System Architecture for Delay Tolerant Media Distribution for Rural South Africa

Adriano Galati
Disney Research
Zurich, Switzerland

Theodoros Bourchas
Disney Research
Zurich, Switzerland

Sandra Siby
Disney Research & ETH
Zurich, Switzerland

Stefan Mangold
Disney Research
Zurich, Switzerland

***Abstract*—Wireless communication offers access to information even to users living in areas where little to no access to affordable communication channels is available. Delay Tolerant Networks (DTNs) enable content distribution in such areas, using mobility of devices and avoiding the need for traditional network infrastructure. In DTNs, data is passed from mobile device to mobile device, whenever possible, in an intelligent way. DTNs have the potential to reach out to under-served regions where cellular Internet access (3G, LTE, and beyond) might be expensive or unavailable. We are interested in DTNs for distributing media from cities to under-served rural areas. The content is distributed to the target destinations, using either public transportation or commuting vehicles such as taxis, equipped with wireless DTN-enabled devices. At each target destination, a micro-entrepreneur business is established with the help of our network: Micro-entrepreneurs use DTN-enabled projectors (also referred to as cinemas-in-a-backpack) to deliver entertainment content at low cost, and exploit the opportunity to create a micro-business around the show events. In this paper, we introduce the DTN system setup, present performance results of laboratory tests and test with a local commuter train of periodic and predictable mobility. Further, we present the target scenario and specific technical challenges. We aim to explore opportunities for a rural, under-served region in the north of Pretoria, South Africa.**

***Index Terms*—Delay Tolerant Networks, Mobile Cinemas, IBR-DTN**

I. Introduction

Despite the constantly increasing number of mobile computing devices and the growth of mobile Internet access, only 31% of the developing world's population can access the Internet [1]. 90% of 1.1 billion households around the world that are still unconnected are in the developing world. Moreover, residential fixed-broadband services are still expensive in developing countries, accounting for just over 30% of the average monthly GNI per capita. We want to reach out to these regions with a low-cost approach for media distribution. It is our objective to enable scalable network access and a global footprint of media distribution services, everywhere in the world. In this paper, we develop and test a system architecture that uses Delay Tolerant Networks (DTNs) [2], [3] to unleash new mobile growth opportunities, with particular regard to rural areas. DTNs can provide a viable, low-cost alternative to cellular wireless communication networks in areas that are underserved [4]. There is growing interest in opportunistic networks, as a special case of DTNs (in which routes are established only if nodes are within reach of each other), because of their ability to provide flexible multi-hop connectivity by leveraging intermittent contacts among mobile radio devices. Opportunistic networking employs the store-carry-forward paradigm where data is stored locally by mobile devices, carried while moving and forwarded when coming within the transmission range of another device. Such devices communicate only with their direct neighbors using local radio communication like Wireless Local Area Networks (WLANs). DTN nodes may send packets of arbitrary size, also termed bundles. A bundle is the protocol data unit of the DTN bundle protocol. Since bundles may be as large as several megabytes or even gigabytes, the contact duration may become the limiting factor for bundle forwarding. Communication links may not last long enough to even transmit a single message. Therefore, support for partial bundle transfers may enable communication over short contact durations and avoid wasting link capacity with incomplete transmissions [5]. DTN applications must be able to tolerate the delays resulting from the unavailability of nodes in the network. If requirements of fast delivery are loosened, data such as email, photograph, podcasts and videos can be distributed in a delay tolerant way. In this paper, we present our device design, including the hardware and software components, the chosen delay tolerant network protocol and the software architecture. We evaluate the system performance with the help of laboratory

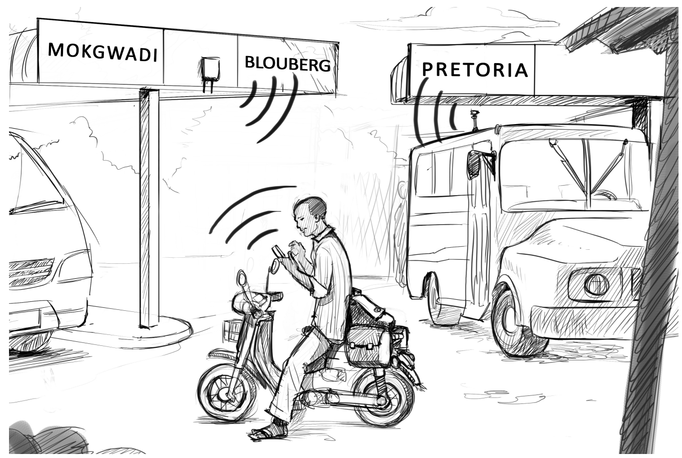

Fig. 1: © Disney - Micro-entrepreneurs can connect to a fixed infostation placed at the taxi rank or to mobile infostations carried by taxis or by other micro-entrepreneurs.

Fig. 2: Taxi stations in Pretoria and Hammanskraal, South Africa. During morning and evening peak time, taxis operate as shuttle buses with pre-determined pathways and predictable mobility. We plan to equip fifty vehicles with mobile infostations.

tests and additional stress tests on an outdoor commuter train. The design and the performance evaluation are part of the project MOSAIC_2B [6] that intends to provide data communication to remote and rural areas in South Africa, focusing on asynchronous communication in order to reduce the cost of connectivity. The target scenario in rural South Africa is outlined in Section II and the system components are presented in Section III. Results of experiments conducted in two different settings are described in Section IV. Section V provides a brief summary of related work and is followed by the conclusions in Section VI.

II. Use Case Scenario

This project's goal is to develop and test a new framework that uses DTNs to unlock new mobile growth opportunities, for communities and entrepreneurs in rural areas. Instead of relying on cellular data, we use a DTN approach to provide affordable technical ways for micro-entrepreneurs to obtain and distribute multimedia contents, and to run their business. We are interested in exploring if such new ways of distributing content can provide new growth opportunities for community members. Mobile cinema entertainment, possibly combined with educational content for healthcare, will be the use case. Micro-entrepreneurs will be provided with low-complex, small cinema-in-a-backpack systems, which allow them to deliver educational and entertainment content in remote villages. Cinema-in-a-backpack is a mobile, easy to use working environment, which enables entrepreneurs to project movies and to run their micro-businesses. Multimedia content will be delivered with the help of DTN-enabled mobile infostations. Infostations are battery-powered Wireless Local Area Network (WLAN)-enabled devices placed in taxis and taxi-stations. Entrepreneurs are also equipped with an infostation which enables them to be part of the network and access the distributed media content. Entrepreneurs can receive media content while sharing their own network resources. Infostations act as peers helping to broadcast the content. The content is first downloaded from a server to a fixed infostation, i.e., the gateway. This fixed infostation is placed in a taxi station located within a 3G/LTE covered area of the city of Pretoria (South Africa) (see Figure 2). From this point, data are sent epidemically throughout the DTN network once infostations are in radio range. The mobile infostations serve as intermediate relays (data mules), which carry the content between the server and final destination, which in our case, is an entrepreneur's mobile cinema device. Multiple entrepreneurs have access to the DTN and may obtain different media at the same time. In the simplest form of the use case scenario, micro-entrepreneurs can download content from the fixed infostation at the taxi rank in Pretoria or whenever they are in contact with other DTN nodes. Being located far away from Pretoria, micro-entrepreneurs can receive multimedia content carried by taxis when they travel in their surroundings, or from a second fixed infostation placed at the taxi ranks in Hammanskraal (Figure 2), a small town 42 km north of Pretoria, which serves several rural communities. In such areas, cellular network coverage is unavailable or expensive for locals. Once micro-entrepreneurs are in the proximity of the DTN, they can download the content by means of their WLAN-enabled mobile cinema devices. There are, at most, 150 taxis travelling between Pretoria and Hammanskraal taxi stations every day, which are potential data carriers between these two locations. By exploiting such knowledge of the network topology, micro-entrepreneurs can refer to the second taxi station in Hammanskraal, which is closer to their villages than Pretoria, to download multimedia content. We aim to equip fifty of such taxis with infostations. Taxis do not follow any timetable; they usually travel between Pretoria and Hammanskraal taxi ranks, using pre-determined pathways, for three hours in the morning and three hours in the evening. During these peak times, they work mostly as shuttle-buses: They stop at the taxi ranks for some time to let passengers get on and off the vehicle. During the rest of the day, they are in Pretoria for normal taxi service around the city.

III. System Components

Infostations are wireless routers equipped with external memory storage, battery supply, USB hub, GPS receiver and 3G dongle (see Figure 3). The TP-Link TL-MR3040 Ver. 2.0 has been chosen as the WiFi router in the infostations. The infostation's components and wireless specifications are listed in Table I. A USB hub is connected to the router and used to accommodate the 3G dongle, the GPS receiver and the memory storage. All the infostations have sufficient memory space to store the data received from other infostations. The cellular network, when available, and the GPS receiver will

TABLE I: TP-Link TL-MR3040 2.0: Specification

Parameter	**Feature**
Interface	USB 2.0 for cellular modem, micro USB for power
CPU speed	400 MHz
Memory	4 MB Flash, 32 MB RAM
Chipset	Atheros AR7240
Wireless	IEEE 802.11bgn
Frequency	2.4 GHz ISM band
Data Rate	up to 150 Mb/s
EIRP	up to 20 dBm

be used to help enhance the DTN network. The 3G dongle will allow each infostation to send useful information, system and network performance metrics and mobility traces (GPS coordinates) in real time. The purpose is to monitor the system and detect failures or unexpected behaviour. All infostations, except those carried by the micro-entrepreneurs, are connected to the battery of the taxis (mobile infostations) or to the electrical power system of the taxi stations (fixed infostations) and continuously powered up. The infostations have been configured with an OpenWrt bleeding edge release [7] named Barrier Breaker, an embedded operating system based on the Linux kernel which provides a fully writable filesystem with package management. IBR-DTN bleeding edge [8], [9] release, a C++ implementation of the Bundle Protocol [10] designed for embedded systems, is used as the framework for our DTN application. IBR-DTN provides different routing schemes and supports the TCP and UDP convergence layers, the Bundle Security Protocol [11] and IPND neighbour discovery specifications [12]. The cinema-in-a-backpack device consists of the following components: a tablet, a mobile infostation, a projector, speakers, and battery. Mobile infostations carried by the micro-entrepreneurs allow them to be part of the DTN network. Such infostations will reassemble the received data bundles if they are the recipients, and make the content available. Micro-entrepreneurs can access the multimedia content by means of the tablet, either by USB cable or ad-hoc WiFi connection. The projector connects to the tablet via HDMI/VGA. The chosen pico-projector and speakers are shown in Figure 4. Micro-entrepreneurs are provided with a rechargeable external battery, as power supply might not be available at all times.

IV. Experiments

We have conducted initial experiments aiming to assess the performance of the selected wireless devices and IBR-DTN. For that, we set up two scenarios with mobile and fixed network topology respectively and test the forwarding of data with different bundle payload sizes from a sender to a receiver. We present data delivery results, which are given by the ratio of the amount of data received to the total amount of data sent. We further analyze delay as the time taken for data to travel from source to destination across the network. We also observe the impact of storing bundles at intermediate nodes while forwarding.

A. Periodically Disconnected Network

To assess the performance of our DTN wireless devices in a periodically disconnected environment we set up a network topology by deploying three wireless infostations in an outdoor commuter train in the city of Zurich and analyzed the forwarding of data with different bundle sizes from one sender to one receiver. We used the train (which goes up and down a small hill every few minutes) as a testbed to evaluate the performance of such infostations when there is no end-to-end path. The commuter train has two stops located at a distance of 176 metres from each other. The vertical distance between the stops is 41 metres. Two railway carriages travel between them in opposite directions. These carriages have a maximum speed of 2.5 metres per second (see Figure 5). The average frequency of departure is approximately 2.5 minutes, depending on possible delays due, for example, to boarding and disembarking of passengers. The two carriages depart from the two opposite stops at the same time and always meet in the middle. We placed an infostation at each end

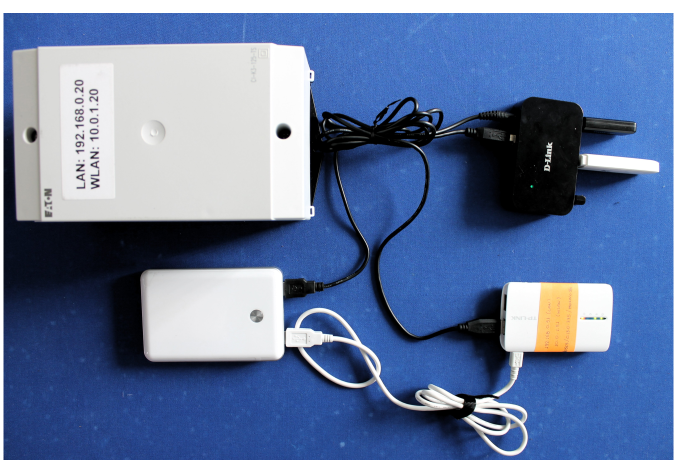

Fig. 3: TP-Link TL-MR3040 router, portable battery, USB hub, GPS receiver, 3G dongle, and external data storage.

Fig. 4: Pico-projector and speakers for the cinema-in-a-backpack device.

Fig. 5: Commuter train with predictable and repeated mobility pattern used to evaluate the system performance.

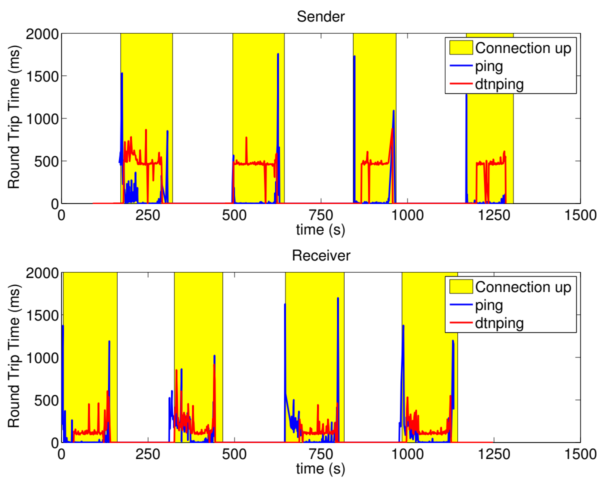

Fig. 6: Contact times of the mobile infostation with the sender and receiver measured by ping, dtnping and connection up/down.

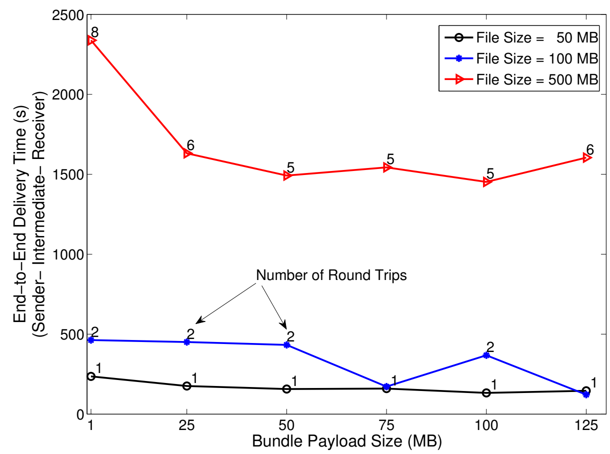

Fig. 7: Delivering different amount of data with different bundle sizes in the commuter train scenario.

of the track (fixed infostation), one acting as the sender and the other as the receiver, and one infostation in one carriage (mobile infostation), acting as a data mule between the two stops. At every carriage stop, the mobile infostation was at a distance of four meters from the fixed one. Note that we assumed the same distance between the nodes in the fixed network topology presented in Section IV-B. We synchronized each run manually to ensure that when the mobile infostation reached the sender, it had data to carry to the receiver. We did this by starting the data sending process at the sender when the second carriage, the one without the infostation, was at the sender side. This meant that IBR-DTN started creating data bundles and had them ready by the time the carriage equipped with the mobile infostation reached the sender side. We employed a well known routing protocol in delay tolerant networks, epidemic [13], often used as a benchmark by the delay tolerant network research community. It is a resource hungry protocol because it does not use any knowledge of the system to forward messages. Epidemic provides a theoretical upper bound in terms of delivery ratio when the buffer size is infinite. Such a routing protocol might be employed in the South African scenario (described in Section II). To confirm that the intermediate node was never in contact with both the sender and the receiver simultaneously, we plot in Figure 6 its contact times and inter-contact times [14], [15] with the two fixed infostations by continuously pinging them. Contact time is the duration of a single set of consecutive sightings of the same node. Inter-contact time is the elapsed time between two non-consecutive sightings of the same node. We show results from `ping`, `dtnping`, and `connection up/down` traces. `dtnping` is a command line tool of IBR-DTN used to send bundles of 64 bytes payload size. `ping` and `dtnping` measure the round-trip time at two levels of abstraction, the network and the bundle layer respectively. `connection up/down` traces were extracted from the IBR-DTN log. Before forwarding bundles between two devices, a connection is set up if within radio range of each other. By analyzing `connection up/down` traces, the mobile infostation shows a minimum contact time of 124 seconds and a maximum contact time of 170 seconds. By analyzing `ping` traces, the mobile infostation shows a minimum and a maximum contact time of 114 and 157 seconds respectively (avg). However, the traces in Figure 6 show the mobile infostation perceiving `connection down` up to ≈ 13.875 seconds after the last ping received. We extracted an aver-

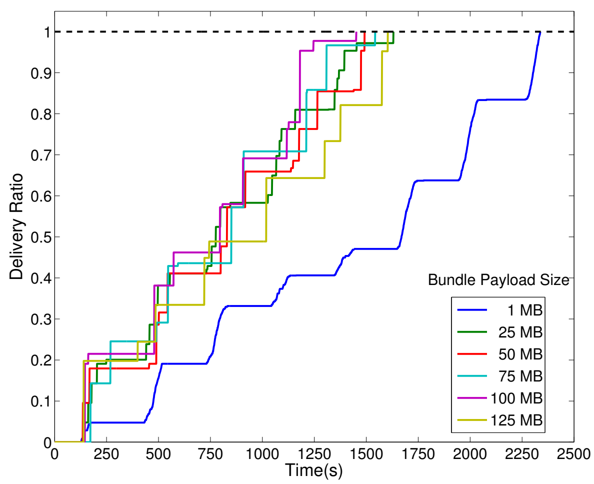

Fig. 8: Delivery Ratio over time in commuter train scenario.

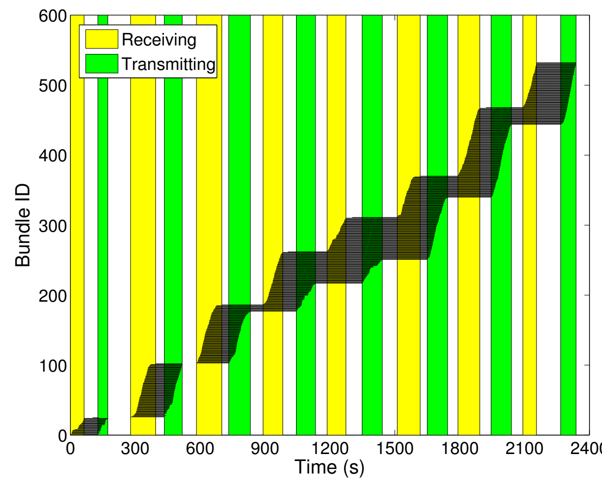

Fig. 9: Bundle Storage Time at the Intermediate Node in the commuter train.

age inter-any-contact time [15] of 16.375 seconds (from the connection up/down traces) for the mobile infostation. Inter-any-contact time is the time elapsed between two successive contacts with any device. We recorded the mobile infostation being isolated from both of the fixed infostations between 5 and 29 seconds. The average inter-any-contact time derived from the ping traces is 26.71 seconds. Besides, the difference between the `dtnping` and `ping` provides an estimate of the processing time of the dtnping bundles at DTN layer. The extracted difference between `dtnping` and `ping` average round trip times is $\approx 207ms$. The higher time taken by a dtnping as compared to a ping shows the extra time taken at the bundle layer to process the dtnping bundles. Thus, perceiving a connection down event some time after the last ping is received, indicates some delay at bundle layer to detect a loss of connection. In Figure 7, we present the delay exhibited by sending 50MB, 100MB, and 500MB from one train stop to the other, with varying bundle payload sizes. The number of round trips shows how many times the commuter train travels between the stations. For the three distributions, the delivery time does not seem to be influenced by the payload size if it is bigger than or equal to 25MB. This suggests that the number of bundles impacts the delivery time till a certain point with respect to the amount of data sent. The small deviation in the number of round trips, observed in some cases, is mainly due to the fact that the contact duration between the mobile and the fixed infostations is not constant, as shown in Figure 6. As a result, the longer the contact duration, the more data is forwarded, so as to lead to shorter delivery times. High number of smaller bundles increases the network overhead and the processing delay and consequently the delivery time. In Figure 8 we analyze the delivery ratio over time of the 500MB data file with several bundle payload sizes. As expected, the distribution with smaller bundle payload size (1MB) expresses lower delivery ratio with respect to the others, which roughly follow the same behaviour. In the commuter train scenario, it took around 38 minutes to deliver 500MB data file in bundles of 1MB payload size. However, splitting the data file in larger bundles helped deliver the content in shorter time, no longer than 25 minutes. In order to better understand the behaviour of DTN nodes in receiving and forwarding bundles, we extract their waiting time at intermediate nodes. Note that the intermediate node is the mobile infostation placed in the carriage. Figure 9 illustrates how long each bundle waits at the intermediate node before being forwarded to the receiver. Upon acknowledgment of reception, the transfer is completed, bundles are purged and memory space is freed at the intermediate node. We consider bundles of 1MB payload size created from a 500MB file. The bundle IDs are shown on the y-axis, in the order they are received from the sender during the contact times (highlighted in yellow in Figure 9). As the mobile infostation is never in contact with the sender and the receiver at the same time, it will store, carry and forward them as soon as it is in contact with the receiver. The white bands in Figure 9 show the inter-any-contact times [15] of the mobile infostation while travelling up and down in the commuter train. The plot shows that not all the bundles are delivered during a single contact with the receiver (highlighted in green in Figure 9); some of them wait at the intermediate node up to three round trips before being forwarded. It is also worth noting that the bundles are forwarded in the same order they are received. This is not always the case when the intermediate node is continuously in contact with the sender and the receiver, as in the network scenario presented in the next section.

B. 2-Hop Fixed Network

As a proof of concept, we assessed the selected infostations in forwarding data of different bundle payload sizes in a fixed 2-hop network topology. For that, we placed three infostations in line-of-sight with each other and set up a static route from

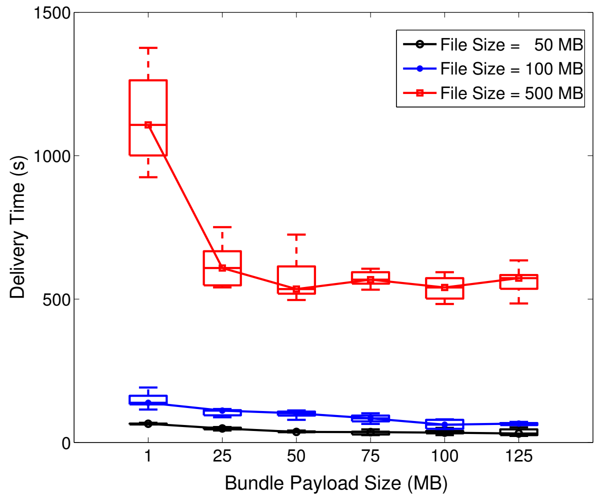

Fig. 10: Delivering different amounts of data with different bundle sizes through 2-hop forwarding in a fixed network topology.

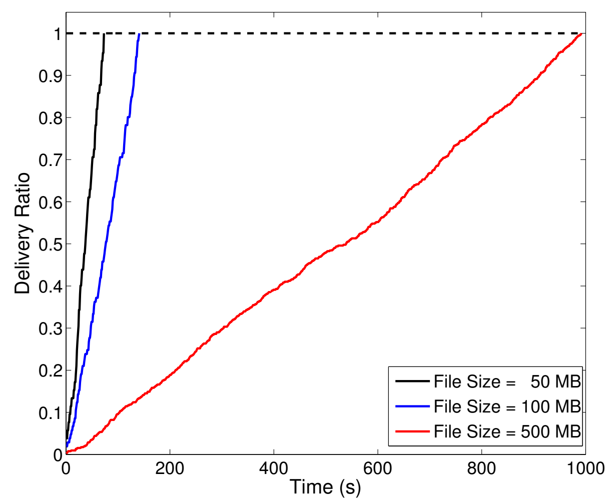

Fig. 11: Delivery ratio of different amount of data, 50MB, 100MB and 500MB, with 1M bundle size through 2-hop forwarding in a fixed network topology.

the sender to the receiver through the intermediate node. The intermediate node was at a distance of 4 metres from the sender and the receiver. Note that this was the shortest distance from the intermediate node in the commuter train scenario. Different amounts of data were bundled with different payload size by the sender and forwarded to the receiver. The test was repeated with six different bundle payload sizes, from 1MB to 125MB, as in the previous experiment. Figure 10 shows the total delivery time of 50MB, 100MB, and 500MB, bundled with different payload sizes. We observe that the behaviour of such delivery time distributions resembles the one presented in Figure 7, but with smaller delay. Similar to the train scenario, the bundle payload size does not seem to have a significant impact on the delivery time when it is above 25MB. Such results suggest that the number of bundles affects the network performance up to a certain point. Thus, the data traffic starts experiencing higher delay with small bundle size and increasing network load. Figure 11 shows the delivery ratio of a transmission of each data file with 1MB bundle payload size. It takes approximately 60 seconds to deliver 41MB, 37MB and 20MB of the 50MB, 100MB and 500MB respectively. This shows that network load has an impact on the forwarding of bundles. As presented in the commuter train scenario, we further investigate the waiting time of bundles at the intermediate node in the fixed network topology. In Figure 12, the waiting time of bundles at the intermediate node is illustrated. We consider bundles of 1MB payload size created from a 500MB file. Observing the bundle IDs, the order in which bundles are received by the intermediate node is not the same as the order in which they are forwarded to the receiver. This is confirmed by the zoom-in plot of Figure 12 which shows that bundles received later at the intermediate node may be forwarded earlier than previously arrived bundles. By default, incoming bundles are immediately queued to be transmitted if a connection exists and the transmission queue can handle more bundles. Otherwise, bundles are temporarily stored and wait to be transmitted. However, IBR-DTN assigns higher priority to incoming bundles, rather than to the ones already stored to be queued for transmission. Therefore, stored bundles might have to wait for some time before being queued for transmission. A *FIFO* method is adopted to handle stored bundles. Such behaviour is different from the one expressed in Figure 9 where the intermediate node is either receiving or transmitting bundles. We also investigate the average storage time at the intermediate node for each bundle payload size of different data files in Figure 13. As expected, large bundles express higher average storage time. We also observe that a large number of small bundles results in a higher network load and leads to an increase in the storage time. This is because the intermediate node might not be able to accommodate all the incoming bundles in the transmission queue. Such bundles will be temporarily stored and retrieved afterwards for transmission. A high number of bundles might increase congestion at the intermediate node, while large bundles would take longer time before being acknowledged as completely forwarded and purged. To investigate this behaviour further, we plot the delivery ratio of a 500MB file, transmitted in bundles with varying payload sizes in Figure 14. As expected, all of the distributions, with the exception of the 1MB, show similar behaviour and complete the delivery approximately at the same time. We also calculate the time taken by the receiving infostation to merge the bundles, once all of them have been received, and build the file that was originally sent. The average merge times of different bundle payload sizes for each file size are shown in Table II. As expected, the higher the number of bundles, the longer it takes to build the file.

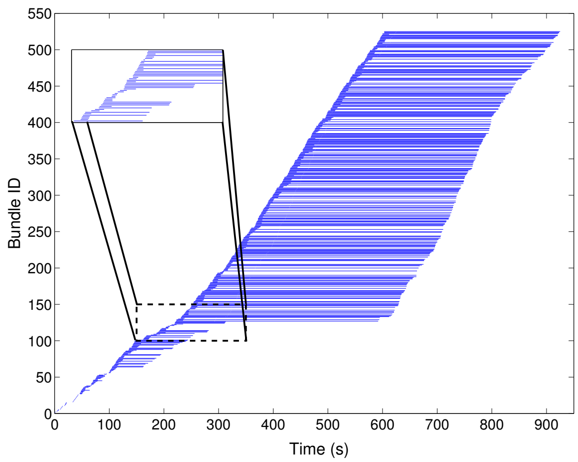

Fig. 12: Waiting time of each bundle at intermediate node.

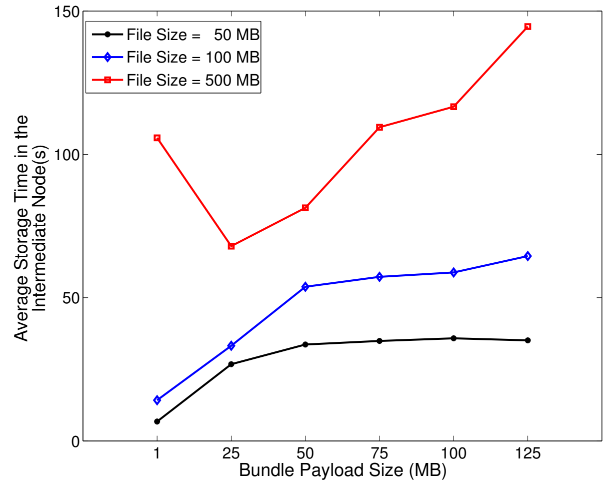

Fig. 13: Average Storage Time of bundles at intermediate node.

TABLE II: Average merge time (s) for different file and bundle sizes.

File size (MB)	Bundle Payload Size (MB)					
	1	25	50	75	100	125
50	106.2	66.4	45.8	N/A	N/A	N/A
100	225.6	110.8	112.4	79.5	84.4	N/A
500	1336.6	561.5	511.5	489.4	506.1	503.8

V. Related Work

Considerable work has been carried out by the scientific community to devise reliable routing strategies in DTNs [4], [16]–[19]. Wireless networks exploiting public transport systems have been attracting attention in recent years. Initial work focusing on rural environments in developing regions where buses connect a number of villages spread over a large area is conducted by [20]–[22]. Their common goal is to provide network access for delay tolerant applications such as e-mail and non-real time web browsing. DakNet [20] uses computers with a disk and Wi-Fi radio attached to buses on a bus route between villages. E-mails and other data are downloaded to the village and uploaded to the Internet or to other villages along the bus route. On the same bus network, a system of throwboxes [23], [24] was deployed to enhance the capacity of the DTN. KioskNet [25] is also a network of rural Internet kiosks that provide data services in remote regions. Vehicles with on-board computers ferry the data between the kiosks and gateways connected to the Internet. In these cases the set of neighbors for every node is usually small and does not change frequently over time; usually encounters are highly predictable. TACO-DTN [26] is a content-based dissemination system composed of fixed and mobile infostations that allow mobile users to subscribe to certain contents for a period of time. Campus bus networks designed to serve students and faculties who commute between colleges or from/to nearby towns are proposed in [27]–[29]. In these settings opportunistic networks are usually characterized by a relatively small number of nodes when compared to a fully fledged urban environment. Scaling up in terms of number of nodes, urban environments generally offer a considerable number of bus lines, densely deployed, to enable people to commute inside a city. Bus networks in urban environments are usually characterized by many contact opportunities and frequent contacts [30]–[33]. In [30] the authors propose a commercial application based on a multi-tier wireless ad-hoc network called Ad Hoc City. It provides Internet access by means of Access Points responsible for a geographical area. Using the same real data set, [31] propose a cluster-based multi-copy routing algorithm for intra-city message delivery. Here nodes are clustered based on their encounter frequency. To reduce the overhead effect of multiple copies, [32] propose an optimal stopping rule when forwarding. In [33] the public transport system of Shanghai is used to test the performance of a single-copy probabilistic forwarding mechanism. A recent work about performance analysis for deployment at urban scale is presented in [34]. In this work, the authors analyzed inter-contact times of the Zurich and Amsterdam transport systems discovering that they follow an exponential distribution. Based on their findings, they are able to predict the performance of the epidemic routing protocol using a Markov chain model.

VI. Conclusion

Rural areas of developing regions often suffer from low speed network infrastructures, if they have any at all. This limits access of local populations to content and services that may provide economic opportunities. DTNs enable content distribution in such areas, using mobility of devices and avoiding the need for a physical network infrastructure. They can provide a viable, low-cost alternative to cellular wireless communication networks, unlocking mobile growth opportunities, for communities and entrepreneurs in rural areas. In this work, we describe the architecture of a DTN-enabled content

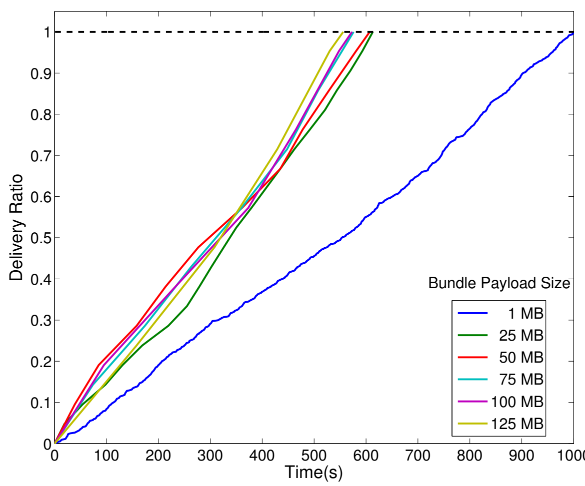

Fig. 14: Delivery ratio of 500MB for different bundle sizes in a 2-hop fixed network topology

distribution system for rural South Africa. We evaluate system performance and present real-world performance results in a commuter train environment, as well as in a fixed network scenario. Our results shed light on the influence that the bundle payload size and the number of bundles have on the performance of the network. Based on our findings, we intend to evaluate our devices in a scenario which will accurately represent rural areas in developing regions.

VII. Acknowledgments

The MOSAIC-2B project is partially funded by the EU FP7 framework program for research for research, technological development and demonstration under grant agreement no.611796. We thank Johannes Morgenroth and the team of Lars Wolf at Techn. Univ. Braunschweig, Germany, for provisioning software and support of their IBR-DTN. We also thank the Disney Lab Artists, Maurizio Nitti and Alessia Marra, for providing artworks.

References

[1] The World in 2013, ICT Facts and Figures. *ITU Technical report, Geneva, Switzerland*, 2013.

[2] Kevin Fall. A Delay-tolerant Network Architecture for Challenged Internets, 2003.

[3] V. Cerf, S. Burleigh, A. Hooke, L. Torgerson, R. Durst, K. Scott, K. Fall, and H. Weiss. Delay-Tolerant Networking Architecture. RFC 4838.

[4] Sushant Jain, Kevin Fall, and Rabin Patra. Routing in a Delay Tolerant Network. In *Proceedings of the 2004 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications*, SIGCOMM '04, pages 145–158, 2004.

[5] Mikko Pitkanen, Ari Keranen, and Jorg Ott. Message fragmentation in opportunistic dtns. In *Proceedings of the 2008 International Symposium on a World of Wireless, Mobile and Multimedia Networks*, WOWMOM '08, pages 1–7, Washington, DC, USA, 2008. IEEE Computer Society.

[6] MOSAIC_2B. Mobile Empowerment for the Socio-Economic Development in South Africa. http://mobile-empowerment.org.

[7] OpenWrt. Wireless Freedom. https://openwrt.org.

[8] W.B. Pttner L. Wolf S. Schildt, J. Morgenroth. IBR-DTN: A lightweight, modular and highly portable Bundle Protocol implementation. *Electronic Communications of the EASST*, pages 1–11, 2011.

[9] IBR-DTN. A modular and lightweight implementation of the bundle protocol. http://trac.ibr.cs.tu-bs.de/project-cm-2012-ibrdtn.

[10] K. Scott and S. Burleigh. Bundle Protocol Specification. RFC 5050 (Experimental), November 2007.

[11] S. Symington, S. Farrell, H. Weiss, and P. Lovell. Bundle Security Protocol Specification. RFC 6257 (Experimental), May 2011.

[12] D.Ellard, R.Altmann, A.Gladd, and D.Brown. DTN IP Neighbor Discovery (IPND) draft-irtf-dtnrg-ipnd-02 , November 2012.

[13] A. Vahdat and D. Becker. Epidemic Routing for Partially Connected Ad Hoc Networks. *Technical Report CS-2000-06, Department of Computer Science, Duke University*, 2000.

[14] J. Crowcroft C. Diot R. Gass A. Chaintreau, P. Hui and J. Scott. Pocket Switched Networks: Real-world mobility and its consequences for opportunistic forwarding. *Technical Report UCAM-CL-TR-617, University of Cambridge, Computer Laboratory*, February 2005.

[15] J. Scott R. Gass J. Crowcroft P. Hui, A. Chaintreau and C. Diot. Pocket switched networks and the consequences of human mobility in conference environments. *in Proceedings of ACM SIGCOMM first workshop on delay tolerant networking and related topics*, 2005.

[16] Q. Yuan, I. Cardei, and J. Wu. Predict and Relay: an efficient routing in disruption-tolerant networks. *ACM MobiHoc*, 2009.

[17] S. Nelson, M. Bakht, and R. Kravets. Encounter-based routing in DTNs. *IEEE INFOCOM 2009*, April 2009.

[18] A. Orda and R. Rom. Shortest-path and minimum-delay algorithms in networks with time-dependent edge-length. *Journal of ACM, 37*, 1990.

[19] S. Merugu, M. Ammar, and E. Zegura. Routing in space and time in networks with predictable mobility. *Technical report, School of Computer Science, Georgia Tech, Atlanta, USA*, 2004.

[20] A. Pentland, R. Fletcher, and A. Hasson. DakNet: Rethinking Connectivity in Developing Nations. *IEEE Computer*, 37(1):78–83, 2004.

[21] C. T. De Oliveira, R. B. Braga, D. M. Taveira, N. C. Fern, and O. C. M. B. Duarte. A predicted-contact routing scheme for Brazilian rural networks. *in Electrical Engineering Program, COPPE/UFRJ*, 2008.

[22] M. Demmer and K. Fall. DTLSR: Delay Tolerant Routing for Developing Regions. *ACM Workshop on NSDR*, 2007.

[23] W. Zhao, Y. Chen, M. Ammar, M. Corner, B. Levine, and E. Zegura. Capacity enhancement using throwboxes in dtns. *in In Proc. Intl. Conf. on Mobile Ad hoc and Sensor Systems*, pages 31–40, 2006.

[24] N. Banerjee, M. D. Corner, and B. N. Levine. Design and Field Experimentation of an Energy-Efficient Architecture for DTN Throwboxes. *ACM Transactions on Networking*, 18(2):554–567, April 2010.

[25] S. Guo, M.H. Falaki, E.A. Oliver, S. Ur Rahman, A. Seth, M.A. Zaharia, and S. Keshav. Very Low-Cost Internet Access Using KioskNet. *ACM Computer Communication Review*, 37(5):95–100, 2007.

[26] G. Sollazzo, M. Musolesi, and C. Mascolo. TACO-DTN: A Time-aware Content-based Dissemination System for Delay-Tolerant Networks. *ACM Int. Workshop Mobile Opportunistic Networking (MobiOpp)*, 2007.

[27] J. Burgess, B. Gallagher, D. Jensen, and B. N. Levine. Maxprop: Routing for vehicle-based disruption-tolerant networks. *In Proc. INFOCOM '06*, pages 1–11, April 2006.

[28] X. Zhang, J. Kurose, B. N. Levine, D. Towsley, and H. Zhang. Study of a bus-based disruption-tolerant network: mobility modeling and impacton routing. *in MobiCom '07: Proceedings of the 13th ACM int. conf. on Mobile computing and networking*, pages 195–206, 2007.

[29] A. Balasubramanian, B. Levine, and A. Venkataramani. Dtn routing as a resource allocation problem. *in Proceedings of the 2007 conference on Applications, technologies, architect ures, and protocols for computer communications, ser. SIGCOMM '07, ACM*, pages 373–384, 2007.

[30] J. Jetcheva, Y.-C. Hu, S. PalChaudhuri, A. Saha, and D. Johnson. Design and evaluation of a metropolitan area multitier wireless ad hoc network architecture. *in Mobile Computing Systems and Applications*, pages 32–43, October 2003.

[31] S. Ahmed and S. Kanhere. Cluster-based forwarding in delay tolerant public transport networks. *32nd IEEE Conference in Local Computer Networks, 2007*, pages 625–634, October 2007.

[32] C. Liu and J. Wu. An optimal probabilistic forwarding protocolin delay tolerant networks. *in MobiHoc '09*, pages 105–114, 2009.

[33] M. Sede, L. Xu, L. Da, W. Min-You, L. Minglu, and S. Wei. Routing in large-scale buses ad hoc networks. *in Wireless Communications and Networking Conference, 2008*, pages 2711–2716, 2008.

[34] L. D. Hartog, T. Spyropoulos, and F. Legendre. Using public transportation as a DTN backbone: Mobility properties and performance analysis. *in Proceedings of AOC 2010*, 2010.