Eagle Eye: A Dual-Radio Architecture in Delay Tolerant Networks

Linghe Kong*, Tianji Li§, Min-You Wu*, Wei Shu†
*Shanghai Jiao Tong University, Shanghai, China
§Hamilton Institute, NUI Maynooth, Ireland
†University of New Mexico, USA
Email: *{linghe.kong, mwu}@sjtu.edu.cn, §tianji.li@nuim.ie,†shu@ece.unm.edu

***Abstract*—In most delay tolerant network (DTN) applications, mobile nodes utilize WiFi radios to obtain local information and transmit data. One bottleneck on DTN delivery performance is the short communication range of the WiFi radio. Rather than designing efficient protocols on WiFi based DTN, we propose a novel dual-radio architecture by adding a long-range low-bitrate eagle eye (EE) radio on every node. This EE radio can "see" real-time movement information of nodes in a significantly large range, and so much early scheduling can be done with this radio when compared with WiFi which is still in charge of data transmissions. Benefiting from this cooperative dual radios architecture, we design distributed EE routing protocol for minimizing delivery delay in DTNs. Through our prototype implementation with 7 EE devices and simulations based on real trace data of 4000 taxis in Shanghai, we show that the proposed architecture is able to achieve as low as 40% of the average delay with traditional DTNs.**

I. Introduction

Delay tolerant networks (DTNs) [9] has emerged as a complementary type of communicaton network to existing ones. Application examples of DTNs include the Pocket Switch Networks (a Bluetooth-enabled DTN) [6], the ZebraNet (a sensor network for ecological monitoring) [26], the DieselNet Project [29] of UMass, the Cartel Project [12] of MIT, the ocean sensor networks [17], and the interplanetary Internet [4].

The primary issue of DTNs is to transmit messages from the source node to the destination node reliably. Hence, maximizing the delivery ratio is an intuitive metric to measure the quality of a DTN. However, in DTNs, a message is rarely actually "lost". Rather, the network may unable to deliver messages within an acceptable amount of time. Thus, we follow the same method as Jain et al. [13] and select the metric of minimizing the delivery delay as the objective of this work.

It is challenging to design a practical approach to reduce delays in DTN. First, DTNs are generally infrastructureless, a packet thus has to reach its destination by solely relying on intermittent contacts among nodes using a store-carry-and-forward paradigm. Second, nodes in DTN are mobile. They obtain others' real-time movement state in their communication range through local information exchanges. Hence, the communication range of a radio plays an important role in DTNs.

Unfortunately, communication ranges in DTNs are usually limited. For example, in WiFi based DTNs, this range is at most in the order of hundreds meters. Some techniques are proposed to improve performance hindered by the limited WiFi ranges, e.g., MIT Pothole Patrol [8]. Stationary relays are also proposed to help nodes forward data, e.g., the Throwboxes project [3], and shared infostation model in Ad hoc networks [21].

Rather than designing efficient WiFi schemes, we consider a dual-radio architecture called Eagle Eye (EE) that adds an additional long-range low-bitrate radio with negligible cost on current DTN nodes. To our best knowledge, EE is the very first dual-radio architecture for improving performance in DTNs. It consists of three major hardware components: An Atheros AR9285 WiFi card, a HOLUX M1000GC GPS and an ADI ADF7020 FSK/ASK transceiver. The former two components are equipped on existing DTN nodes as well, with the WiFi card delivering the actual data packets and the GPS logging movement related information. The ADI transceiver (EE radio) is the novel component in our architecture, which can reach ranges up to 10 times larger than WiFi does. Note that the two radios work in a parallel due to their different operating frequencies in 433MHz and 2.4GHz.

An immediate advantage with this architecture is that movement information in much larger area can be collected due the the covering ranges of the EE radio. We hence use the EE radio to exchange movement information, and keep using the short-range high-bitrate WiFi radio for data transmissions. The information exchanged by the EE radio includes node ID, current location, velocity, time, etc. With this information, we design a distributed and cooperative routing protocol. In particular, for each sender or forwarder, we design a utility function to estimate the expected delivery delay via nodes in the range of the EE radio; and the WiFi radio transmits the data to the relay with the minimum expected delivery delay.

To investigate the performance gains, we used a test-bed consists of seven EE devices, which were carried by volunteers driving in campus scenarios. MP3 files were transmitted in this experimental network. Results shows the significant improvement of delivery delay and delivery ratio by the EE architecture in a DTN prototype.

For further studying the performance in a large-scale s-

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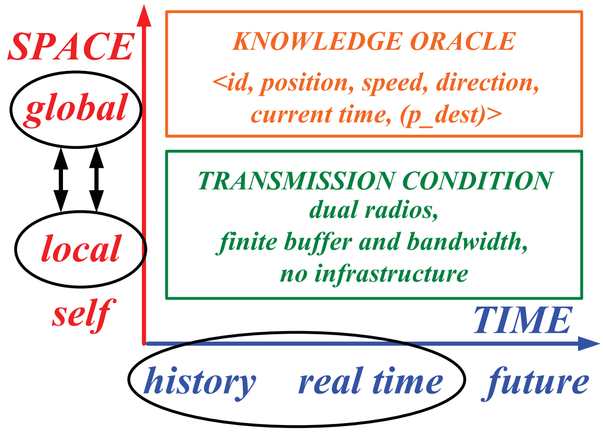


Fig. 1. The information location of Eagle Eye architecture in time-space dimensions.

cenario, we used computer simulations based on real trace data of 4000 taxis from the Shanghai urban vehicular network (SUVnet) project [28]. The simulation results show that the EE is able to achieve as low as 40% average delay compared to the DTN without EE and only 10% more than the optimal delay.

The rest of this paper is organized as follows. Section II compares EE with related works. Section III presents the prototype of the EE platform. In Section VI, we describe the routing algorithm for DTN nodes with EE. The prototype implementation is in Section V. Section VI describes the performance evaluation in a large scale real trace based simulation. Finally, we present concluding remarks and outline the directions for future work in Section VII.

II. Related Work

DTN is advocated in [9]. Early research has been focused on reducing delivery delays. Under the diversity of assumptions in different dimensions, various approaches have been proposed for performance improvement.

In the space dimension, Jain et al. [13] propose the oracle based routing framework. This framework indicates that the designed protocols with more information have higher delivery ratios and lower delay. After that, many global information based routings are firstly proposed such as Minimum Expected Delay (MED) [13], the space time routings [18], the Earliest Delivery (ED) [13]. Unfortunately, in WiFi based DTNs, the global information is hard to get. Then, self or local information (the movement information of other nodes in the WiFi range) based approaches are developed. For instance, the resource allocation method RAPID [2], and the Context-Aware Routing (CAR) protocol [19]. Due to the long range radio, the study of EE architecture makes up the vacant space between local and global knowledge as shown in Fig. 1.

In the time dimension, plenty of routings are based on history records. e.g. Minimal estimated expected delay (MEED) [14], the MV routing [5] and the PROPHET protocol [16]. These algorithms only perform well in the DTN that the future contact will be similar to the history such as the bus networks. However, the EE architecture is applied in a general DTN scenario, which uses not only the history information but also the real-time information by EE radio. (The future information is only adopted in the theoretical solution such as ED in [13] but hard to get in practical case.)

For the knowledge oracle, the general movement information includes the node id, position, speed, direction and current time. Nevertheless, the real-time position of the destination node (p_dest) involves in the disputes. In [11], DAER routing considers that any nodes know the dynamic p_dest. While in some situations, p_dest is unknown. For instance, the spray and wait protocol [23] uses the last observed location instead of the real p_dest approximately. In this work, we set the p_dest is an optional information. Without the p_dest, the EE could carry out well. Furthermore, with this optional information, the EE could performs better.

For the transmission condition, epidemic protocol was proposed in [24]. This method can perform optimally if the bandwidth and the buffers on mobile nodes are infinite, or the exponential growing data replication would lead to the network congestion. Limited by the hardware, recent radio and storage cannot be infinite in the DTN nodes. In our EE architecture, the buffers and bandwidth are finite.

Infrastructures are proved to improve performance in DTNs by additional APs [3], the Infostation model [10] and Shared Wireless Infostation Model (SWIM) [21]. But fixed devices demand additional cost and do not suit the dynamic DTNs. Therefore, EE is set no additional infrastructures.

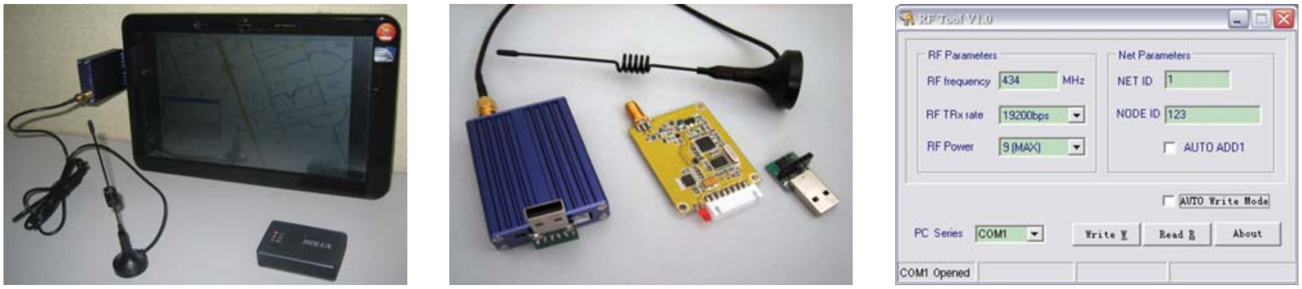
Dual-radio architectures are studied in many wireless network fields [1], [7], [27]. The closest one to EE is the Throwboxes [3], which serve as the stationary infrastructure to detect the close nodes in one radio and transmit data in another radio. In our work, we consider adding EE radios on the mobile nodes, which is cheap and appropriate for the dynamic networks.

III. The Eagle Eye Platform

A. Hardware and Software

The hardware of the EE platform consists of three components: an ADI transceiver, an Atheros WiFi card and a HOLUX M-1000C GPS. All components connecting to a KRT S1 tablet PC as shown in Fig. 2(a). The ADI transceiver (EE radio) links the PC by USB, the GPS connects by Bluetooth and the WiFi card is built in the PC.

The WiFi and GPS are equipped on existing DTN nodes as well. The distinctive component is the low-bitrate long-range EE radio. A picture of the EE radio box and its inside chipset is shown in Fig. 2(b). The used chipset is an ADI ADF7020 FSK/ASK transceiver, with parameters shown in Table I. Communication between this modular and the PC is via a standard USB port (under virtual serial port protocol). EE radio is in charge of the real-time movement information exchange. Since the size of information is tiny, EE radios work under CSMA/CA protocol. Note the cost of this general modular is cheap.



(a) Our prototype of Eagle Eye platform.

(b) The device of EE radio. The left box contains the actual chipset on the right side.

(c) The user interface of the tool we designed to control the parameters of the EE radio.

Fig. 2. The hardware and software of Eagle Eye platform.

The Atheros AR9285 wireless card serves as the high-bitrate short-range modular for transmitting the actual data packets. It works in the ad-hoc mode in IEEE 802.11b/g 2.4Ghz channels in our tests.

The HOLUX M-1000C GPS is used to log the real-time location information. It can be connected to the tablet PC and report the location information via Bluetooth. It updates the GPS information once per second. The estimating errors of this device is less than 5 meters on longitude and latitude. The system time is set to the GPS time so that all the platform clocks are synchronized.

The configurations of the tablet PC are listed in Table II. This PC's CPU and hard disk are adequate to run the proposed routing programs and store the experimental data. Due to its small form factor, this PC can be carried around for testing. The optional p_dest information can be manually input into the PC, which imitates the application of GPS navigator.

To control the Atheros card (such as setting transmission frequencies, power and bitrates), we use the "iwconfig" tool in the operating system. For the GPS device, HOLUX provides the tools to log and exchange information with the PC. For controlling the EE radio, we write a simple tool, with interface shown in Fig. 2(c). It can be used to change the RF parameters (including working frequency, rate and power) and to configure the net parameters (net ID for distinguishing the different networks and node ID for distinguishing the nodes in the same networks). For transmitting information in the EE radio, we use the general serial port debug tool SSCOM.

B. *Difference in Communication Ranges*

The basic impetus of adding the EE radio is to take advantages of its far-reaching coverage. To confirm this case, in campus scenarios, we performed a series of outdoor tests to compare the differences of communication ranges between the short range WiFi and the long range EE radio.

For the WiFi, we measure the average goodput received at different distances between two Eagle Eye platforms. In these experiments, the operating frequency is 2.422GHz, and the transmission power is set 100mW. Multiple physical layer rates are available in WiFi cards, and the covering ranges of these rates are not the same. To correctly measure the coverage, we compare the goodputs of three fixed transmission rates: 6, 24, 54Mbps. (IEEE 802.11g support 8 different rates: 6, 9, 12, 18, 24, 36, 48, 54Mbps, we choose the lowest, middle, and highest from them.) The results are shown in Fig. 3(a). There are a few observations can be made from this figure. First, the covering distance and the transmission rate are inversely related. Second, the upper bound of communication distance is 200 meters when the physical layer rate is 6Mbps and the distance is 50m when the rate is 54Mbps.

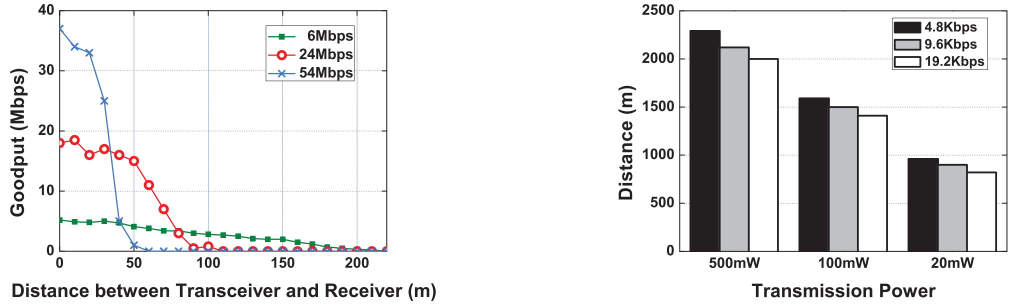
To test the communication range of the EE radio, we measure the achieved distance of the information from the source platform to the destination one. The source platform is deployed at a fixed place. Through SSCOM, it kept sending message "Hello" once per second. And the destination platform is moving and listening. The achieved distance is defined as the maximum range that the moving destination can clearly receive the "Hello" messages. We compare the achieved distance when the source platform works at three transmission power: 500, 100, 20mW (The highest, medium

PARAMETERS	VALUE
RF rates	4.8, 9.6, 19.2 Kbps
RF frequencies	418–445Mhz (stepping 1Khz)
Transmission power levels	0–9 (9==500 mW, 0==20mW)
Build-in buffer	256 bytes
Size	50mm*43mm*14mm

TABLE I
PARAMETERS OF THE EE RADIO.

PARAMETERS	VALUE
CPU/Disk/Memory	Intel Atom 1.4Ghz/160G/2G
Screen	10.2 inch touch screen
Operating system	Ubuntu 10.04
Wireless Card	Atheros AR9285
Size	226mm*167mm*25mm

TABLE II
PARAMETERS OF THE KRT S1 TABLET PC.



(a) Measured goodput at different distances for different rates of WiFi radio.

(b) Maximum communication distance at different transmission powers for different rates of EE radio.

Fig. 3. The results of communication range investigation between WiFi radio and EE radio.

and lowest power of the supported ones) and at three rates: 4.8, 9.6, 19.2Kbps. From the results in Fig. 3(b), we can see that 2500 meters can be reached (when the transmission power is 500mW and the used bitrate is 4.8Kbps) and even the shortest range is 820 meters (20mW and 19.2Kbps), which is a very promising observation.

IV. Eagle Eye Routing

A. Problem Statement

We model a DTN as a set of mobile nodes. Each node moves independently in the two dimension plane. All nodes equip the EE platforms. The storage and bandwidth of nodes are finite. A data packet can be transmitted from source node to destination node directly or via intermediate nodes. The total number *n* of mobile nodes is given. The transmission speed is much faster than movement speed. A source node only knows the ID number of the destination node but no its real-time location information.

The transmission ranges of any node are modeled as two concentric disks, which are shown in Fig. 4(a). Two nodes transfer large data packets to each other within their short range radio*r*. We call them near-neighbors (NNs). And the small information packets can be exchanged within *R* of two nodes within long range radio, $(R >= r)$. We call them far-neighbors (FNs).

In this network, each node broadcasts an real-time movement information tuple $< id, px, py, v, \theta, t, dx, dy >$ to its FNs where id, $< px, py >$, v, θ t, and (dx, dy) are its node ID, its current location, its current velocity, its current angle between the movement direction and the positive horizontal axis, the current time, the location that the node will move to (Note that $< dx, dy >$ is NOT the destination of the data packets.), respectively. The (dx, dy) information is optional. In some cases, the p_dest is known. e.g., most GPS navigators on vehicles are allow to input destination and feedback the shortest path to there. If the $< dx, dy >$ cannot be input, the last observed location is used to instead of $< dx, dy >$ like the method in [23]. This tuple broadcasting to the FNs essentially informs that this node is moving from $< px, py >$ to $< dx, dy >$ at the speed of v with an angle of θ at time t.

Upon receiving such a tuple, each node kept it in a data structure $HI_{8,n}$ where 8 is the number of items in the tuple, and n is the number of nodes in the whole DTN network. That is, $HI_{8,n}$ table is a snapshot of the partial real-time and partial history DTN topology. This table is initialized with *Null* for each record. If an node is encountered in range R, its record will be updated.

Subject to above assumptions, the objective of this study is to develop the routing for EE architecture in DTN in order to achieve the minimum delivery delay.

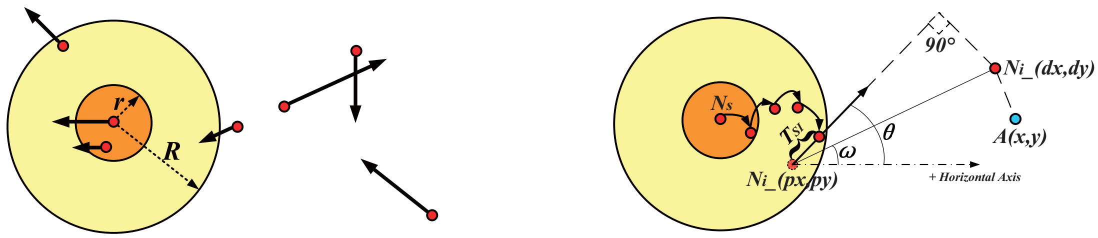
B. Routing Overview

Since the future information is unknown, it is impossible to achieve the optimal delay according to the oracle based optimal theory in [13]. Consequently, we develop the practical and distributed EE routing algorithms to approximate $min(T_{delay})$ for every message delivery.

The basic procedure of the EE routing algorithm is: (1) Between each step, first, the source node selects the best next relay in all the FNs. The best next relay means that it will lead to the minimal delivery delay. Afterwards, the actual data is delivered from source node to the selected next relay by multi-hop of the short-range radio. (2) A data is transmitted step-by-step until arriving the destination node.

The advantages of EE routing algorithm are: (1) The best next relay is selected among the FNs but not NNs. The correctness of the best next relay is higher. (2) The real-time movement information of all nodes in R range is known because of the information exchange in EE radio. Recall the assumption of transmission speed $>>$ movement speed, we can compute the relatively precise delay and path from source node to the best next relay in a short period by existing deterministic routing algorithm such as ED [13].

Depending on the number of copies of a data message that may coexist in the network, two major categories of hop-by-hop routing pattern is defined: single-copy and multiple-copy. In single-copy case, each message has only a single custodian. On the other hand, multiple-copy may generate multiple copies of the same message which can be routed independently for



(a) The model of EE delay tolerant networks.

(b) The next relay selection analysis.

Fig. 4. DTN Routing with EE architecture.

increasing the efficiency and robustness while consuming high buffer and bandwidth.

C. Single-Copy EE routing algorithm

The single-copy EE routing algorithm is based on the best next relay selection. Our algorithm makes use of the following definitions and theorems.

Definition 1. *The delivery delay from the source node N_s to the destination N_d via intermediate node N_i is*

$$f(N_i) = T_{SI}(N_s, N_i) + T_{ID}(N_i, N_d), \tag{1}$$

where T_{SI} and T_{ID} is the time that node N_s forwards its packets to node $N_i \in V(N_s)$, and that N_i to N_d. The set $V(N_s)$ is the set of far-neighbors.

Definition 2. *The best next relay is the far-neighbor $N_{i,best}$ that minimizes the delivery delay, i.e.,*

$$f(N_{i,best}) = \arg min(f(N_i)). \tag{2}$$

To simplify the calculation of the expected delivery delay $f(N_i)$, we have the following three theorems.

Theorem 1. *If $T_{SI}(N_s, N_i)$ is finite, then*

$$\begin{aligned} f(N_i) &= T_{PD}(N_i(px,py), N_i(dx,dy)) \\ &\quad + T_{DA}(N_i(dx,dy), A(x,y)), \end{aligned} \tag{3}$$

where T_{PD} is the time that the node N_i moves from current location $N_i(px,py)$ to destination location $N_i(dx,dy)$, and T_{DA} is the time that N_i transmits the packets from $N_i(dx,dy)$ to $A(x,y)$, where $A(x,y)$ is the last recorded location of the destination node in $HI_{8,n}$.

Proof: If $T_{SI}(N_s, N_i)$ is finite, then

$$T_{ID}(N_i, N_d) = T_{car} + T_{DA}(N_i(dx,dy), A(x,y)), \tag{4}$$

where T_{car} is the carrying duration from the time that N_i meets the source N_s to the time that N_i moves to $N_i(dx,dy)$. See Fig. 4(b) for an illustrating example. Note that it takes the same duration for both N_s and N_i travelling to their meeting location, which means that

$$T_{car} = T_{PD}(N_i(px,py), N_i(dx,dy)) - T_{SI}(N_s, N_i). \tag{5}$$

Substituting Eqns. 4 and 5 to Eqn. 1, we get Eqn. 3. ■

Recall that each node now has the table $HI_{8,n}$, with which we solve Eqn. 3 via the following two theorems.

Theorem 2. *The upper bound of the time $T_{PD}(N_i(px,py), N_i(dx,dy)) = \frac{L}{v}$ where L is defined in Eqn. 6, $\omega = \arctan(\frac{dy-py}{dx-px})$ and θ is the current traveling angle of N_i.*

$$L = \begin{cases} (\sin|\theta-\omega| + \cos|\theta-\omega|)\times & \\ \sqrt{(dx-px)^2 + (dy-py)^2}, & |\theta-\omega| < 90^\circ \\ \infty, & otherwise \end{cases} \tag{6}$$

Proof: The upper bound of time T_{PD} is the duration that N_i carries the data by itself from location $N_i(px,py)$ to $N_i(dx,dy)$ because the transmission speed is always faster than movement speed. If $|\theta-\omega| \geq 90^\circ$ (i.e., if node N_i is moving away from its next location $N_i(dx,dy)$ temporarily), we do not use it for relaying and so set $T_{PD} = \infty$. It does not mean that the node will never be used in the future. If this node turns back to the middle of the other relays and the destination node, it can still be found by our algorithm. When $|\theta-\omega| < 90^\circ$, we approximate that the longest distance that node N_i travels between location $N_i(px,py)$ and $N_i(dx,dy)$ is the sum of the two right-angle sides shown in Fig. 4(b), which is trivial to be calculated using triangle equations.■

Theorem 3. *The upper bound of the time T_{DA} is*

$$T_{DA}(N_i(dx,dy), A(x,y)) = \frac{\sqrt{(Ay-dy)^2 + (Ax-dx)^2}}{\overline{v}}, \tag{7}$$

where $\overline{v} = \frac{\sum_{i=1}^{n} v_i}{n}$ is the average velocity of all the nodes in the DTN, and v_i is the velocity of node i.

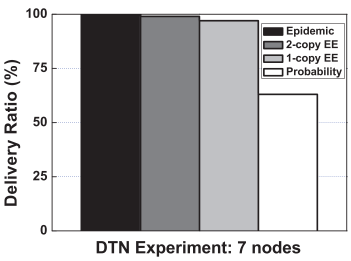
Proof: The upper bound of the time T_{DA} is the time that a node (which may or may not be N_i) carriers the data and moves from (dx,dy) to $A(x,y)$. We do not know at this stage which node will carry the data since the EE radio can not cover the nodes outside the range R. To calculate T_{DA} therefore, we use the average velocity of all the nodes(i.e., the fifth column of the table $HI_{8,n}$) in Eqn. 7. ■

Summarizing the above three theorems, searching for the best next relay is now equivalent to searching for the minimum of $f(N_i)$, i.e., searching for the minimum of the upper bounds of T_{PD} and T_{DA}. With this computational method to select the next relay, we design the corresponding routing algorithm

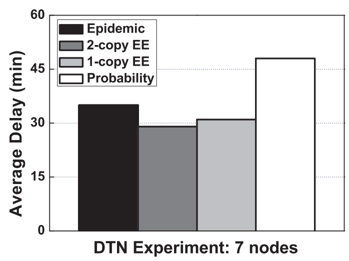
(a) The Eagle Eye platform is set in a vehicle.

(b) The Eagle Eye platform is carried by a student and moves in the campus.

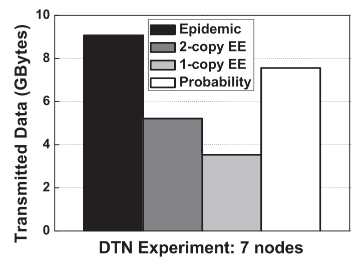
(c) The map of the campus, which is area for the 7 nodes moving.



(d) The performance of delivery ratio.



(e) The performance of average delay.



(f) The transmitted data.

Fig. 5. The set and the results of the prototype implementation.

for the DTN with EE radio. The pseudo-code of the algorithm is shown in Algorithm 1.

For the single-copy routing, we substitute $m = 1$ in the algorithm. Since the source node only know the ID of the destination node, lines 1-2 is the step to collect the location information of N_d from all FNs through EE radio. The function of line 4-9 is to select the latest observed location of N_d as the relatively precise position. For all FNs, line 11-18 computes the expected delivery delay according to the proposed utility function Eqn. 3 and the multi-hop path by ED [13]. After ascending sort the $HI_{8,n}$ by the expected delivery delay in line 19, the WiFi radio can transmit data packets according to the multi-hop path to the best next relay selected in line 20-23. Then each relay node repeat this algorithm until the data packets arrive the destination node.

D. Multi-Copy EE Routing Algorithm

In DTNs, sending duplicate data is sometime used to ensure high delivery ratio and low delivery delay [22]. In this case, multiple next relays are needed to help forwarding. Our EE routing algorithm can be extended to search for multiple next relays (by setting the value of m) for this aim. For example, if we send 2 copies for each data packet, our algorithm can simply return the nodes with minimum and the second minimum results of $f(N_i)$.

The m-copy EE routing algorithm carries out as follows: When there is a data packet to be sent, the source node N_s runs the m-copy EE routing algorithm and pick the best m next relays from FNs in the range of EE radio. Then, the WiFi radio transmits m copies of the data to the selected m relay nodes. After the relay nodes receive the data packet, they begin to carry out the single-copy EE routing algorithm. So there are only m copies of data transmitted in the DTN until the destination node obtains the data.

V. Prototype Implementation

A. Implement Configuration

We implemented a 7-node prototype system. Three EE platforms of this system are carried by volunteers (see Fig. 5(b)) randomly walking in an area approximately 2.3*1.3 km^2 on the campus of Shanghai Jiao Tong University (see Fig. 5(c)), and the other four are equipped in four cars (see Fig. 5(a)) running in the same area.

The short range WiFi radio is working in the 2.422GHz frequency band with a transmission power of 100mW and a fixed transmission rate of 54Mbps. The EE radio is working in the 434MHz frequency with a transmission power of 20mW and a rate of 19.2Kbps. All the seven nodes are synchronous by GPS time. We adopted CSMA/CA method to avoid the collisions in the EE radio. Since the size of each information tuple (8*4Bytes) is only 32Bytes and the interval of the tuple broadcast of every node is 1 second, the rate 19.2Kbps is adequate to support the CSMA/CA on seven nodes even some retransmissions happen.

$$\frac{19.2Kbps}{32Bytes \times 8 \times 1s} = 75 > 7 \tag{8}$$

Our experiments are conducted between 14:00–16:00 from July 27 to July 30, 2010. Four algorithms are tested in the four days respectively. They are epidemic routing [24], probability

Algorithm 1: The m-copy EE routing algorithm

Input: $N_d(ID)$, $HI_{8,n}$
Output: NextRelay, PathtoNextRelay
Notations:
t_{now}: current time
m: the number of copies to send
$|V(N_s)|$: the number of far-neighbors (FNs) of source N_s
$F[V(N_s)]$: array for delivery delays via all FNs
$Path[V(N_s)]$: array for paths to all FNs
$N_d[3][V(N_s)]$: array for known locations of N_d from all FNs
Main procedure:
Broadcast $N_d(ID)$ to all FNs
Receive $N_d(t, dx, dy)$ from FNs and keep in $N_d[3][V(N_s)]$
/*Search for latest known location of N_d */
$Ax \leftarrow N_d[1][0]$, $Ay \leftarrow N_d[2][0]$
for {i=1, i++, $i < |V(N_s)|$} **do**
  if $\{(t_{now} - N_d[0][i]) < (t_{now} - N_d[0][i-1])\}$ **do**
    $Ax \leftarrow N_d[1][i]$, $Ay \leftarrow N_d[2][i]$
  end if
end for
/*Search for the best nextrelay(s) */
for {i=1, i++, $i < |V(N_s)|$} **do**
  $T_{PD} \leftarrow (L(HI_{1,i}, HI_{2,i}, HI_{6,i}, HI_{7,i}, HI_{4,i})/HI_{3,i}$
  $T_{DA} \leftarrow \sqrt{(HI_{6,i} - Ax)^2 + (HI_{7,i} - Ay)^2}/HI_{3,i}$
  $T_{SI}, Path[i] \leftarrow ED(HI_{8,|V(N_s)|}, HI_{0,0}, HI_{0,i})$
  if { $(T_{SI} == \infty)$ } **do** $F[i] = \infty$
  else if do $F[i] = T_{PD} + T_{DA}$
  end if
end for
Sort($HI_{8,|V(N_s)|}$, $Path(|V(N_s)|)$) by $F[|V(N_s)|]$
for {i=1, i++, $i < m$} **do**
  NextRelay(i) $\leftarrow HI_{0,i}$
  PathToNextRelay(i) $\leftarrow$ Path[i]
end for

routing [22], 1-copy and 2-copy routing algorithms. In the probability routing scheme, a node forwards its copy to an encountered non-destination node with probability $p = 0.5$, and to a destination node with $p = 1$. During the first hour (i.e., 14:00–15:00) of everyday's test, each node generates a 4MB MP3 file per minute to send to a random destination node. And during the second hour (i.e., 15:00–16:00), there is no new files to be sent. However, the generated files are still transmitting in the DTN. We define that the data is lost in two cases. One is that the data cannot arrive at the destination node before 16:00, another is that the number of forwarding times of a data packet reaches 10, which is the threshold of time-to-live (TTL) we set.

B. Implement Results

In Fig. 5(d), we show the delivery ratio of the four schemes. As we can see, almost all the packets are delivered with the epidemic (100%), 1-copy (97%) and 2-copy (99%) EE routing algorithms, while with the probability routing, around 60% data reaches the destination. In such a relatively small and closed system, epidemic and EE routing algorithms can ensure the delivery ratio. Yet, the forwarding number of probability method is easy to exceed the TTL.

In Fig. 5(e), we illustrate the average delay of the packets arrive at the destination during the tests. Note that in 2-copy EE and epidemic routing, the delivery delay is recorded the duration from the data sent by the source node to the first duplication is got by the destination node. It can be seen that our 1-copy (31mins) and 2-copy (29mins) algorithms achieve a little lower delays than the epidemic routing (35mins), and the probability routing incurs the highest delays. Since there are many copies of data in the networks, the epidemic and probability approaches perform worse than the EE routing algorithms.

The obvious advantage of EE routing algorithms against the epidemic routing is illustrated in Fig. 5(f) where we plot the total amount of data transmitted in the whole network during the tests. As can be seen, in order to achieve the similar delivery ratio and average delays shown in Fig. 5(d) 5(e), EE routing protocols transmit less than 1/2 of the amount of data than the epidemic routing does. In particular, the epidemic routing transmitted in total 9.1GB, while our 2-copy routing send 5.2GB and the 1-copy routing transmits only 3.5GB.

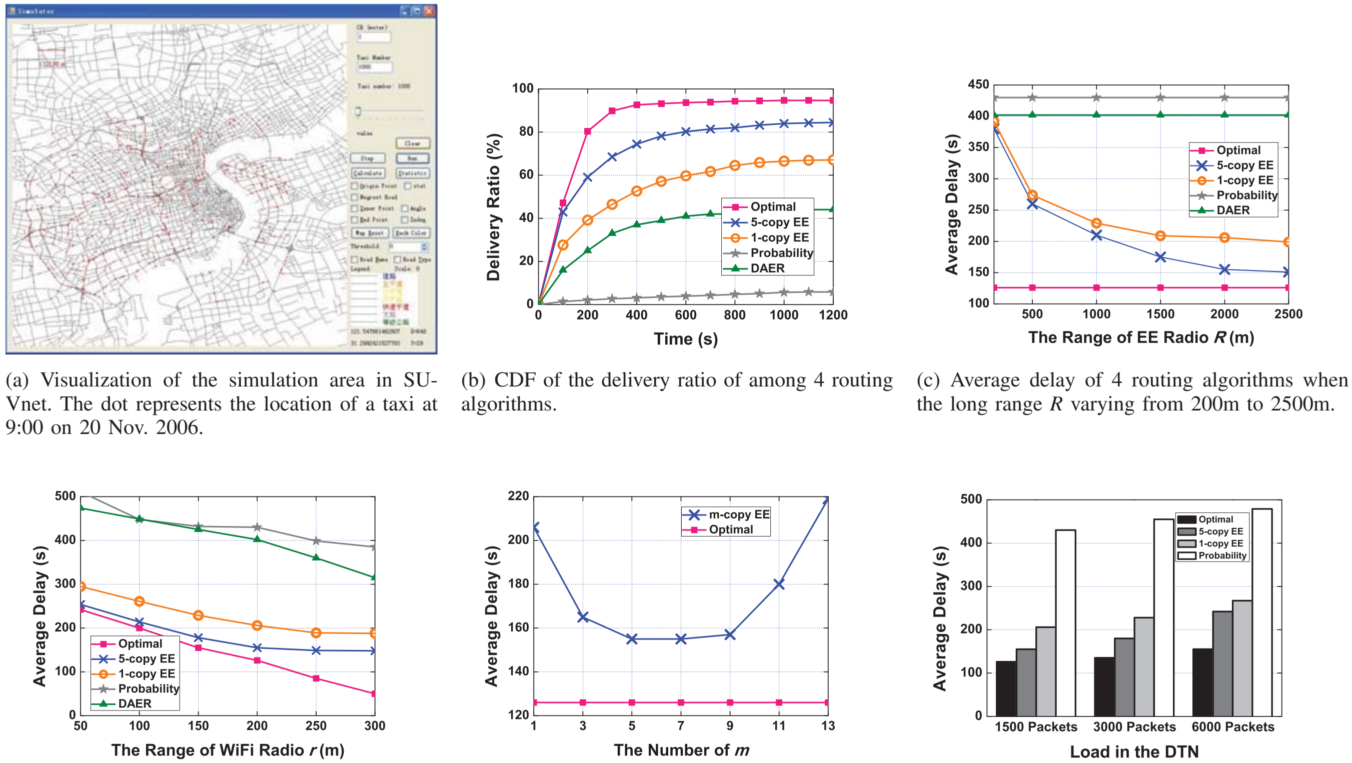
VI. Performance Evaluation

A. Simulation Set

To evaluate performance in large scale scenarios, we conduct extensive simulations based on the real traces of the Shanghai urban vehicular network (SUVnet) project [28]. This trace data is collected from over 4000 taxis equipped GPS. From this data, we selected the downtown area of Shanghai with an area of about 102 km^2 as shown in Fig. 6(a). To fix some incomplete/faulty GPS information in the trace data, we use the same interpolation and revising methods in [11]. The actual data we used in that from 9:00 to 9:20 on 20 Nov. 2006. Since the SUVnet is an open system in which taxis entered and left the considered area from time to time, the actual number of taxis varies from 2380 to 2937 in our simulations.

The default set is: the EE radio range $R = 2000m$, and the bandwidth is $19.2Kbps$; the WiFi radio range $r = 200m$, and the bandwidth is $6Mbps$. The size of data packet (bundle) is 1MB. In the simulation 20 minutes, 1500 packets are generated in the first 5 minutes uniformly. The source and destination nodes are randomly selected in the all nodes. The buffer is set 32MB. If the transmission load is heavy in the DTN, the buffer will be used up. The replace rule is to remove the packet that has the longest lifetime from it is generated. TTL is set 100 forward times. We set that any node inputs the p_dest information when it change the destination.

We compare the performance of five schemes: optimal routing, probability routing, DAER routing [11], 1-copy and m-copy EE routing algorithms of our own. In order to find the minimum delay value, the optimal routing is based on epidemic method but the buffer and bandwidth is assumed infinite. Then, the first copy arrive the destination node has the optimal delay. We did not use the epidemic routing in the simulations. The reason is that in such a large-scale networks, epidemic routing consumes plenty of resources and leads to network congestions, thus the epidemic routing is not practical nor efficient. Moreover, DAER is one of the current DTN routings for delivery delay improvement. The



(a) Visualization of the simulation area in SUVnet. The dot represents the location of a taxi at 9:00 on 20 Nov. 2006.

(b) CDF of the delivery ratio of among 4 routing algorithms.

(c) Average delay of 4 routing algorithms when the long range R varying from 200m to 2500m.

(d) Average delay of 4 routing algorithms when the short range r varying from 50m to 300m.

(e) Average delay of m-copy EE routing algorithm when m varying from 1 to 13.

(f) Average delay in different transmission load DTNs. 1500, 3000, 6000 packets are generated in the first 5 minutes in the network.

Fig. 6. The set and results of the simulation.

most assumptions of DAER are the same as the EE but only one WiFi radio on nodes and the p_dest is known. The performance results among these five schemes are shown and discussed in the next subsection.

B. Performance Analysis

The CDF of the delivery ratio is shown in Fig. 6(b). Since the taxis were moving in and out of the considered area, some packets that carried out cannot be delivered to the destination nodes in the simulations. As a result, even the optimal algorithm achieves 94.6% delivery ratio. Same as in the prototype results, our 5-copy and 1-copy routing algorithms outperform the DAER or probability algorithm significantly. We find that the delivery success rate of EE methods is acceptable. Especially, when the number of copies increases from 1 to 5, the rate raises about 17% and just 7% to the optimal one.

We then test the impact of the EE radio R. In Fig. 6(c) we plot the delivery delay against varying R from 200m to 2500m. There are a few observations can be made. First, the performance of the optimal, DEAR and probability algorithms remain the same since they do not use the long range radio. Second, a large R leads to low delivery delay for EE algorithms as expected. There is a tendency that when R become infinity, the EE algorithm will approximate the optimal delays. Third, even when $R = 200m$, benefiting from the parallel operating of dual radios, EE algorithms perform also a little better than DAER as shown in Fig. 6(c). Forth, the delay is 380s and 392s for 5-copy and 1-copy algorithms in $R = r = 200m$, and 401s for DAER algorithm. Considering the 147s and 151s in $R = 2500m$, the performance decrease more than 60% when the DTN adds EE architecture.

We further studied the impact of the range r of short range WiFi radio (See Fig.6(d)). While our algorithms keep performing well, when $r > 200m$ the achieved average delays tend to remain. This is so since the whole network is now better connected with large r and thus the dependency on the EE radio is less pronounced.

We can observe that the performance of 5-copy EE algorithm is always better than the 1-copy EE one. Then we study the impact of the number of duplications that changes from 1 to 13 and plot the result in Fig. 6(e). The delivery delay is decreasing when m is increasing from 1 to 5 obviously. But when m is varying from 9 to 13, the EE algorithm behaves worse and worse. The reason is that too many copies of data in the network result to the congestion and increase the waiting time of data transmission. In our simulations, the number of 5 is the relative good value for optimizing the delivery performance.

In the last test, we vary the network load by sending 1500, 3000 and 6000 packets in the first 5 minutes of the simulations. The results in Fig. 6(f) demonstrate that the proposed algorithms outperform the other schemes regardless of the traffic load.

VII. Conclusions

Aiming to gain more real-time movement information in large range, thus to reduce the delivery delay in DTNs, we propose the very first architecture called Eagle Eye. The additional long-range low-bitrate radio is the novel component in this architecture, with which the EE radio can "see" ranges up to 10 times larger than WiFi does. We also design the *m*-copy EE routing algorithm special for this architecture to select the next relay(s) with minimum expected delivery delay. The prototype implementation and real trace based simulation verify the feasibility and show the great improvement on accelerating delivery process in DTNs with the dual-radio architecture.

Using such kind of combined architecture is a new concept in DTNs, several aspects remain to be studied in the future. Firstly, we limit the inquiry messages within one-hop far-neighbors. Multi-hop inquiry may lead to more accurate destination information but result to broadcast storm. Tradeoff this dilemma is worth to further study. Second, collisions between far-neighbors happen rarely in this work due to the sparse nature of DTNs. In dense DTNs however, we need a mechanism to resolve collisions. Third, it is possible that not all nodes in the same DTN are equipped with the EE platforms. Performance in this heterogeneous networks will be considered.

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