Available online at www.sciencedirect.com
ScienceDirect
Journal of Computer and System Sciences 72 (2006) 1134–1143
www.elsevier.com/locate/jcss

Systematic performance modeling and characterization of heterogeneous IP networks ☆

Alessio Botta, Donato Emma, Antonio Pescapé *, Giorgio Ventre

Consorzio Interuniversitario Nazionale per l'Informatica, Naples, Italy
Dipartimento di Informatica e Sistemistica, Università di Napoli "Federico II", Naples, Italy

Received 27 February 2005; received in revised form 31 July 2005

Available online 28 February 2006

Abstract

Accurate measurement and modeling of IP networks is essential for network design, planning, and management. Efforts are being made to detect the state of the network from end-to-end measurements using different techniques and paradigms. In this paper we propose a novel concept to use in the modeling of real network scenarios under measurement and analysis. We called this new concept *Service Condition*. We explain our proposal's motivations and we use some simple examples to show how to apply the *Service Condition* concept to the study of real heterogeneous network scenarios. To show the real applicability of our proposal, preliminary results from a performance evaluation study over real heterogeneous networks (where the integration of LAN, WLAN, ADSL, UMTS, and GPRS is present) are given.

Keywords: QoS performance evaluation and modeling; Integration of wired and wireless systems; Real testbeds

1. Introduction

In the last decade networks have changed and the variety of applications and services that can be provided over packet switched networks has strongly increased and keeps on increasing.

One of the current challenges is the integration of infrastructures, protocols, and platforms. Over this integrated and heterogeneous scenario users need to access all kind of services (Voice, Data, Video, …) everywhere, every time and using any device they want.

IP (Internet Protocol) is the most used network protocol in telecommunication networks, but it does not represent the best protocol to support all applications. For this reason, in a performance evaluation framework, it is important to study the behavior of the applications in terms of QoS (Quality of Service) parameters. Such performance evaluation should take into account used devices (e.g. Linux PCs, Workstations, Laptops, Mobile Phones, PDAs, …), used

☆ A short version of this paper appears at First International IEEE Workshop on Performance Modeling in Wired, Wireless, Mobile Networking and Computing (PMWMNC-2005). This work has been partially supported by the Italian Ministry for Education, University and Research (MIUR) in the framework of the WEB-MINDS FIRB Project, PRIN 2004 QUASAR project, and finally by the E-NEXT IST European project.
* Corresponding author.
E-mail addresses: abotta@napoli.consorzio-cini.it (A. Botta), doemma@unina.it (D. Emma), pescape@unina.it (A. Pescapé), giorgio@unina.it (G. Ventre).

0022-0000/$ – see front matter
doi:10.1016/j.jcss.2005.12.003

transport protocols (UDP, TCP, SCTP), and used access network technologies (e.g. wired LANs, WLANs, xDSL, GPRS, UMTS, ...). Also, the wide diffusion of smart devices with wireless connections (WLAN, GPRS, UMTS, ...) has triggered the development of new applications over new and complex network infrastructures.

The study of the behavior of QoS parameters over these heterogeneous network scenarios helps in several stages such as *testing* (defining applications suitability), *planning* (defining applications requirements), and the *analysis and definition* of (new or existing) communication models.

Therefore the need for accurate and innovative network monitoring and measurement paradigms has become an important challenge to be dealt with and to study these novel network scenarios a precise framework and a systematic approach are needed.

There are several works on the performance evaluation of WLAN carried out by means of real measurements. A performance study on wireless LAN in a vehicular mobility scenario is presented in [1]. In [2] the performance of a real campus area network are measured moving on several parameters: received power, walls and floors separating two radio interfaces and finally interfering traffic. In [3] the authors present a comprehensive study on TCP and UDP behavior over WLAN taking into account radio hardware, device drivers and network protocols. [4] shows performance measurements carried out on a real MAN in order to evaluate the real throughput. In our opinion, all these cited works contain optimal research results but they present two main deficiencies: (i) they are related to scenarios where the heterogeneity degree is very low; (ii) there are no systematic approaches to the real performance measurements.

In this paper we present the *Service Condition* (*SC*) concept as a mechanism to cope with the high heterogeneity level of today's networks. The SC concept may be also useful when a rigorous specification is needed for the measuring, monitoring, and modeling of particular real network conditions.

More precisely, here we point our attention on the performance evaluation of some of the more interesting heterogeneous scenarios where there is the integration among LAN (wired and wireless), GPRS, UMTS, and ADSL networks.

A preliminary and seminal definition of the *SC* concept was provided in a network and service management framework in [5].

The rest of the paper is organized as follows. Section 2 introduces and explains the *SC* concept, whereas Section 3 shows how this concept can be useful in a performance evaluation framework. Section 4 shows how we used the *SC* concept to measure Quality of Service (QoS) parameters in real heterogeneous networks. Section 5 presents a summary of the experimental analysis results. Section 6 ends the paper with concluding remarks.

2. Network heterogeneity and service condition

Currently, a problem to cope with and, at the same time, an opportunity to exploit is the "*heterogeneity*". In pervasive and ubiquitous computing scenarios, several questions arise when we want to describe the way a service should be implemented to correctly fit requirements contained, for example, in a subscribed Service Level Agreement. Current networks represent a complex mixing of non-homogeneous variables:

- Heterogeneous network environments: Intermediate Systems, Access Networks, End Users Devices, Operating Systems (OSs), Service Types, etc.
- Dynamic User Behavior: Handover, Handoff, MultiModal Applications, etc.

For example, with respect to terminals, networks, and services we have:

1. *Terminal heterogeneity*, terminal devices can range from high-performance workstations, to Personal Digital Assistants (*PDAs*), down to advanced mobile phones.
2. *Network heterogeneity*, even if we consider as dynamically variable only the part that is closest to the user (i.e. the so-called *access* or *edge network*), we have a quite large number of options to deal with. Wired (LAN, xDSL, ...), wireless (WLAN, Bluetooth, ...), and mobile networks (GPRS, EDGE, UMTS, ...) could be taken into account.
3. *Service heterogeneity*, services may have different characteristics in terms of media involved (audio, video, ...), of their format (coding, compression, ...), and of their typology (synchronous, asynchronous, transactional, ...).

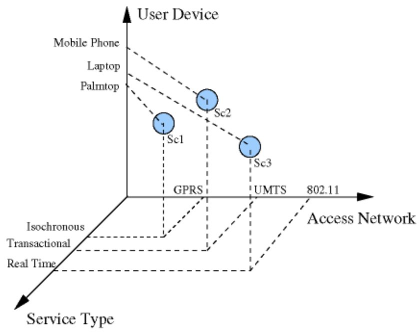

Fig. 1. Service conditions in a $3D$ space.

In this complex scenario, we introduce a *specification* to cope with:

(i) *Dynamic network changes*;
(ii) *Dynamic user behavior*; and
(iii) *Systematic measurement procedures*.

We called this concept "*Service Condition*." It is defined as *a point in a multidimensional space composed of all considered key variables* (access network, user device, operating system, application, time, ...). This point describes a particular combination of independent *working conditions* that characterize *how a user accesses to a service*. For example, in a 3-dimensional space composed of the *Service Type*, *Access Network*, and *User Device* sets, we have the result depicted in Fig. 1.

2.1. Modeling end-to-end communications by using the Service Condition concept

In this Section we show how to use the *SC* concept to simply model real communications between end nodes. Let us consider a multidimensional space composed of four key sets:

1. access network ∈ AN where:

   AN = {Ethernet (10/100/1000), WLAN 802.11 b, GPRS, UMTS, ADSL, ...};

2. user device ∈ EuD where:

   EuD = {Laptop, Palmtop, PC Desktop, Advanced Mobile Phone, Workstation, ...};

3. operating system ∈ OS where:

   OS = {Unix, Linux, Windows, Linux Familiar, ...};

4. service type ∈ ST where:

   ST = {Transactional, Real Time, Isochronous, ...}.

Using the Cartesian Product tool we have the following *Service Condition Space*:

$$\mathrm{SC} = (\mathrm{EuD}) \times (\mathrm{OS}) \times (\mathrm{ST}) \times (\mathrm{AN}). \tag{1}$$

A "*Service Condition*" represents a "4-*tuple*" in this 4-dimensional space. Thus, in general, exploding this concept we have an n-*dimensional space* where 'n' is the *heterogeneity level* or *heterogeneity degree*. Furthermore, if we consider as a variable also the time, we obtain an $(n+1)$-dimensional space. Therefore, from a practical point of view, by using the *SC* concept, we are able to categorize and characterize network scenarios in which different combinations of *end-users' devices*, *OSs* and *end-users' applications* are taken into account, and in which different typologies of networks are present.

3. Performance evaluation and Service Condition

The *SC* concept may be useful in performance evaluation studies and in particular, thanks to it, it is possible to draw a sort of *cause* vs. *effect* diagram. First, let us to take into account a real scenario where two end systems need to communicate. For the sake of simplicity we can assume two ends among those present in Fig. 2 where a real heterogeneous network is depicted. It represents the scenario where we performed our experimental analysis presented in Section 4.

The first step towards the definition of a systematic measurement approach is the definition of a *network conceptual schema*. All end-to-end communications can be collapsed in the same general schema. In Fig. 3 such conceptual schema is depicted. Two communication entities, a sender and a receiver, are directly connected through an IP network. Indeed, the end-to-end communications differ for the type of used network, its configuration, the type of host, and used OS. By changing these parameters we define several strictly related *SCs*. The S_A and R_A legends are used in Fig. 3 to indicate the sender and receiver application. More precisely, summarizing, we used a *conceptual model* composed of:

- 2 communication entities, parametric with respect to:
  - Typology of device (Laptop, iPaq, Workstation).
  - Typology of OS (Linux, Windows).
  - Traffic patterns.
- A channel, parametric with respect to:
  - The transport protocol (UDP, TCP, SCTP).
  - The network configuration of both access networks (Ethernet, ADSL, IEEE 802.11 b with AP and ad-hoc IEEE 802.11 b, UMTS, GPRS).

Therefore, in a performance study of heterogeneous networks we can use *SC* in the following way: we can model the communications between two ends by using the points of the *SC space*. More precisely, the single instances of the two ends will be represented by well defined points in the *SC space* (see Fig. 1). Adopting this *modus operandi* we represent such communications by using relations between *SC points*. For example, Fig. 4 represents a situation where at one side there is a user that works in a scenario where several handoffs are possible and he is communicating with a server at his own enterprise.

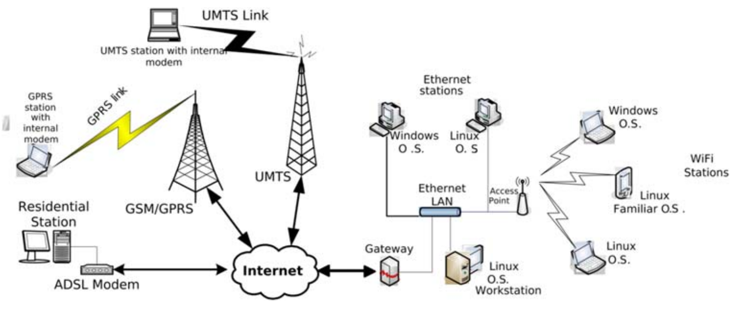

Fig. 2. A real Heterogeneous Network.

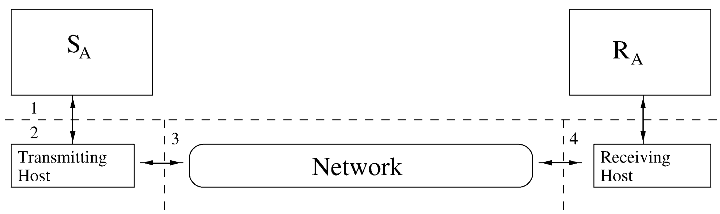

Fig. 3. Network conceptual schema.

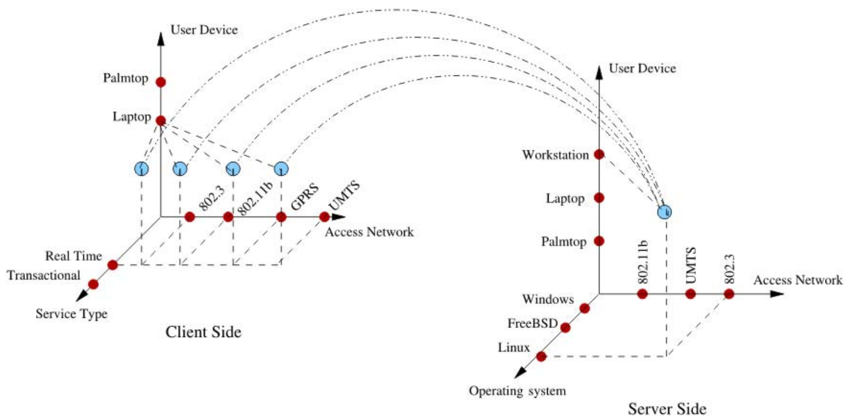

Fig. 4. SCs in end-to-end communications.

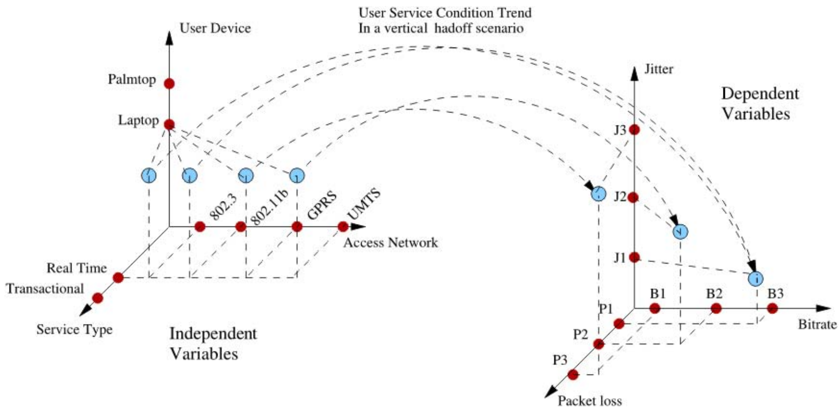

Fig. 5. SCs and QoS parameters.

As for defining of a sort of *cause* vs. *effect* diagram, by using tools for network measurements [6,7] we are able to completely characterize the end-to-end performance in terms of *delay*, *packet loss*, *jitter*, and *throughput* during the entire performance evaluation interval time.

Therefore, considering four sets (Bitrate (B), Jitter (J), Delay (D), and Packet Loss (PL)) and using the Cartesian Product tool we have the following *QoS parameters Space* (in the rest of the paper *QoS space*)

$$\text{QoS} = \big[(\text{B}) \times (\text{J}) \times (\text{D}) \times (\text{PL})\big] \in R^4. \tag{2}$$

By considering the *SC Space* as the *independent* multidimensional space and the *QoS parameters space*[1] as the *dependent* multidimensional space we define a close and well defined relationship between the current *SC* and the measured QoS parameters. Due to the fact that the *SC* at server side of Fig. 4 is fixed, in Fig. 5 the relation between the several *Service Conditions* and the perceived QoS parameters is depicted. By using this kind of association between *SC space* and *QoS space* we could also trace the sub-space of the *SC*s that are linked to points in QoS space fulfilling a given application requirements (*admissibility sub-space*). Also, thanks to the proposed concepts, we can simply derive the perceived QoS level associated to a particular *SC*. For instance, the SC concept and the related relationship with the QoS space could be useful to systematically study complex network scenarios like the ones presented in [8].

Also, for example, in a heterogeneous scenario where handoffs are present, beside to a rigorous framework for performance evaluation, *SC* could be used to trace the user/network behavior and to determine the contents adaptability.

[1] As for the physical interpretation, QoS and SC spaces are different in that the former is defined as the Cartesian Product of homogeneous sets (Real numbers), whereas in the latter each component represents an unordered set of discrete and finite values.

4. Experimental analysis

In this section we show how to use the *SC* concept to represent measures of QoS parameters over heterogeneous IP networks. This analysis has been conducted by using D-ITG [6], a traffic generator capable of using a lot of probability distributions to profile the Inter Departure Time (*IDT*) and the Packet Size (*PS*) random variables of generated packets. Moreover, D-ITG has the capability of logging both sent and received packets. Such feature enables us to locate the testbed's part responsible for the measured performance, so it is possible to isolate the network from device dependencies. Before to step into experimental details, it is worth mentioning that we repeated each test several times. In the following graphics the mean values across 20 test repetitions are reported.

Due to space limitations, in this paper we focus just on four configurations among all the studied ones (Fig. 2) [10]. We present the results first in a classical fashion, then by using the SC concept. The four configurations analyzed in the following subsections are the ones highlighted in Fig. 2 with continuous, dashed, dashed-dotted, and dashed-double-dotted lines. The analyzed configurations may be representative of real situations where users connected to the Internet are listening to Internet radio stations that are based on HTTP for the audio streaming. For this situation we will consider only the throughput and the jitter as QoS parameters because they are the most important in such case [9]. This experimental analysis has been conducted by using D-ITG which generated probing packets with $\mathrm{IDT} = 1/100$ s and $\mathrm{PS} \in \{64, 128, 256, 512, 1024\}$ bytes. This combination produces CBR traffic patterns ranging from 51,2 kbps to 819,2 kbps. This choice permits to correctly study scenarios where the GPRS network is present.

Ethernet → GPRS *scenario.* This first configuration is composed of a Windows XP equipped Laptop using TCP to communicate with a Linux workstation, where the first of them has a GPRS connection and the other one has a LAN card. The configuration is the one depicted with a dashed (green) line in Fig. 2. This configuration constitutes a point, said sc_1^2 (where the superscript represents the dimension of the SC space it belongs to and the subscript identifies the point in such space), in a SC^2 space, where SC^2 is the Cartesian Product between two SC spaces ($SC^2 = SC \times SC$). In particular, in mathematical terms:

$$sc_s^1 = (2, 1, 1, 4), \qquad sc_{r1}^1 = (1, 2, 1, 1), \qquad sc_1^2 = \left(sc_s^1, sc_{r1}^1\right) = (2, 1, 1, 4, 1, 2, 1, 1).$$

The correspondence between points in the SC space and relative configuration parameters can be found in Table 1.

Ethernet → UMTS *scenario.* This configuration is depicted with a continuous (red) line in Fig. 2. It also constitutes a point (said sc_2^2) in a SC^2 space. In mathematical terms:

$$sc_s^1 = (2, 1, 1, 4), \qquad sc_{r2}^1 = (1, 2, 1, 2), \qquad sc_2^2 = \left(sc_s^1, sc_{r2}^1\right) = (2, 1, 1, 4, 1, 2, 1, 2).$$

Table 1
Variables values and relative configuration for the considered SC space

Variable	Value	Correspondence
EuD	1	Laptop
	2	Workstation
	3	PC Desktop
OS	1	Linux
	2	Windows XP
ST	1	Transactional (TCP based)
	2	Real Time (UDP based)
AN	1	GPRS
	2	UMTS
	3	ADSL
	4	Ethernet
	5	802.11 b

Ethernet → ADSL *scenario.* This configuration is the one depicted with a dashed-double-dotted (cian) line in Fig. 2. Its description in mathematical terms is:

$$sc_s^1 = (2, 1, 1, 4), \qquad sc_{r3}^1 = (3, 1, 1, 3), \qquad sc_3^2 = \left(sc_s^1, sc_{r3}^1\right) = (2, 1, 1, 4, 3, 1, 1, 3).$$

Ethernet → 802.11 b *scenario.* This configuration is depicted with a dashed-dotted (blue) line in Fig. 2. Its description in mathematical terms is:

$$sc_s^1 = (2, 1, 1, 4), \qquad sc_{r4}^1 = (1, 1, 1, 5), \qquad sc_4^2 = \left(sc_s^1, sc_{r4}^1\right) = (2, 1, 1, 4, 1, 1, 1, 5).$$

4.1. Experimental results

First, we explain experimental results in a classical fashion (Figs. 6 and 7), then we present the same results using *SC* (Fig. 8).

Figure 6 shows the bit rate measured in the four analyzed configurations with a three-dimensional plot. In it we can see that the maximum achieved bit rates were of 819.21, 603.93, 118.63, and 40.63 Kbps with the 802.11 b, ADSL, UMTS and GPRS, respectively, all obtained with a PS = 1024 bytes. In Fig. 7 the jitter measured in the four analyzed configurations is shown with a three-dimensional plot. We can see that the jitter attained values up to 0.001, 0.025, 0.083, and 0.327 s with the 802.11 b, ADSL, UMTS, and GPRS, respectively, all achieved with a PS = 1024 bytes.

In Fig. 8 the best trade-off between bit rate and jitter are presented by using a *SC* plot. In such figure the points of the independent variables space (*SC space*) are linked to the points of the dependent variables space (the *QoS space*). Due to the fact that the *Service Condition* at sender side is fixed (i.e. an Internet radio), in Fig. 8 the relation between the several *SCs* and the measured QoS parameters is depicted. With such plot it is immediately visible the relationship

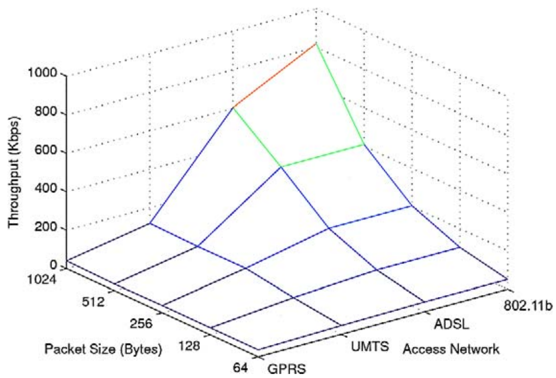

Fig. 6. Bitrate vs. packet size and AN.

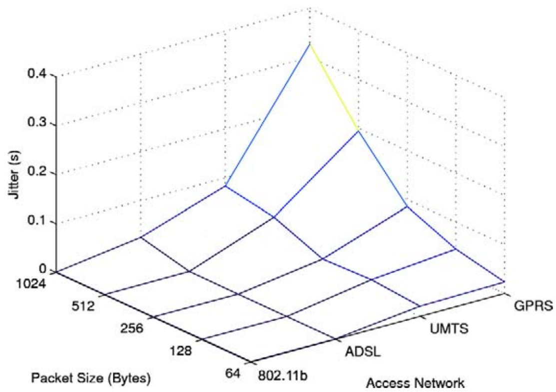

Fig. 7. Jitter vs. packet size and AN.

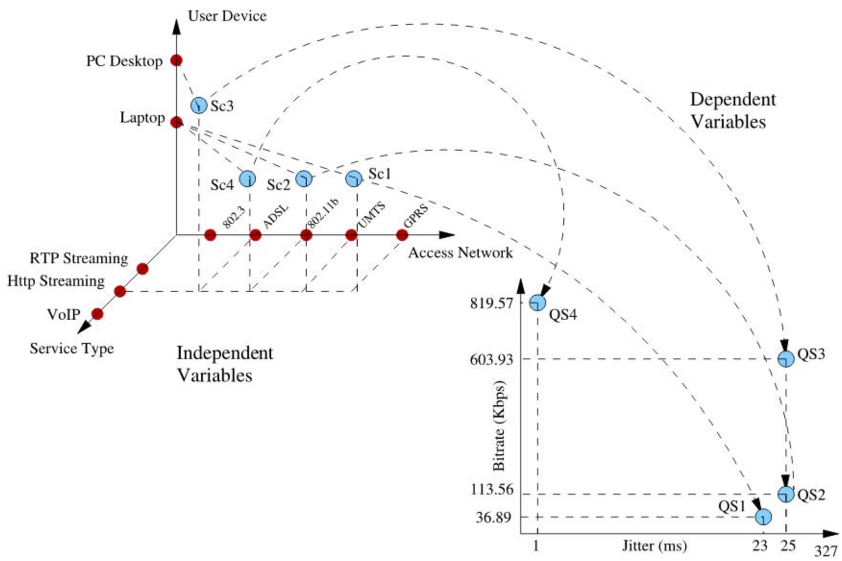

Fig. 8. "Service condition" plot.

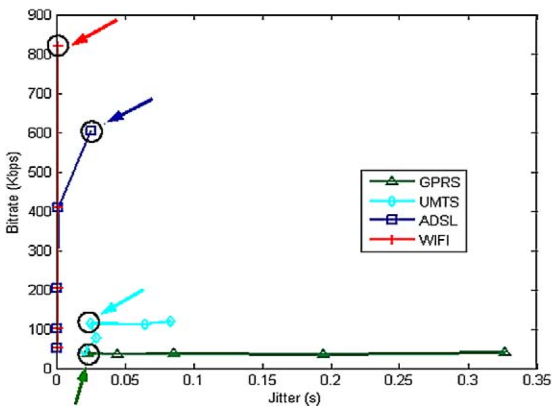

Fig. 9. QoS space plot for all PS.

between the configuration parameters and the measured QoS ones. Sketching the results in this way it is possible to easily recognize if a given *SC* is suitable for the requirements of a given application. Indeed our sample application of the Internet radio has minimum bit rate and maximum jitter requirements; they change depending on required audio quality and on available buffers. The QoS points depicted in Fig. 8 form a sub-space of the QoS space shown in Fig. 9. This sub-space is composed of the points that—varying the dimension of the packets—best fulfill the considered application requirements. Therefore it can be used to identify the *admissibility sub-space*. In Fig. 9 it is possible to see that in the GPRS case the point depicted in Fig. 8 was achieved with a PS = 64 bytes. In the UMTS case the best trade-off point was obtained with a PS = 256 bytes. Finally in the ADSL and 802.11 b cases it was achieved with the maximum used PS = 1024 bytes.

5. Summary of results

As previously said we tested a large number of heterogeneous network configurations. In this paper, in order to show the capability of the *SC* to handle heterogeneous network performance, we pointed our attention to the four described in Section 4. For a complete results analysis refer to [10]. In this section, we report a summary of results of the complete analysis. Thanks to the use of our systematic measurement approach we are able to list some lessons we learned:

(i) PDA (at both sender and receiver sides) presents very low performance with several NICs;
(ii) in TCP case, at sender side the maximum throughput with 802.11 b is equal to 1.1 Mbps;
(iii) GPRS presents very high RTT and jitter values. These parameters reach their maximum value in the case of GPRS → UMTS (and vice versa);
(iv) in the case of 802.11 b with two stations, the ad-hoc mode configuration presents performance greater than the infrastructural configuration (with AP);
(v) up to PS equal to 512 bytes, TCP reaches better performance than UDP;
(vi) GPRS and UMTS networks present the best performance with PS greater than 512 bytes. In the case of PS equal to 32 and 64 bytes, the GPRS connection is intermittent (we experimented several network flappings).

6. Conclusion

In this work we introduced a systematic approach to cope with the complexity of a performance evaluation framework. More precisely, we have introduced a new concept we called *Service Condition* to cope with the heterogeneity of today's networks. The *SC* concept may prove useful in end-to-end network communication modeling as well as network measurements and performance evaluation studies.

To show the applicability of the proposed approach, in this paper we presented some of our measurements of QoS parameters over real networks characterized by a high level of heterogeneity in terms of access networks, end user devices, operating systems, and protocols. Furthermore, thanks to the proposed *Service Condition* concept we have depicted the relation between different *SCs* and the relative QoS parameters. Therefore, we have shown the importance of setting up a precise framework for the performance evaluation of a complex scenario like that of Fig. 2 where a large number of *SCs* are involved. Along with the proposal of a novel concept to model network conditions (that can be used also in other field of networking such as network management, network traffic modeling, network security, QoS algorithms, TE algorithms, ...) we found the best PS as a function of the analyzed *SCs*.

Currently, we are using our systemic approach to evaluate the performances of other heterogeneous scenarios. Also, we are working on the packet level characterization of several applications and protocols in order to use more realist traffic patterns in our network performance evaluation studies.

Finally, the presented results as well as the whole approach can be also used as reference for the development of wireless communication applications over multiservice and heterogeneous networks.

Acknowledgment

The authors thank Alberto Dainotti for his valuable support and hints.

References

[1] J.P. Singh, et al., Wireless LAN performance under varied stress conditions in vehicular traffic scenarios, in: Proceedings of the 56th Vehicular Technology Conference, VTC 2002, Fall, vol. 2, IEEE Comput. Soc., 2002, pp. 743–747.
[2] A. Messier, J. Robinson, K. Pahlavan, Performance monitoring of a wireless campus area network, in: Proceedings of the 22th IEEE Conference on Local Computer Networks, LCN '97, IEEE Comput. Soc., November, 1997, pp. 232–238.
[3] G. Xylomenos, G.C. Polyzos, TCP and UDP performance over a wireless LAN, in: Proceedings of INFOCOM '99 (2), IEEE Comput. Soc., 1999, pp. 439–446.
[4] J.C. Amaro, R.P. Lopes, Performance analysis of a wireless man, in: Proceedings of the IEEE International Symposium Network Computing and Applications, NCA 2001, IEEE Comput. Soc., October, 2001, pp. 358–361.
[5] M. D'Arienzo, A. Pescapé, G. Ventre, Dynamic service management in heterogeneous networks, Int. J. Network System Management (ISSN 1064-7570) 12 (3) (September, 2004) 349–370.
[6] S. Avallone, et al., D-itg, distributed Internet traffic generator, online available at: http://www.grid.unina.it/software/ITG, as of July, 2005.
[7] L. Cottrell, Network monitoring tools, On line available at: http://www.slac.stanford.edu/xorg/nmtf/nmtf-tools.html, as of July, 2005.
[8] H.J. Leen, M.S. Kim, J.W. Hong, G.H. Lee, QoS parameters to network performance metrics mapping for SLA monitoring, KNOM Rev. 5 (2) (2002).

[9] M. Alves, et al., New measurements with the RIPE NCC test traffic measurements setup, in: Proceedings of Passive and Active Measurements, PAM, March, 2002, pp. 66–75.

[10] A. Botta, et al., Performance evaluation of heterogeneous network scenarios, Technical report TR-DIS-102004, Dipartimento di Informatica e Sistemistica, October, 2004.