Vehicular Wireless Burst Switching Network: Enhancing Rural Connectivity

Farid Farahmand[1], Ankitkumar N. Patel[2], Jason P. Jue[2], Vasco G. Soares[3], and Joel J. Rodrigues[3]
[1]Department of Computer Electronics and Graphics Technology
Central Connecticut State University, New Britain, CT 06050
[2]Department of Computer Science
The University of Texas at Dallas, Richardson, TX 75083
[3]Institute of Telecommunications, Networks and Multimedia Group, Portugal
Dep. of Informatics, University of Beira Interior, Covilhã, Portugal
farahmandfar@ccsu.edu, jjue@utdallas.edu, vasco_g_soares@est.ipcb.pt, joel@ubi.pt

Abstract

This paper introduces a network architecture called Vehicular Wireless Burst Switching (VWBS). The main objective of this architecture is to provide low-cost connectivity solution for isolated and dispersed regions with no networks infrastructure. The proposed architecture is based on the concept of Delay Tolerant Networks (DTN) and can be applied to various scenarios, including rapid deployment of emergency communication systems when all communication links have failed. In this paper, we present an overview of VWBS networks and show how their performance, in terms of average packet delay, can be improved using store-and-forward devices called relay nodes. Furthermore, we introduce several heuristic algorithms which can be used to place minimum number of relay nodes. Through computer simulations, we compare the performance of the algorithms and their tradeoffs. We conclude our work by examining possible open research issues in VWBS.

1. Introduction

In spite of its astonishing growth around the globe in the last two decades, the Internet is still far from becoming universal. There are still vast numbers of areas in the world, which have no Internet access. In majority of these areas high cost and/or environmental conditions prohibit construction of any durable infrastructure and effective traditional wireless networks to provide Internet access. For many communities utilizing technologies such as Very Small Aperture Terminal (VSAT), microwave dishes and WiMax antennas are simply not feasible. For example, monthly fees for VSAT in Africa can be as high as $5000 per month per Mbit/s. WiMax technology, typically, requires high equipment cost, expertise, and considerable planning. Microwave dishes require line-of-sight and hence, become very susceptible to obstacles such as buildings or trees and its performance can easily be affected under various environmental conditions such as high humidity.

Lack of universal broadband connectivity continues to create serious gaps between poor and rich communities. Studies have shown that by connecting to the digital world, underprivileged communities can benefit from economic prosperity, social stability, and the personal and professional development of its members [1]. These studies emphasize that the Information Communities Technologies (ICTs) can bring the digital technologies to the isolated and marginalized communities and help ensure their integration into wider society at the local, national, and international levels.

In the past several years, a growing number of pilot projects have been focusing on bringing connectivity to seemly unreachable and disconnected rural communities in an inexpensive manner. DakNet (or WiFi Postal System) was one of the first practical approaches, which aimed to connect rural communities in India to the Internet. DakNet [2] used a unique combination of physical and wireless transport to offer data connectivity to regions lacking communication infrastructure. In this system, mobile access points (MAPs) with omnidirectional antennas are mounted on vehicles regularly traveling to rural areas. Upon contact with rural e-kiosks in each area, MAPs can upload or download data. E-kiosks are capable of storing the incoming data until they are processed and delivered to their end-users. Through this unique system villages can exchange emails and multimedia messages. The Saami Network Connectivity (SNC) project focused on establishing Internet connections for the Saami population of Reindeer Herders, who live in Swedish Lapland with a yearly cycle dictated by the national behavior or reindeers [3].

In South Africa, the Wizzy Digital Courier Service, was designed to provide digital access to schools in remote villages [4]. In this system, a courier on a motorbike, equipped with a USB storage device, travels from a village school to a large city, which has permanent broadband Internet connectivity. Motivated by DakNet, the Message Ferry (MF) project [5] also aimed at developing a data delivery system in disconnected areas. In this system communications between remote villages is performed using mobile nodes called message ferries. Mobile nodes can often be mounted on cars, buses, boats, etc. Such networks are also referred to as *transit networks* or networks with *mechanical backhaul* [6].

The aforementioned transit networks offer radical and cost effective solutions which fall into a newly defined class of networks known as the Delay/Disruptive Tolerant Networks (DTNs) [7-9]. DTNs on a general abstraction, include networks characterized by (a) sparse connectivity, where end-to-end path between source and destination may not exist, (b) long or variable delay, (c) asymmetric data rate, and (d) high error rate. Similar characteristics can be associated with the problem of providing connectivity to disconnect and highly partitioned rural communities. Consequently, protocols and architectural assumptions used for traditional ad hoc networks can no longer be applicable to such networks. The key concept in delay-tolerant networks is to allow nodes to store the data until proper links become available.

In this paper we propose a DTN-based architecture called Vehicular Wireless Burst Switching (VWBS). In this architecture vehicles act as mobile routers and physically carry the data between e-kiosks in isolated regions. Relay nodes are store-and-forward devices which allow data drop and pickup by bypassing mobile routers (e.g., buses). The e-kiosks (also known as community tele-centers) essentially act as access node providing connection to individual end-users; it offers varieties of services such as receiving and sending documents, email, voice mail, etc. e-kiosks can also operate as entertainment, educational, or health centers. For example, residents can order the latest movies and songs; students can request on-line course materials (equivalent to distance learning); patients can send their medical history, receive prescriptions, and communicate with doctors. Figure 1 shows an example of a vehicular wireless burst switching network. Note that as shown in the figure, one or more of the e-kiosks are assumed to have direct access to the Internet. Furthermore, some e-kiosks may also be equipped with VSATs. Figure 2 abstracts the role of VWBS as an underlying network to provide access to partitioned regions.

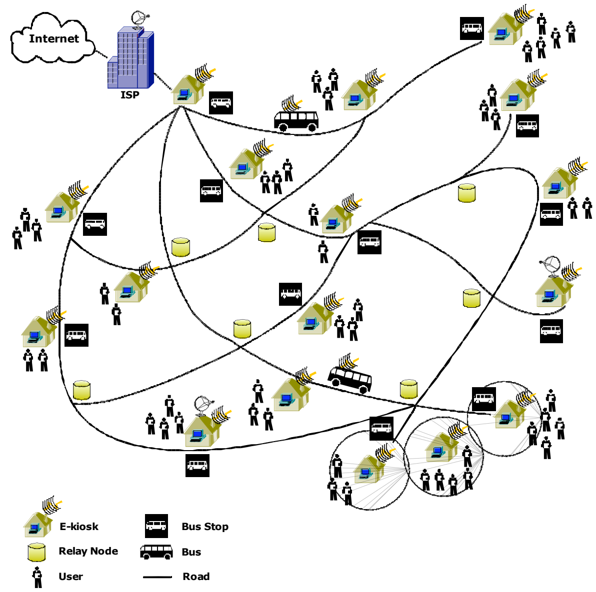

Figure 1. An example of a vehicular wireless burst switching network and its components. Examples of isolated regions are circled.

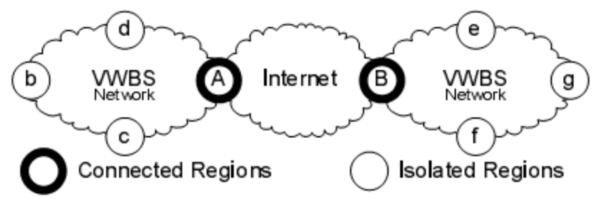

Figure 2. An abstract model for VWBS application.

The e-kiosk receives and transmits data packets (e.g., IP packets) from/to its reachable end-users. In the inbound direction, data packets received by the e-kiosk are assembled into basic units, referred to as *data bursts*, which are then transported over the transit network. In the outbound direction, incoming data bursts are disassembled into data packets and sent to appropriate end-users. Packet assembly into data bursts results in fewer packet processing and routing decision, which in turn can be translated into lower cost.

The main contribution of this paper is analyzing VWBS network cost in terms of number of relay nodes. Relay nodes can improve network performance in terms of average packet delay and packet loss, while providing total connectivity between sparse regions. We introduce several heuristic algorithms to solve the relay node placement problem in the VWBS network as a special case of DTN. Our main motivation for developing these algorithms is to minimize the number of relay nodes used in the network such that the total traffic between all source-destination node pairs is maximized.

It is worth mentioning that VWBS was initially motivated by the Affordable Internet Access Project [10] and its main objective is to provide low-cost and reliable connectivity solution for isolated and disconnected areas with no or unreliable data network infrastructure. However, applications of VWBS architecture can go far beyond our focus in this paper. For example, VWBS can be implemented in cases where natural disasters have destroyed telecommunication infrastructure or when communication links are not available due to lack of maintenance. VWBS network can also be used to disseminate information about potentially existing hazards and surrounding environmental dangers in a disaster recovery scene.

The remainder of this paper is structured as follows. In Section 2, we elaborate on network model and assumptions. In Section 3, we describe the problem and its constraints. In Section 4, we present several heuristic algorithms to minimize the number of relay nodes in the network. In Section 5, we compare the performance of the proposed algorithms. Finally, Section 6 provides conclusions and future works.

2. Network Model

In this section we describe the network architecture and assumptions under study.

2.1. Network Architecture

The architecture of VWBS network must be based on real assumptions and practical field applications. We start by describing three different node types used in VWBS architecture, namely (a) e-kiosks, (b) relay nodes, (c) mobile routers.

E-kiosks are access points to VWBS network and they are strategically located to support their surrounding users. Individual end-users are, typically, connected to e-kiosks through low-range low-power radio frequency signals such as 802.11 wireless protocols. The intergroup routing of individual IP packets to the end-users within each isolated region can be based on commonly known protocols such as dynamic source routing (DSR) [11]. In general e-kiosks can provide three distinct functionalities:

- Tele-center: functioning as a multi-purpose community center or cyber cafe where individuals can send and receive emails and other types of digital files and documents.
- Hub: providing access to the ISP through legacy net-works (VSAT, LAN, etc.). Individual users connected to the hub can access the Internet directly.
- Gateway: forwarding the data packets through the VWBS network. In this case, incoming IP packets in the inbound direction with the same properties (e.g., priority, e-kiosk destination, etc.) are aggregated into basic units, referred to as *data bursts*. Data bursts are stored and transported over the transit network upon link availability (i.e., when a mobile router becomes available). Clearly, the gateway is responsible for translating the IP addresses into VWBS equivalent e-kiosk address. In the outbound direction, the received data bursts are disassembled into IP packets, transmitting them to the end-user.

Mobile routers are mounted on vehicles (e.g., buses) and act as store-carry-forward devices. Upon contact (time interval during which data exchange is possible) mobile routers can communicate directly to other routers and/or to e-kiosks. Mobile routers can also exchange data bursts between one another via relay nodes. Clearly, mobile routers require considerable storage capacity in order to store the incoming data bursts until they are forwarded and their appropriate delivery is ensured.

Relay nodes are also store-and-forward devices which receive data bursts from the mobile routers and store them until the proper link is available. The main function of these nodes is to allow data exchange between various mobile routers. Relay nodes are typically stationary and located at intersections where mobile routers meet, as shown in Figure 1. Generally, relay nodes have large storage requirements; hence, depending on the traffic volume, they may be equipped with hard drives with capacity of several thousands of Giga bytes.

We note that e-kiosks operate at IP layers and can potentially communicate with mobile routers and relay nodes. However, mobile routers and relay nodes receive and transmit data bursts. Furthermore, relay nodes must have low-cost and low-power requirements and must be readily available for deployment. For example, one can envision solar-powered relay nodes, which have minimum intelligence and simply store and forward data bursts upon request by bypassing mobile routers.

The control messages in VWBS network architecture include information such as message priority, destination, timing constraint, etc. In general, control messages require low bandwidth. Consequently, when other means of communications are available, control messages can be carried out-of-band, possibly on a different network layer, namely, cell phone network. Such hybrid architecture can be particularly advantageous for communities where many of its residents have access to cell phones and text messaging, however, no reliable Internet connection exists. For example, consider a scenario in which a student can request for electronic class lectures by sending a text message to the university server. Upon receiving the request, the server sends the electronic lecture files using the VWBS network. Figure 3 illustrates this example.

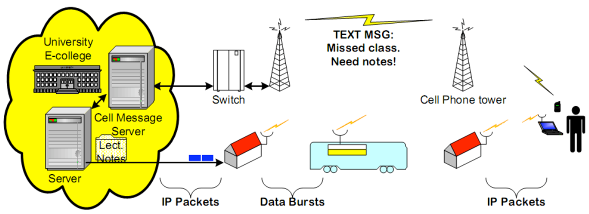

Figure 3. Using VWBS network to provide distance learning.

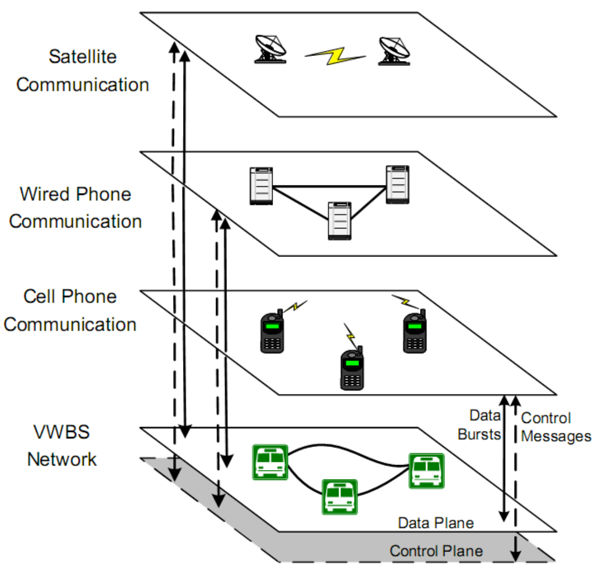

Figure 4. Interfacing VWBS network and other networks.

Figure 4 depicts possible interactions between VWBS and other networks. As this figure suggests, VWBS can utilize other networks as its control layer. Furthermore, the data transfer can potentially be switched between VWBS and other network layers, resulting in lower overall data transfer delay and higher reliable delivery. For example, it is possible that after receiving data bursts, an e-kiosk passes them to the VSAT network in order to forward the data to its final destination. In this paper we assume that all data bursts remain on the VWBS and there are no interactions between VWBS and other networks. The actual link technologies used between end-users, e-kiosks, relay nodes, and mobile routers depend on converge and economical considerations. The access methods can range from wired lines to satellite communications or low-powered radio capabilities (e.g., 802.11 a/b/g). Ultra-wideband (UWB) radio, which operates at extremely low-power with large data capacity, is also another promising link technology.

2.2. Network Assumptions

In our study, we consider the following basic assumptions:

- The traffic matrix is provided in advance and vehicle routes are pre-assigned and fixed.
- The traffic can only be exchanged between mobile routers and relay nodes, and between mobile routers and e-kiosks; hence, there is no direct transmission between mobile routers.
- Bandwidth is infinite once nodes come in contact with one another.
- Relay nodes have limited storage due to limited cost constraint, while mobile routers have no storage limitation.
- All the transported traffic, including control messages, remains on VWBS network and there is no interaction between VWBS and other networks.
- VWBS network is IP-centric and e-kiosks receive IP packets from individual end-users. All packets have the same priority.

3. Problem Description

The relay node placement problem can be described as follows: Given a network configuration, the traffic load between source-destination pairs, and the maximum number of available relay nodes, the objective is to determine where to place relay nodes in the network, such that the performance of the network is maximized. The given network configuration includes the vehicular routes, which have been pre-determined based on available road system, e-kiosk locations, which are typically at bus terminals acting as access points to VWBS, and crossing points, where at least two bus routes intersect one another.

We measure the network performance in terms of average packet delay and the number of installed relay nodes. Minimizing average delay lowers the time that data bursts spend in the network, reducing contention for resources in networks. Hence, lowering delay will indirectly improve the network throughput. On the other hand, placing more relay nodes at crossing points can increase the cost of the network. Hence, by limiting the number of installed relay nodes the cost of the network can be lowered.

4. Heuristic Algorithms

In this section we describe several heuristic algorithms in order to maximize the network performance in terms of delay or network cost.

4.1. Minimizing Relay Node (MRN) Algorithm

In this heuristic algorithm, we maximize relay node usage to reduce the number of required relay nodes. No new relay nodes are added unless all existing ones have been fully utilized. A pseudo code description of the MRN algorithm is given below:

Step 1: Given the traffic matrix $\Lambda = \lambda(s, d)$ with data rate requests between each s and d node pair being $\lambda(s, d)$, make a copy $Q = \Lambda = \lambda(s, d)$.

Step 2: Select source-destination pair with the largest traffic, i.e., $q(s, d)_{max} = max[q(s, d)]$.

Step 3: Find the route for $q(s, d)_{max}$ using the *least* number of existing relay nodes, such that the total data stored by each relay node is not greater than its maximum capacity, C_r.

a. If no such path exists, add a new relay node and find the path with the *least* number of relay nodes between $q(s, d)_{max}$.

b. Set $q(s, d)_{max} = 0$ and return to *Step 3* until all nonzero traffic demands are satisfied.

Step 4: Count the number of relay nodes carrying traffic.

4.2. Minimizing Delivery Time (MDT) Algorithm

In this algorithm we assume that all crossing points act as relay nodes. Once all traffic demands are routed, the number of relay nodes that carry traffic is counted. In general, MDT algorithm is similar to MRN with the exception of *Step 3*, which must be modified as follows:

Step 3: Find the route with the shortest delivery delay for $q(s, d)_{max}$ such that the total traffic stored by each relay node is not greater than C_r. If there is more than one such path use the one requiring the lowest hop count.

The main motivation for this algorithm is its simplicity. Furthermore, the key advantage of MDT is the potential ability to minimize the average packet delivery time by allowing data exchange at all crossing points.

4.3. Minimizing Relay Node and Delivery Time (MRD) Algorithm

This heuristic algorithm minimizes the average message delivery time subject to adding the least number of new relay nodes. The basic difference between this algorithm and MRN is that rather than focusing on minimizing the least number of relay nodes, data bursts are routed on the path with the shortest delivery time. The main motivation for this algorithm is to provide a compromise between the previous two algorithms. All steps in MRD algorithm are similar to MRN except *Step 3*, which must be modified as follows:

Step 3: Find the route with the shortest delivery time for $q(s, d)_{max}$ such that minimum number of relay nodes are added. Ensure that the total traffic stored by each relay node is not greater than C_r.

4.4. Example

We now illustrate the performance of the above algorithms using the simple example shown in Figure 5. In this example we have 10 stationary nodes (e-kiosks). Numbers on each path indicate the average message delivery time carried by the bus. We assume relay nodes have already been assigned to intersections B, C, and D. We are interested to route 10 units of traffic from node 1 to node 6 and all relay nodes have sufficient storage capacity for this request. The routing resulted from implementing the above algorithms will be as follows:

- *MRN*: In this case we find the route with the least number of existing relay nodes that is 1 → D → 6; hence the delivery time delay will be 12 and no new relay node is required.
- *MDT:* In this case we find the route with the shortest delivery time between the two nodes, that is 1 → A → 6; hence, the delivery time delay will be 4 and one new relay node is required.
- *MRD*: In this case we find the path with the shortest delivery time requiring the least number of new relay nodes that is 1 → B → C → 6; hence, the delivery time delay will be 6 and no new relay nodes will be required.

Note that in the above example if relay node C has no storage capacity left, MRD will perform similar to MDT.

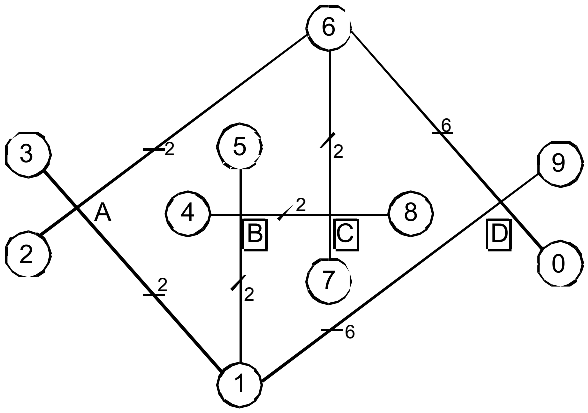

Figure 5. Example of a VWBS network with ten nodes and four cross points. Numbers on each path indicate the average message delivery time carried by the bus.

5. Performance Analysis

In this section we present the experimental results and compare the performance of the aforementioned algorithms. We model *N* nodes distributed in 10 × 10 Km^2. We assume the transmission range of each mobile node (bus) is 10 meter with transmission rate of 1.0 Mbps, moving at a speed of 40 *Km/hr*.

Figure 6 shows the performance of the proposed algorithms in terms of average packet delay as the network load increases. We assume the total number of nodes in the network and the total number of intersections is 20 and 10, respectively. As expected, MDT results in the in the lowest average packet delay when compared with MRD and MRN algorithms. This figure also compares the performance of the proposed algorithms with the case when all intersections have relay nodes with infinite storage capacity. The motivation for this plot is simply comparing the performance of our algorithms with the best possible case and finding the lower limit. We emphasis that the average delay in this case is directly related to the network throughput.

As the storage capacity of each relay node increases, more paths will be available and lower average packet delay is expected, as shown in Figure 7. This figure suggests that the performance of MDT, as the relay buffer size increases, improves compared to MRN and MRD algorithms.

We now look at the case where the accepted delivery time is given and we run each algorithm to obtain the minimum number of relays nodes throughout the network. Figure 8 suggests that for a given value of average packet delay, the MRN algorithm results in lowest number of relay node requirements, offering the best cost-saving solution. Note that MRD algorithm provides a compromise between MRN and MDT algorithms in terms of total number of relay nodes and average packet delay.

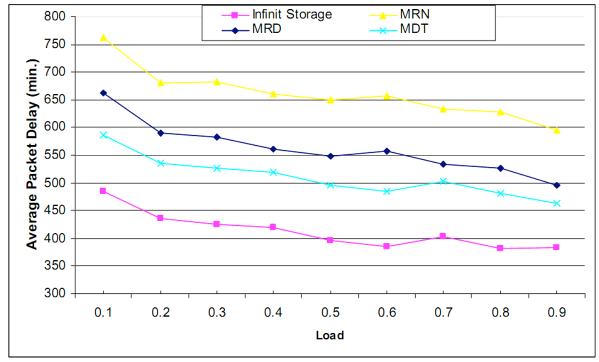

Figure 6. Delay as a function of load; assuming *N* = 20 and total number of intersections is 10.

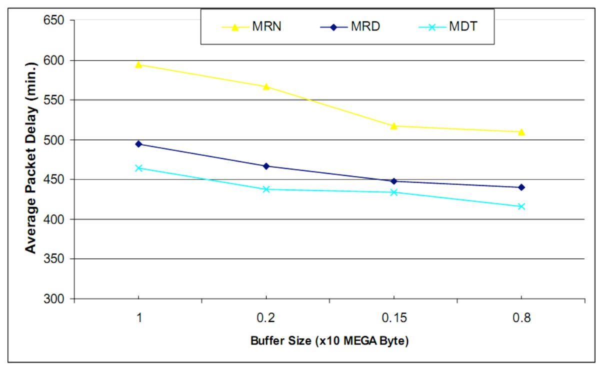

Figure 7. Delay as a function of relay node buffer size; assuming *N* = 15 and network load is 0.45.

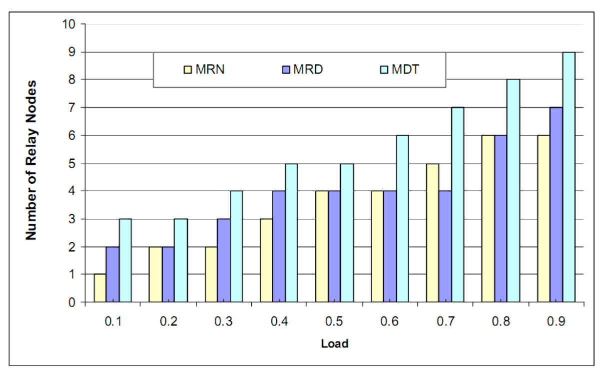

Figure 8. Number of relay nodes as a function of load; assuming *N* = 40, total number of intersections is 12 and accepted average delay is 500 min.

6. Conclusions and Future Work

We presented a DTN-based architecture called Vehicular Wireless Burst Switching. The objective of this architecture is to provide low-cost connectivity for isolated rural areas when high cost and/or environmental conditions prohibit construction of any durable infrastructure and effective traditional wireless technologies. In this preliminary study, we focused on network performance of VWBS as more relay nodes are added. We developed several heuristic algorithms, which can improve the overall network performance and provide solution to relay node placement problem, and compared their performance.

Vehicular Wireless Burst Switching is a challenging topic with open research issues that require innovative approaches and further investigations. It is not clear how the proposed algorithms perform if buses and e-kiosks have limited storage capacity, or how the network performance is impacted if communications between buses and between e-kiosks are allowed. The network performance should be investigated under dynamic traffic assumption, and the topology knowledge about the mobility pattern and speed should be considered.

Study of VWBS performance using various routing protocols, such as geographical routing protocols [12] and node cooperation [13], as well as content storage and retrieval protocols [14] and burst fragmentation [15, 16] are also among other open research issues that must be addressed.

Acknowledgments

Part of this work has been supported by the Group of Networks and Multimedia of the Institute of Telecommunications – Covilhã Lab, Portugal, and by the Euro-FGI Network of Excellence of Sixth Framework Programme of EU.

References

[1] International Telecommunication Union, "World Summit on the Information Society, Geneva 2003 - Tunis 2005", http://www.itu.int/osg/spu/wsis-themes/, accessed at September, 2007.

[2] A. Pentland, R. Fletcher, and A. Hasson, "DakNet: Rethinking Connectivity in Developing Nations", in *IEEE Computer*, vol. 37, 2004, pp. 78-83.

[3] A. Doria, M. Uden, and D. P. Pandey, "Providing connectivity to the saami nomadic community", in *2nd International Conference on Open Collaborative Design for Sustainable Innovation*, Bangalore, India, 2002.

[4] "Wizzy Digital Courier", http://www.wizzy.org.za/, accessed at January, 2008.

[5] W. Zhao and M. H. Ammar, "Message ferrying: proactive routing in highly-partitioned wireless ad hoc networks", in *The Ninth IEEE Workshop on Future Trends of Distributed Computing Systems, 2003*, 2003, pp. 308-314.

[6] A. Seth, D. Kroeker, M. Zaharia, S. Guo, and S. Keshav, "Low-cost Communication for Rural Internet Kiosks Using Mechanical Backhaul", in *ACM MOBICOM*, 2006.

[7] DTNRG, "Delay Tolerant Networking Research Group", http://www.dtnrg.org/wiki, accessed at December, 2007.

[8] K. Fall, "A Delay-Tolerant Network Architecture for Challenged Internets", in *ACM SIGCOMM*, 2003.

[9] V. Cerf, S. Burleigh, A. Hooke, L. Torgerson, R. Durst, K. Scott, K. Fall, and H. Weiss, "Delay-Tolerant Networking Architecture", RFC 4838, April 2007, ftp://ftp.rfc-editor.org/in-notes/rfc4838.txt

[10] "Affordable Internet Access Project for Underdeveloped Communities", http://www.ccsu.edu/technology/aitislab/ghana/index.htm, accessed at January, 2008.

[11] D. B. Johnson and D. A. Maltz, "Dynamic Source Routing in Ad Hoc Wireless Networks", in *Mobile Computing*, Kluwer Academic Publisher, vol. 353, 1996.

[12] I. Leontiadis and C. Mascolo, "GeOpps: Geographical Opportunistic Routing for Vehicular Networks", in *IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, 2007. WoWMoM 2007.*, Espoo, Finland, 2007, pp. 1-6.

[13] A. Panagakis, A. Vaios, and I. Stavrakakis, "On the Effects of Cooperation in DTNs", in *COMSWARE*, Bangalore, India, 2007.

[14] J. Ott and M. J. Pitkanen, "DTN-based Content Storage and Retrieval", in *IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, 2007. WoWMoM 2007.*, Espoo, Finland, 2007.

[15] K. Fall, "Messaging in Difficult Environments", in *IETF/IAB Workshop on Messaging*, 2004.

[16] M. Demmer, E. Brewer, K. Fall, S. Jain, M. Ho, and R. Patra, "Implementing Delay Tolerant Networking", Intel Corporation, 2003.