Experimental Analysis of Heterogeneous Wireless Networks

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Abstract. Packet loss and delay in Internet degrade the quality of requested services like VoIP (Voice over IP) or Video Streaming. In novel network scenarios where wired and wireless connections are melted together, a real measure of these parameters is fundamental in a planning process of new services over novel network infrastructures. Nowadays networks are heterogeneous in terms of access network technologies (wired LAN Ethernet 10/100/1000, Wireless LAN - 802.11a, 802.11b, 802.11g -, GPRS, UMTS, GSM, Bluetooth, ...), end-users' devices (workstation, PC desktop, Laptop/Notebook, PDA, Advanced Mobile Phone, ...) and finally operating systems (Unix, Linux, Win 98/NT/2000/XP, Win CE, Linux Familiar, OS Embedded, ...). In this work we provide a heterogeneous network performance characterization with respect to delay and throughput in UDP and TCP environments. In order to determine our results we use an innovative traffic generator named D-ITG (Distributed Internet Traffic Generator). Results presented in this paper can be used as performance references for development of wireless communication applications over multiservice and heterogeneous networks.

Keywords: Heterogeneous networks, wireless networks performance analysis.

1 Introduction

In the last years network capacity has increased at a dramatic rate. At the same time the proliferation of the web has resulted in an exponential increase in the number of "surfing users" supported by the Internet. These users are becoming increasingly sophisticated and demand high-bandwidth, low-delay network services at affordable prices. These services' request is made on new "heterogeneous integrated and mobile" networks. In fact, as technology continues its dramatic progress, making possible new and improved applications, we experience the creation of new paradigms and changes in the way technology impacts every day's life.

Always-on connectivity, location-awareness, and environment-aware products are among these new paradigms. Smart devices, portable devices, wireless communications appear to be the underlying principles of a new revolution in technology. Pervasive computing deals with a wide range of information access methods enabled by mobility, wireless, small embedded systems, and broadband technologies [1]. Integration of fixed and portable wireless access to IP networks presents a cost effective and efficient way

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to provide seamless end-to-end connectivity and ubiquitous access in a market where demands of mobile Internet have grown rapidly and predicted to generate billions of dollars in revenue.

This work provides a performance characterization of a real heterogeneous scenario where wireless and wired connections and where a wide range of end user device are present: in our real scenario we use PDA (Personal Digital Assistant), notebook/laptop, PC desktop and finally workstation. As far as this whole of end systems there is a wide range of operating systems present in our scenario. Measures were carried out on a testbed which reproduces (on a small scale) a real prototype of a heterogeneous mobile and integrated network. The study of the network behavior has been realized using D-ITG (*Distributed Internet Traffic Generator*) which provides a set of powerful tools for traffic patterns generation and results analysis. We present our experimental results and at the same time we analyze and validate theoretical assumptions on wireless performance behavior carried out in [2].

The paper is organized in 6 sections. After this introduction, in the next section the motivations and the reference framework on which our work is based are presented. Functionalities and main concepts regarding the D-ITG platform are shown in section 3. The experimental setup where our work has been carried out is presented in section 4, discussing the main issues related to our heterogeneous scenario and describing the measuring procedure. Section 5 reports the obtained experimental results. Finally, section 6 provides some concluding remarks and issues for research.

2 Motivation and Related Work

One of the most innovative concept and, at the same time, the most difficult challenge for all network engineers is actually that of “integration”: a unique and pervasive network scenario for the support of all the traffic (data, voice and video). A unique infrastructure but, above all, a unique protocol, the protocol IP, glue of all applications on different platforms: situations in which wireline world and wireless world are melted together are nowadays realities and the actual trend is the definition of a global communication paradigm, independent from the particular network technologies.

Among the many innovations introduced in the IP networks, an interesting challenge is to bring services like telephony and video transmission on the same infrastructure used for data traffic. This process relies on using QoS (*Quality of Service*) approach and at same time on the precise characterization of used heterogeneous network scenario. For these reasons, performance and experimental analysis of wireless networks is currently an important research issue. There are several simulation and analytical studies on wireless channel performance [15] [16], whereas in this work, we test a real heterogeneous mobile environment made by heterogeneous (wired and wireless) network, heterogeneous users’ device (Laptop, PDA, Advanced Mobile Phone, Workstation,...) and finally heterogeneous operating system. Our scenario is heterogeneous in terms of:

- access network technologies (*WLAN 802.11*, *wired Ethernet 10/100 Mbps*)
- end-users’ devices (*PDA*, *Laptop*, *PC desktop*)
- end-users’ operating systems (*Linux Embedded*, *Linux*, *Windows XP/ 2k/CE*)

Over this heterogeneous scenario we carried out a complete performance study of a real heterogeneous and integrated mobile network. In a situation where a roaming user sends traffic both to another roaming user and to a fixed position, experimental results on throughput and delay (using both UDP and TCP connections) are presented. We assess our results showing the different performance (between roaming end-nodes) at different distances.

Before presenting our results and in order to provide a general framework a brief state of the art related to other similar works is presented. A performance characterization of ad hoc wireless networks is presented in [3]. The paper examines impact of varying packet size, beaconing interval, and route hop count on communication throughput, end-to-end delay, and packet loss. In [4] a new performance model for the IEEE 802.11 WLAN in ad hoc mode is presented. Three adjustable parameters are presented: packet fragmentation factor, buffer size, and maximum allowable number of retransmissions. In the work there is the measure the system performance by unsing three parameters: throughput, delay, and probability of fail to deliver.

In [5], three techniques for composite performance and availability analysis are discussed in detail through a queuing system in a wireless communication network. In [6] there is a study on network performance of commercial IEEE 802.11 compliant WLANs measured at the MAC sublayer in order to characterize their behavior in terms of throughput and response time under different network load conditions.

A performance study on wireless LAN in a vehicular mobility scenario is presented in [7]. In [8] the performance of a real campus area network are measured. In order to carry out the results the authors used three performance monitoring software: CWINS Wireless Benchmarking tool, Harris LAN Evolution Software and WaveLan Diagnostic Software. Performance measuring has been carried out moving on several parameters: received power, walls and floors separating two radio interfaces and finally interfering traffic. In [9] the authors present a comprehensive study on TCP and UDP behavior over WLAN taking into account radio hardware, device drivers and network protocols. [10] presents a performance measurements carried out on a real MAN in order to apprehend the real throughput.

3 Distributed Internet Traffic Generator (D-ITG)

The successful evolution of network research is tightly coupled to the ability to design simple and accurate models with the propriety (and possibility) of traffic patterns reproducibility. Traffic theory suggest us the application of mathematical modeling to explain traffic performance relationship with network capacity, traffic demand and experimented performance.

One of the applications of traffic models is the generation of synthetic, yet realistic traffic to be injected into a network, in order to simulate the behavior of a multitude of real traffic sources. In the case of studies related to the Internet, simulations should reflect not only the wide scale of real scenarios, by also the rich variety of traffic sources, in terms both of protocol typologies and of data generation patterns.

The purpose of the *Distributed Internet Traffic Generator* [11] [12] [13] is to build up a suite that can be easily used to generate repeatable sets of experiments by using a reliable and realistic mixture of available traffic typologies. By using configurable scenario procedures on individual machines, and by coordinating the actions of these network devices, with D-ITG is possible to generate many traffic test-cases that could be originated by a typical network scenario made of large number of users and network devices, as well as by different network topologies.

We believe that D-ITG shows interesting properties when compared to other traffic generators. A centralized version and two kinds of distributed generators have been implemented. In the first distributed version there is a log server that is used by senders and receivers for data logging. Both communications between senders and log server and receiver and log server are carried out using both TCP/IP transport protocols: UDP and TCP. In the second distributed version, processes of both senders and receivers have been implemented using MPI library [14]. By separating generation and log processes, it has been eliminated the interference problem between them, which results in better overall performance.

By eliminating interference problems the distributed version is able to replicate theoretical traffic figure imposed at sender side with greater accuracy. Furthermore in a heterogeneous mobile scenario made by communications between PDA or PocketPC, using this distributed version it is possible to generate high traffic rate on the mobile device and at the same time to log sent and received traffic on a server present in the wired network: this modus operandi provide an alternative way to data logging on device where the storage capacity is very small.

Due to the nodes' limited resource (RAM, storage capacity, video dimension, ...) in wireless ad hoc networks, scalability is crucial for network operations. In particular a distributed approach to network communication using collaborative mechanism permits reaching comparable performance respect to wired scenario. Indeed using a log server for sender and receiver logging phase we can assure greater performance when we use PocketPc too.

In order to carry out a complete characterization of heterogeneous integrated and mobile networks D-ITG has been ported on several different operating systems: Linux, Windows, and embedded operating systems. With respect to this last platform in our testbed we used PDAs where is running the Linux FAMILIAR - kernel 2.4.18 version, and original source code, with little modifications, has been ported on this destination platform using a cross-compiler version of gcc. Currently we are working on a porting on WinCE platform too.

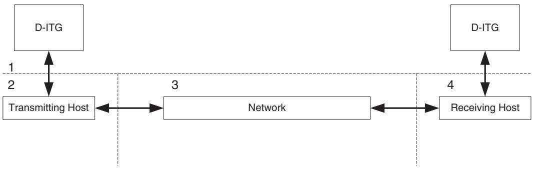

Fig. 1. Testbed Schema

4 Experimental Setup Description

The goal of our analysis is the performance characterization of heterogeneous networks in which wireless links are present. In order to pursue this objective a set of experimental setups with similar characteristics has been chosen. All tests can be collapsed in a same general scenario, depicted in figure 1, where two communication entities, a D-ITG transmitter and a D-ITG receiver, are directly connected through an IP network channel. Indeed, as represented in figure 1, the tests differ for the type of used network (3), its configuration (3) and the type of host (2-4) that executes the D-ITG platform. Others parametric elements, like generated traffic patterns, have not been changed, using only periodical sources, with fixed packet size (PS) and fixed inter-departure times (IDT) between packets. In table 1 the complete set of parametric elements used in our tests is summarized. In the case of ad-hoc configuration, we have experimented more situations, allowing to the two communicating hosts to move at various mutual distances.

The characterization has been carried out for both IP transport protocols (UDP and TCP) in three different traffic conditions:

- *low* traffic load $(\leq 1.2Mbps)$
- *medium* traffic load $(\leq 4.0Mbps)$
- *high* traffic load $(\leq 5.12Mbps)$

These three traffic conditions are related to three different real traffic loads and at the same time three different load conditions in theoretical wireless channel models. For every traffic condition, we have analyzed three type of hosts configuration: (i) classic configuration, with only laptop and workstation devices, (ii) pocket receiving configuration, where the receiving host is always a PocketPC, and (iii) pocket transmitting configuration, where the transmitting host is always a PocketPC.

Table 1. Parametric Elements

Testbed Element	Description	Set of Elements
1 - D-ITG	Protocol IDT Packet Size	{UDP, TCP} $\{\frac{1}{100}, \frac{1}{1000}, \frac{1}{10000}\}$ s {64, 128, 256, 512, 1024, 1500} bytes
2 - Tx-Host	Typology of host	{Workstation, Laptop, PocketPC}
3 - Network	Network typology and configuration	{Wired-Wired, Wired-Wireless, Wireless-Wireless, With or Without Access Point(AP), ...}
4 - Rx-Host	Typology of host	{Workstation, Laptop, PocketPC}

In order to characterize a system like that one depicted in figure 1, measured metrics are the (source/destination)-bandwidth (UDP and TCP protocols) and the delay deviation (mean and standard deviation) with respect to the time of the first received packet (UDP only). For each measured parameter, several trials have been performed in the same operating conditions.

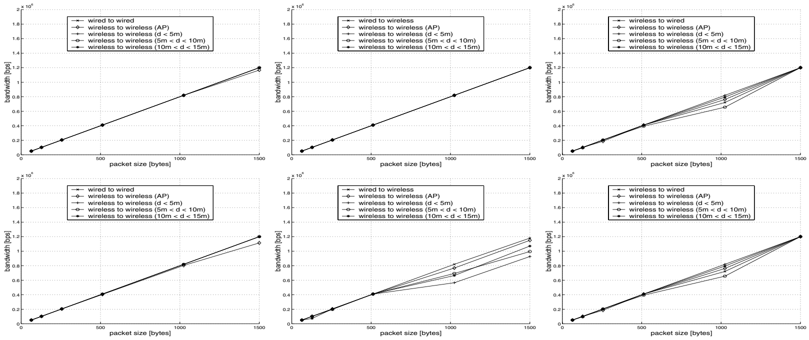

Fig. 2. UDP transmission(top)/receiving(bottom) bandwidth for IDT = $\frac{1}{100}$ s

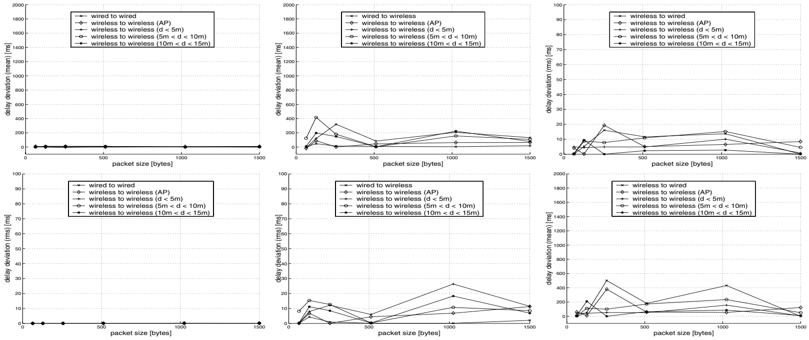

Fig. 3. Mean(top) and standard deviation(bottom) of the delay deviation for IDT = $\frac{1}{100}$ s

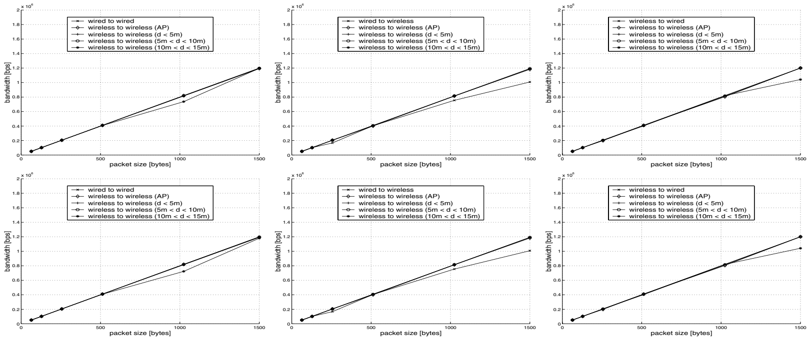

Fig. 4. TCP transmission(top)/receiving(bottom) bandwidth for IDT = $\frac{1}{100}$ s

Table 2. Picture Legend

Legend	Description
wired-to-wired	Connection between two workstation through Ethernet 10/100 Mbps network
wired-to-wireless	Connection between the workstation and the laptop/pocketPC through AP
wireless-to-wireless (AP)	Connection between laptop and pocketPC through AP
wireless-to-wireless ($d \leq x$)	Connection between laptop and pocketPC in ad-hoc mode in a range of x meters

Table 3. Technical details on experimental setup

Host/Device	Description
Laptop1	IBM T23, Mobile Intel PIII 1133 Mhz, Main Memory 128 MB, Cache 256 KB, O.S. Linux Red Hat 9.0 – kernel 2.4.20-18.9
Laptop2	Acer TravelMate 351 TE: PIII 700 Mhz, Main Memory 128 MB
Workstation1	PC sender, Intel PII 850 Mhz, Main Memory 128 MB, Cache 256 KB, dual boot Operating Systems: Linux Red Hat 7.1 – kernel 2.4.2-2, Windows XP Professional Service Pack 1
Workstation2	PC receiver, Intel C 400 Mhz, Main Memory 64 MB, Cache 128 KB, O.S. Linux Red Hat 7.0 - kernel 2.4.2-19
PocketPC	Compaq iPAQ H3850, Intel StrongARM 206 Mhz, Main Memory 64 MB, Flash ROM 32 MB, O.S. Linux FAMILIAR – kernel 2.4.18
Access Point	Orinoco Ap1000, 11Mbps (802.11b), Multi Channel support
Wireless LAN cards	WiFi ORINOCO 11Mbps GOLD

5 Perfomance Analysis and Experimentation

In this section we present measures obtained in the various cases. We step from showing and analyzing the results for *low* load traffic condition, then we present the results for *medium* and finally for *high* traffic load. In table 3 details on used devices are depicted.

In next figures we show comparative analysis on mobile environment using roaming user in three stage of space ($d \leq 5\ m$, $5\ m \leq d \leq 10\ m$, $10\ m \leq d \leq 15\ m$). In the three different traffic conditions we use different packet size dimensions. Indeed in the first traffic profile we can use a packet size dimension up to 1500 bytes (according to *low* traffic load). In the second traffic profile we use a packet size dimension up to 512 bytes (according to *medium* traffic load). Finally in the third traffic profile we use only one packet size dimension equal to 64 bytes (according to *high* traffic load).

5.1 Low Traffic Load

Test results for *low* traffic load are depicted in figures 2, 3 and 4. For *low* traffic load we mean a traffic state in which we are far from the saturated wireless channel condition.

The sending/receiving bandwidth is reported in figures 2 and 4, using respectively UDP and TCP transport protocols. Instead, in figure 3 the behavior of the delay deviation with respect to the time of the first received packet is reported.

First row of figures 2 and 4 represents the behavior observed by the transmitting host, while the second one represents the behavior observed by receiving host. The first row of figure 3 shows mean delay deviation behavior, while the second one represents the delay standard deviation for all considered configuration. In all these figures, the left columns is related to a situation in which the communication entities are two workstations, or one workstation and one laptop; instead, the others two columns are related to a scenario in which the transmitter (right) or the receiving (center) host is always a PocketPC, while the transmitting/receiving one can be a workstation (wired element) or a laptop (wireless element). In table 2 the complete reference for the legend used in these and in the following graphs is reported.

In order to have a reference curve, it has been generated also the diagram related to direct wired connection, in the *workstation to workstation* classical configuration. From the bandwidth diagrams produced for the several configurations, two aspects are clearly depicted: (i) the communication is reliable and (ii) the degradation of the performance is due to the smaller computational power of the adopted devices (PDAs). It is interesting to notice that TCP suffers the losses mainly, having a different behavior with respect to UDP; TCP indeed interprets the losses like due to congestion phenomena and reacts consequently, reducing the maximum transmittable rate and emphasizing the phenomenon of bandwidth reduction. Of particular interest is the case of 1500 bytes packets, where the packet dimension exceeds MTU (Maximum Transfer Unit), the maximum allowable dimension of a MAC data unit. The fragmentation produces the duplication of the total number of transmitted packet and it exacerbates the throughput reduction of the wireless channel.

Analysis of the delay diagrams demonstrate that the strong sensitivity of the delay deviation is function of the used configuration and the used hosts: when a wireless link is used, the arrival time of the first packet is little meaningful respect to the total delay. For this reason a measure of mean and standard deviation is useful. Moreover, the delay diagrams also demonstrate the uncorrelation between the perceived bandwidth and the packet delay.

5.2 Medium Traffic Load

The test results for *medium* traffic load are depicted in figures 5, 6 and 7. For *medium* traffic load we mean a traffic state in which we are closed the saturated wireless channel condition. In order to quantify the proximity to the saturated channel condition, in the diagrams of the throughput it has been brought back also the diagram obtained from the Bianchi theoretical model [2]. In [2] a simple analytical model to compute the saturation throughput performance of the 802.11 is presented. The model assumes a finite number of terminals and ideal channel conditions and it is suited for any access scheme employed. The model shows that performance of the basic access method strongly depends on the system parameters, mainly packet size dimension and number of stations in the wireless network. Such model gives us a bound to the maximum traffic load that can cross the channel at the MAC layer of the ISO/OSI stack, therefore it supplies a useful bound for the traffic at the upper layer. Using our experimental results, we can also provide a practical validation of the Bianchi theoretical model.

Diagrams organization is equal to the that one present in the subsection 5.1. In this load condition it turns out with more evidence the dependency from the host typology and the used transport protocol. TCP still demonstrates of being more sensitive to the losses respect to UDP. However, regarding the previous case we can observe the greater sensitivity respect to packet dimension of the wireless configurations, especially of those with PocketPC.

The delay diagrams confirm that the strong sensitivity of the delay deviation in function of the used configuration and the used hosts, and prove, when a wireless link is used, that the arrival time of the first packet is little meaningful of the total delay. However, regarding the previous case we can observe a greater tie between the observed throughput reduction and delay variations.

5.3 High Traffic Load

Test results for *high* traffic load are depicted in figures 8, 9 and 10. For *high* traffic load we mean a traffic state in which we are in the saturated wireless channel condition, and every station has always a packet ready for the transmission.

With respect to previous cases we have analyzed only a transmission condition where the packet size is equal to 64 bytes. Indeed, for whichever packet dimension the channel turns out saturated: longer packets carry to a greater channel busy time for delivered or collided packet, and it only leads to a greater number of losses from the sender side for network interface saturation. The organization of the diagrams is the same one of the previous cases, the only difference is in having brought back the transmission and reception plots in the same area using histogram diagrams (in this case we have changed the figures model because we have only one packet dimension).

It is interesting to notice the behavior of UDP and TCP in the several analyzed configurations: TCP reacts to the saturation condition limiting the demanded transmission bandwidth, while UDP endures a highest packet loss. This behavior is caused from the presence of a flow-control mechanism in the first protocol, and from the ability to the congestion control of TCP to optimize the use of a high loaded channel.

6 Conclusions and Issues for Research

In this work we presented a general framework for traffic analysis and performance characterization in heterogeneous mobile networks. This work steps from the assumption that a current realistic scenario must consider the fusion of wired and wireless connection and several kinds of user devices. A number of tests conducted on our real testbed yielded important characteristics such as throughput and delay under various network loads. Our results demonstrate, in the low traffic load situation, the uncorrelation between the perceived bandwidth and the packets delay. In the other two traffic load situations we observed a greater tie between the observed throughput reduction and delay variations.

The paper presents a complete experimental analysis in UDP and TCP scenarios with respect to throughput and delay. The fundamental contribution of our work was the clear definition of which system's elements are responsible of network performances

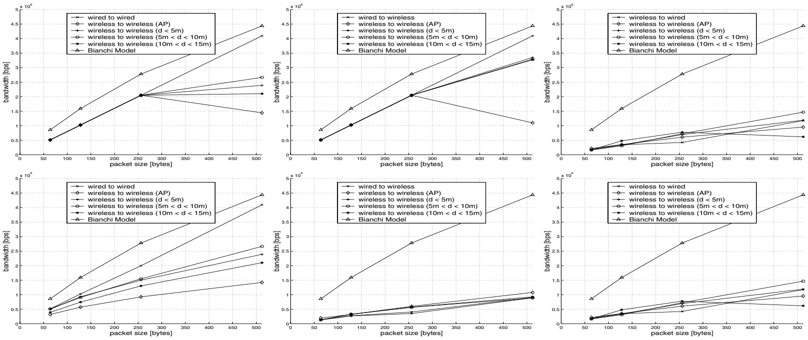

Fig. 5. UDP transmission(top)/receiving(bottom) bandwidth for IDT = $\frac{1}{1000}$ s

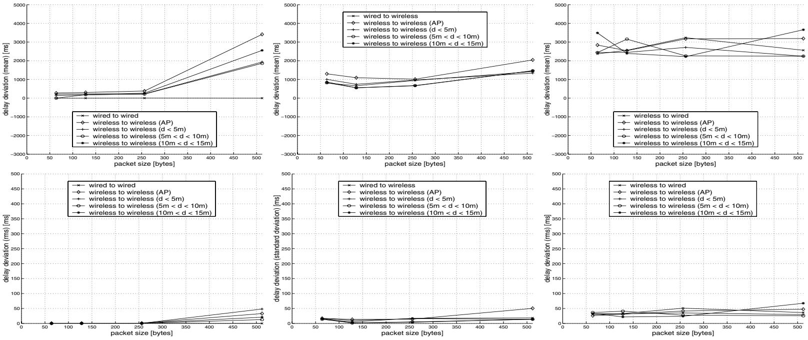

Fig. 6. Mean(top) and standard deviation(bottom) of the delay deviation for IDT = $\frac{1}{1000}$ s

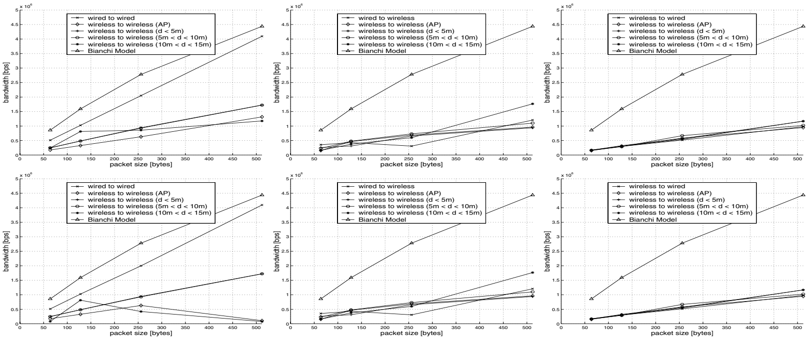

Fig. 7. TCP transmission(top)/receiving(bottom) bandwidth for IDT = $\frac{1}{1000}$ s

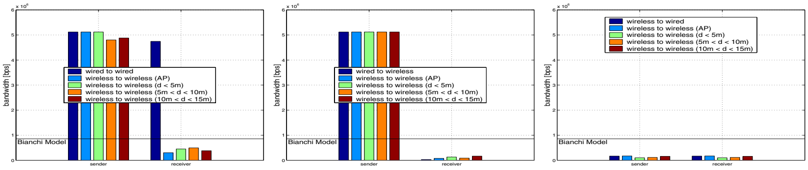

Fig. 8. UDP transmission/receiving bandwidth for IDT = $\frac{1}{10000}$ s

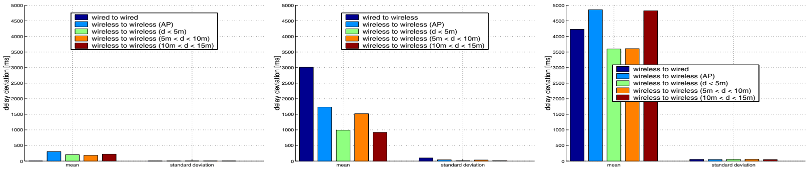

Fig. 9. Mean and standard deviation of the delay deviation for IDT = $\frac{1}{10000}$ s

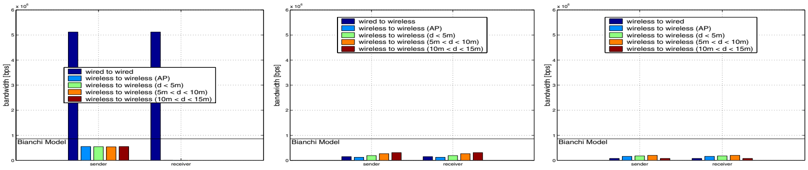

Fig. 10. TCP transmission/receiving bandwidth for IDT = $\frac{1}{10000}$ s

degradation and how to use different protocols impacts observed on the traffic behavior. Furthermore, using our results the analytical model presented by Bianchi [2] is validated. We have demonstrated that it is useful as a upper bound reference throughput in the case of real traffic scenarios.

Results showed in this work can be used as references for development of wireless communication applications. Indeed in a planning phase of innovative applications over heterogeneous networks is necessary a complete parametric network characterization. Currently, our testbed allows experiments on a small-scale. We will test the system behavior on a realistic network of a much wider-scale. Furthermore we are working on a similar analysis presented in this paper in a scenario where interference due to Bluetooth and IrDA communications are present. Finally, using D-ITG capabilities we will test a similar scenario using different traffic patterns made by different stochastic IDT and PS distributions according to several theoretical traffic models.

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