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A novel networking architecture for mobile content delivery in urban transport systems

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Abstract Today, the media content delivery in intermittent connected networks has become increasingly critical. This paper studies content exchange among mobile commuters in urban transport systems. Our work is inspired by two facts: (1) the commuters in urban transport systems tend to take regular routes to the same place every weekday and their paths exhibit a high degree of temporal and spatial regularities; (2) the rapid development of broadband wireless technologies such as IEEE 802.11n makes fast data transfer possible. We first propose a new disconnection-tolerant network infrastructure, which reinforces the connectivity of intermittent connected mobile commuters and uses store-and-forward routers to increase their encounter opportunity, and in turn achieves efficient media content delivery among them. Then a router-centric prediction method is designed to collect passengers' historical path information to determine the best delivery scheme. We evaluate the feasibility and the performance of the proposed infrastructure as well as the delivery scheme, using real data set from an urban transport system. The simulation results demonstrate the proposed system is highly practical in terms of the memory usage of routers and the maximum achievable data transfer rate.

Keywords Networking architecture · Mobile content delivery · Urban transport systems

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1 Introduction

Nowadays, people live in urban areas spend significant time on urban transport systems [1–3]. Most commuters carry mobile devices such as smart phones and portable computers, which are usually equipped with WiFi or Bluetooth. In such high-speed vehicle environments, data access through cellular networks is either costly or too low-speed (for instance, the ideal speed of 3G under driving environment is only 144 Kbps). As an alternative, short-range communications (SRC) provide a cheaper approach to transfer the content [4, 5] (e.g., news, video clips, music files) during the connection time of two devices. With SRC, two mobile devices can exchange and share contents when both are physically close enough to be in the communication range of each other. Apparently, SRC has many advantages over the traditional infrastructure-based solutions. First, it is infrastructureless and can still work when network infrastructure is unavailable or out of order; second, high bandwidth connection can be established between two devices using SRC. However, SRC usually forms a multi-hop intermittent-connected network with changing topology and there is no guarantee of an end-to-end connection between two mobile devices. Furthermore, the connection may last for such a short time, not long enough to finish transferring a media content file. As a result, to ensure effective content delivery in such an intermittent-connected network is indeed a challenge.

In urban transport systems, the connection between two commuters is rare and short, and commuters have limited control of the length of connection time [6, 7]. The routing between mobile devices in an urban transport system can not be solved by only using the opportunistic method [8, 9], as it is a large-scale network and commuters are distributed over the whole city. Therefore, media files may have to be retransmitted through several hops to the destination. On the other hand, most commuters have their own mobility schedule [10, 11] and their daily mobility patterns show great spatial–temporal correlations. It may incur many problems when predict-based routing schemes [12, 13] are used in such a network, as two devices are assumed to be connected only when both are on the same vehicle (bus or train) simultaneously. This condition is too rigid to meet in practice. As observed in [4], a commuter usually follows the same route day by day with however a slightly varying time schedule. So a commuter has less time of meetings with "familiar strangers" [14] than the number of his/her individual travels. For the above reasons, in this paper, we focus on leveraging co-route properties to enforce the connectivity between mobile commuters.

Our work is motivated by the following two facts. First, the wireless speed continues to increase rapidly. As a result, it is possible to transmit a great deal of data during the short time of a connection (tens of seconds) using broadband wireless access [15]. Second, on the one side, the commuters in urban transport systems tend to take regular routes to the same place every weekday and their paths show a high degree of temporal and spatial regularities. On the other side, the use of RFID cards for electronic payment has been introduced in many city transport networks for years [16, 17], which is designed for easy payment and faster movement through ticket check-points. More importantly, it allows us to monitor the commuters' movement, and thus their regularity in routes can be recorded in the system [4, 18]. We aim to propose a feasibility network infrastructure with three design goals: low cost, high bandwidth and disconnection-tolerant. Our proposed network infrastructure is a clean-slate approach and seamlessly complementary to cellular data services.

Our contributions mainly include (1) a Novel Cache-and-Forward Architecture (NCFA) for media content delivery in public transport systems and (2) Co-Route-based Media content Forwarding scheme (CRMF) for multi-hop content sharing in NCFA. In NCFA, routers with high speed wireless access and large storage are deployed on every train/bus and all stations. There are two kinds of routers, station routers (deployed at each station) and vehicle routers (installed inside each bus/train). Those high-performance routers can enforce the connectivity of commuters all over the city grid. A commuter can first deliver the media files to vehicle routers; then through the interactive exchange between the vehicle routers and the station routers, the content can be finally forwarded to another commuter as the destination by vehicle routers. A vehicle router (or a station router) can find the next right station router (or a vehicle router) to forward data based on the historical path information of commuters in urban transport systems. Our proposed forwarding scheme CRMF leverages co-route information, which helps the current router to find intermediate routes with the highest probability to the destination. A simple example is illustrated in Fig. 1. Alice takes regular route from station A to station D at her usual time. During her journey, she wants to deliver a particular media file to her friends Bob and Carol. Bob is another commuter who travels to work along the same train line as Alice does, but he is often half an hour later than Alice. Although Bob and Alice take the same bus/train route, there is no chance for them to meet each other and thus SRC can never happen between their devices. On the other hand, Carol takes her usual route from station E to F at the same time as Alice but traveling on different lines, so they cannot encounter each other during their journeys. However, after the vehicle router receives content copy from Alice at Station B, it can deliver the content to station C, which is the intersection of the residual route of Alice and the regular route of Carol. As a result, Carol can finally get the content from the vehicle router, which gets the content from the station router in station C at the sojourn time. For the same reason, the vehicle router can deliver the content to any stations in the intersection set of the residual route of Alice and the regular route of Bob to guarantee that Bob will finally get the content copy.

The remainder of this paper is organized as follows. In Sect. 2, we introduce some related work. Section 3 describes the system model and the architecture of NCFA in detail, and explains how to record the co-route pattern. Section 4 proposes two versions of CRMF: a basic version and an enhanced version. Section 5 evaluates the performance of proposed schemes, and presents the simulation results. Finally, conclusions are drawn in Sect. 6.

2 Background and related work

Content delivery in multi-hop intermittent connected networks has been studied in the past few years. A number of routing proposals focus on taking advantage

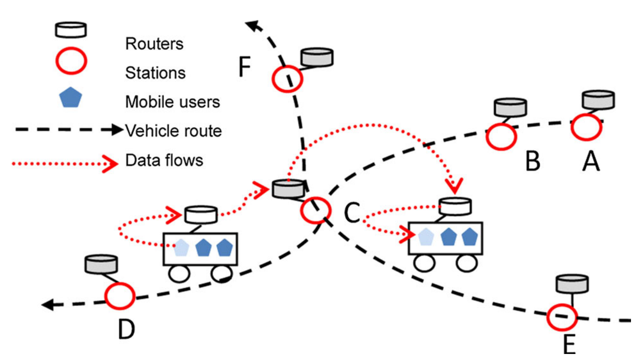


Fig. 1 System model and architecture

of opportunistic connections among mobile nodes to spread packets in a multi-hop way [8, 9, 19]. But it is impossible to use opportunistic method in a large scale network to deliver the media content from the source node to the destination node at sometimes and the delay may be very long. Knowledge about human connectivity and social interaction has also been employed to improve the routing performance in multi-hop DTNs [12, 13, 20]. However, most of the former studies require a lot of long connections among mobile nodes or they do not consider media content delivery. BlueTorrent [21] proposes a way to effectively share media content in spite of short link duration; it divides content into a number of small pieces, and mobile users can exchange whatever pieces that are available. BlueTorrent is actually a peer-to-peer approach, and it only performs in a $100 \times 5\ \mathrm{m}^2$ small moving area, so it is not suited for large scale networks due to the sparse distribution of mobile users and the limited storage of mobile devices. In this paper, we focus on the media content sharing or delivery in large scale urban transport systems. The moving area of mobile devices are no longer restricted to a campus or grid area, but over the whole city.

A large number of work deal with the media content sharing in the intermittent connected networks. In [22], storages equipped with Bluetooth and WiFi support, which are called bluespots, are placed on all buses in the public transportation systems. Passengers can get their favorite media contents from the bluespots, and the bluespots can renew their contents according to passengers' interests when the bus arrives at a bus stop. Bluespots is only a content distribution system and can not transfer media content between mobile devices/passengers. City commuters often stay together on the same bus or train for a large amount of time, so they could share content with fellow commuters through mobile device equipped with wireless technology [18]. This kind of system provides an approach for data sharing for mobile users in public transportation systems. Historical collocation and social information can be used to determine the best content source. The approach in [4] does not focus on the routing or multi-hop delivery, but on the behavior of pair-wise interactions. Although the above approaches could be applied to large scale network, they only allow for single hop interactions.

Other approaches are designed to reinforce connectivity on demand to deal with disconnection or "disruptions". Cache-and-Forward (CNF) network infrastructure [23], a clean-slate architecture, has been optimized for mobile content delivery. While the CNF network uses large storage routers to enforce the connectivity of mobile users and is suitable for large scale networks, it is not disconnection-tolerant. In [24], Seth proposes a network architecture for disconnected kiosks in developing countries, where vehicles serve as the mechanical backhaul to move data from kiosks to the Internet gateways. Compared to cable and cellular network, the proposed architecture in [24] provides a low-cost and reliable connectivity to rural kiosks; however it is applied only to the kiosks in rural areas. In [25], the authors propose the use of wireless nodes called throwboxes, which act as relays, creating additional contact opportunities for the bus in the UMass transport systems. By creating a greater number of contact opportunities, the performance of the network is consequently improved. However, throwboxes aim to deal with the intermittent connectivity of moving vehicles rather than the mobile commuters in the urban transport systems. Based on the historical trajectories of passengers, [26] proposes a co-route delivery scheme, which enables packets to be delivered by mobile vehicles. However, it neglects the spatial distribution of commuter flows and redundant copies of a packet are sent out, which results in a waste both in bandwidth and storage.

In this paper, our goal is to propose a network structure for media content delivery between mobile users in urban transport environment, where connection time is rather short and usually uncontrollable. Our proposed architecture is disconnection-tolerant, low cost and appropriate for content sharing in large scale networks. The most unique feature of NCFA is that commuter flows are spatially and temporally relevant. Based on the historical path information of commuters, on the one hand, a vehicle router (or a station router) can find the next station router (or a vehicle router) to forward media files; on the other hand, we can estimate the number of the packets to be transferred at each station to achieve load balancing. Thus in our forwarding scheme, we take advantage of these and install routers on vehicles, which are used to enforce the connectivity of commuters. Different from [26], in the forwarding scheme for station routers, we study the spatial distribution of commuter flows and estimate the number of the packets to be transferred at a certain period of time. We firstly ensure the delivery of the packets whose destination is a regular commuter of the current station, to balance the traffic and reduce the data rate in peak hours. As for the forwarding scheme for station routers, a record is kept for every packet which has to be transferred to other routes, to ensure that it is transferred to a route only once. The proposed delivery scheme, based on co-route mobility patterns of both mobile commuters and public transport vehicles, achieves much better performance. In addition, our work utilizes the real-world dataset in transport systems for the performance evaluation.

3 System model and architecture

In this section, we first introduce the proposed NCFA architecture, which provides reliable hop-to-hop transport of media files for mobile users with intermittent connections. We then describe how co-route patterns are recorded over time and leveraged to estimate future co-route pattern.

3.1 NCFA network model

The NCFA network model is depicted in Fig. 1. Routers with high speed wireless access and large storage are deployed inside vehicles and at stations. Media files are first transferred from a source commuter to the current vehicle router. Through data exchange among routers, media files can be finally forwarded to the destination router and eventually arrive to the destination commuter. Each station router needs one wireless interface, which uses high-speed wireless technologies. In fact, Airgo Networks have already announced their new AGN100-WiFi chipset utilizing a multiple antenna system extending WiFi data rate to 108 Mbps several years ago. Vehicle routers are slightly different from the station routers. On the one side, they require a high-speed WiFi network card, as the main card for communications with station routers. On the other side, several additional interfaces, such as Bluetooth port and/or WiFi port, are needed for communications with commuters, similar to the Bluespot in [22]. As a result, it is possible for mobile devices to exchange media content with vehicle routers at the same time. In NCFA, station routers act like the transit depots, which receive media files from one bus router and relay them to the other bus router. Vehicle routers have two functions: (1) serve as the data mule and move media files from one station to the other station, and (2) work as the data center for commuters to send/receive certain media files to/from.

The delivery schemes we will propose in the next sections are based on the following assumptions:

– The data transfer between commuters and routers is triggered by mobile commuters.
– The communications between two routers are interference limited and data transfer speed will not be too much affected.
– The sojourn time is long enough to transfer media files. Technologies in Cabernet [15] have reduced the connection time to 400 ms between open wireless access point (AP) and high speed moving vehicles. From our own experience, the sojourn time is usually from 10 s to several minutes (especially in the peak hours), so the amount of media content which can be transferred between two routers during the sojourn time can reach as much as hundreds of megabytes. From [4], two mobile devices only take 2–3 minutes to transfer 5 MB media files while using Bluetooth technology on a busy train. As a result, we can assume that commuters have enough time to transfer/retrieve the media content to/from vehicle routers.

3.2 Co-route pattern

From the above analysis, NCFA network architecture is designed to enable media content delivery between mobile commuters. Delivery schemes will be proposed for NCFA so as to limit the copies of media content stored inside the network. The design goal is to achieve a high delivery performance while retaining a low cost. As we have mentioned before, city commuters often follow regular routes day by day, they often get on a vehicle at one station and get out at the other station. As a result, if vehicle routers forward media files to those stations between the start station and the end station of a commuter, the media file delivery probability to this commuter would be much higher than forwarding to other stations. The relationship among commuters and stations is studied in this paper and we propose that a router only forwards content copies to those routers which have higher contact probability with destination commuters.

To perform this scheme, each router must know the associated forwarding metric for each destination commuter. A simple technique to measure this forwarding metric is to keep a profile for regular commuters. Each vehicle router logs all its previous passengers, and records the mean frequency (the number of traveling per month) for each passenger. The higher the mean frequency, the greater the likelihood the passenger takes this vehicle. However, this metric is less informative since the spatial regularity is ignored. In our approach, the mean frequency of passengers is kept separately for each segment in a certain vehicle route. That is, we divide the vehicle route into several segments (usually the number of stations on this route). All segments belonging to a certain commuter's journey must keep the mean frequency of the commuter. All the vehicles on the vehicle route keep a record of regular commuters who are divided by segments. This detailed profile of the passengers mean frequency is kept in the form of vehicle profile, and all vehicles keep one copy of their vehicle profiles. Each station router also keeps a station profile for its regular passengers. This station profile can be obtained directly from vehicle profiles. Each station router first gets vehicle profiles from the vehicle passing by, then extracts all its regular passengers from its profiles, and finally records the mean frequency for each passenger and keeps detailed information in the form of the station profile.

4 Co-route based forwarding algorithms

In this section, we describe co-route distributed forwarding strategies. Basically, historical co-route information is used to predict the contact opportunity. We illustrate how these predictions can further be used by forwarding process to maximize the chance of delivery rate and reduce the delay and the number of media content copies. It is assumed that both the vehicle and the station routers have already collected one copy of their own regular commuters profiles. We will introduce two delivery algorithms, referred to as the basic scheme and the enhanced scheme, respectively. The basic scheme considers no spatial distribution of commuter flow, while the enhanced scheme takes the spatial distribution into consideration and greatly reduces the delivery delay and the number of media content copies storing in the network.

4.1 Basic forwarding scheme for vehicle routers

After a commuter gets into a urban transport system, if he/she wants to deliver a media file to one of his/her friends, he/she first delivers one copy of the media file to the current vehicle router on which he/she stays. As soon as the vehicle router receives the file, it transmits the media files to its own delivery queue (DQ). When the vehicle runs along its route and stops at a station, the vehicle router has to find out exactly which file in the DQ can be transmitted to the current station using the following algorithm.

According to the destination commuter of the media file, all media files in the vehicle router DQ are classified into three categories first:

- RC: the destination commuter of this kind of media files is a regular commuter of the current station.
- RF: the destination commuter of this kind of media files is a regular commuter of station routers in the following route.
- NRCF: the destination commuter of this kind of media files is neither a regular commuter of the current station nor any station routers in the following route.

Then RF-type medial files have to be transferred to some station routers in the following route other than the current station router, otherwise retransmission will be incurred. As a result, the vehicle router only forwards RC-type and NRCF-type media files to the current station router. After the delivery, RC-type and NRCF-type media files need to be removed from the DQ of the vehicle router. Detailed procedures are outlined in Algorithm 1. The vehicle stops at station i, and p denotes media files in the vehicle router's DQ.

Algorithm 1 Forwarding Scheme for Vehicle Routers

Parameter: $B[i][\,]$ stores the regular commuters for the ith station in the vehicle route in the vehicle profile; $S[i]$ is the regular commuter of the current station i.

Sort Phase for Basic Scheme:

for all $p \in DQ$ **do**
  if $p \text{->} destination \in S[\,]$ **then**
    $p \in RC$; **break**;
  end if
  for $k = i + 1; k < ROUTELENGTH; k++$ **do**
    if $p \text{->} destination \in B[k][\,]$ **then**
      $p \in RF$; **break**;
    end if
  end for
  if $p \notin RC$ **and** $p \notin RF$ **then**
    $p \in NRCF$; **break**;
  end if
end for

Sort and Calculate Phase for Enhanced Scheme:

for all $p \in DQ$ **do**
  if $p \text{->} destination \in S[\,](assuming B[i][\,])$
  and $\notin \forall_{i<k\leq ROUTELENGTH} B[k][\,]$ **then**
    $p \in ROC$; **break**;
  else
    $p \in NROC$; **break**;
  end if
end for

$packetNext = \sum_{i\leq k\leq ROUGHLENGTH} \mu_{r,n,k} \times P_k$

$packetT? = Num_{ROC} : (\frac{packetGot+packetNext}{rStation})$

4.2 Enhanced forwarding scheme for vehicle routers

While using the basic scheme, we find that the amount of data transfers between vehicles and some stations are extremely large at a single time. This results from the spatial distribution of commuter flows. In other words, more people pass through some particular stations (referred to as hot stations, or HSs) than other common stations. As a result, more media files will be transferred to those stations at a single time and the link between vehicle routers and station routers could become the bottleneck since the connection time is relatively short and the wireless rate is limited.

The enhanced scheme is designed to balance the number of media files to be transferred in the whole route. The proper number of media files delivered in the current station is calculated and the proper packets which would not affect the success delivery rate and the delay time are selected. By using the enhanced method, we can reduce the number of media files transferred between the vehicle routers and station routers at a HS at a single time. At the same time, we can also relieve the maximum storage capacity of those HSs.

We divide all the packets in the DQ of the vehicle routers into two classes. We note that a packet may have more than one destinations, hence we denote those whose destination is a regular commuter of the current station but not a regular commuter of any station in the following route, as regular commuter only for current station (ROC) packets, and non-ROC (NROC) packets otherwise. The main idea of the enhanced scheme is to firstly ensure the delivery of the ROC packets and part of NROC packets are selected to be transferred to the current station, in order to balance the traffic. In the enhanced scheme, the vehicle routers first compute the number of packets that should be transferred to the current station. Let's first see some definitions: i denotes the current station. *packetT* is the number of packets which have to been transferred to the current station. *packetGot* is the number of packets that already exist in the DQ. *rStation* is the number of station in the following route. Num_{ROC} is the number of packets which belong to the first class, *packetNext* is the number of packets which will be added to the vehicle DQ in the following route. We can roughly obtain the value of *packetNext* as

$$packetNext = \sum_{i \le k \le ROUGHLENGTH} N_{r,n,k} \times P_k$$

where $N_{r,n,k}$ is the number of people getting on board nth vehicle at the kth station in the route r; we assume that the number of people getting on board the nth vehicle at the kth station in the route r is normally distributed $X \sim N(\mu_{r,n,k}, \sigma^2_{r,n,k})$. In this paper, we use $N_{r,n,k}$ to represent $\mu_{r,n,k}$. P_k represents the probability that those commuters deliver a packet to the vehicle routers. From the above, *packetNext* is a proportion function of the people getting on board the vehicle in the following route. In all, the value of *packetT* can be obtained as

$$packetT = max\left\{Num_{ROC}, \left(\frac{packetGot + packetNext}{rStation}\right)\right\}$$

In the enhanced scheme, we have to transfer all the ROC packets the station. If the Num_{ROC} is less than $(packetGot + packetNext)/rStation)$, there is a need to select $((packetGot + packetNext)/rStation) - Num_{ROC})$ packets in the second class to deliver to the current station.

If the media files have not been delivered during the whole route, a copy of files will be forwarded to the last station router. A more formalized expression of the vehicle router enhanced forwarding scheme is shown in Algorithm 1.

4.3 Forwarding scheme for station routers

As long as station routers receive the packets from the vehicle routers, those packets are transferred to the delivery queue (DQ) of the station routers. There are two kinds of packets in the DQ of station routers: for the first kind, the packets do not have to be transferred to other route and can be directly transferred (DT) to the vehicle on which the destination node is taking; for the second kind, as the packets' destination nodes do not pass by the station, the packets have to be retransmitted (RT) to the other vehicle routers. For the DT packets, the station router only checks whether the destination node is on the current vehicle route, if so, it transfers the packets to the vehicle routers. We fix that the vehicle router will first transfer a list of its current passengers to the station router when it parks at the station. In order to reduce the copies of media content in the network, we describe our packets-control mechanism for those RT packets at full length. Every packet keeps a record of the route it has been transferred to. When the vehicles park at the station, the station router first finds the RT packets. If a packet has not been transferred to the current vehicle route, it could be transferred to the vehicle router, and both copies of it (in the vehicle router or the station router) keep the record of the current vehicle route. Otherwise, the station router does not relay the packets to the vehicle router. By doing so, the maximum number of copies of a media file in the network can be calculated. There are at most $2^{ROUGHNUMBER} - 1$ copies for a certain media file in the whole network. The details of this station router forwarding scheme can be found in Algorithm 2.

Algorithm 2 Station Router Forwarding Scheme

Parameters: $p.proute[\,]$ represents the route packet p has been transferred to; $V.route$ denotes the current vehicle V's route; $T[\,]$ is the current commuter on the current vehicle.

for all $p \in$ DQ **do**
  if $V.route \in p.proute[\,]$ **then**
    forward the packet p to the vehicle;
  end if
  if $p \in$ DT **and** $p\text{->}destination \in T[\,]$ **then**
    forward the packet p to the vehicle;
    delete p from DQ;
  end if
end for

Our co-route based forwarding algorithms are distributed, and one motivation of them is to exploit resource conservative policy. Each router only needs to keep the record of local regular passengers, rather than the whole routing information and seasonal patterns of all passengers. More importantly, both the station routers and the vehicle routers only have to store a small portion of the media files, as a result, routers do not demand a large-size storage to store commuter information and temporary media data. Furthermore, the commuters keep no record of the social interactions, which helps to reduce the storage consumption and computational burden of their mobile devices.

5 Evaluation

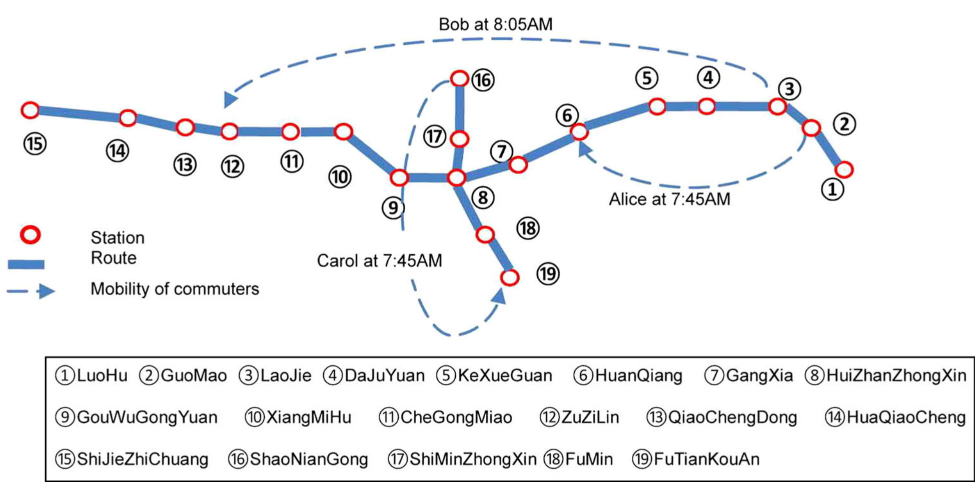
In this section, we evaluate the effectiveness of our proposed network structure through several experiments. We begin with a description of our data set. Then we describe the simulation methods and settings, and finally we discuss the results of the simulations in detail.

5.1 Dataset

In this paper, we use the real world topology and timetable of the ShenZhen subway [27]. The topology is shown in Fig. 2, from which we can see that, there are total 19 stations and 4 routes: route 1 is from LuoHu to ShiJieZhiChuang, route 2 is from ShiJieZhiChuang to LuoHu, route 3 is from ShaoNianGong to FuTianKouAn, and route 4 is from FuTianKouAn to ShaoNianGong. The first train for all the route is at 6:30 a.m. and the last train is at 23:00 p.m. For routes 1 and 2, the trains departure every 15 min. For routes 3 and 4, the trains departure every 20 min. The train timing strictly follows the operation timetable of ShenZhen subway.

We generate the passenger dataset according to the measurement statistics in [10], which record the daily mobility pattern of the city commuters, and analyze the temporal and spatial patterns of the human flows in ShenZhen urban transport systems. In Fig. 3, there are obvious daily peak hours, and the volume of traffic during peak hours occupies almost half that of the whole day. This is due to the daily life pattern that most commuters begin their work around 9 a.m. and go back home around 18 p.m. We intensively add the small variance to the regular traveling time. Each commuter either travels to/from work along her/his usual route, or takes the day off from work. In

Fig. 2 An example of the transport system



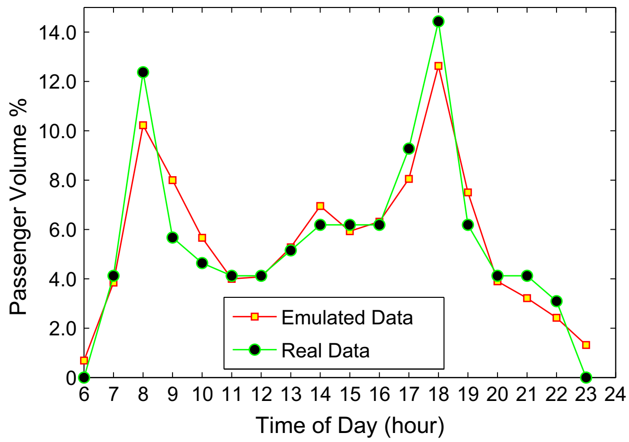


Fig. 3 Public transit temporal patterns in weekdays

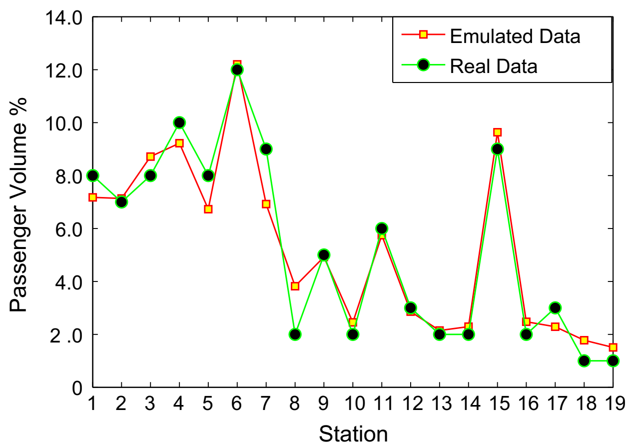


Fig. 4 Passenger volume distribution at different stations

Fig. 4, if we take a close look at the human flows across stations, it can be found that some stations are much more busy than others. In our emulated dataset, the source and destination stations for each regular commuter are determined by the check-in and check-out proportion of different stations as well as the daily connections for different stops. Regular traveling time for commuters is based on the public transit temporal patterns. It is noted that we only generate the dataset with temporal and spatial patterns of the human flows for weekdays.

5.2 Simulation methods and settings

The performance metrics used to evaluate a delay-tolerant network infrastructure include the successful delivery rate, the average delay time, and the average copies of packets. In this subsection, we compare the proposed algorithms with the optimal results of alteration version epidemic methods [8], which only rely on the connection of commuters and take no advantage of any additional communication resources. That is, their deployment cost should be smaller than that by using our proposed algorithms despite their relatively poor performance. We assume that two commuters are able to transfer media content when they are on the same vehicle simultaneously. Often the epidemic can achieve the best delivery rate and the shortest delivery delay. Nonetheless, the average copies of packets by using this scheme are very high. In our experiments, we choose the shortest path from the source node to the destination node, and only record the copies of packets in the shortest path as the optimal average copies of packets from the source to the destination. As a result, we obtain the optimal performance for epidemic (OPE) in each performance metric without the reinforce connectivity.

We set N commuters ($1000 \leq N \leq 5000$) in each experiment. The default number of commuters is 5000 in our simulation. The journey pattern of commuters complies with the patterns in [10]. The attendance rate means the probability that a commuter follows the same route day by day. In our experiments, the attendance rate varies from 0.1 to 0.8, and the default value is 0.6. In each simulation, we vary one of the two variable parameters and keep the other parameters default. At the beginning of the simulation, every node sends 20 media files to 20 randomly selected destination nodes. The total simulation time in each experiment is 5 days (120 h). A media file is considered to be successfully delivered if one of its copies has been sent to its destination before the end of the simulation.

5.3 Simulation results

5.3.1 Performance analysis

This subsection presents the simulation results of our proposed infrastructure-based solutions and compares our results to the best performance with none-enforcement of connections. How the simulation parameters affect the network performance is also discussed in this section.

First we study the performance in term of the delivery rate, the delay, and the buffer cost with varying attendance rates. Figure 5(a–c) shows that for all the three delivery methods, the success rate increases as the attendance rate increases. The higher the attendance rate is, the more likely the commuters possess similar seasonal movement patterns. When the attendance rate is low, that is to say commuters seldom use public transport or rarely keep to their job timetable, our proposed methods has no advantage over OPE. However, as the attendance rate increases to 30 %, our co-route approach can achieve 75 % successful rate, while the successful rate is surprisingly close to 0 using OPE. When the attendance rate is greater than 50 %, the successful rate of our proposed methods approaches 100 %, in contrast to 53 % using OPE at the 80 % attendance rate. The average delay decreases as the attendance rate increases, as the connection opportunity increases.

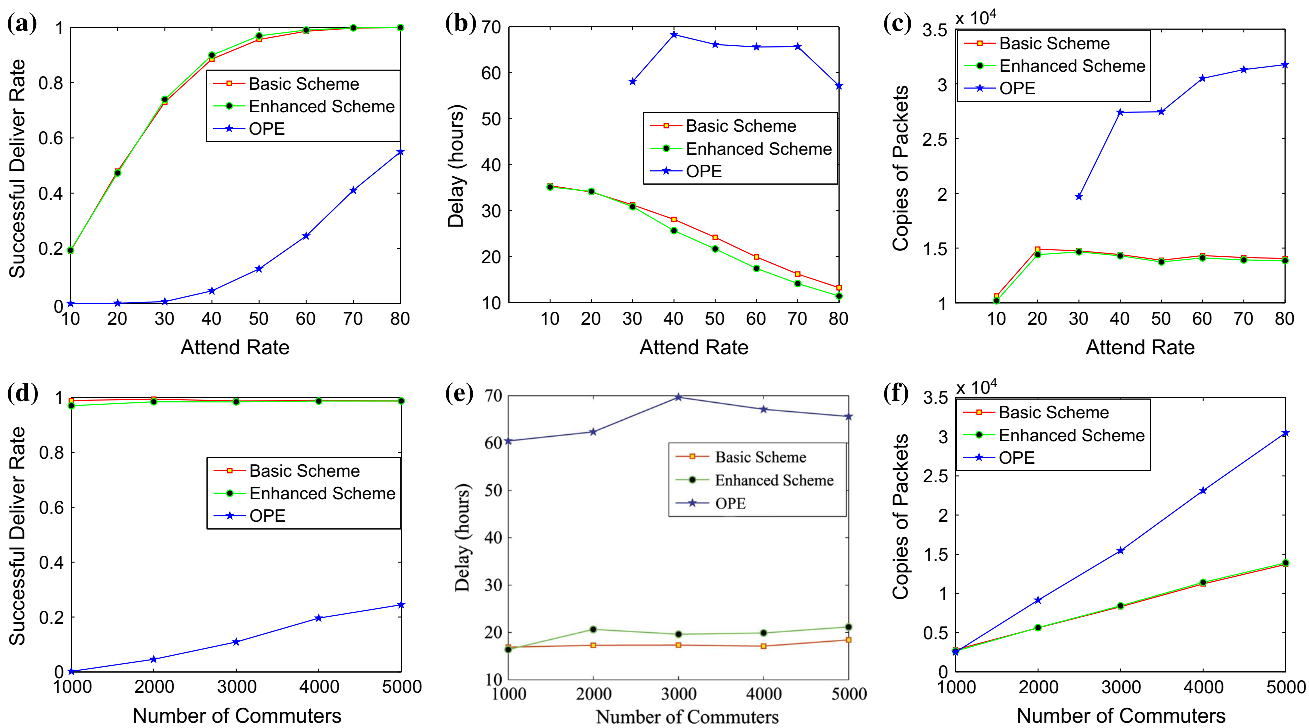


Fig. 5 Delivery rate, delay and buffer cost versus the number of commuters and the attendance rate

When the attendance rate achieves 80 %, the delay is only 1142 hours with our enhanced scheme and 13.24 for the basic scheme, which implies that Alice can receive the media file sent in the morning, on her route back home after work. And this is consistent with the temporal patterns of the human flows in Fig. 3, in which the time interval between two peaks is nearly 10 h. However, the delay for OPE is almost 60 h, as the connection between two specific commuters in the urban transport is rare and short. The average copies of packets for OPE is much higher than ours: the packets have to been transferred through several hops until reaching the destination since OPE only exploits the intermittent connection of commuters.

We also study the outcome caused by the increasing number of commuters in Fig. 5(d–f). We vary the number of commuters from 1000 to 5000, and observe that there is no significant change in term of delivery rate and average delay, and average copies of media contents also remain the same as our proposed schemes. However, for OPE, the delivery rate is increasing, as in a large-scale network, more commuters result in more connection opportunities. We can see from the above results, although the delivery rate increases with the increase of the contact opportunity, the minimum hop count also rises, which means the packets have to be retransmitted more hops before being delivered to the destination nodes. Our proposed schemes do not rely on the connection of mobile users but on the mobility pattern of individual commuters, thereby exhibiting better stability over other methods.

5.3.2 Feasibility analysis

The feasibility of our proposed network architecture is discussed in this subsection where we quantitatively evaluate the the maximum storage and the maximum data transfer rate required for routers. We set up our experiment as follows: 5000 commuters take the subway to/from work place with the attendance rate 60 %; once entering into the urban transport system, they deliver one copy of the media content to a randomly selected destination. As a result, there are about 6000 packets in a single day. The maximum data transfer rate between station routers and vehicle routers is obtained in a 5-day-length time frame. Furthermore, the maximum number of the copies of the media content in each station routers is also recorded at a single time slot in the 5-day-length experiment.

Figures 6 and 7 depict the performance of the basic scheme and the enhanced scheme respectively. During the transmission process, the packets can be divided into two categories: one includes those transferred from the vehicle routers to the station routers (BtoS), the other includes those transferred from station routers to the vehicle routers (StoB). And we study the maximum number of BtoS/StoB packets, as well as the maximum/average number of sum of all the packets at each station. It can be seen that the curve for StoB exhibits consistence with the fluctuation of BtoS.

From Fig. 6, we can see that two routers have to transfer 56 packets at most in a single time slot for the basic scheme,

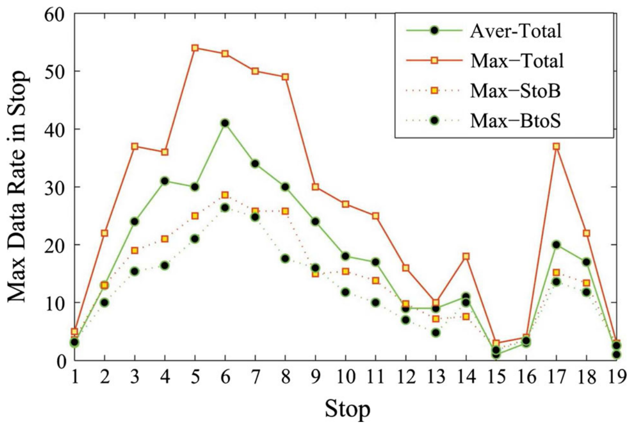


Fig. 6 Maximum data rate at each station with the basic scheme (the y-axis represents the number of packets during one stop)

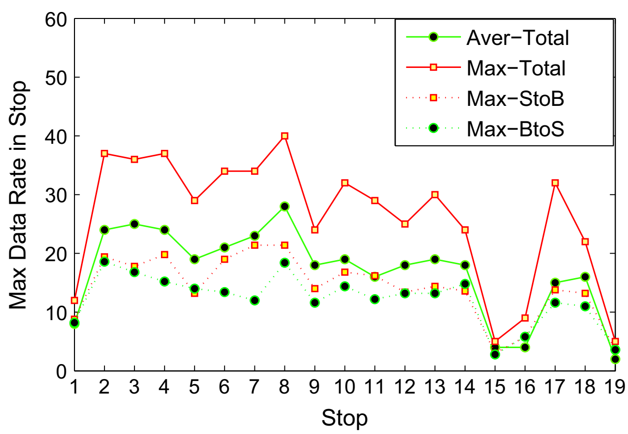


Fig. 7 Maximum data rate at each station with the enhanced scheme

while the maximum number of packets transferred in a single time slot is only 41 packets in the enhanced scheme, which is shown in Fig. 7. This indicates that the maximum transfer data rate is effectively reduced. As the connection time is short and the bandwidth between two WiFi devices is limited, if we assume the average size of each packets is 5M, the maximum data size transferred between two routers at one time slot is 205M with our enhanced scheme. On the other hand, we can see that the curves in Fig. 7 are smoother than those in Fig. 6, which validates the performance of our scheme in traffic balancing.

In Fig. 8, we set a larger variation for the maximum packets number between station routers in our basic scheme. Due to the higher flow of commuters at some stations, if the received packets are directly delivered to the next station as in the basic scheme, it is possible that some station routers could receive more packets than the others. In contrast, with our enhanced scheme, the curve of the maximum number of packets at each station is smooth, as it leads to a balanced distribution of the packets across stations. As a result, with the enhance scheme, we can reduce the maximum buffer size at

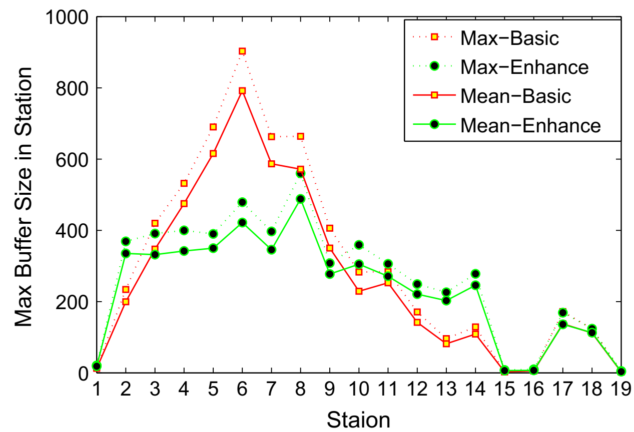


Fig. 8 Max required buffer size for each station (the y-axis represents the number of packets stored in the station routers)

the station router from 875 to 546 (noted that there are 4 station routers requring buffer size more than 600 with the basic scheme but none station requires buffer size more than 600 with the enhanced scheme). If we assume the average size of each packet is 5M, we can derive that the maximum required buffer size is 2730M, which is set at station 8. And accordingly, the maximum required buffer size for each station can be computed in this way. The fact that the maximum buffer size is <10 % of the packets transferred in a single day implies that, if 20,000 packets with the size of 5M are transferred everyday, the maximum storage size required for station routers is <10G. We capitalize that our proposed delivery scheme is distributed and as a result, and additional routes will not change the maximum data rate and the maximum buffer size.

6 Conclusion

In this paper, we propose a novel cache-and-forward network structure for media content delivery in urban transport systems. The proposed network architecture is a clean-slate approach and seamlessly complementary to the traditional wide area cellular data networks. Our approach takes advantage of vehicle mobility patterns and human regular movement behaviors, and can be applied to large-scale and intermittent networks. We also design two memory-based forwarding schemes to ensure the routing of media content in such a network.

Our proposed schemes have a better performance in terms of delivery rate, delay, average copies of packets over methods without enforcement of connection. The proposed enhanced scheme, which can reduce the maximum data rate in the our system by considering human flows of the urban transport, makes our system of more feasibility. We test the feasibility of our infrastructure and delivery scheme based on real data set. Simulation results demonstrate that our propose network architecture is feasible for mobile content sharing, and our algorithm for content delivery performs well.

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