Exploiting Parallel Networks in Intermittently-Connected Mobile Environemts

Lara Deek, Serouj Jamijian, Sarah Thoubian, Khaled Harras, Hassan Ali Artail
Department of Electrical and Computer Engineering
American University of Beirut
Beirut, Lebanon
{lba07, svj02, sat08}@aub.edu.lb

Abstract – **The rapid increase and proliferation of mobile wireless technologies has led to the rise of new problems that fall under the umbrella of challenged networks, namely, intermittent network connectivity. This diversity in wireless devices, along with their convergence, has granted users access to multiple heterogeneous networks available in parallel. Nowadays, a user generally expects to be connected in all places at all times. To better meet this expectation, we propose a system that takes advantage of intermittent connection opportunities while exploiting other networks available in parallel. We build our system over the parallel networks architecture, ParaNets, which suggests using parallel heterogeneous networks simultaneously as data and control channels. Our system adopts the Data Bundling System for Intermittent Connections (DBS-IC), previously proposed as a stand-alone architecture for intermittent connectivity, and integrates it with the ParaNets architecture. We evaluate our system by fully implementing a ParaNets-enabled version of DBS-IC and thoroughly testing it over emulated network conditions representing multiple networks available in parallel. Characteristics of these networks are adopted based on real-life data on 802.11, 3G cell, and satellite networks. Our results show how minimal exploitation of parallel networks largely optimizes both cost and delivery rate.**

Keywords- DBS-IC; ParaNets or Parallel Networks;

I. INTRODUCTION

The increase in the popularity of the internet in our modern day world has been followed by the development and expansion of mobile technologies that bring the user connection regardless of his/her location/mobility. As a result, the demand of and dependency on constant network connectivity regardless of location is increasing. Alongside this multiplicity of wireless devices is the current convergence of different network technologies. This provides communication alternatives for the user through the use of one or more devices that have access to heterogeneous networks. However, due to user mobility in such technologies, there will be spurts of connection followed or interrupted by periods of no connectivity. In such cases, data may not have completed its transfer before a disconnection occurred which causes the data to be re-grouped or re-transmitted. This case of intermittent connectivity is a prominent issue and will lead to problems such as user frustration, complete failure of applications, as well as large latencies. Standard internet protocols - TCP/IP - were designed based on the assumptions of *good* network conditions. These assumptions are clearly far too optimistic in mobile network conditions. Hence, there is a need for new and innovative architectures that take into consideration the inherent intermittence and increasing heterogeneity of mobile networks

The system we propose takes advantage of the availability of multiple heterogeneous networks in parallel in order to enhance the mobile internet experience for the end-user in a challenged network environment and create an image of constant connectivity. We build our system over the parallel networks architecture, ParaNets [1], which aims to exploit the current convergence of technologies by utilizing alterative networks in parallel with the intermittent wireless connection to best-serve a challenged network. It allows challenged network protocols to operate over heterogeneous networks that are simultaneously available though one or more devices.

We adopt the Data Bundling System for Intermittent Connections (DBS-IC) [2] as our challenged network architecture and integrate it with the ParaNets architecture. DBS-IC addresses and helps to solve intermittent connection problems by providing the user with as much data as possible during the short periods of connection. The system we present and implement is a DBS-IC engine which operates over the ParaNets architecture.

The aim of our project is to evaluate the ParaNets-enabled DBS-IC system by fully implementing it. We identify the tradeoffs between different data transmission strategies in terms of cost, throughput, and time to receive viewable data from varying uses of the WLAN, cellular, satellite, or multiple of these channels in parallel. The maximum cost of data delivery is a user-defined constraint according to which we make network selection decisions. By studying the data delivery process of the proposed system under different data and transmission constraints for the cellular, satellite, and WLAN connections, we identify the effects of using the alternative networks (the cellular and satellite networks) on both cost – which is set by the user – data delivery time, as well as throughput. Furthermore, we tested our results while dealing with multiple parameters and decision issues thereby highlighting the need for investigation of this topic to improve the overall mobile-user experience. Last, these studies are performed for different intermittent connectivity models in order to provide a wider range of study of our system under different environments and in order to arrive to more conclusive results.

We test our implemented system under emulated network conditions. We chose emulation because it provides flexibility in the design in terms of controlling a range of satellite, cellular, and wireless connection characteristics (such as delay, and downlink/uplink speeds) - characteristics of these networks are adopted based on IEEE 802.11, 3G cell, and

LEO satellite networks. Results show a linear to exponential decrease in data transmission time with respect to cost – depending on the connectivity model – due to higher utilization of parallel networks. Minimal exploitation of parallel networks optimizes both cost and data delivery time in comparison to using single networks alone by a factor of 1.73. We also observed significant improvements in terms of throughput.

The rest of this paper is structured as follows: in section II, we discuss the related work; in section III, we present our system components and operation; then, in section IV, we describe our evaluation techniques, followed by results; finally, we conclude in section V.

II. RELATED WORK

In this section of the paper, we will discuss the related work. We begin with work that has addressed challenged network environments and systems that have been designed to deal with such challenged environments. We also refer to research that has dealt with communication over satellite and cellular network and, finally to papers that propose systems or solutions to deal with intermittent web browsing.

A challenged network was first defined by Fall in [3] as a network that experiences mobility, frequent disruption of network availability, high round trip time, and high packet drop rate. Networks characterized by one or more of these challenges are called *Delay Tolerant Networks (DTNs)* [5]. Researchers have studied DTNs with a major focus on routing issues in such extreme environments [3]. While our system focuses on delivering bundled data from a wired stationary device to a mobile node, the same bundling and opportunistic delivery concepts are applied in DTNs. However, the recent focus and existing research on DTN's has been shifted towards addressing and studying transport layer issues in extreme networking environments as well as focusing on forwarding techniques and routing algorithms, which our system is not concerned with. Our project takes a different approach from DTN's by taking advantage of the safely routed messages instead and presenting a study of the availability and use of alternative network paths in addition to WLAN in the data transmission process.

As described in the introduction, DBS-IC is an architecture for intermittent connections that takes advantage of periods of connectivity to provide the user with as much viewable data as possible. It predicts which data the user will request and prefetches the data before the user explicitly requests it - thereby attempting creating an image of constant connectivity. According to an article on how predictive prefetching improves World Wide Web latency [4], predictive prefetching significantly reduces the average access time. Additionally, DBS-IC proactively takes advantage of the periods of connection by grouping user-requested data into a packet called a *bundle* and delivering it to the user incrementally in the form of *mini-bundles*- which are pieces of the complete data bundle.

ParaNets is a recently proposed architecture for challenged networks which utilizes alterative networks in parallel with the intermittent wireless connection to best-serve a challenged network. By taking advantage of other networks of communication such as the cellular and satellite networks and in the absence of the traditional wireless medium, the period of communication between nodes increases; connectivity and communication can be carried out through the cellular and satellite networks which have wider ranges. In ParaNets, the parallel cellular and satellite networks are treated as channels that can be used depending on the size and type of the message. ParaNets simulation results on top of the Delay Tolerant Mobile Network (DTMN) have shown that the use of cellular and satellite networks as alternative channels which support the challenged wireless network significantly improve the performance of the challenged network by providing alternative paths when the WLAN connection is broken.

Research on the integration of heterogeneous networks - namely cellular, satellite, and WLAN networks - has focused mostly on intersystem handoffs and on battling inherent TCP/IP unsuitability to challenged environments [6], [7], [8]. CAP [9] and APHOHN [10] are examples of architectures built for such purposes. However, the networks are not utilized to best serve the intermittently-connected network by factoring application layer parameters into decision making – such as user preferences, size and type of data, or cost.

The ParaNets-enabled DBS-IC system distinguishes itself from previous work in a number of ways. We examine the use of parallel heterogeneous networks to improve the performance of a challenged network when there has been little to no research in that respect. In this work, *Exploiting Parallel Networks in Intermittently-connected Mobile Environments*, we try to create an image of a more ubiquitous connection by making use of alternative parallel networks to send data over. We incorporate user-defined parameters, namely, cost, into the network selection process rather than depending only on the size and type of the message. In so doing, we use the cellular and satellite connections to deliver data as well rather than just control information.

III. SYSTEM ARCHITECTURE

In this section, we present an overview of the ParaNets-enabled DBS-IC. We first describe the system components of our design and their overall operations. Then, we follow with a detailed description of our system architecture by discussing our decision criteria based upon which we send information over the available heterogeneous networks.

A. System Components and Operation

Our suggested system incorporates ParaNets into the DBS-IC architecture. The major components of our selected design are the components of the DBS-IC system – namely the stationary agent (SA), the mobile agent/s (MA), and the access point (AP) – as well as the cellular base station, and the satellite. The generic architecture of our proposed system with multiple user support is depicted in Fig.1. The SA is an entity with storage and processing capabilities that is connected to the Internet; it can be represented by an Internet Service Provider (ISP). The SA prefetches the information requested by the MA/s: it contacts the file servers, e-mail servers, and website servers and collects and stores the information until the MA is in a situation to receive its requested information – i.e. is connected. The information that the SA will prefetch for the MA depends on both a predictive method whereby the SA keeps record of the information the user has requested to view in past sessions and a method whereby the MA informs the SA of what it would like to access.

The access point provides WLAN (802.11) connection in a restricted range, resulting in connection intermittence. On the other hand, the cellular base station and the satellite provide cellular and satellite connections in a wider range and hence both of these connection are assumed to be ubiquitous in our architecture. The details and characteristics of the WLAN, cellular, and satellite connections that we emulate are

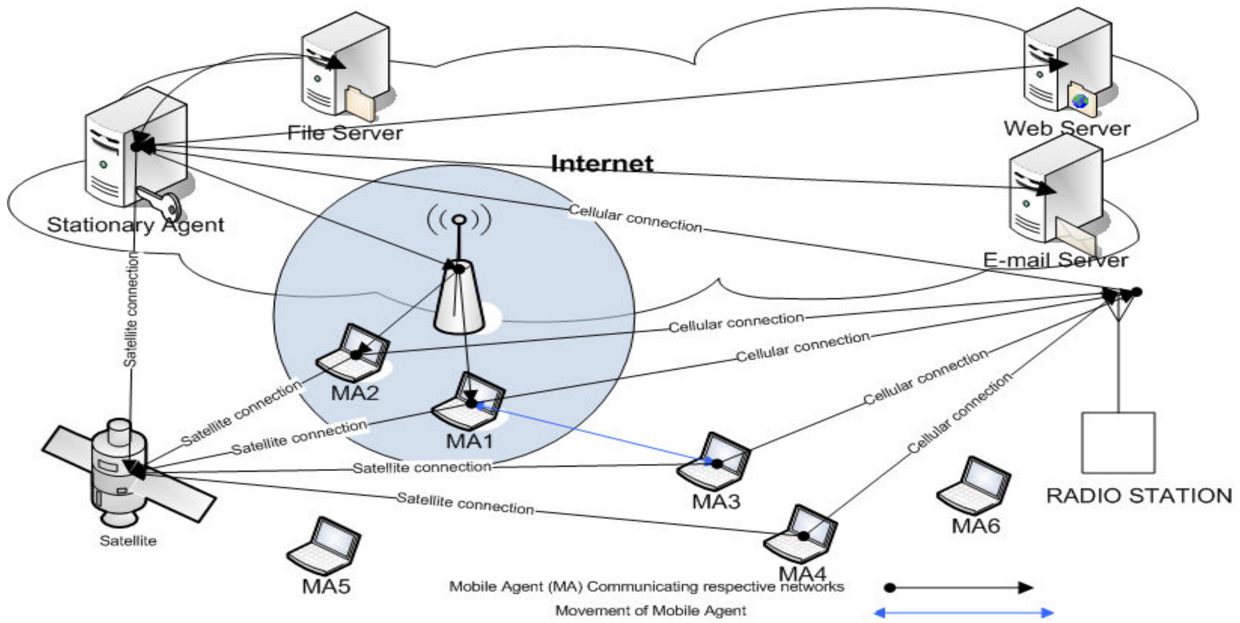

Fig. 1. System Architecture of DBC-IC with ParaNets

explained in the *Evaluation Setup and Environment* section of the *System Evaluation*. The cellular and satellite connections are used as alternative networks over which to communicate.

B. Design Criteria

In this section of the paper, we discuss some of the important parameters in the DBS-IC architecture. We then list our assumptions and describe the design criteria of our system.

Some of the important DBS-IC parameters that are most relevant to our work are:

Priority: A user-defined parameter that is communicated from the MA to the SA during connection establishment. It determines which mini-bundle is deemed more important by the user, and accordingly, it is used by the SA to send the user's more important data first.

Type of Data: A User-defined parameter which identifies the size of the data to be sent.

Intermittent Connectivity Model: A network parameter which indicates the average connection and disconnection periods based on the speed of the MA. The faster the MA is moving, the smaller the connection periods, and the more the system has to rely on alternative networks to optimize data transmission.

In our proposed system, we assume ubiquitous cellular and satellite connections. We are not concerned with horizontal handoffs within either of these two connections, whereas horizontal handoffs in the IEEE802.11 network are taken into consideration.

The criteria we have used to determine the extent of utilization of each network are the following:

Cost: A user-defined parameter which informs the SA of the cost that the user is willing to incur to obtain data. This metric determines the frequency of use of the costly communication networks- namely, the cellular and satellite. The less the cost, the less we rely on the alternative networks to transmit data, and the less the overall cost. In order to incorporate ParaNets into the DBS-IC architecture, we introduced a decision making process for network selection based primarily on the user-defined cost. For low cost, we favor the wireless channel and assign it the responsibility for delivering most of the mini-bundles. As the cost increases, more and more of the responsibility is relayed to the cellular and the satellite channels as shown in Fig.3.

Characteristics of Satellite and Cellular Connections: In [11], the downlink data performance of guaranteed transmission in LEO satellite is compared with that in cellular architectures. It was found that the cellular network had a higher maximum stable throughput and a lower end-to-end delay than the satellite. Due to these distinctions between the satellite and cellular networks, we use the cellular connection more frequently for data transmission rather than the satellite for a given user-defined cost metric.

IV. SYSTEM EVALUATION

In this section, we present an evaluation of the ParaNets-enabled DBS-IC architecture. The primary goal of our evaluation is to study the implementation strategies and improvements that ParaNets brings to DBS-IC. We begin by discussing the evaluation setup and environment: we describe the technologies we use to perform our testing, as well as the setup and methods; we discuss the reasons behind our choice of network parameters and environment for evaluation; then, we present our cases for data transmission: control cases and cases for advanced evaluation of our system over heterogeneous networks. Finally, we discuss the set of results that achieved our desired goals.

A. Evaluation Setup and Environment

Our System setup is displayed in Fig. 2 and detailed specs of our system hardware are listed in Table II. The SA is run on a machine with a stable connection to the internet, with four 100 Mbps full-duplex switched Ethernet connections. The MA is located on an intermittently connected machine with three Ethernet network cards. The MA is connected to the SA through an 8-port switch. Each of the SA and the MA has three interfaces connected to the switch where each interface mimics the characteristics of the satellite, cellular, or WLAN connection. In order to emulate the satellite, cellular, and WLAN connection characteristics, we have used the Linux built-in traffic shaper. We modify the delays and uplink and downlink data rates for each of our networks according to Table III using the commands in Table I. For the delays, we use normal distribution values which realistically approximate delays in real-life conditions.

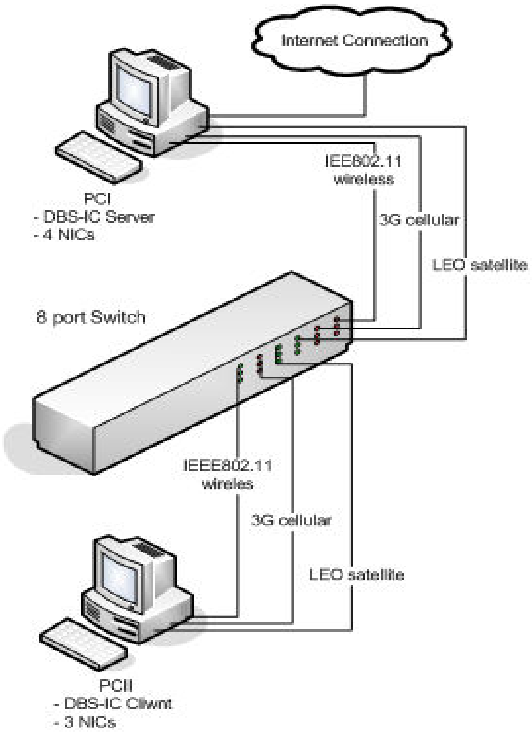

Figure 2. Testing Setup

By monitoring the effectiveness and behavior of ParaNets-enabled DBS-IC, we determine how to improve and assign transmission of data to each of the heterogeneous networks. Therefore, we conducted a series of runs for a set of scenarios to establish the over-all pattern of the effects of sending types of data (of particular size) on the time it takes to receive the data, the cost, and throughout. After an over-all pattern is established, we deduce the functionality of each network and the improvement such a setup would bring to DBS-IC. We implement ParaNets-enabled DBS-IC over emulated network conditions that mimic heterogeneous networks running in parallel. We chose to implement our system over emulated networks in order to obtain more realistic results and to create a more controllable and flexible environment for testing. We conducted our tests in the lab and used the results obtained in previous driving test studies to accurately and realistically choose our parameters (Table III).

In our setup, the SA gathers and bundles the information (files, e-mails, and web pages) and sends them to the MA. The content of the data that the SA is bundling is irrelevant for our purpose. The main concern for our setup is for the bundle to be of a particular size and for it to be prefetched at the moment the MA requests the data. Bundle size is the size of the compressed data that is transmitted between the SA and the MA. This bundle is divided into a specific number of mini-bundles that is varied between 1 and 10 mini-bundles.

The parameters we use are listed in Table III and are divided into two main types: user-defined parameters and network parameters.

For the WLAN connection, the average round trip time between the MA and the SA is measured to be around 68 ms when the MA is placed in a remote location and 2 ms when the MA is placed in the same lab with the SA. As determined in previous work [2], the round trip time affects the functionality of the mini-bundles and contributes greatly to the communication overhead associated with mini-bundles. We mimic intermittent connectivity by examining different intermittent connectivity models with unique connection and disconnection durations, as discussed by Gass et al. [12]. We select two intermittent connectivity models as listed:

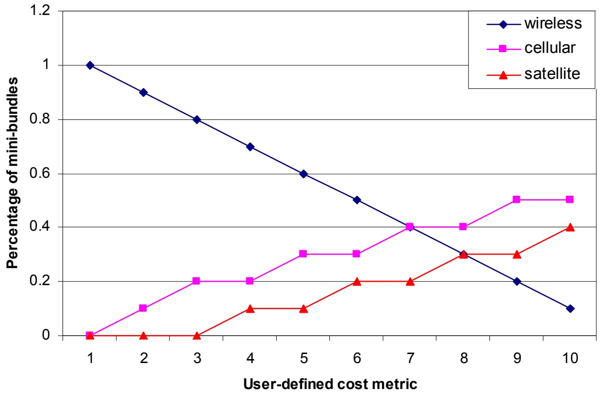

Figure 3. Data transmission schedule – percentage of data to transmit over each network depending on the user-defined cost

1) *Downtown Driving Model:* This model is characterized by a connection period of 40 seconds followed by a disconnection period of 15 seconds.

2) *Downtown Walking Model:* This model is characterized by a connection period of 120 seconds followed by a disconnection period of 20 seconds.

We emulate the WLAN connection based on the IEEE 802.11 standard. The most popular 802.11 standards are 802.11a, 802.11b, and 802.11g where 802.11g is the most recent. According to [12], 802.11 technologies can be used for in-motion networking; they present a measurement of 802.11b networking involving a user in a moving car and a wireless access point (AP). Since 802.11g is backwards compatible with 802.11b and is in wide use nowadays, we emulate the characteristics of 802.11g connection as listed in Table III.

For the cellular connection, we emulate 3G characteristics of a cellular network [6], [13]. The alternative to 3G would be 2G. However, current research claims that future-generation wireless networks focus on 3G [14], [15]; on the other hand, 2G mobile users are decreasing and are becoming less widespread. The characteristics of a 3G network are listed in Table III.

For the satellite connection, we emulate the characteristics of Low Earth Orbit Satellites (LEO's). LEO's are closest to the Earth and therefore have the lowest delay among satellite types. Since delay has significant effect on the experience of the internet user, LEO satellites are preferred for internet connectivity. Geosynchronous Earth Orbit Satellites (GEO's) achieve better utilization of the bandwidth for large file transfers, whereas LEOs are preferred for small file transfers [16]. Since our system exhibits user mobility, we are assuming relatively small file transfers (a maximum of 40MB). Hence, LEOs are more suitable for our needs. The LEO satellite characteristics we assume in our work are listed in the Table III and are based on previous work [16], [17].

The metrics we use to evaluate the performance of the ParaNets-enabled DBS-IC system are the following:

Data Delivery Time: The time between when the user requests to view particular data and when the data is actually viewable on the MA. This is quantified as the average time for the user to receive a mini-bundle.

Data Throughput: The rate at which data is being received by the MA.

B. Results

We ran the modified DBS-IC system for different user-defined costs, varying the cost from 1 (low cost) to 10 (high

TABLE I. TRAFFIC CONTROL COMMANDS

Controlled Parameter	Command
Downlink Speed	tc qdisc add dev $IF[1] root handle 1: htb default 30 tc class add dev $IF[1] parent 1: classid 1:1 htb rate $DNLD[2]
Uplink Speed	tc qdisc add dev $IF[1] root handle 1: htb default 30 tc class add dev $IF[1] parent 1: classid 1:1 htb rate $UPLD[3]
Delay	tc qdisc add dev $IF root netem delay $DELAY[4] $ERROR[5] $PROBABILITY-DIST[6]

[1]$IF: network interface
[2]$DNLD: download limit
[3]$UPLD: upload limit
[4]$DELAY: nominal delay
[5]$ERROR: maximum delay variation about nominal value
[6]$PROBABILITY-DIST: probability distribution of delay

TABLE II. HARDWARE SPECIFICATION

Hardware Components	SPECS
Network Interface Cards	VIA technologies, Rhine-III, 10-100Mbps speed Fast Ethernet Adapter
Operating System	Fedora Linux Core 6
PC Desktop Computers	DELL Precision 340, Intel Pentium 4 - 2.53GHz, 128 MB

TABLE III. NETWORK PARAMETERS

Parameter		Value Range	Nominal Value
Bundle Size		10 MB to 40 MB	20 MB
Number of Mini-Bundles		1 to 20 mini-bundles	10 mini-bundles
Mini-Bundling Technique		Merged	Merged
Prefetched Data		100%	100 %
WLAN (802.11g)	Intermittent Connectivity Model	Downtown, Suburb, Highway, Walking	Downtown
	Connection Duration	15 sec to 120 sec	40 sec
	Disconnection Duration	10 sec to 30 sec	15 sec
	Received Channel Power Indicator (RCPI)	0 – RCPI_Max	RCPI_Max
	Data Rate	19 – 54 Mbits/s	54 Mbits/s
	Round Trip Time (RTT)	2 ms to 68 ms	(60 ± 10) ms
Satellite	Round Trip Time (RTT)	150 ms to 300 ms	(200 ± 50) ms
	Data Rate	5 – 10 Mbits/s	10 Mbits/s
Cellular (3G)	Received Signal Strength (RSS)	0 – RSSI_Max	RSSI_Max
	Round Trip Time (RTT)	80 ms to 100 ms	(100 ± 25) ms
	Data Rate (Downlink)	14.4 Mbits/s	14.4 Mbits/s
	Data Rate (Uplink)	5.8 Mbits/s	5.8 Mbits/s
Information Type		Type of Data – Control messages	-

TABLE IV. USER-DEFINED PARAMETERS

Parameter	Value Range	
Type of Data	File – Web – E-mail	
Priority	1 - 20	
Cost	Metric	1 – 10
	Commercial Estimate (¢/data transmission)	0 - 250

TABLE VI. BASE CASES AVERAGE BUNDLE DELIVERY TIME

Mobility model	First base-case: wireless only	Second base case: cellular only
Downtown walking	538 sec	413 sec
Downtown driving	674 sec	

TABLE V. CELLULAR/SATELLITE COMMERCIAL COSTS

Parameter	Value Approximation	
Network connection	Cellular	Satellite
Cost (¢/sec)	0.5	0.9

cost), while keeping the other parameters set to their nominal value. We measured the average time to receive a mini-bundle at the client from multiple runs for each cost. We ran our tests for one MA over the the two mobility models described above, namely the downtown walking model and the downtown driving model. A subset of the results is shown in Fig. 4 – 7. We compare these results against two selected base cases as shown in Table VI; the first base case is the ParaNets-disabled DBS-IC system which makes no use of the parallel networks available, thus transmitting all the data over the intermittent IEEE802.11 network. In the seocnd base case, we use a different strategy whereby all the data is transmitted over the cellular network. Our advanced strategy generates a data transmission strategy - as described in the *System Architecture* section and shown in Fig. 3 – whereby the mini-bindles are divided over the three networks based on the user-defined cost as well as the benefits of each network.

Our results affirm that there is an apparent trade-off between the time to receive the mini-bundles and the cost incurred. In Fig. 4 we observe that as cost increases, the total data delievery time exhibits linear decrease in the case of the downtown driving model and almost exponential decrease in the case of the downtown walking model. This is because for low costs, the data retrieval time is highest, since the costly networks are being utilized minimally and most of the data is being transmitted over the intermittent network.

Table VI shows our base case results. We measured the average data delivery time per bundle when operating DBS-IC over one network – wireless or cellular – each at a time. Our measurements show that low-cost ParaNets-enabled DBS-IC delivers the data approximately 2.17 times faster than the ParaNets-disabled DBS-IC system for the downtown driving model and almost 1.73 times faster for the downtown walking model. Similar improvements are observed in comarison to our second base-case which uses the cellular network only. This strategy is out-performed by low-cost ParaNets enabled DBS-IC both in terms of cost and in terms of data delivery time.

Another important metric that we measured to evaluate our system is data throughput. The results in Fig. 7 show that as cost increases, the ParaNets-enabled DBS-IC bridges the gap between the throughputs experienced in the two mobility models. Hence, at high costs the system experiencing higher intermittence (the downtown driving model) achieves throughput comparable to its more stable counterpart (the downtown walking model). Therefore, ParaNets-enabled DBS-IC users can go at faster speeds with negligible deterioration in throughput provided they are willing to incur the extra cost.

V. DISCUSSION

From the results obtained, we can confirm and quantify the tradeoff between time and cost from varying utilizations of the parallel networks in the implemented ParaNets enabled DBS-IC system. In this section of the report, we propose a data transmission strategy that optimizes the data transmission process by minimizing two pivotal parameters: total time (to receive the bundle) and total cost (of using costly networks – namely satellite and cellular). We suggest deriving equations for both total time and total cost and a constraint, all in terms of three variables: the size of data sent over wireless “w”, cellular “c”, and satellite “s” respectively. By optimizing these variables with respect to both time and cost, a balanced tradeoff between time and cost will be achieved and hence a more controlled strategy of using parallel networks.

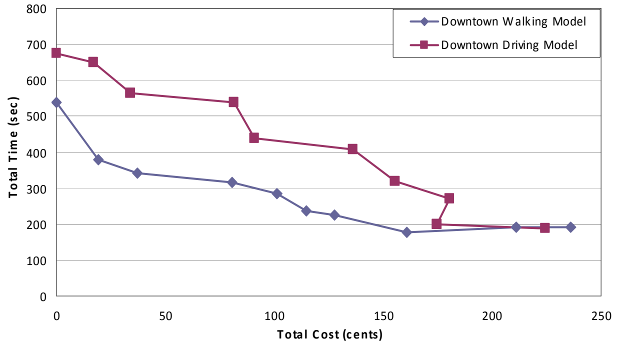

Figure 4. *Data retrieval time* vs. *cost*

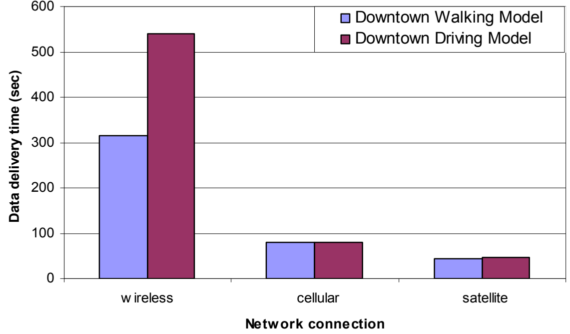

Figure 5. Data delivery time over wireless, cellular and satellite for low cost (4)

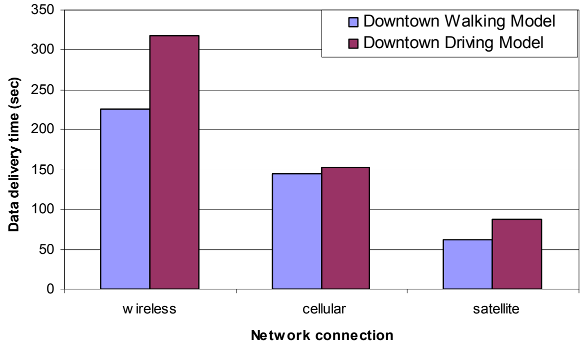

Figure 6. Data delivery time over wireless, cellular and satellite for high cost (7)

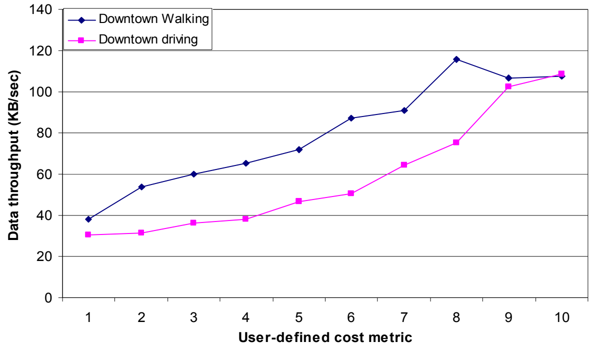

Figure 7. *Data throughput* vs. *cost*

VI. CONCLUSION

In this paper, we have presented and fully implemented an integrated system of ParaNets with the DBS-IC architecture and presented a strategy of using parallel networks for data transmission. We identified the tradeoffs between different transmission scenarios and observed that ParaNets-enabled DBS-IC out-performs scenaios that utilize only one network both in terms of cost and data-retrieval time – even with minimal exploitation of the alternative networks. Our results also show that the ParaNets-enabled DBS-IC system exhibits a significant tradeoff between cost and data delivery time. We can conclude that incorporating ParaNets into the DBS-IC architecture leads to more efficient data transmission and creates more effective opportunities for communication during the periods of disconnection of the challenged network.

For future work, the ParaNets-enabled DBS-IC system would benefit from a more sophisticated and intelligent decision-making procedure that optimizes the data transmission process based on additional parameters - such as by incorporating the client's mobility rate into the selection of the data-transmission channels.

Another important aspect to be studied is the scalability of the ParaNets-enabled DBS-IC, which can be quantified by the load that is placed on the SA in relationship to the number of MA/s that have access to it and are using its services.

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