DAWN: A Density Adaptive Routing for Deadline-Based Data Collection in Vehicular Delay Tolerant Networks

Qiao Fu, Bhaskar Krishnamachari, and Lin Zhang*

Abstract: Vehicular Delay Tolerant Networks (DTN) use moving vehicles to sample and relay sensory data for urban areas, making it a promising low-cost solution for the urban sensing and infotainment applications. However, routing in the DTN in real vehicle fleet is a great challenge due to uneven and fluctuant node density caused by vehicle mobility patterns. Moreover, the high vehicle density in urban areas makes the wireless channel capacity an impactful factor to network performance. In this paper, we propose a local capacity constrained density adaptive routing algorithm for large scale vehicular DTN in urban areas which targets to increase the packet delivery ratio within deadline, namely Density Adaptive routing With Node deadline awareness (DAWN). DAWN enables the mobile nodes awareness of their neighbor density, to which the nodes' transmission manners are adapted so as to better utilize the limited capacity and increase the data delivery probability within delay constraint based only on local information. Through simulations on Manhattan Grid Mobility Model and the real GPS traces of 4960 taxi cabs for 30 days in the Beijing city, DAWN is demonstrated to outperform other classical DTN routing schemes in performance of delivery ratio and coverage within delay constraint. These simulations suggest that DAWN is practically useful for the vehicular DTN in urban areas.

Key words: delay tolerant networks; node density adaptive routing; deadline-based data collection; channel capacity

1 Introduction

The Delay Tolerant Networks (DTN) are networks where contemporaneous end-to-end paths are unstable or unlikely. Routing in such networks is different from those in wired or well-connected wireless networks, because of its characters of extremely long delay, frequent failure of link and opportunistic

- Qiao Fu and Lin Zhang are with the Department of Electronic Engineering, Tsinghua University, Beijing 100084, China. E-mail: fuqiao1@gmail.com; linzhang@tsinghua.edu.cn.
- Bhaskar Krishnamachari is with the Ming Hsieh Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA. E-mail: bkrishna@usc.edu.
- ∗ To whom correspondence should be addressed.
  Manuscript received: 2013-03-24; accepted: 2013-04-17

connections[1]. Therefore, researchers have proposed the DTN routing to exploit the opportunistic conductivities amongst a group of mobile wireless nodes and to deliver data in a "store-carry-forward" manner[2-8]. By tolerating certain amount of delay, such routing schemes make data transmission in DTN possible and increase the throughput. Therefore, DTN routing technologies have been widely used in the intermittently connected and decentralized scenarios, such as the disaster rescue, wildlife monitoring, field work, etc.

Recently, with the maturation of the Vehicle-to-Vehicle (V2V) communication technologies and the standardization and upcoming enforcement of the IEEE 802.11p in the automotive industry, vehicular network becomes a promising technology. Applications in vehicular networks include not only the "active

safety services", but also the infotainment, which provides useful information and on-board entertainment applications[9]. Large scale urban sensing applications have also drew people's attention these days, including remote metering, environmental sensing, etc.[10]

Although these services can be supported by a wireless infrastructure (e.g., 3G), the cost of doing so is high and may not be possible when such an infrastructure does not exist or when the service is intermittent[11]. Since immediate message delivery is not a necessity for infotainment and urban sensing, these tasks can be supported by DTN. By tolerating certain amount of delay, the vehicular DTN enjoy very low deployment and operational costs. Moreover, in case of disaster, the wireless infrastructure may be damaged, whereas vehicular DTN can be used to provide important traffic, rescue, and evacuation information to the users.

The vehicular network enjoys several advantages in supporting DTN routing. First, since vehicles can provide substantial electricity supplies and transport bulky hardware, neither the power nor the storage will create system design issues. Furthermore, the movement of the vehicles is statistically predictable because of the road constraint and the human behavioral habits. Therefore, the routing algorithms can utilize the vehicle's geographic location information to make precise data forwarding or duplication decisions so as to achieve good performance.

Nevertheless, in DTN deployed in urban areas, the challenges for routing algorithms are still huge. In urban areas, the density of vehicles fluctuates fiercely in time and location. For example, the vehicle density at intersections or during the traffic jams could be high enough to cause packet congestions in the channel, while in suburbs or at night, vehicles can hardly encounter or communicate with others[12]. The heterogeneity of the vehicle density makes the volume of data exchanged upon vehicle encounters at different geographic locations and time highly diversified, which will cause a channel utilization problem. In the areas or time of low car density, part of the channel capacity could be wasted, while in the areas or time of high car density, the network will suffer packet loss due to excessive channel contention. Therefore, the constraint of wireless channel capacity should be carefully considered as an impact factor in the routing algorithm design in large scale urban DTN. But, to the

best of our knowledge, so far there is still not a practical and implementable routing algorithm for DTN which takes channel constraint into consideration.

Moreover, in most infotaiment and urban sensing applications, there exists a deadline, beyond which packets are considered obsolete. For example, in real time urban environment monitoring applications, data generated many hours ago may be considered useless since the environment may have changed greatly during that time. Therefore, such a deadline restriction should be taken into consideration when evaluating the DTN performance. However, conventional DTN routing algorithms normally seek for either higher throughput or smaller delay, which may not be an accurate measurement for the network performance in large scale urban DTN.

In this paper, we propose a local capacity constraint density adaptive DTN routing algorithm, namely Density Adaptive routing With Node deadline awareness (DAWN), to remedy the impact of node density heterogeneity, so as to improve the deadline-based network performance. Unlike traditional DTN models, DAWN considers the local capacity limitation of the wireless channel, especially for the case in which the throughput is restricted by congestion. Moreover, a heuristic measurement of network performance is proposed to measure the packet delivery ratio within deadline. Unlike other conventional DTN routings, such measurement takes both the network throughput and the delay of the packet into consideration. Because of the deadline restriction characteristic of most urban sensing and infotaiment applications, such deadline-based data collection measurement is rather practical and accurate in realistic deployments. In DAWN, a deadline-based utility function for each sensory data packet is defined, which indicates the probability that this packet can be delivered successfully to the base stations within the delay constraint. The replication procedure is density adaptive and each node chooses to replicate the packets with highest utility gain estimation under capacity constraint. Note that even though we propose DAWN in a field-gathering model, where the destination of the packets is only the base stations, DAWN can be easily extended to scenarios where destinations can be any node in the network. Simulation results based on Manhattan Grid model and Beijing taxi trajectories[13], show that DAWN outperforms other traditional DTN routing schemes in the performance of delivery ratio

and coverage area within delay constraint.

2 Related Work

As the key component of DTN, a large number of routing protocols have been proposed based on various assumptions regarding the connectivity and mobility patterns. Vahdat and Becker[14] propose the first routing protocol for DTN, namely the Epidemic Routing Protocol. Its idea is almost the same as the flooding routing scheme in traditional ad hoc networks. When an intermediate node receives a message, it will broadcast to all its neighbors, and thus information disseminates in a flooding manner. It is intuitive to consider the Epidemic routing as an unconstrained optimization to maximize the performance of the throughput. However, in real world deployments, especially in large scale, resource constraint scenarios like the one we are facing in the urban DTN, careful consideration of the complicated tradeoff between the performance and the resource cost, and adaptation to the heterogeneity of the network is a must for sophisticated protocols.

In Ref. [2], a vehicular based DTN routing protocol called MaxProp is proposed to address the resource constraint scenarios. MaxProp uses several mechanisms to define the order in which packets are transmitted and deleted in order to better utilize the network resource. However, it is not explicitly addressed how to optimize a specific routing metric using MaxProp. In Ref. [15], a resource allocation protocol called RAPID is introduced. RAPID is designed to explicitly optimize an administrator-specific routing metric, such as minimizing average delay, minimizing missed deadline, or minimizing maximum delay. RAPID translates the routing metric to per-packet utility and determines at every transfer opportunity if the marginal utility of replicating a packet justifies the resource used. However, RAPID requires the flooding of information about all the replicas of a given message in the queues of all nodes in the networks in order to derive the utility. In scalable networks such as the urban DTN, such information is difficult to achieve and information flooding also requires tremendous network resource.

Besides simply maximizing the performance, several approaches have been introduced to control the copy of packets based on Epidemic algorithm. One successful case is the Spray and Wait (S&W)[16], in which each packet is only transmitted L times by the source

node. Packets are then held by the relay nodes and delivered to the destination until they meet. This approach obviously reduces the overhead, and achieves acceptable network performance under the random waypoint model. However, S&W manifests apparent disadvantage in large scale network considering the fairness of the coverage. Packets generated near the base stations have more chance to be collected than those generated far away.

Some protocols assume the network topology can be predicted and intermediate nodes can estimate the chance of reaching the destination. Based on this estimation, the intermediate nodes decide whether to store the packet or send it to other nodes who enjoy better chance to reach the destination (see Refs. [17-22]). In Ref. [17], the authors propose a routing scheme called Probabilistic Routing Protocol Using History of Encounters and Transitivity (PROPHET). PROPHET estimates a probabilistic metric called delivery predictability at every node a, for each known destination b. This metric indicates how likely the node will be able to deliver a message to the destination. When two nodes meet, they compare each other's delivery predictability for each destination, and transfer packets to the party that has higher probability of reaching the destination. Since nodes make choices based on a priori information, the average cost per packet delivery of PROPHET is lower than that of Epidemic. Nevertheless, such approach strongly relies on mobility prediction. Performance can be improved when more precise prediction is made, and a specific link quality estimation for urban DTN should be proposed.

There are algorithms successfully optimize the network performance to some extend. The queue-differential backpressure routing scheme is shown by Tassiulas and Ephremides[23] to be throughput optimal in terms of being able to stabilize the network under any feasible traffic rate vector. The basic idea of such scheme is to prioritize transmissions over links that have the highest queue differentials, so that packets are flowing in the network as if pulled by gravity to the destination. Further research shows that backpressure scheme performs well under high traffic condition. On the contrary, when the traffic is low, backpressure scheme becomes inefficient in terms of packet delay, since many other nodes apart from the destination may also have a small or 0 queue size. In Ref. [24], the authors propose an

adaptive redundancy backpressure scheme to reduce delay under low load conditions, while at the same time preserving the performance and benefits of traditional backpressure routing under high traffic conditions. Such advantage is achieved by creating copies of packets in a new duplicate buffer upon an encounter, when the transmitters queue occupancy is low. These duplicate packets are transmitted only when the original queue is empty. In this way, the algorithm builds up gradients towards the destinations faster and reduces packet looping. However, such scheme does not guarantee deterministic delay for the packets.

The routing algorithms stated above ignore the effects of network contention on performance arguing that its effect is small in sparse intermittently connected networks. Nevertheless, some recent work has shown through simulations that ignoring capacity constraint leads to inaccurate and misleading results. In Ref. [25], the authors propose an analytical framework to model network contention to analyze the performance of any given DTN routing scheme for any given mobility and channel model. They then calculate the expected delay for representative DTN routing schemes, namely direct transmission, Epidemic, and S&W, with capacity constraint in the network for the random direction, the random waypoint, and the more realistic community-based mobility model. They point out through these delay expressions that ignoring capacity constraint can lead to suboptimal or even erroneous decision. The authors also point out some directions to modify the existing S&W scheme in order to decrease the delay when capacity constraint is taken consideration. However, no practical and implementable heuristics is proposed in the ongoing work.

Density adaptive routing schemes have also gained interests recently. In Ref. [26], the authors point out that routing algorithms, such as Epidemic and S&W, perform poorly in density dynamic networks, such as the RollerNet examined in the paper. Based on observation of the RollerNet, which is obtained from a rollerblading tour that consists of 15,000 people, the authors propose the Density-Aware Spray and Wait (DA-SW), a measurement-oriented variant of the S&W algorithm that tunes, in a dynamic fashion, the number of message copies to be disseminated in the networks. In Ref. [4], an Epidemic-based density adaptive routing scheme called ECAM is proposed. ECAM limits the maximum times

of message transmission among nodes to control flooding. Transmission times decrease exponentially with hop counts so that less transmissions would be allowed as packets disseminate. Simulation results show that ECAM successfully decreases overhead without delivery rate reduction. All these algorithms realize the influence of density to networks and the importance of adjusting message copies with network density, but none of them aims at urban DTN, where extreme heterogeneity presents. How to detect local density, and to tune message replication with network density in large scale urban DTN are problems remain unsolved. The characteristics of routing algorithms for DTN are summarized in Table 1.

In this paper, we consider both local channel capacity constraint and heterogeneous node density for the DTN, and propose a capacity constrained and density adaptive routing algorithm to improve the delivery ratio within the delay constraint. In our algorithm, the local capacity is better utilized to improve the packet delivery ratio within deadline, and the impact of fluctuant nodes density has been taken into account as well.

3 DAWN

In this section, we will first propose a network model for DTN taking consideration of network capacity constraint. The notation "First Passage Time" is then explained addressing the time for a mobile node to first meet the base stations, which will be used in the estimation of utility value in DAWN. The DTN routing scheme DAWN is then proposed in detail.
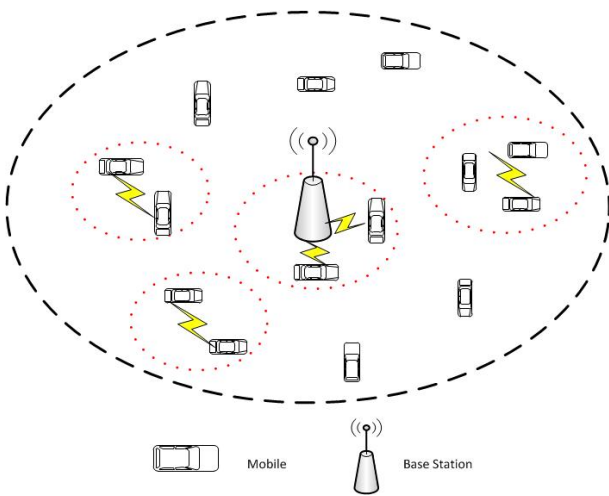
3.1 Network model

The following algorithm and simulations are considered under the data collection network model stated as follows, in which packets are generated by the mobiles, and are intended to be uploaded to the base stations. Such network model can be utilized for data collection and distribution in urban sensing and infotainment applications. Nevertheless, application of DAWN is not limited to such data collection model. DAWN can be easily extended to support vehicle to vehicle data routing like any other DTN routing algorithms by simply replacing the utility function to corresponding scenarios.

The data collection network model consists of M mobile nodes and one or more static data gathering base stations (See Fig. 1). The M mobile nodes move within the field following a certain mobility pattern. Each

Table 1   DTN routing algorithms.

Routing	Flooding dissemination	Resource constraint	Copy control	Link estimation	Density adaptive	Design for VSN	Performance optimization	Deadline aware
Epidemic[14]	✓	×	×	×	×	×	×	×
MaxProp[2]	✓	✓	×	×	×	✓	×	×
RAPID15	✓	✓	×	×	×	×	✓	×
Spray and Wait[16]	✓	×	✓	×	×	×	×	×
PROPHET[17]	×	×	×	✓	×	×	×	×
BWAR[24]	✓	×	×	×	×	×	✓	×
ECAM[4]	✓	×	✓	×	✓	×	×	×
DA-SW[26]	✓	×	✓	×	✓	×	×	×

Fig. 1   Network model.

mobile generates fix-length data packets at a certain rate while traveling. Each packet can be denoted by the tuple of its source node and the generation time, denoted by (s, t_0), and it shall be delivered to the base stations before a deadline T_{MAX}. The data gathering base stations can be located in arbitrary spots in the field and collect the sensory data packets from mobile nodes.

Both the mobile nodes and the base stations are equipped with short range communication devices, the limited bandwidth of which constrains the volume of data deliveries over wireless link when multiple nodes are in each others' transmission range and competing the channel. We assume that in this case, only a number of K packets can get through in unit time due to channel capacity constraint. The constraint K is determined by the Media Access Control (MAC) and physical layer. For example, when IEEE 802.11p standard is utilized for mobiles communication, there exists a maximum number of packet input, input larger than which will cause collision and decrease the number of packets getting through the network and

being received by the destinations[27]. Such optimal number of input can be defined as the capacity constraint K in our model. The local network density is defined as the number of nodes within transmission range. Such definition is rational since only the nodes within transmission range can compete the channel and replicate packets.

3.2   First passage time

Definition 1 (First Passage Time) The First Passage Time (FPT) is defined as the interval between the time a mobile node starts from a certain spot and the time that it first meets the base stations.

The FPT can be defined for any mobility model. Intuitively, the distribution of FPT can be related to the location of the starting spot, the size of the map, and the velocity of the mobile nodes. However, there is not a close form solution for the Comulative Distribution Function (CDF) of FPT in such data collection model even for the simple mobility models such as random walk on the torus.

We could achieve the CDF of FPT from either numerical simulations (for mobility models such as the Manhattan Grids) or empirical data (for real world vehicle mobility patterns) as a reference for the following calculations. Figure 2 shows the CDF of FPT for the Manhattan Grid Model and the Beijing taxi trajectories with single base station located.

The Manhattan Grid Model uses a grid road topology that fully manifests the movements of vehicles in urban areas, where the streets are in an organized manner. It is often used in vehicular network evaluations because of its similarity to the urban street networks. In a Manhattan Grids, the mobile nodes move in horizontal or vertical direction with a velocity of one grid each time slot on the urban map, and choose directions with identical probability at each grid point. The borders of
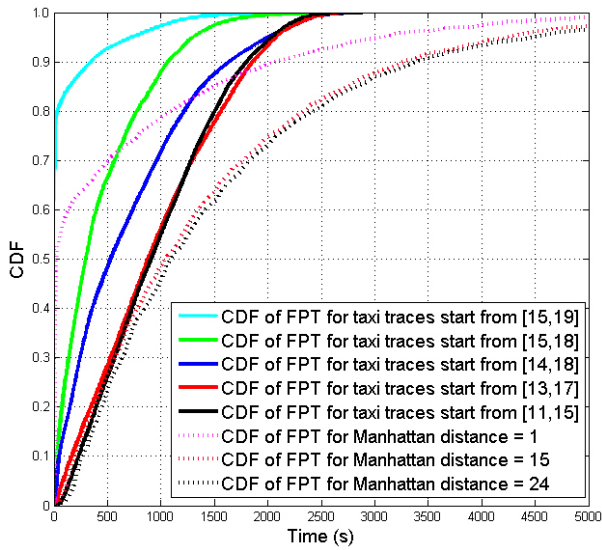
Fig. 2   The CDF of FPT for Manhattan Grid Model and Beijing taxi trajectories.

the Manhattan Grids are cyclic, that is, the mobile nodes getting out of the network through one side of the border will enter the network through the other side. Such assumption guarantees that the following evaluations will not be influenced by the border effects. Moreover, this Manhattan Grid Model reflects the situation in real deployments. In large cities with wide area coverage, the area will be divided into multiple zones, each of which is equipped with a base station, and the base stations are connected by a wide-band backbone network. In such scenarios, with negligible border effects at the edge of the whole coverage area, each base station and its zone is equivalent, and their borders can be considered cyclic since vehicles are free to move in and out of the borders. Therefore, the Manhattan Grids provide a pretty good approximation of the real world multi-base-station situation. Each curve for the Manhattan Grid Model in the figure is the results of 10^8 simulation experiments. *Distance* is the Manhattan distance, i.e., the sum of horizontal and vertical distance in number of grids, between the start and end points. In each experiment, mobile node starting from a certain *distance* moves according to the Manhattan Grid Mobility Model. The time it takes to first meet the base station, which can be addressed as an FPT sample, is then counted. We calculate the frequency of the FPT samples and derive the statistic CDF for FPT.

The curves for Beijing taxi trajectories are obtained from the Beijing taxi trajectory data set of 27, 848

taxis traveling for 15 days from May 16, 2009 till May 30, 2009[13]. The data set includes taxi trajectories ranging between 39.759°N and 40.023°N latitude, and 116.209°E and 116.544°E longitude, the area inside the fifth-ring road of Beijing. The curves are derived using the same methods as in Ref. [28], in which FPT for seabird traveling is studied. We divide the area of 26.3 km × 33.5 km into 26 × 33 coordinates with each coordinate of 1 km × 1 km. The base station is located at coordinate (15, 19) with a communication range of 500 m. We then calculate the frequency of the FPT samples of taxis starting from each coordinate to the base station to derive the statistic CDF of FPT for the Beijing taxi trajectories. The statistics of such CDF of FPT in Beijing is relatively coarse grained in space, this is because we used enough data from each cell to guarantee the validity. CDF of FPT for scenarios where more than one base station located can also be drawn with the same method.

Note that FPT for vehicle to vehicle data routing can also be defined as the time it takes for a mobile node to first meet the destination mobile. The CDF of FPT for mobiles following the random walk model can be found in Ref. [29], and can also be utilized in the following utility calculation of DAWN. In this case, DAWN can be easily extended to scenarios where destinations are mobiles rather than static base stations.

3.3   DAWN

DAWN models DTN routing as a utility-based resource allocation problem. At a specific time, all the copies of a specific packet compose a packet company $p_{(s, t_0)}$. Upon any of the copies in the data company arriving at the base stations, the packet is considered delivered. The DAWN algorithm executes when nodes are within each others' transmission range. Nodes then make local decisions to replicate packets to all the other nodes within range. DAWN remedies the impact of density heterogeneity and capacity constraint and improves the packet delivery probability by taking careful considerations on the following two aspects for each node within each others' transmission range at each time slot, namely the quota to replicate, and the selection of replication.

3.3.1   How many packets to replicate

Since the capacity within transmission range is constrained, each node is assigned with a certain quota to transmit packets according to the node density within range. As stated above, the optimal input K is decided

by the channel. Given K, each node in the range is assigned with $\dfrac{K}{\lambda_l(t)}$ input, in which $\lambda_l(t)$ indicates the density, that is the number of the mobile nodes within transmission range of mobile node l at time t. Since the mobile node density is slowly varying with time, this number can be estimated by the history encounters of the node. Each node may learn $\lambda_l(t)$ by counting the source nodes it has communicated with. Local mobile node number is estimated by each node as the average of this number in history encounters. In order to guarantee the accuracy of density estimation, time window for the estimation should be carefully chosen according to the network density variation feature. Such time window can be optimized at each communication opportunity by minimizing the error between estimation and actual density.

When local density is low and the node is assigned with enough input, all the transfer requirements can be satisfied. In this case, the forward strategy is almost the same as Epidemic, which has been proved to be optimal in none capacity constraint situation. When local density increases and the assigned input is not enough for the node, each node will make decisions on which packets to replicate in order to improve the overall network performance.

3.3.2 Which packets to replicate

For most urban DTN applications, there exists a delay constraint T_{MAX}, beyond which packets are considered wasted. Therefore, the performance measurement to increase the delivery ratio of packets within deadline is more practical and fundamental. To make the replication decisions, DAWN introduces a utility value for each packet indicating the delivery probability of the packet within the delay constraint. And nodes always replicate the packets with highest utility gains in order to better utilize the limited capacity.

Definition 2 (Packet Utility) The utility value of the packet company $p_{(s,t_0)}$ at time t, denoted by $U_{(s,t_0)}^t$, is defined as the probability that after time t, if no further replication happens, at least one of the copies will reach the destination before the deadline.

Due to packet replication, the packet utility value is increasing with time. If at time τ, packet $p_{(s,t_0)}$ is replicated only by mobile node l, then the utility gain of packet $p_{(s,t_0)}$ due to this replication, defined as $\Delta U_{(s,t_0)}^{\tau,l}$, is as follows:

$$\Delta U_{(s,t_0)}^{\tau,l} = 1 - (1 - U_{(s,t_0)}^\tau)\overline{\Phi}_l(\overline{\tau})^{\lambda_l(\tau)} - U_{(s,t_0)}^\tau$$

$$= (1 - U_{(s,t_0)}^\tau)(1 - \overline{\Phi}_l(\overline{\tau})^{\lambda_l(\tau)}) \tag{1}$$

where $\overline{\Phi}_l(t) = 1 - \Phi_l(t)$ is the Complementary Cumulative Distribution Function (CCDF) of FPT for the location of mobile node l at time τ, and $\overline{\tau} = T_{\mathrm{MAX}} - \tau + t_0$ is the remaining time. Notice that the function $\Phi_l(t)$ here should be the corresponding CDF of FPT that address the scenario, which means different $\Phi_l(t)$ should be used if the number and positions of the base stations change. DAWN can also be extended to the situation where the destinations are mobile nodes rather than static base stations given the CDF of FPT of the relays and the destinations.

$U_{(s,t_0)}^t$ is a global parameter indicating the utility value of packet company $p_{(s,t_0)}$ at time t. In practice, such global parameter is difficult to derive since it needs to spread information of each packet to the entire network. So DAWN introduces a distributed way to estimate the utility value of each packet. At each replication, the packet utility value is updated by both the source node and the intermediate nodes as the original packet utility value $\hat{U}_{(s,t_0)}^t$ (which is known by the source node) pluses the $\Delta U_{(s,t_0)}^{t,l}$. Because local estimation loses the global picture, the estimated utility value $\hat{U}_{(s,t_0)}^t$ is upper bounded by $U_{(s,t_0)}^t$.

When network is dense and only part of the packets can be replicated, packets that own higher utility gain will be transmitted with higher priority. Note that such utility gain estimation is not precise since we do not consider the global packet replication scheme. However it claims low communication and computing cost since it does not require any global information transmission.

Since it is adaptive to density changes in networks, DAWN can increase the delivery probability of packets within delay constraint in dynamic networks where capacity is constrained by successfully avoiding network congestion. Moreover, this algorithm is completely distributed. Neither center node nor information exchange is needed in the network to collect density information. Nodes only have to calculate the number of nodes in its communication range to estimate local node density and make forward decision. The pseudo code of DAWN is shown in Table 2. Simulations on Manhattan Grid Model and Beijing taxi trajectories show that DAWN outperforms all other traditional DTN routing protocols in the performance of packet delivery ratio and coverage within delay constraint.
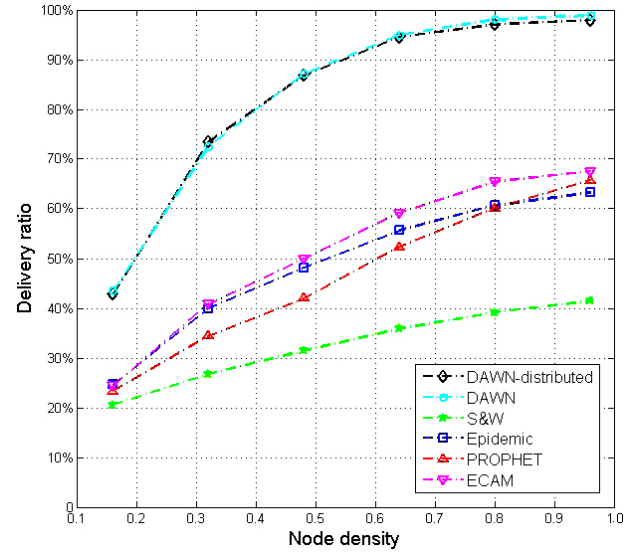
Table 2   Pseudo Code of DAWN.

Algorithm DAWN
For each node
1: update density estimation $\hat{\lambda}_l(t)$
2: calculate the assigned input $K_{\text{assigned}} = \frac{K}{\hat{\lambda}_l(t)}$
3: calculate self-required input K_{require}
4: rank packets according to $\Delta U^{t,l}_{(s,t_0)}$ in decreasing order,
5:        IF $K_{\text{require}} < K_{\text{assigned}}$
6:            all input requirements be satisfied
7:        ELSE
8:            transfer K_{assigned} packets successively
9:        END
10: update utility value $U^t_{(s,t_0)}$ for each packet
11: END

Fig. 3   Delivery ratio v.s. node density in Manhattan Grid simulation.

4   Simulations

4.1   The Manhattan Grid simulations

To analyze the performance of DAWN, we first simulate on a 25×25 Manhattan Grids, which is considered as a proper abstraction for the metropolitan areas. In the Manhattan Grid Model, each mobile generates packets according to a certain rate $\eta_s = 0.05$ packet per time slot. The time constraint of each packet is 100 slots. A base station locates in the center of the network, and the communication range is assumed to be zero, which means nodes can only communicate when they are at the same grid point. In our simulation, four other traditional DTN routing algorithms, namely Epidemic, S&W, PROPHET and ECAM, are compared with the DAWN algorithm. Furthermore, in DAWN, two approaches which respectively achieve packet utility value in a global manner and a distributed estimation manner are both considered.

Figure 3 compares the delivery ratio within time constraint of different routing algorithms in terms of node density changing. It shows that DAWN outperforms all other protocols with considering of local network capacity constraint. As is shown, the delivery ratio traces of all algorithms increase when node density increases, and the delivery ratio of DAWN is about 20% higher than that of Epidemic, PROPHET, ECAM and S&W when node density is low. DAWN performs even better with high node density, and about 98% collected packets can be delivered to the base station. It suggests that DAWN takes full advantage of network capacity and also efficiently avoids network congestion as network becomes dense. Meanwhile,

the performance of distributed global utility estimation method is compared with that of the global utility aware method, and the results show that they have approximate performance. It means that our distributed estimation method is feasible to estimate the utility value.

To achieve a global view of the coverage of different routing schemes, we calculate the delivery ratio of the packets generated at each grid point and count the percentage of grids that enjoy a delivery ratio of more than 50%, as is shown in Fig. 4. From these results we notice that DAWN not only enjoys higher delivery ratio, but also covers larger areas with high delivery ratio than the other routing schemes. By introducing FPT into the utility function, DAWN gives packets generated far from the base station higher probability to be replicated in the network than other schemes. This makes sense because comparing with packets generated near by, packets generated far away may need more time to disseminate in the network and finally reach the base station.

4.2   Taxi trajectory based simulations

Based on the Beijing taxi trajectory database, which contains 30-day GPS records from May 1st, 2009 till May 30th, 2009 of 27 848 taxis in Beijing, DAWN is simulated to compare with other routing algorithms. The trajectories from May 16th till May 30th are utilized to study the FPT of the taxis. And the following simulations are conducted using trajectories from May 1st till May 15th, after invalid traces being
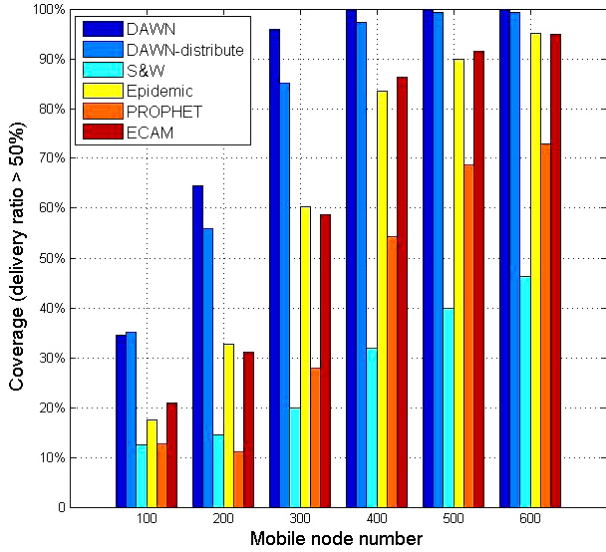
Fig. 4   Percentage of grids that attain delivery ratio > 50% in Manhattan Grid simulation.

removed, and the area within the fifth-ring road of Beijing is considered.

In the simulation, a base station is set at the location of the center of the Beijing city. The communication range for each taxi is 100 meters, and that of the base station is 1000 meters, typical for V2V communication. Taxis generate packets according to a certain rate $\eta_s = 0.05$ packet per minute. The time constraint of each packet is 250 minutes.

As is shown in Fig. 5, the delivery ratio of all routing algorithms in terms of the number of taxis increases when the number of taxis increases, and DAWN shows apparent advantage over other routing schemes. Its delivery ratio is about 15% higher than that of Epidemic and PROPHET, and about 40% higher than that of S&W and ECAM. Since this simulation utilizes authentic trajectories, PROPHET obtains better performance than the simulations on Manhattan Grids as the link prediction comes into play. Meanwhile, ECAM suffers performance decay as the network becomes scalable and packets can hardly disseminate sufficiently before the exponential rule in ECAM stops them from transferring. It also shows that the delivery ratio of DAWN can reach about 70% when using only 3000 taxis in a 881 km² city area. Such results suggest that using DAWN can effectively collect and transmit data in urban DTN.

To show the coverage property of DAWN, we divide the area of 26.3 km × 33.5 km into 263 × 335 blocks with each block of 100 m × 100 m. Figure 6 shows the percentage of blocks that enjoy a delivery ratio
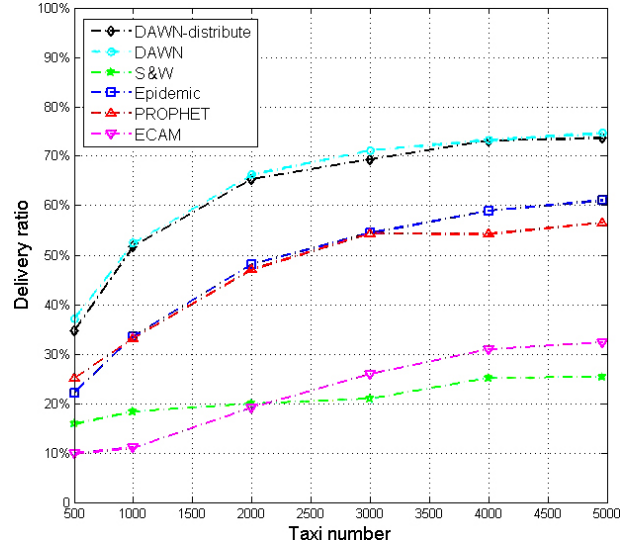

Fig. 5   Delivery ratio v.s. taxi number in taxi trajectory simulation (1 base station).
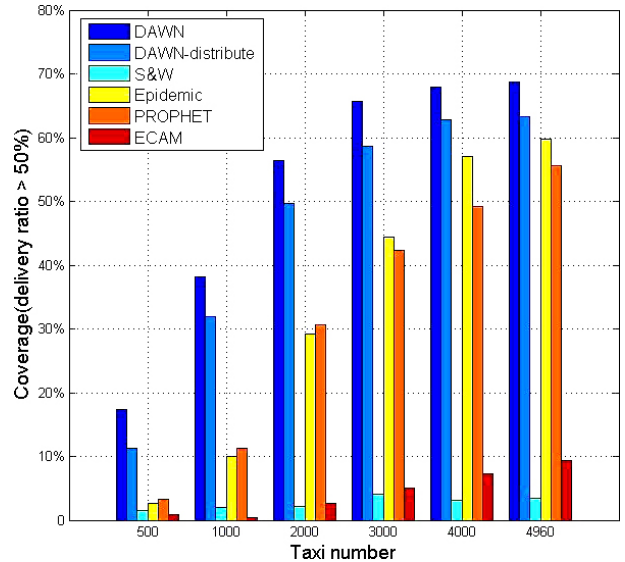

Fig. 6   Percentage of blocks that attain delivery ratio > 50% (1 base station).

of more than 50%. From the results we can see that DAWN enjoys high delivery ratio in more than 60% of the area of Beijing when using only 3000 taxis, while Epidemic and PROPHET mainly collect packets near the base station and S&W and ECAM achieve low delivery ratio in the whole area of Beijing. Such superiority guarantees the large portion of the urban area can enjoy acceptable delivery ratio of the messages collected.

In practical applications, more than one base station will be deployed in the network to increase the delivery ratio and decrease delay. DAWN can be easily extended to the situation where more than one base station is

located by simply utilizing the CDF of FPT for multiple base stations when calculating the utility incremental value. We further deploy 4 base stations, respectively located at $(70, 80)$, $(70, 240)$, $(200, 80)$, $(200, 240)$, and decrease the communication range of each base station to 500 m, which is half of that of the simulations with only one base station. Figures 7 and 8 respectively show the delivery ratio within time constraint in terms of taxi numbers and the percentage of blocks that enjoy a delivery ratio of more than 50%. From the simulation results, we can see that the delivery ratio of all the routing algorithms increase because of the extra deployment of base stations, and DAWN still outperforms all other schemes. The delivery ratio reaches 75% with only 3000 taxis and almost 80% with 4960 taxis, which are nearly 20% higher than that of Epidemic and PROPHET and 45% higher than that of S&W and ECAM. DAWN also enjoys high delivery ratio in nearly 70% of the area of Beijing when using only 3000 taxis, when other routing schemes mainly cover the areas around the base stations. With better allocation of the base stations, for example, to locate the base stations at the spots where more taxis pass by, performance can be further improved.

Figures 9 and 10 respectively show the delivery ratio within time constraint in terms of taxi numbers and the percentage of blocks that enjoy a delivery ratio of more than 50% when 4 base stations are located at the top 4 points with the highest taxi passing rate, namely $(128, 160)$, $(138, 160)$, $(139, 181)$, and $(128, 170)$. From the results we can see that the delivery ratio of DAWN is more than 80% with 3000 taxis, and the coverage of DAWN improves to more than
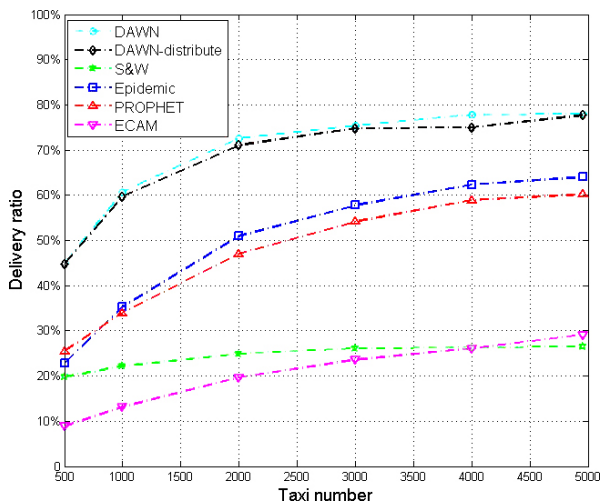

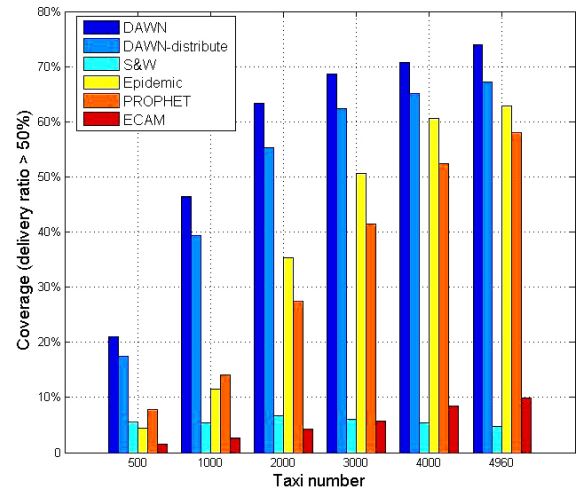**Fig. 7   Delivery ratio v.s. taxi number in taxi trajectory simulation (4 base stations).**

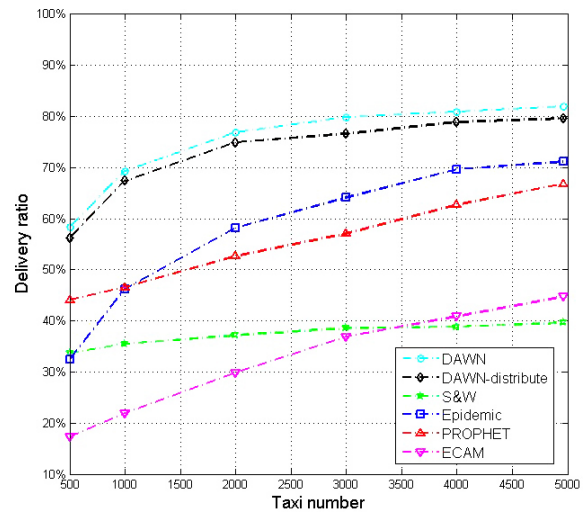**Fig. 8   Percentage of blocks that attain delivery ratio $> 50\%$ (4 base stations).**

Fig. 9   Delivery ratio v.s. taxi number in taxi trajectory simulation (with better base station locations).

70%. Such results further prove the effectiveness of DAWN in large scale DTN.

5   Conclusions

In this paper, we firstly propose a model that fully manifests the special features of vehicular DTN with consideration of the limited local channel capacity caused by wireless interference. We further propose a heuristic and accurate network performance measurement for the large scale DTN which evaluates the network throughput within deadline. A routing scheme for DTN, called DAWN is then introduced to improve the packet delivery ratio within deadline where network capacity is constraint. The core idea of DAWN is to adjust forward strategy and protocol parameters based on local node density with the awareness of local channel capacity. In DAWN, a utility
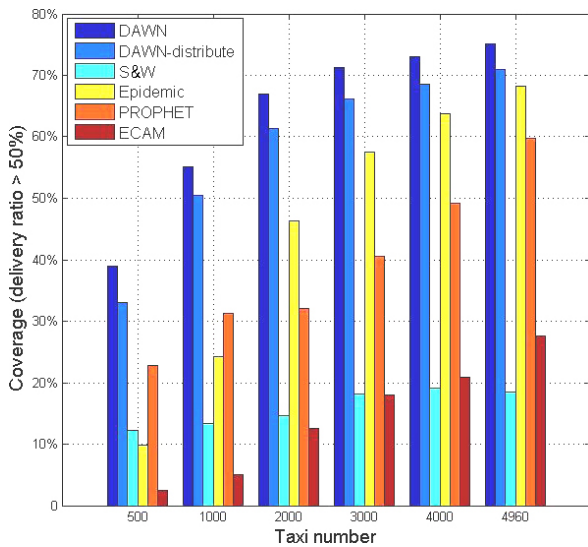
Fig. 10 Percentage of blocks that attain delivery ratio >50% (with better base station locations).

value suggesting the delivery probability of the packets within time constraint is maintained for each packet by each mobile node. Mobile nodes in each cell decide how many packets to broadcast and which packet to broadcast independently based on information of local density and the packet utility gain. Simulations on both Manhattan Grids and Beijing taxi trajectory database show that DAWN outperforms all other protocols in terms of delivery ratio within deadline. The delivery ratio of DAWN is about 35% higher than those of other routing protocols in Manhattan Grids, and about 20% higher in Beijing taxi trajectory-based simulation with only one base station. The delivery ratio further increases when more base stations are deployed and better located. In simulations based on Beijing taxi trajectories, the delivery ratio of DAWN reaches 70% with only 3000 taxis and one base station, and 75% with 4 base stations, and reaches 80% when the 4 base stations are carefully located at the spots where more taxis pass by. Simulation results also show that DAWN enjoys better fairness across the coverage area, while other routing algorithms only attain acceptable delivery ratio near the base stations. The percentage of blocks that reach a delivery ratio of over 50% is over 60% when using only 3000 taxis and one base station, the percentage boosts to 68% when 4 base stations are deployed, and 72% when the base stations are located at spots where more taxis pass by. Such performance metrics suggest that DAWN may perform quite well in large scale vehicular DTN deployments.

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Qiao Fu received her BS degree in Electronic Engineering from Tsinghua University in 2010. She is currently a Master candidate at Department of Electronic Engineering, Tsinghua University. Her research interests include MAC and network layer algorithms in mobile wireless sensor networks.

Bhaskar Krishnamachari received his BEng in Electrical Engineering at The Cooper Union, New York, in 1998, and his MS and PhD degrees from Cornell University in 1999 and 2002 respectively. He is currently an Associate Professor and a Ming Hsieh Faculty Fellow in the Department of Electrical Engineering at the University of Southern California's Viterbi School of Engineering. His primary research interest is in the design and analysis of algorithms and protocols for next-generation wireless networks.

Lin Zhang received his BS degree in 1998, MS degree in 2001, PhD degree in 2006 all from Tsinghua University. He is currently an associate professor at Tsinghua University. His current research focuses on sensor networks, data and knowledge mining, and information theory. He is a co-author of more than 40 peer-reviewed technical papers and five U.S. or Chinese patents applications. Lin and his team were also the winner of IEEE/ACM SenSys 2010 Best Demo Awards. In 2010, he received Excellent Teaching Awards from Tsinghua University.