Send architecture: a user subscribes a movie, and then the source node reads the subscription table and sends the movie to the subscriber one by one*

3.3 Subscription management

1) When a subscriber receives the content subscribed on the CSP, it sends a response message to the CSP and removes the subscription of this content from the subscription table.

2) If a subscriber does not receive the subscribed content after the deadline of the subscription, the CSP prompts the user of the failure of the subscription. Then the user can download the content through 3G, or extend the deadline of the subscription. If the user does not extend the deadline, the CSP removes the subscription of the content from the subscription table on CSP. Meanwhile, the subscription is removed from the subscription table on the user's device, too.

3) As the deadline of a subscription is created by the subscriber, the deadlines of different subscriptions are different. And, it is not necessary that the clocks on all devices are synchronous because the CSP maintains the total subscription table.

4) Each node accesses the CSP to check the subscription table every 10 minutes or 30 minutes through 3G, so the 3G traffic load of a SMT is very low.

3.4 Cellular network traffic offloading analysis

During the data dissemination from the source to the destination, some relays might be interesting in the content as well. When a node receives

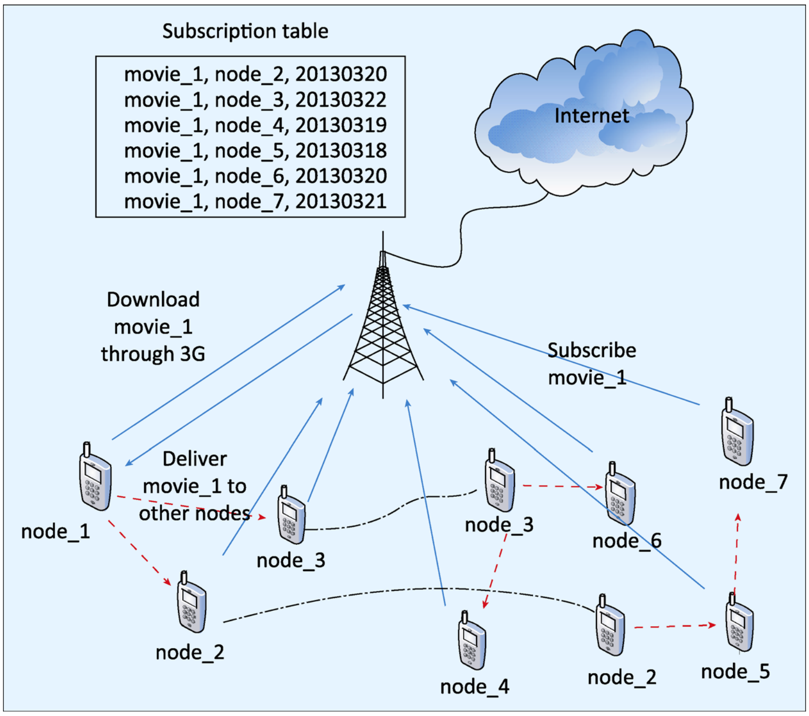

Fig.3 *When a relay receives a content that is subscribed by itself, the relay removes itself from the subscription table*

a content that also subscribes, it sends a response message to the CSP and removes itself from the subscription table. As the node does not download the content through 3G, the load on the cellular network is released. In Figure 3, node_2, node_3, node_4, node_5 and node_6 subscribe movie_1, and only node_1 downloads movie_1 through 3G. Node_1 accesses the subscription table on the CSP and knows that some other nodes subscribe movie_1. It sends movie_1 to node_2 and node_3 when the WiFi connections exist. Node_2 and node_3 continue to send the content to others when WiFi connections exist. Finally, all nodes get movie_1 before the deadline of each subscription. Since only one node downloads movie_1 through 3G, 85.7% of the cellular network traffic is offloaded.

IV. Opportunistic Forwarding Protocol: HPRO

In Subscribe-and-Send architecture, different opportunistic forwarding protocols can be employed. In this section, we introduce a novel opportunistic forwarding protocol.

4.1 Assumptions

The disk of an SMT can be as large as 4 GB, 8 GB, or 16 GB, so the buffer is not a constraint in DTN. We assume that an SMT has a free buffer large enough for all the messages that it originates. However, the SMT will not use all its buffer space to store the messages originated by others. We assume that each node has a fixed-size buffer for carrying messages and that the node must manage its finite buffer space. When a node begins to receive a message from a neighbour, it must have free buffer space to store the message. A node deletes the oldest messages from its buffer when it has no free buffer space to receive new messages.

4.2 Protocol definition

We introduce a novel DTN opportunistic forwarding protocol termed High PRobability Opportunistic (HPRO) forwarding. The idea of HPRO is to transfer the messages when the number of contacts/neighbours is larger than or equal to a certain threshold limit, so that the message has higher probability of being delivered to the destination. As the node densities of different network scenarios are different, this threshold value cannot be constant and should vary based on the node density. On the other hand, as the node is mobile, the nodes density around the node changes continually. The node updates the threshold periodically. We refer to this threshold value as area contact (ac). It denotes the number of contacts within the transmission area, i.e., the number of neighbours of a node identified in the last update period. The period of updating ac is set according to the MAC protocol and depends on the application type.

The HPRO algorithm can be summarized as follows:

Step 1. Check the number of neighbours of a node, n. If $n \geqslant \mathrm{ac}$, the node begins the transfer process and sets $n = \mathrm{ac}$; otherwise, go to Step 2.

Step 2. Set $n = \mathrm{ac}$; wait until the next round of checking neighbours and go to Step 1.

With HPRO, a node makes the delivery determination based only on the node densities that are open to all nodes to detect. It does not need the encounters to provide any private information, such as the social status. This makes privacy protection an additional advantage of HPRO.

4.3 Parameter analysis

We study the influence of the parameter ac on the delivery ratio. Assume nodes are located within the experiment area randomly and the nodes density is λ . Therefore, $|\pi r^2|$ denotes the number of nodes within a circular region, $|\pi r^2|$. Then, the probability of there being at least ac nodes within $|\pi r^2|$ by the Spatial Poisson [21] is:

$$\Pr(|\pi r^2| \geqslant \mathrm{ac}) = 1 - \sum_{i=0}^{\mathrm{ac}-1} \frac{e^{-\lambda \pi r^2} (\lambda \pi r^2)^i}{i!} \quad (1)$$

If $\mathrm{ac}_2 > \mathrm{ac}_1$, then $\Pr(|\pi r^2| \geqslant \mathrm{ac}_2) < \Pr(|\pi r^2| \geqslant \mathrm{ac}_1)$. This indicates that if ac is large, the chance that a node has so many neighbours is low, and it hardly sends its bundles to other nodes. Therefore, the probability that the destination receives the bundle proportionally decreases.

R. Groenevelt et al. [22] studied the number of receivers of a specific bundle within certain time duration with Epidemic. In our opinion, Epidemic could always be considered as a special case of HPRO with $\mathrm{ac} = 1$. Following Ref. [22], we developed Eq. (2) to compute the number of receivers of a specific bundle under HPRO:

$$I(t) = \frac{N}{1+e^{-\beta_{\mathrm{ac}}Nt}(N-1)} \quad (2)$$

where $I(t)$ is the number of receivers of a specific bundle within certain time duration, N is the total number of nodes, β_{ac} is node meeting rate, and t is the time period .

If the nodes move within a limited region, as per the currently used and popular mobility models, and if their transmission range is smaller than the length of region, the pair-wise meeting rate β_2 can be calculate using Eq. (3):

$$\beta_2 \approx \frac{2\omega r E[V^*]}{L^2} \quad (3)$$

where r is the transmission range, L is the length of the region, V^* is the relative speed between two nodes and $E[V^*]$ is the average relative speed, and ω is a constant for the mobility model. For example, $\omega \approx 1$ if the mobility model is random direction; $\omega \approx 1.368$ if the mobility model is random waypoint.

The opportunities that a node forwards its bundles to neighbours under HPRO are less than that of under Epidemic. The ratio between β_{ac} and β_2 is as shown in Eq. (4) inferred from the spatial Poisson research:

$$\frac{\beta_{\mathrm{ac}}}{\beta_2} = \frac{P(|\pi r^2| \geqslant \mathrm{ac})}{P(|\pi r^2| \geqslant 2)} \quad (4)$$

$$\beta_{\mathrm{ac}} = \frac{P(|\pi r^2| \geqslant \mathrm{ac})}{1\text{-}P(|\pi r^2|=0)\text{-}P(|\pi r^2|=1)}\beta_2 \quad (5)$$

Let there be M bundles totally. The delivery ratio equation is as follows:

$$\text{Delivery ratio} = \frac{\text{delivered messages}}{\text{total}} \approx \frac{\sum \frac{I(t)}{N}}{M}$$

As the value of ac varies depending on the local node densities, it is difficult to study the influence of different values of ac on the delivery ratio. To simplify the study, we set ac as a constant value for ac in each round of simulation. Figure 4 shows the delivery ratio for different values of ac under HPRO.

Figure 4 shows that for higher value of ac, the increase in the delivery ratio curve is slower. In fact, the number of neighbours depends on the node's local node densities and the transmission range of nodes. If the node density is high and a node's transmission range is large, the node would have many neighbours. Instead, if the nodes density is low and a node's transmission is short, a node has few neighbours consequently. We can certainly take that, if other parameters are constant, the larger is the ac, the longer is the latency.

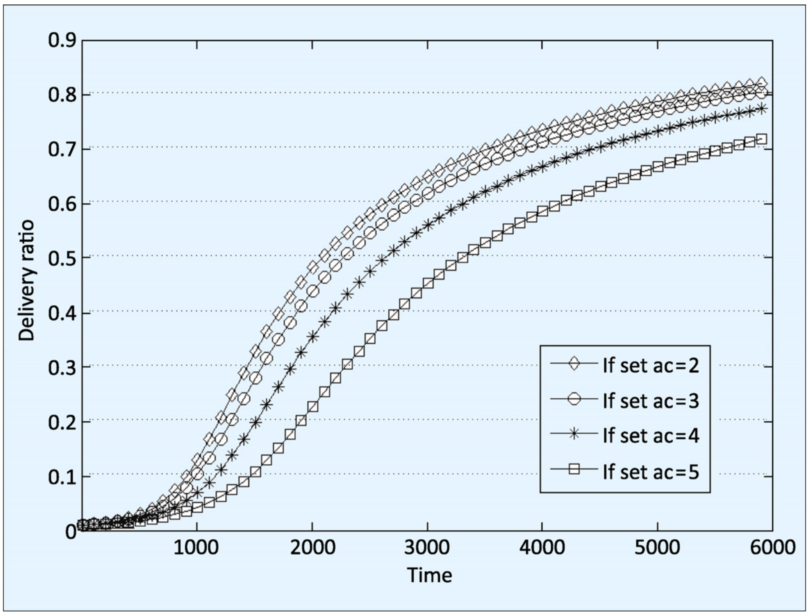

Fig.4 *Delivery ratio under different ac*

V. SIMULATION

5.1 Simulation setup

We employ the Opportunistic Network Environment (ONE) simulator to evaluate the forwarding performance and traffic offloading performance. In the simulator, nodes travelled only on the roads of Helsinki. The simulation considered six groups: two groups of people walking, three groups of cars whose speeds are between 7 to 10 m/s and another group of cars whose speeds are between 2.7 to 13.9 m/s. In each round of simulation, the numbers of nodes of each group range from 20 to 60. We assume the transmission range of all nodes to be the same at 100 meters. The transmission speed is 10 MB per second. The simulation time is 5 000 seconds. A message event generator creates data every 25 to 35 seconds, and the source and destination of each data are selected from all nodes randomly. The size of the content

Table I *Delivery ratio under different updating ac periods* (N=180, *buffer*=100 *MB*)

Duration/s	0.1	0.5	1	2	5	10
Delivery ratio	0.898 2	0.940 1	0.934 1	0.922 2	0.898 2	0.796 4

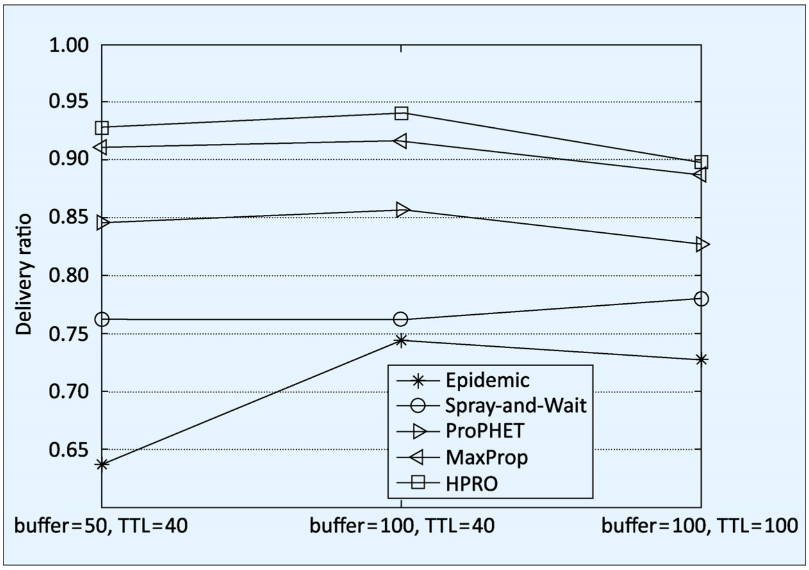

Fig.5 *Comparison of delivery ratio under different buffer sizes and TTLs* (N=180, *updating period*=0.5 *s*)

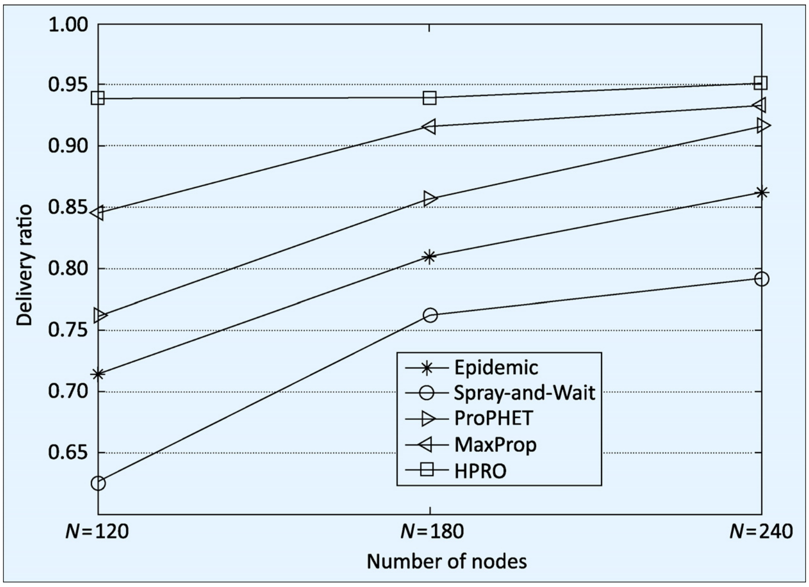

Fig.6 *Comparison of delivery ratio under different number of nodes* (*buffer*= 100 *MB, TTL*=40, N=180, *updating period*=0.5 *s*)

is between 5 000 KB and 10 MB. We also assume that all nodes participate in the data dissemination.

5.2 Result 1: comparison of opportunistic routing protocols

5.2.1 Comparison of the delivery ratio

To find the most effective opportunistic routing protocol for Subscribe-and-Send architecture, we compared HPRO, Epidemic, Spray-and-Wait, PRoPHET, and MaxProp opportunistic protocols respectively. Epidemic, Spray-and-Wait, PRoPHET, and MaxProp are widely used in opportunistic routing studies and performance evaluations.

When we employed HPRO protocol, ac was updated periodically. Table I lists the delivery ratios for different updating intervals at which the ac is updated. We find that if the interval is very short or very long, the delivery ratio is not very high. If the interval is very long, such as 10 s, the number of times that a node checks the neighbours decreases. Thus, the chances of transmitting the messages and the delivery ratio decrease. If the interval is very short, such as 0.1 s, the neighbours of a node probably does not change because of the short time interval but the node still asks the neighbours what messages they have. The frequent ask-and-answer process wastes the wireless channel, so it does not have enough available channels to transmit the content. This results in the decreasing of the delivery ratio when the period is very short.

Figure 5 shows the delivery ratios of different opportunistic protocols. We find that the buffer size and Time to Live (TTL) of a content affect the delivery ratio performance. It shows that under the same TTL, the delivery ratio of each opportunistic forwarding protocol increases with the increase in the buffer size from 50 MB to 100 MB because each node has more buffer space to save more bundles. Under the same buffer size 100 MB, the delivery ratio of each opportunistic forwarding protocol decreases with the increase of the TTL from 40 to 100 minutes except Spray-and-Wait. If the TTL is very long, the time from when a file is received until it is removed from the node's buffer is long so that the node does not have enough free buffers to receive new files. Figure 6 indicates that under different buffer sizes and TTLs, the delivery ratio of HPRO is higher than that of the other four DTN forwarding protocols.

Figure 6 shows the delivery ratio of opportunistic forwarding protocols under different node densities. The delivery ratio of HPRO is larger than 0.94 under different node densities. Given three different node densities, the delivery ratio of HPRO is the largest among the five DTN protocols, which suggests that the delivery performance of HPRO is better than that of Epidemic, Spray-and-Wait, ProPHET and MaxProp protocols. For each DTN forwarding protocol, the delivery ratio increases with the increase in the number of nodes because more nodes are involved in the forwarding process. This result strongly suggests that message duplicating can increase delivery performance.

5.2.2 Comparison of the average latency

Figure 7 shows the average latency of five opportunistic forwarding protocols. This figure shows that if more nodes are involved in the forwarding process, the average latency decreases. The average latency of Spray-and-Wait is higher than that of HPRO, Epidemic, PRoPHET, and MaxProp, which proves that limiting the number of the copies of a message will increase the delivery latency. Among them, the average latency of HPRO is shorter than that of the other four under different nodes densities, so HPRO can increase the delivery ratio and decrease the delivery latency simultaneously. As we have known, the delivery performance of HPRO is higher than that of the others, so the Subscribe-and-Send employs HPRO as the default opportunistic routing protocol.

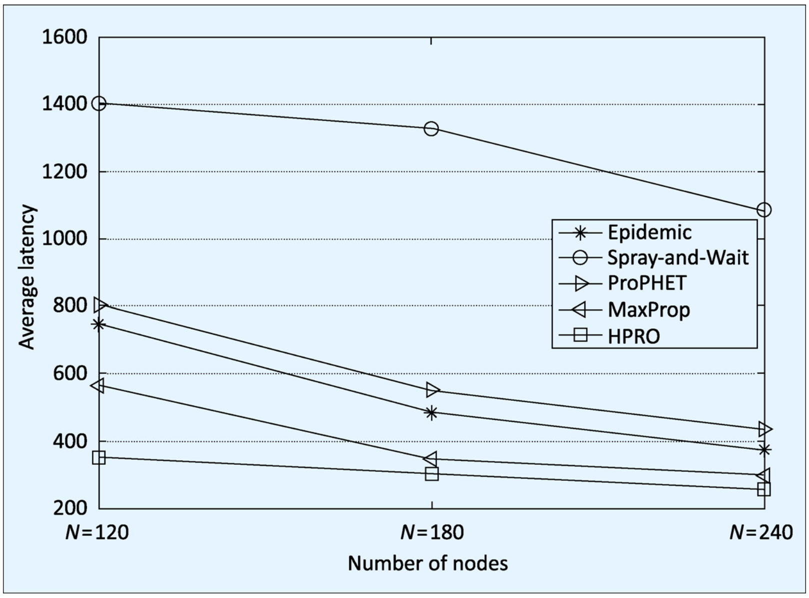

Fig.7 *Comparison of average latency under different numbers of nodes (buffer=100 MB, TTL=40, N=180, updating period=0.5 s)*

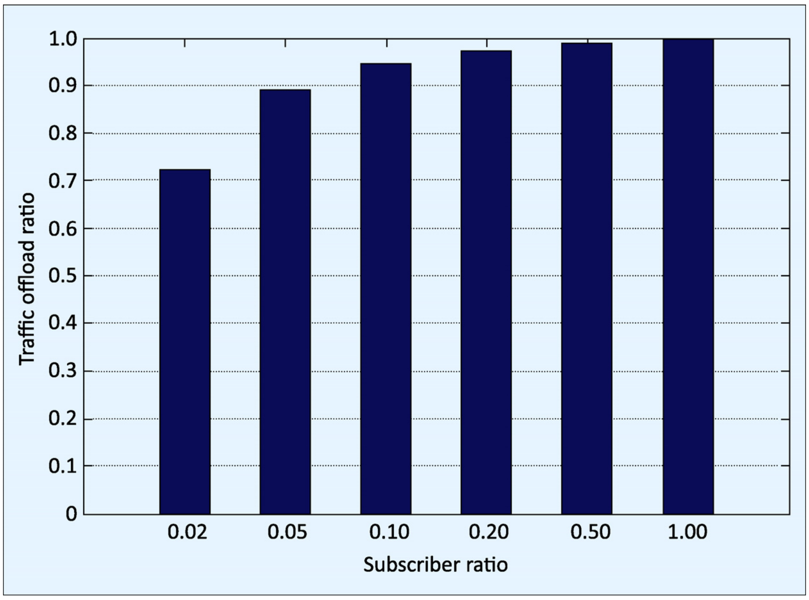

Fig.8 *Traffic offloading ratios under different subscriber ratios*

5.3 Result 2: Traffic offloading performance

5.3.1 Traffic offloading ratio

We assume that all nodes participate in the data dissemination, but only parts of all nodes are interested in each data. Subscriber ratio means the number of subscribers over all nodes. Figure 8 shows the traffic offloading ratios of HPRO under different subscriber ratios. It indicates that the traffic offloading ratio increases with the increasing of subscriber ratio. In the simulation, when the subscriber ratio is equal to 1, the traffic offloading ratio is 99.4%. Even when the subscriber ratio is only 0.02, Subscribe-and-Send with HPRO as the routing protocol can offload 72% of the cellular network traffic.

5.3.2 Compare with 3G

Figure 9 shows about 53% contacts are between 10 to 20 seconds and the probability of the contact time being shorter than 10 seconds is 12.8%. So, about 87.2% contacts are longer than 10 seconds. Here we assume the bandwidth of WiFi is 10 MB/s, so a node can finish sending 100 MB data to a receiver in a contact

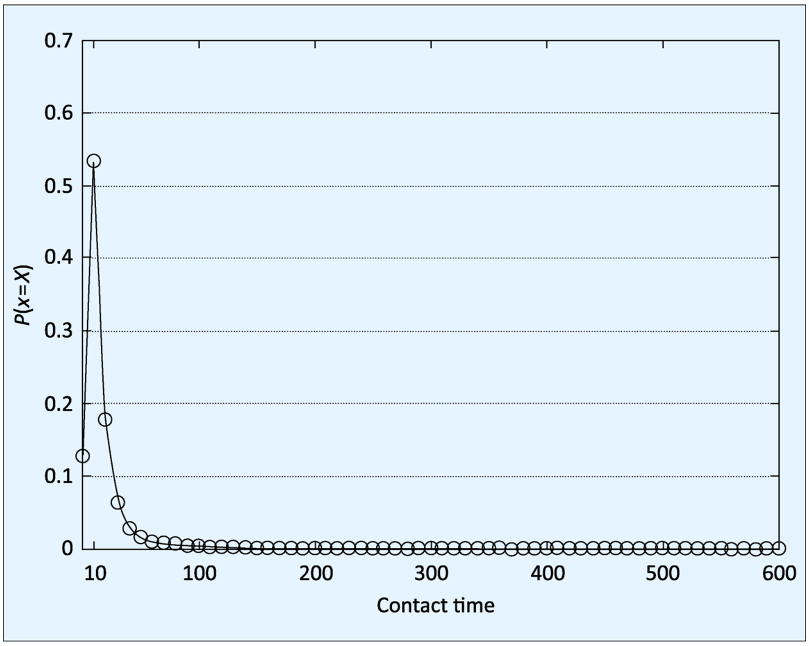

Fig.9 *Contact time distribution*

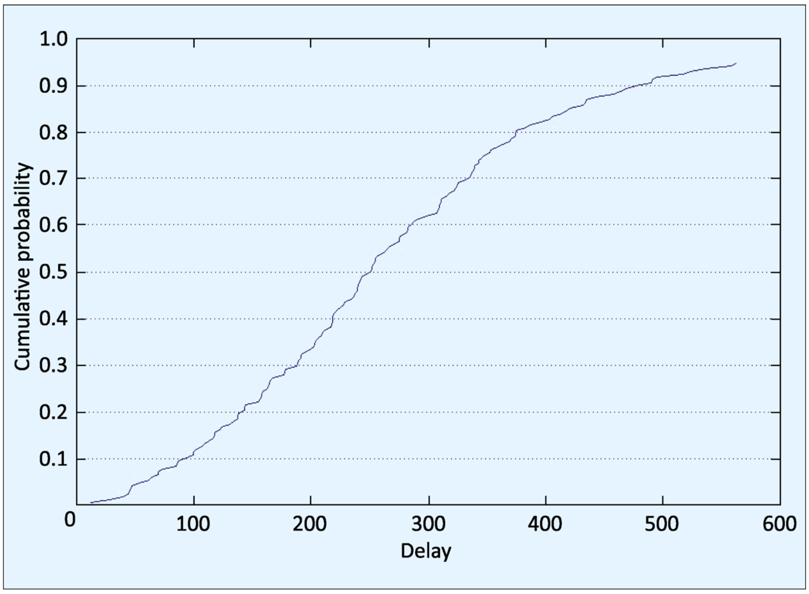

Fig.10 *Cumulative probability of the latency of HPRO*

time. Even if we assume the maximum size of a bulk file is 100 MB, the probability of transferring the file to a receiver within all contacts is higher than 87.2%.

In this paper, two message latency deadlines were tested: a tight 1 minute delay and a more relaxed 10 min delay. Figure 10 shows the cumulative probability of the latency of HPRO. It shows about 95% delays are shorter than 600 seconds (10 minutes) and about 26.8% delays are shorter than 1 minute. Applications that can tolerate some delay in the delivery process (e.g., file transfers), such as 10 minutes, can take advantage of the WiFi ad hoc communication. Indeed, some data that do not have to be downloaded at the instant are used, and they can be smoothly pre-fetched into mobile devices. The delay is from the time when a source node sends a message to the time when the destination receives the message.

We assume nodes in Subscribe-and-Send check the subscription table on the CSP every 10 minutes. As about 95% delivery delays are shorter than 10 minutes, the probability that a subscriber can receive a 100 MB file in 20 minutes is $87.2\% \times 95\% = 82.84\%$. If the subscriber downloads the 100 M file from the infrastructure, it will cost the subscriber 83.3 minutes to finish the downloading at a practical 2G bandwidth of 20 KB/s and cost the subscriber 8.3 minutes at an average practical 3G bandwidth of 200 KB/s and 5 dollars. As we see, when people download a bulk file through 3G, they have to wait for minutes and pay much money for it. For most users, 20 minutes' or even 1 hour's delivery delay is tolerant if the file can be received freely.

VI. Discussion

Narseo V. et al. studied the issue of 3G On-Loading (3GOL) that is an emerging study field [23]. 3GOL study is based on the assumption that the wired broadband connection is constrained in some areas. In this scenario, they proposed to employ several 3G devices to augment the downlink and uplink capacity. Actually, the 3GOL study is not opposite to our offloading study. 3GOL falls in the space of bandwidth aggregation schemes indeed, but the traffic load on the cellular infrastructure is not released. As authors concluded, 3GOL cannot assist all wired connections or at all times. It only assists select applications at particular time when they become constrained at the wired broadband connection. Our study does not concern the wired network. We study how to release the traffic load on the cellular infrastructure by opportunistic routing.

Who will use it? Different kinds of users could profit from Subscribe-and-Send. In some cities, users pay for downloading data through the cellular network. The more files a user downloads or uploads through the cellular network, the more money the user pay to the operator. In this scenario, operators profit from users' data traffic, so users would like to use Subscribe-and-Send to get data and to save money. Secondly, some Internet CSPs, such as YouTube Company, have to pay a lot for the Internet bandwidth they rent from the cellular network operators every year. They are eager to apply the offloading technology to release the bandwidth load and save the bandwidth fee.

VII. CONCLUSION

Currently cellular networks do not have enough capacity to accommodate the exponential growth of mobile data requirement. Operators increase the cellular network bandwidth via HSPA and LTE. Another solution is to apply delay tolerant networking technology to transferring bulk data through free wireless communication, e.g., WiFi. We proposed Subscribe-and-Send architecture and an opportunistic routing protocol for it. In Subscribe-and-Send, a user subscribes contents through the cellular network infrastructure but does not download the subscribed content. Some users who have the contents deliver the contents to other subscribers through WiFi with HPRO protocol. Using HPRO, a content carrier sends its content when the number of its neighbours is larger than or equal to a certain threshold that varies based on the carrier's local node density. The simulations demonstrated that Subscribe-and-Send architecture with HPRO can offload cellular network traffic effectively. The Subscribe-and-Send architecture can be used by SMT users and CSPs to save the cellular network traffic.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China under Grants No. 61100208, No. 61100205; the Natural Science Foundation of Jiangsu Province under Grant No. BK2011169; and the Foundation of Beijing University of Posts and Telecommunications under Grant No. 2013RC0309. Pietro Lio' is supported by the EU FP7 Project RECOGNITION: Relevance and Cognition for Self-Awareness in a Content-Centric Internet.

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