The Ad Hoc Return Channel: a Low-Cost Solution for Brazilian Interactive Digital TV

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Abstract

The upcoming terrestrial digital television technology brings a new class of services to traditional TV sets. A set-top box may, for example, access the Internet and send e-mail. The interactive return channel makes these new services possible. This channel allows TV viewers to interact by sending data back to the TV broadcaster. In this article, we analyze the viability of a wireless ad hoc network to implement the return channel. For this purpose, an ad hoc network is a low-cost and flexible solution. We evaluate the performance of an ad hoc return channel using the IEEE 802.11 wireless technology for different Brazilian geographical scenarios. The results show that ad hoc networking is a promising solution for the return channel of Brazilian interactive digital TV.

1 Introduction

Television is a high penetration vehicle for distribution of media content. One key reason to its great success is that spectators receive easy-understanding information. Terrestrial broadcast TV uses a base station that transmits radio frequency signals using high-positioned antennas. Thus, signals are efficiently broadcast, within a transmission range that covers millions of receivers in dense-populated regions.

The two basic functions of TV are entertainment and dissemination of information. Terrestrial digital TV, however, can offer a variety of new functionalities. Digital TV improves the quality of audio and video streams and enables new services such as e-government and Internet access. Today, the Brazilian government is making a strong push to define its digital TV standard. The Brazilian Digital TV System research project[1] was launched to

[1]Started in March 2005, this project is a consortium of universities and enterprises to standardize the Brazilian Digital TV System. More information is available at http://sbtvd.cpqd.com.br

investigate the technologies that can be used by digital TV and the facilities which digital TV can offer.

In Brazil, more than 90% of residences have a TV set, but less than 10% have Internet access [1]. Many Brazilians are close to the poverty line and have restricted access to interactive media. Therefore, one important aspect of the Brazilian digital TV is that it must be used to help the inclusion of low-income people into digital world, at low cost and with high penetration. For many years, TV learning has been a success in Brazil, especially in the education of the illiterate population. With digital TV, a student will be able to interact with the teacher. Other key applications for low-income populations are in the area of health care. For example, a citizen will be able to book a medical appointment using the TV set-top box.

The new services of digital TV are possible with the adoption of an interactive channel, also called a return channel. This channel allows TV spectators to interact by sending data back to the TV broadcaster. Different technologies can be used for the return channel, such as ADSL, CDMA, etc. In this article, we analyze the viability of an ad hoc community network to build a shared return channel. In this solution, the TV set-top boxes are nodes of the community network and all the traffic is routed to a gateway that forwards the traffic to the TV broadcaster. The main advantages of an ad hoc return channel are: an ad hoc community network does not require a telecommunication infrastructure, multihop communications can reach long distances, and other Internet services can be provided with no additional costs.

The connectivity and the capacity of ad hoc networks is the subject of many studies [2, 3], but most performance evaluation studies consider homogeneous ad hoc networks. Our analysis is distinguished by the characteristic that all traffic is forwarded to and from a specific node, the gateway, which becomes the bottleneck of the network. Another characteristic is the activity period of a node. As it is associated with a TV set, we can expect that some nodes will be off-line during the day. We analyze connectivity to learn how many nodes must be on to guarantee a minimum "infrastructure" to provide access to all network users. We study network capacity by looking at the saturation throughput and the impact of multiple hops.

This article is organized as follows. Section 2 presents several technologies for implementing the return channel for digital TV. Section 3 introduces the ad hoc return channel. Section 4 describes the Brazilian reference scenarios. The simulation parameters and the results are shown in Section 5. Finally, Section 6 concludes this work and presents some future directions.

2 Return Channel Technologies

The Brazilian government selected five eligible technologies for the digital TV return channel. Among these, there are wired and wireless technologies, as illustrated in Figure 1. This section describes CDMA 1xEV-DO, WiMAX, PLC, and ADSL. The IEEE 802.11 Ad Hoc solution is detailed in Section 3. Table 1 summarizes the main characteristics of the five technologies, considering the present Brazilian scenario. In this table, availability refers to network connectivity.

Table 1: Characteristics of the technologies for the Brazilian return channel.

	IEEE 802.11 Ad Hoc	**CDMA 1xEV-DO**	**WiMAX**	**PLC**	**ADSL**
Subscription	No	Yes	Yes	Yes	Yes
Infrastructure cost	No infrastructure, only the gateway	High	Medium	High	High
Network Availability	High with at least 20% of nodes on	High	High	High	Very high
Transmission rate (Mbps)	Up to 54 depends on # of users and # of hops	Up to 2.4 downlink 0.153 uplink	Up to 70 depends on # of users	Up to 200 depends on # of users	Up to 24 downlink at 600 m 4 downlink at 3.7 km 1 uplink
Range	hundreds of meters	tens of kilometers	tens of kilometers	hundreds of meters	few kilometers

2.1 CDMA 1xEV-DO

The CDMA2000 standard was designed for third generation (3G) cellular networks. CDMA2000 1xEV-DO (Evolution-Data Optimized) is an evolution tailored to support data applications, such as VoIP, HTTP, and file transfers. It defines a downlink from base station to access terminals and an uplink in the reverse direction. Assuming that, in Internet applications, most data flows towards the users, the downlink and uplink transmission rates are asymmetric. The commercial Release 0 of CDMA2000 1xEV-DO achieves rates up to 2.4 Mbps on downlink and 153 kbps on uplink using single 1.25 MHz CDMA carriers. Revision B will reach rates up to 73.5 Mbps and 27 Mbps on the down and up links, respectively. For the downlink, it uses TDM and a fair scheduling algorithm to assign time slots to users. For the uplink, it applies a CDMA scheme. It also provides adaptive rate, congestion, and power control mechanisms to improve network efficiency [4].

The use of CDMA as the digital TV return channel requires base stations to provide connectivity to users. Although cellular networks typically have higher ranges than other wireless LAN technologies, such as IEEE 802.11, every set-top box must be directly connected to a base station, which demands a costly infrastructure. Especially in dense urban scenarios, a higher number of base stations are needed adding to expenses. Besides, CDMA operates in a licensed band reserved for cellular telephony companies. Hence, the CDMA return channel requires commercial agreements between TV broadcasters and cellular telephony companies.

2.2 WiMAX

The IEEE 802.16 standard [5], or WiMAX (Worldwide Interoperability for Microwave Access), is a wireless technology for Metropolitan Area Networks. WiMAX was developed to solve the last-mile problem, offering an alternative to DSL and cable broadband access technologies. IEEE 802.16 defines two systems: WirelessMAN, which uses licensed bands, and WirelessHUMAN, which employs license-free bands. The main mode of operation is point-to-multipoint, where a base station provides access to several clients with up to 70 Mbps PHY rate. A WiMAX tower services users within tens of kilometers. Every service, even those that are not connection-oriented, is mapped to a connection, thus easily supporting different levels of quality of service (QoS). WirelessMAN has four distinct PHY layers. The first, WirelessMAN-SC, uses single-carrier modulation and operates on frequencies between 10 and 66 GHz. Such high frequencies require line of sight communication, being used to interconnect WiMAX towers. The other three WirelessMAN PHYs operate primarily on 5-6 GHz licensed frequencies. WirelessMAN-SCa is also based on single-carrier modulation, whereas WirelessMAN-OFDM and OFDMA are both based on OFDM modulation. The PHYs operating at frequencies below 11 GHz allow non-line-of-sight communication. WirelessHUMAN uses one of the last three PHYs, but on license-free frequencies.

The OFDM PHY also supports a mesh mode, where a centralized or distributed scheduling system coordinates the nodes transmissions. The distributed mode is similar to IEEE 802.11 ad hoc mode. The point-to-multipoint mode centralizes the traffic in the base station, increasing the infrastructure costs of the system, unlike the ad hoc solution for the return channel.

2.3 PLC

Most work in PLC (PowerLine Communications) is concentrated in low-voltage (LV) networks, such as in-home and last-mile technologies. The in-home technology is concerned with data transmission using residential electrical wiring. Currently, its principal standard is HomePlug Audio Visual (HomePlug AV [6]), which reaches data rates up to 200 Mbps. HomePlug AV uses a mix of TDMA and CSMA/CA. TDMA reserves the medium, ensuring a limited delay for interactive applications. On the other hand, CSMA/CA is used for reliable file transfers to fully use the medium capacity during bursts of data. To deal with the constraints of the medium, such as attenuation, noise, and impedance variations, HomePlug AV uses advanced signal processing and FEC techniques. Nevertheless, the electrical medium still represents the major obstacle to high-speed data communication, since it was not designed to carry data.

HomePlug AV can be extended to medium-voltage-low-voltage (MV-LV) transformers to provide network access in the last mile. Nevertheless, the size of the network depends on the number of users, the distance of the residences, and the type of cables in the neighborhood. Using PLC as a return channel profits from the already available electrical infrastructure. In Brazil, however, the quality of electrical installations is extremely variable. Especially in underserved communities, the electrical infrastructure is precarious and includes many illegal installations. Thus, changing the entire infrastructure or remodeling it would be cost prohibitive. Moreover, the use of the electrical infrastructure also implies financial agreements with the electricity companies. An external link to a backbone can be provided at the transformer by fiber optic, wireless radio, Gigabit Ethernet, or medium-voltage power lines. No matter which technology is used in the backbone, additional expenses are needed to introduce equipment for signal conversion on each one of the numerous transformers of a neighborhood.

2.4 ADSL

The xDSL (Digital Subscriber Line) term refers to a family of technologies which use POTS (Plain Old Telephone Service) copper-wire lines to carry data. ADSL (Asymmetric DSL) [7] is currently the technology most used for last-mile Internet access. The term asymmetric refers to the different capacities of the uplink and downlink as in PLC. ADSL was first designed with video on demand and related services in mind, where the amount of data transferred to the user is normally larger than the upload traffic.

ADSL uses Frequency Division Multiplexing (FDM) to isolate the POTS, uplink and downlink traffic. The basic idea of ADSL is to reserve the frequencies from 0 to 25 kHz for telephone service. Then, depending on the standard, the frequencies from 25 kHz to 2.2 MHz are used to carry data. The frequency band reserved for the downlink is larger than that reserved for the uplink, thus allowing higher downlink bit rates.

Standard ADSL uses the frequency band up to 1 MHz on the copper wires, with 256 downlink sub-channels. Theoretically, each sub-channel can carry up to 60 kbps, leading to a maximum downlink rate of approximately 15 Mbps. Nevertheless, telephone wiring imperfections prevent transmission at such rates. Typical implementations of Standard ADSL operate at 1.5 to 9 Mbps, depending on the quality of the line and on the distance from the DSLAM (DSL Access Multiplexer), the equipment which has to be installed in the telephone company central office. Nevertheless, DSL systems standards are evolving. ADSL2+ reaches up to 24 Mbps downlink and 1 Mbps uplink. The latest evolution is called VDSL (Very high speed DSL), which uses a 12 MHz band and achieves transmission rates up to 55 Mbps.

The use of ADSL as a return channel is technically viable. Nevertheless, there are disadvantages. It requires investment from the telephone companies, which are not necessarily involved in the digital TV business. Then, POTS service in Brazil does not reach the underserved population. One reason is the lack of widespread infrastructure. The second is that, today, POTS (and thus ADSL) access is paid for through a monthly subscription, which poor people cannot afford. Further, TV broadcasters may not be willing to depend on the phone company to implement their return channel. Thus, even if higher transmission rates could be achieved by using ADSL technology, a lower cost ad hoc solution could still be a winner.

3 The Ad Hoc Return Channel

The IEEE 802.11 ad hoc mode eliminates network infrastructure, and consequently stations must communicate directly between each other. If the destination is out of range, the neighbors cooperate as routers and forward data packets over multiple hops. Hence, the ad hoc mode represents a flexible and low-cost solution for the return channel. Other advantages of the ad hoc mode are self-organization and self-configuration.

This article analyzes the ad hoc return channel based on the IEEE 802.11g standard, which reaches data rates of up to 54 Mbps [8]. IEEE 802.11 operates at 2.4 GHz, a license-free ISM band. This also helps keeping the cost low. In the ad hoc return channel, a forwarding node is a TV set-top box or access terminal. There is also a gateway, which connects the community network to the Internet and to the TV broadcaster. Every node must be able to communicate with the gateway, directly or through multiple hops. The signal of the TV broadcaster is sent using terrestrial diffusion and the interactivity information must go back through the return channel, as depicted in Figure 2. Access terminals provide network connectivity, forwarding data packets to the gateway. Obviously, the gateway may become a bottleneck, in which case more gateways can be incrementally deployed. These gateways will be installed in low-income communities by a non-governmental organization, a community organization subsidized by the government, or by the TV broadcasters association. It is worth mentioning that about 50% of the Brazilian economy is informal and low-income population cannot afford monthly fees. Using the ad hoc return channel the user has neither a fixed cost nor a subscription. Hence, the advantages of an ad hoc return channel are four-fold. First, it provides the required characteristics for the main interactive TV applications. Second, ad hoc networking is inexpensive, flexible, and can be incrementally deployed. Third, even if low-income people have to buy a set-top box, they do not have to pay monthly subscription, which is very important in the Brazilian context. Fourth, community ad hoc networks can be used in underserved regions to bring digital inclusion to thousands of citizens.

Despite its low deployment cost, the use of an ad hoc network as a return channel has a drawback, namely, connectivity. Unlike the other technologies, the ad hoc network may not be available because it depends on multihop communications. As the nodes rely on each other to send information to the gateway, these must be a minimum number of set-top boxes turned on to guarantee that users are connected to the gateway. The connectivity of the ad hoc network depends on the number of access terminals in a region, their transmission range, and the interval of time that they are on. The number of access terminals is related to the population density in the region. Also, we assume that residences will have, at least, one access terminal. This is already true for analog TV in Brazil [1] and will probably be true for the digital TV in a few years. The Brazilian government will finance the purchase of the set-top boxes with embedded IEEE 802.11, expecting a large scale production cost to be as low as US$100.00. Another key aspect of connectivity is the interval of time during which the terminals are on. Depending on the habits of the viewers, during a high audience TV show, a large number of terminals are expected to be working. Therefore, an aspect, which we have investigated, is how the fraction of access terminals that are on influences the connectivity of the network. Another important issue is the throughput that can be achieved by ad hoc nodes. IEEE 802.11 uses CSMA/CA to control the medium access. In CSMA/CA, nodes within transmission range of each other contend to transmit data. Hence, increasing the number of terminals results in lower per-node throughput. The different transmission ranges obtained with the possible IEEE 802.11 data rates also affect the throughput. Using lower data rates, the SNR tolerated is lower and consequently the transmission range increases.

4 Brazilian Reference Scenarios

Brazil is a continental-size country and, consequently, has different regions with several demographic, geographic, and social characteristics. In a previous work [9], we chose five scenarios to represent this diversity. In this article, for the sake of brevity, we consider two scenarios: a highly populated urban region with residences in mountains and a highly populated urban region with vertical residences.

The parameters of the two reference scenarios are based on real data obtained from the Brazilian Institute of Geography and Statistics[2]. The first scenario represents Rocinha, the most populated *favela* (slum) of Rio de

[2]Data extracted from http://www.ibge.gov.br/cidadesat

Janeiro. The second scenario of Copacabana is a dense area of Rio de Janeiro, mostly composed of residential buildings. Table 2 lists the parameters of interest for both scenarios.

Table 2: Characteristics of the reference scenarios.

Parameters	**Rocinha**	**Copacabana**
Total area (km^2)	1.4	4.1
Residential area (km^2)	1.4	2.5
Number of residences	17000	61000
Density (res./km^2)	12142	24797
Nodes disposition	grid	3D-grid

As in Brazil 90% of residences have at least one TV set [1], the number of nodes in the network is assumed to be the number of residences in the area. In Copacabana, we suppose that there are 8 floors in each building, each floor is 3 m high, and every building is composed of one residence per floor.

The position of the nodes inside the simulation area depends on the scenario. Figure 3 shows satellite photos of Rocinha and Copacabana, using the same scale and equal-size areas. These figures provide a feeling for the different geographical occupation patterns. A two-dimensional grid represents Rocinha because, although the distribution is not so regular, the residences are very close to each other (Figure 3(a)). A 3D grid is used for the Copacabana scenario, which is mostly composed of buildings (Figure 3(b)). Each floor in the buildings is represented by a two-dimensional grid in the XY plane.

5 Results

The transmission power, the signal attenuation, and the reception sensibility of 802.11 network interfaces are taken into account to evaluate the transmission and the interference ranges of the ad hoc return channel. We assume a transmission power of 18 dBm, or 63.1 mW, typical of many commercial 802.11 routers [10]. The signal attenuation is computed using the path loss model with loss parameter $\beta = 3.9$ [10]. The interference range obtained for Copacabana and Rocinha is 74 m. Another key aspect is the position of the gateway. In our simulations, we always position a single gateway at a vertex of the simulation area, which leads to a worst-case analysis. The simulations employ a confidence level of 95%.

5.1 Connectivity Analysis

This analysis evaluates the fraction of terminals that must be turned on to guarantee that most terminals are connected, as well as the respective physical transmission rate. A terminal is considered connected if it has at least one path to the gateway. We have written a simulator in C to perform this analysis, using the Dijkstra algorithm to calculate the shortest path to the gateway. Then, the simulator calculates the percentage of connected nodes. We place the nodes in a square area according to the real values for residential area and density seen in Table 2. The physical transmission rates range from 1 to 54 Mbps, according to IEEE 802.11g, and for Copacabana, the use of higher-gain antennas is considered.

The nodes that are on are randomly chosen in the grid for each simulation run. In Rocinha (Figure 4(a)), we note a high network connectivity for all PHY transmission rates. At 1 Mbps, only 10% of the on nodes are needed to achieve high connectivity, whereas 30% are needed at 11 Mbps. On the other hand, transmissions at 54 Mbps require that 90% of nodes be turned on. Higher rates demand better SNR to correctly decode the signal at the reception. Hence, increasing the transmission rate means decreasing the transmission range. In Copacabana, Figure 4(b), it is observed that with 5% of nodes on a high level of connectivity is also reached. As Copacabana is composed of buildings, the probability to find at least one on terminal nearby is high. Thus, a high level of connectivity is obtained for a smaller percentage of on nodes as compared to Rocinha. On the other hand, unlike Rocinha, a high connectivity using high PHY rates can only be achieved with

6 dBi gain antennas. Without antennas, the connectivity is not possible at 36 and 54 Mbps because, on average, the distance between the buildings in Copacabana is larger than among the residences in Rocinha. Note that in both scenarios connectivity is achieved with a low fraction of nodes on. Moreover, terminals can reduce the PHY data rate during low-audience periods, increasing the transmission range to conserve network connectivity.

5.2 Throughput Analysis

The throughput analysis evaluates the impact of an increasing number of transmitting terminals in the network-aggregated throughput, as well as in the worst-case individual node throughput. The main goal in this analysis is to estimate the maximum number of terminals that can simultaneously transmit at a minimum acceptable rate. For this set of simulations, we modified the NS-2.28 simulator to model IEEE 802.11g.

The PHY data rates used in each scenario are chosen according to the results of the connectivity analysis. We used the highest transmission rate that offers 100% connectivity when all the nodes are on, namely, 54 Mbps for Rocinha and 11 Mbps for Copacabana. The terminals send 1500-byte packets at 56 kbps using CBR/UDP. There is neither packet segmentation nor RTS/CTS. The simulation area varies according to the number of terminals, keeping constant the node density, as defined in Table 2.Whenever IEEE 802.11g can be deployed, we assume that it uses short slot times. As the data packets are forwarded through multiple-hops, a routing protocol is necessary. Since the nodes are fixed, we have used the proactive OLSR (Optimized Link State Routing) protocol.

Figure 5(a) plots the aggregated throughput obtained in the network for a varying number of terminals. Note that saturation is achieved with approximately 80 nodes. Afterwards, the throughput decreases as a consequence of an increasing number of collisions. Moreover, the links inside the interference range of the gateway constitute a bottleneck, limiting the maximum aggregated throughput of the network. Nodes located far from the gateway need more hops to deliver their data packets. These packets run through a higher number of contentions to access the medium, thus reducing their individual throughput. Figure 5(b) shows that the saturation of the most-distant node is achieved for a network size close to 60 nodes. This proves that the medium access is unfair, and although the aggregated throughput of the network is still increasing, the farthest node gets the smallest share of the bandwidth. Hence, the throughput of the farthest node must be considered to decide the number of gateways needed to correctly provision the network.

For Copacabana, IEEE 802.11b is used since the transmission rate is 11 Mbps. The results obtained are similar to the results of Rocinha. Figure 5(c) shows that the aggregated throughput saturates near 70 nodes. On the other hand, the throughput of the most-distant node reaches saturation near 40 nodes.

It is important to note that without a previously installed infrastructure, the ad hoc return channel offers a reasonable throughput to more than 40 nodes in the scenarios analyzed. Possibly, in real environments more nodes in the network would be possible since we have performed a worst-case analysis. The deployment of one gateway can serve at least 40 access terminals.

Results concerning a low density scenario are presented in our previous work [9]. We analyzed a rural area where residences are far from each other. The results showed that for this scenario higher gain antennas are needed to guarantee connectivity.

6 Conclusion

A wireless ad hoc network is a low-cost and flexible solution for the Brazilian digital TV return channel. Other eligible technologies for the return channel have some drawbacks in comparison with ad hoc networks. CDMA technology requires a pre-existing infrastructure and commercial agreements between the TV broadcasters and the cellular operators. With respect to WiMAX technology, the point-to-multipoint operation mode centralizes the traffic in the base station, increasing the complexity and infrastructure costs. The use of PLC as a return channel would demand infrastructure investment and would require using the precarious Brazilian electricity distribution system. Finally, the lack of widespread infrastructure for ADSL and the need for financial agreements with the phone companies make the deployment of an ADSL-based return channel difficult.

In this article, we have evaluated the performance of IEEE 802.11 ad hoc networks to verify the suitability of this solution as a return channel. Using simulation, the connectivity and the network throughput of the network have been analyzed, using the parameters of typical Brazilian geographical scenarios.

In the connectivity analysis, we verified that in urban regions it is possible to achieve high connectivity with a reduced number of terminals turned on. For instance, in Copacabana 5% of the nodes need to be on to achieve connectivity at 1 Mbps, and only 10% for Rocinha. Additionally, depending on the scenario, transmission rates up to 54 Mbps can be used. In the throughput analysis, we have verified that a 56 kbps throughput was guaranteed to up to 40 access terminals in the worst case. This result can be used to provision the ad hoc network with a number of gateways to the TV broadcaster.

Acknowledgments

The authors would like to thank CNPq, CAPES, FINEP, FUNTTEL, and FUJB. Also, we would like to thank Timur Friedman for his valuable comments that brought many improvements to this article.

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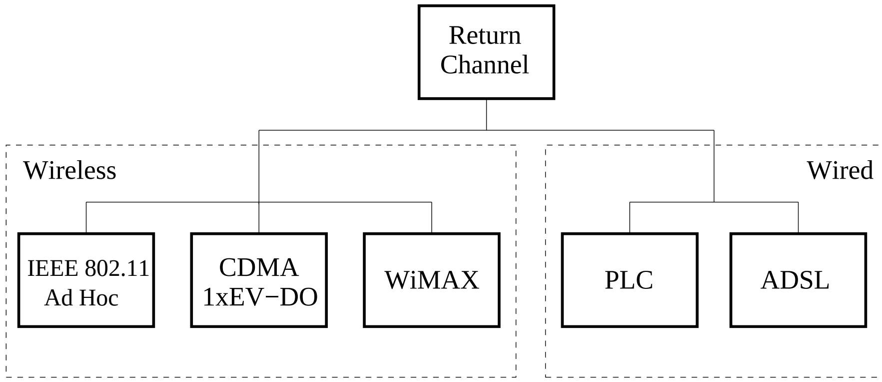


Figure 1: Technologies for the Brazilian return channel.

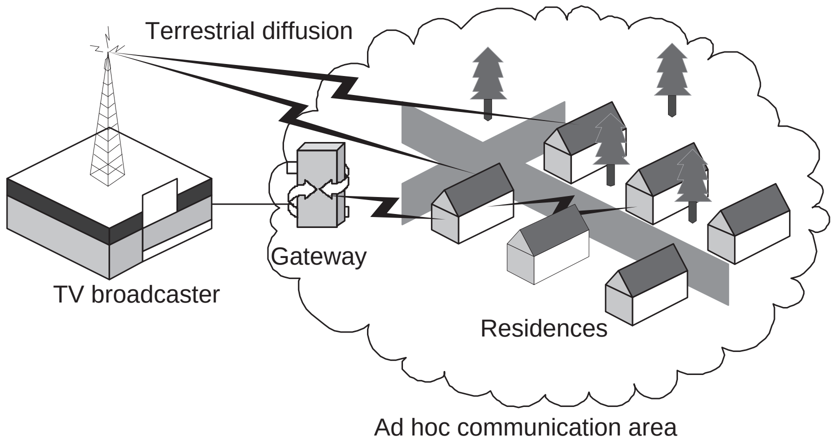
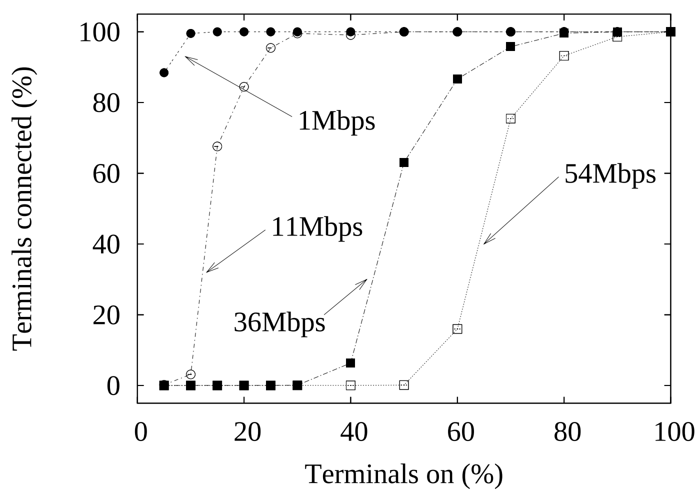


Figure 2: The ad hoc return channel.

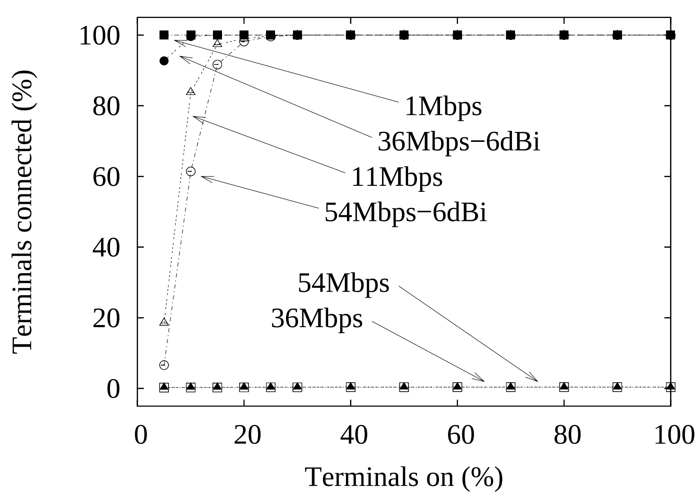
(a) Rocinha.

(b) Copacabana.

Figure 3: Reference scenarios: satellite photos extracted from Google Earth.

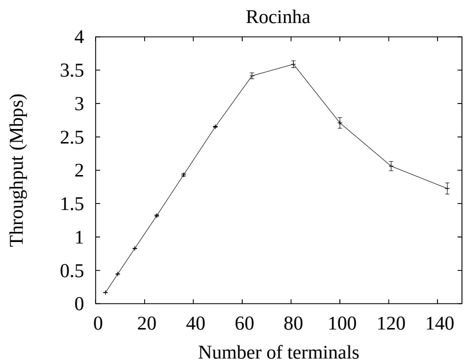


(a) Rocinha.

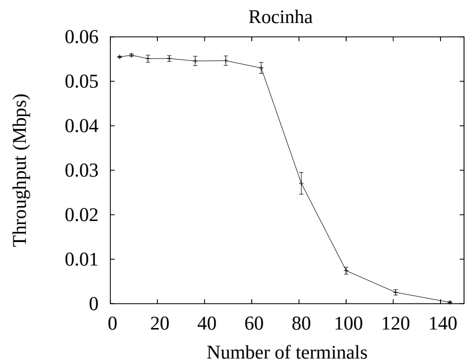


(b) Copacabana.

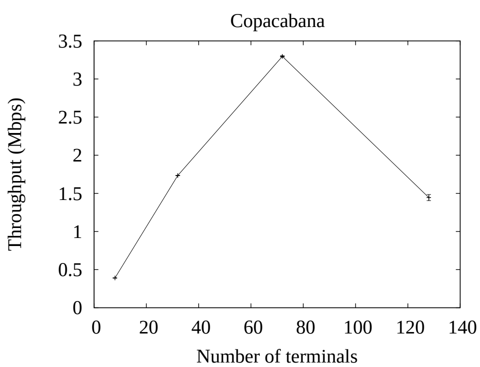
Figure 4: Connectivity.



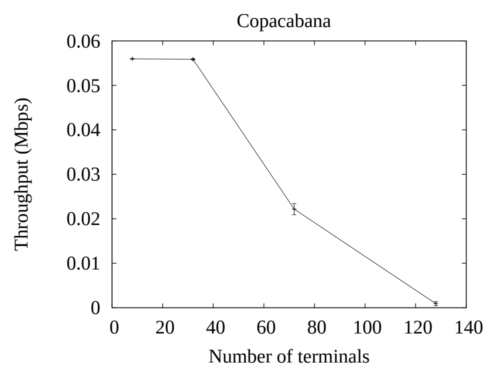
(a) Aggregated throughput.



(b) Farthest-node throughput.



(c) Aggregated throughput.



(d) Farthest-node throughput.

Figure 5: Throughput.