Internet Quality of Service: A Bigger Picture

Thomas Michael Bohnert[†], Edmundo Monteiro[†], Marilia Curado[†], Alexandre Fonte[†], Michal Ries[⋆], Dmitri Moltchanov[‡], Yevgeni Koucheryavy[‡]

[†]University of Coimbra
DEI, Pinhal de Marrocos, PT-3030290
Coimbra, Portugal
`{tbohnert,edmundo,marilia,afonte}@dei.uc.pt`

[⋆]University of Technology Vienna
Gusshausstrasse 25-389, A-1040
Vienna, Austria
`michal.ries@nt.tuwien.ac.at`

[‡]Tampere University of Technology
P.O.Box 553, FI-33101
Tampere, Finland
`{yk,moltchan}@cs.tut.fi`

Abstract. Quality of Service is one of the major research topics in computer communications, not at last reflected by the immense number of work published by today. In fact, continuous innovation is shaping this versatile subject in many aspects and it's nearly impossible to keep track for an individual. For this reason, this paper provides a tutorial-style and comprehensive Internet QoS state-of-the-art about current practices, what are advantages and what yet calls for further research. In order to do so, we present current QoS architectures for Next Generation Networks, explain what are the challenges along with wireless access technologies and introduce latest advances in QoS signalling. Another section rises fundamental questions about QoS routing and new directions in QoS assessment for multimedia services are discussed in a following one. Finally, the paper aims to rise awareness about the ongoing Net Neutrality discussion in the U.S., which is widely unknown beyond the U.S. but bears the potential of dramatically influencing the future of a QoS featuring Internet.

1 Introduction

Only a few subjects ever in the history of computer communications have brought in such controversy like the Quality of Service (QoS) issue in the Internet. What actually divides the No-QoS lobby from its counterpart is swiftly written down; persistent technological advance in switching capacity over demand by real-time services. Indeed, recent advances in Ethernet transmission rate surmounted the 100 Gbps barrier and prompted the IEEE standardisation body to create the IEEE 802.3 Higher Speed Study Group [1]. This in turn can safely be understood as the advent of this technology in a conceivable time frame especially as a first standard is expected already in 2010. Whether this paves the way for the replacement of Synchronous Optical Networking (SONET) in Next Generation Network (NGN) infrastructure [2], or not [3], is another matter but the mere perspective of another high-speed technology certainly fosters the confidence of Content Providers (CP) like IPTV broadcast stations and Video-on-Demand (VoD) providers.

Indeed, belief in solving any network inherent quality impairment by pure resource over provisioning has strengthened so much, that G. Bachula, the Vice President of the Internet2 project, has recently stated under what is termed *Net Neutrality*, that there must be no QoS mechanism deployed to secure the evolution of the Internet as barrier-free communication platform [4]. This considerable statement represents the conclusion of a 3-year QoS deployment study carried out by the Internet2 QoS Working Group [5].

Among other arguments, G. Bachula supports this conviction by global broadband penetration policy. For example, Europe's declared target is at least 95% broadband territorial coverage by 2008 [6]. However, alongside pure broadband provisioning, Europe's policy also embraces the advancement of a QoS featuring Internet implemented by founding ambitious research projects like GEANT2, EuQoS, NetQoS or OpenNet. Reason is, that over provisioning is deemed to be as myopic as Bill Gates' "640k ought to be enough for anybody" vision in 1981. Just as cellular telephones increase the total number of calls including the Public Switched Telephone Network (PSTN), broadband Internet access will sooner or later entail new, ever more data-rate greedy services until demand catches-up with technology, and if only when the latter is pushed to its physical limits.

In fact, there are ample arguments in support of a QoS featuring Internet. This is, not at last, reflected in the versatile advances published in the past as well as those currently in progress by research, development, standardisation bodies and even regulators. Exactly the dynamics in this area is what motivates us to publish this paper, in which we aim to provide a tutorial-style state-of-the- art completed with recent trends in this area of research. In order to do so, Sec.2 is about NGN QoS architectures. It is complemented by Sec. 3, which elucidates challenges incurred by wireless access for NGNs. Latest advances in QoS signalling are presented in Sec. 4 and thereafter, Sec. 5 highlights issues and implications in QoS intra and inter-domain routing. In Sec. 6, the authors provide evidence why research has to look beyond the traditional QoS definition. Finally, Sec. 7 presents a somewhat related issue, headed "Net Neutrality", and closes the paper.

2 QoS Architectures for New Generation Networks

Back to the 90s the major weakness of Internet Protocol (IP) networks was that they did not provide QoS guarantees. Indeed, only the Best Effort (BE) service was supported, so that inadequate performance was frequently obtained by emerged delay and loss sensitive applications. Providing performance guarantees in the Internet is still a challenging task. First studies proposing QoS frameworks for IP networks started to appear in the beginning of 90s within Internet Engineering Task Force (IETF). To support QoS in IP networks, IETF proposed two frameworks. These are Integrated Services (IntServ, [7]), based on connection-oriented resource reservation principle and Differentiated Services (DiffServ, [8]), based on service differentiation approach. IntServ provides deterministic QoS guarantees and requires a signalling protocol in order to inform network elements about the required reservation. In order to distinguish between flows with different QoS requirements DiffServ defines packet marking procedures. It provides relative QoS guarantees to aggregated traffic flows and uses Service Level Agreement (SLA) based connection admission control (CAC) algorithms.

According to IntServ, before data is transmitted, applications set up a path and reserve resources in terms of the link rate share and buffer space. For these purposes a signalling protocol is required. For example, RSVP is a protocol proposed for IntServ [9, 10]. IntServ framework defines two service classes in addition BE service: guaranteed service [11] and controlled-load service [12]. Guaranteed service is targeted on applications that require strict end-to-end delay guarantees. Controlled-load service is an improvement for currently available BE service. It guarantees that the traffic of this service 'will see the network in unloaded condition' [12]. In other words, strict guarantees are provided by guaranteed service and relative guarantees by controlled-load service.

To provide service differentiation capabilities, DiffServ defines the structure and meaning of the Type of Service (ToS) byte in the header of IP packets. Within the DiffServ framework this byte is called Differentiated Services (DS) field. Its value is called DiffServ codepoint (DSCP). Based on this field, DiffServ specification defines a number of packet forwarding treatments in to be implemented in routers. They are called Per Hop Behaviours (PHB). By marking IP packets differently and treating packets in routers appropriately, a number of service classes can be established. Hence, DiffServ is a relative priority scheme.

The IETF DiffServ working group has standardised two PHB groups. Assured Forwarding PHB (AF PHB, [13] is designed for applications that require relative QoS guarantees. There are four classes of PHB identification codes within the AF PHB group. Within each class there are three distinct DSCPs that are used to distinguish services with different packet drop precedence. The other PHB, Expedited Forwarding PHB (EF PHB, [14]) is targeted on applications that require strict guarantees on end-to-end delay and must not suffer from packet losses. Note that DiffServ only defines DS fields and PHBs but it is up to manufacturers how to implement PHBs in routers and to network operators which services to provide.

Although Multiprotocol Label Switching (MPLS) is not considered as a QoS framework for IP networks, it provides a number of advantageous features to network operators. According to MPLS, data are transmitted along the so-called Label Switched Paths (LSP). These paths can be explicitly chosen by network operators [15]. This feature enables effective traffic engineering capabilities [16] compared to classic approaches which use Interior Gateway Protocol (IGP) metrics. LSPs are computed in traffic engineering databases (TED, [16]) in ingress routers using Constrained Shortest Path First (CSPF) algorithm. TEDs are filled by IGP advertisements. For this reason IGP protocols were extended to support advanced link metrics such as available bandwidth on a link [17,18]. Label switched paths are established using either RSVP modification [19] or specifically developed Label Distribution Protocol (LDP, [20]).

Modern QoS-aware networks such as DiffServ, MPLS or DiffServ/MPLS are specifically designed to be flexible enough to reallocate network resources in the best possible way, such that the required performance is provided using minimum amount of resources. Using service differentiation principle, DiffServ provides tight performance bounds to traffic aggregates but requires all packets to follow the same path in a DiffServ domain. This requirement contradicts the hop-by-hop forwarding philosophy of IP protocol. MPLS complements DiffServ providing mechanisms to choose and reserve resources on the best available path for a given traffic [21].

Traffic aggregates in DiffServ, MPLS and joint MPLS/DiffServ networks are still described statically using the token bucket mechanism. Neither classic MPLS bandwidth constraint model nor specific models proposed for DiffServ/MPLS provide dynamic resource description. Unfortunately, neither DiffServ nor MPLS provide standardised methods to automatically describe arriving traffic and dynamically reallocate resources.

Provision of QoS is still a challenging task even in fixed IP networks. Currently, one of the major challenges is to add IP QoS in the reservation mechanisms of wireless network technologies, see Sec. 3, and to propose a consistent end-to-end QoS assurance model for All-IP wireless networks. Since the interworking between wireless networks and the public Internet is one of the most critical aspects in this architecture, QoS provisioning should be based on those frameworks available for IP-based fixed networks.

Finally, generally all QoS technologies that aim on providing guarantees end-to-end, imply that all routers support the chosen architecture. Nowadays, this requirement is not absolutely mandatory, especially for the backbone of Internet networks, where overprovisioning provides a feasible way to guarantee traffic performance [22]. However, access networks, where bandwidth is a scarce resource still require a certain QoS framework to be implemented [23,24].

Nowadays the common practice for Internet Service Providers (ISP) is to offer two services only: guaranteed and BE. Depending on the SLA between the customer and the provider, performance guarantees (with respect to some metrics) are provided for guaranteed service. No guarantees are provided for best effort service. Guaranteed service is mainly used by real-time applications such as voice over IP (VoIP) that require strict QoS guarantees. All other applications use best effort service.

3 QoS Issues in Wireless New Generation Networks

The Radio Access Network (RAN) is one of the weakest points in the NGN framework, NGNs are supposed to be equipped with numerous RANs and therefore the wireless interface becomes a critical point for end-to-end smooth IP networking [25]. Since wireless channels exhibit unstable behaviour due to a number of factors such as multipath fading and shadowing, mainly induced by mobility, recent works of NGN standardisation bodies focus mainly at layers below IP - the main efforts are on improving of wireless channel characteristics and hence carried out on Physical (PHY) and Medium Access Control (MAC) layers.

Being different from wired networks, wireless networks suffer from time-varying and non-stationary channels. This quality variation of the channel is typically expressed by either the variation of the Signal-to-Noise Ratio (SNR) or the Bit Error Rate (BER). These variations in turn result in time-varying, instantaneous transmission bandwidth at higher layers, which leads to unpredictable delay of packets at application layer, especially when Automatic Repeat Request (ARQ) mechanisms are deployed. Since buffer size at MAC layer is finite, such varying service rate can induce buffer overflow due to a bit rate mismatch between packet arrival rate and channel service, resulting in very poor, uncontrollable QoS.

After this general problem statement, the sequel of this section presents more detailed insight in what has been achieved to provide QoS for such IP-oriented wireless technologies, especially focusing on the IEEE standard families 802.11 and 802.16.

The IEEE 802.11 [26] specifications are wireless standards for implementation of Wireless Local Area Network (WLAN) of relatively short range offering high speed access to the Internet with restricted mobility in hotspot areas. The IEEE 802.11 standards specify an air interface between wireless clients and Access Points (AP), as well as among wireless clients only. It addresses both the PHY and MAC layers and is also targeted on resolving compatibility issues between manufacturers of WLAN equipment.

QoS in IEEE wireless networks is usually managed at the MAC layer. The original IEEE 802.11 standard was not addressing QoS issues, but a redundant priority scheme with different interframe spacing was developed to support flows with different priorities. However, all data frames in that standard still have the same priority. Further, the IEEE 802.11 Working Group has been working on QoS enhancements mostly to support differential data frames treatment, eventually bringing the MAC on par with enhancements from Ethernet technology like IEEE802.1q and IEEE 802.1d. This activity resulted in IEEE 802.11e standard [27], which introduces the new Hybrid Coordination Function (HCF) protocol that concurrently uses a contention-based Enhanced Distributed Coordination Access (EDCA), and a polling-based HCF Controlled Channel Access (HCCA) in oder to provide channel access differentiation and hence, QoS to individual flows.

The EDCA is an extension of the Distributed Coordination Function (DCF), the classical contention-based mode of IEEE 802.11. It is designed such that non-QoS-enabled stations can coexist with QoS-enabled station within the same access point. The EDCA introduces a notion of Access Category (AC) distinguishing four traffic priorities, and operates using traffic AC-dependent interframe spacing together with an initial collision window. A dedicated queue is allocated per each AC, and a so-called Virtual Collision Handler assures collision avoidance without actual access to the medium is defined within an AP. On top of that, IEEE 802.11e defines a priority value called Traffic Category Identification (TCID). TCID defines eight priorities based on IEEE 802.1d bridge specification [28]. It also enables to identify traffic flows, using a so-called Traffic Stream ID, in oder to support per-flow resource reservation. Each station is responsible for setting up of such traffic flows and to request resource reservation for them, for example using NSIS [29].

The HCCA, in turn, is a polling-based mode where medium access is controlled by the AP. To implement this, a new concept named Controlled Access Phase (CAP) has been developed. The AP is able to interrupt the contention operation by issuing a CAP polling message at any point in time, given it finds the medium idle for a Priority InterFrame Space (PIFS) period that is smaller than the EDCA interframe spaces, InterFrame Space (DIFS) and Arbitrary InterFrame Space (AIFS), thus granting a polling message with highest priority. It should be outlined that IEEE 802.11e does not explicitly specify the CAP generation discipline but leaves this issue open for research and development. To upper limit the duration a station can transmit (occupy the medium), a new concept called Transmission Opportunity (TXOP) has been introduced. Indeed, a station either in contention or polling operational mode could transmit data for too long time making the medium busy for other stations. That is why TXOP is bounded by a value TXOPLimit defined either by AC settings for EDCA or by AP in case of HCCA. In HCCA mode, when transmission from/to AP is coordinated by a single entity within APs, a scheduler at PHY layer has to be implemented. IEEE 802.11e does not explicitly specify such scheduling mechanisms, but intentionally leaves it open for innovation by research.

802.11e uses QoS nomenclature similar to the DiffServ framework presented above. This is in fact very important since from end-to-end point of view, it is highly desirable that a packet of a certain priority would be properly handled within both, wired and wireless domains. Therefore, to assure QoS in NGN frameworks where IEEE 802.11e technology is employed, AC and DSCP require a unique mapping; one should account that there are four ACs defined while DSCP benefits from up to 64 priority classes.

Typically IEEE 802.11 APs implement an 802.1d bridge interconnecting MAC layers of IEEE 802.11 and IEEE 802.3 supporting up to eight priorities. However, IEEE 802.3 itself cannot grant frame priorities but priority can be implemented using the IEEE 802.1q VLAN tag. Therefore, an IEEE 802.3 MAC frame with correspondent priority value coded by an VLAN tag can be used by IEEE 802.1d MAC bridge for implementation of priority interoperability with IEEE 802.11e, consequently, frames can be differentiated on the wireless domain.

The IEEE 802.16 WirelessMAN technology has been developed with the aim to provide broadband access for access networks and medium sized backhaul links. Indeed, by supporting transmission rates up to 134 Mbps at distances as far as 20 km, while supporting mobility still at 100 km/h, 802.16 provides the long-awaited broadband wireless access not only for impervious areas but also for highly dense areas like city centres where cabling is impossible or too expensive. The IEEE 802.16 standards [30] [31] are a synthesis of time-proven wireless and wired network technologies, namely the above presented IEEE 802.11, the Third Generation Mobile Phone Network (3G), Asynchronous Transmission Mode (ATM) and the Data Over Cable Service Interface Specification (DOCSIS). Only the best features of these technologies have been taken off, tailored and forged into the 802.16 standards. One of the consequences of this design choice is IEEE 802.16's feature rich QoS model, derived from ATMs achievements in this regard [32]. In the sequel of this section we will sketch these QoS features, focusing on Point-to-Multipoint (PMP) mode only.

Two deployment modes have been defined in 802.16, PMP and Mesh. In either mode one station serves as transmission coordination reference. In PMP mode this station is called the Base Station (BS) and is the sole AP for one or many Subscriber Stations (SS) and/or Mobile Stations (MS). All interactions are coordinated by and routed through such a BS. It is supposed to have complete knowledge about all SSs and MSs in range and its scheduler assigns individual transmission opportunities to each of them based on resource availability and QoS commitments.

For PMP mode, different transmission strategies in respect to transmission direction, i.e. Uplink (UL) and Downlink (DL), are defined. For both directions data transmission takes place a separate (sub)frames, while in UL, SS transmit in Time Division Multiplexing Access (TDMA) mode, while in DL the BS broadcasts frames to all receivers in range. Frames at DL and UL are duplexed using either Time Division Duplex (TDD) or Frequency Division Duplex (FDD).

Conceptually, the BS is in charge of resource allocation, and thus QoS, at both DL and UL. However, SSs are able to adapt transmission capabilities, in respect to QoS commitments and channel state information, by communicating with the BS, which in turn assigns new or updated Interval Usage Codes (IUC), a part of UL Channel Descriptor (UCD). The IUC includes modulation, rate, FEC scheme and other parameters of the PHY layer. Uplink and downlink use different IUCs, Uplink IUC (UIUC) and Downlink IUC (DIUC) correspondingly.

The MAC protocol defined by 802.16 is connection-oriented, In other words, both, transport and control flows, use unidirectional logical connections. The outbound MAC associates packets with a so-called Service Flow (SF), which in turn is associated with a logical connection. Every SF is associated with respective QoS parameters, e.g. transmission ordering and scheduling. Service flows can, for instance, map to DiffServ or MPLS flow labels in order to enable end-to-end IP-based QoS. Further 802.16 QoS facilities include four different QoS categories in UL and DL; ARQ, Call Admission Control (CAC) and scheduling. Further, the adaptation abilities of the PHY layer plays also an important role supporting the MAC layer to achieve reliable and controlable QoS.

Much like in 802.11 QoS enhancements, crucial algorithms, like scheduling and CAC, has been intentionally left out of the standard to pass a powerful tool to manufactures and research, for the former especially to distinguish their products [32].

Finally, we'd like to mention the WiMAX Forum, which is an exclusively industry-driven 802.16 certification body. Its aim is to assure multi-vendor interoperability. Part of this mission is to address end-to-end QoS assurance for NGN frameworks and therefore, a special working group is defining an All-IP Mobile WiMAX End-to-End Network Architecture [33]. Its main motivation is to define an compatible 802.16 based network architecture which is seaminglessly integratable into existing networks such as 3G.

4 Advances in QoS Signalling

Quality of Service provision in the Internet needs signalling mechanisms to support resource allocation and traffic control in network elements. The RSVP and MPLS signalling mechanisms, see also Sec. 2 are the principle signalling protocols to support QoS and resource control in todays IP networks.

The above mentioned QoS signalling protocols have limitations related to scalability (the amount of state installed in the network), efficiency (the quantity of signalling messages in the network) and are limited to interdomain operation (they are not adequate for operation in complex scenarios including multiple network operators). To overcome these limitations, new signalling mechanisms are needed with advanced functionalities to deal with different signalling requirements.

Advanced signalling mechanisms need to support on-path and off-path signalling. When signalling messages follow the same path as data messages, it is said that on-path signalling is being performed (also mentioned as path-coupled or in-band signalling). However, sometimes entities that are not on the data path need to be signalled. Signalling protocols that allow the signalling of entities that are not on the data path are called off-path signalling protocols (also mentioned as path-decoupled or out-band signalling). Hybrid signalling solutions using on-path signalling inside each domain and off-path signalling between domains are also possible [34].

Advanced signalling mechanism need also to support explicit or implicit signalling. Explicit signalling is achieved trough explicit messages that can be carried together with user data, in specific packet fields, like in TCP header fields or in separate signalling packets, like in RSVP. Implicit signalling information can be extracted from the normal application flow to trigger reservation mechanisms in network devices. Some signalling solutions combine implicit signalling near the end-systems (to reduce the complexity of end-systems) and explicit signalling inside the network.

Signalling is closely related with the amount of state information stored in the network elements. State information can be stored per-flow or per-flow aggregates. State information can be maintained until explicitly released (hard-state) or expire after a given time limit if not refreshed before (soft-sate). If state information is needed per-flow, signalling also needs to be performed on a per-flow basis; otherwise signalling is only needed to manage the flow aggregates. In soft-state approaches, signalling needs to be periodically issued to refresh the state information. In hard-state approaches signalling is only needed for the establishment and release of state information.

The definition of a signalling scheme is a tradeoff between the application needs and the complexity introduced in the network. Best effort applications only need basic signalling mechanisms for flow, error and congestion control like the ones included in TCP. Multimedia applications, with QoS requirements, can operate smoothly if the network is over-provisioned. In a limited resource environment they will need per-flow or aggregated signalling to support resource reservation and traffic differentiation mechanisms. Thus there is also a tradeoff between the amount of signalling and network resources. Overall, the definition of the signalling mechanisms for the support of real time applications over the global Internet with quality and security is still an open issue. The solution is expected to emerge from the signalling proposals being discussed and standardised at the IETF and the settlement of the above tradeoffs.

The limitations of RSVP have inspired the emerging Next Steps In Signalling (NSIS) framework. NSIS is a signalling framework being developed by the IETF in the context of the NSIS Working Group [29], for the purpose of installing and maintaining flow states in the network. NSIS is based on various signalling protocols, the main one being RSVP. The intention is to reuse RSVP mechanisms whenever possible, since these mechanisms have already been widely tested, but leaving out all unnecessary complexity (e.g., multicast support). It is, thus, a simpler and more scalable approach to resource reservation, when compared to RSVP.

By using a two-layer signalling architecture, the NSIS transport layer and the NSIS signalling layer, signalling transport is separated from signalling applications, allowing the use of the same signalling transport protocol for the support of all signalling applications.

The NSIS transport layer protocol, known as General Internet Signalling Transport (GIST), is responsible for the transport of signalling messages between network entities. The signalling layer contains specific functionality of signalling applications and may comprise several NSIS signalling layer protocols, generically known as NSLPs. With this approach the transport of the signalling messages and the signalling application are separate. Examples of signalling protocols are the QoS-NSLP [35] and the Network Address Translation (NAT) & Firewall (FW) NSLP [36]. This architecture opens the way to develop several emerging signalling applications, of which QoS signalling is the first use case to be implemented.

The initial requirements of NSIS include support for the independence of application signalling and network control mechanisms, ability to place NSIS initiators, forwarders, and responders anywhere in the network through on-path and off-path signalling, transparent signalling through the network (the signalling message are opaque for the signalling transport), grouping of signalling for several micro-flows, flow aggregation, scalability, flexibility, and security.

Although NSIS can work on a per-flow basis, it allows flow aggregation based on the use of the DSCP field or tunnels. Additionally, it works on a hop-by-hop basis, between NSIS-aware nodes (NSIS Entities, NE, also referred to as NSIS hops). Nodes not supporting NSIS are transparent, which means that there is no need for deployment of NSIS in every network entity.

NSIS supports both on-path and off-path signalling. In the case of path-coupled signalling, signalling messages are routed through NSIS entities on the data path only, although between adjacent NEs, the route taken by signalling and data might diverge. In the case of path-decoupled signalling, messages are routed to NEs which are not assumed to be on the data path, but which are aware of it (NEs have to know the path topology). In this case, the signalling endpoints may have no relation at all with the ultimate data sender or receiver.

The NSIS framework is being developed aiming to support the advanced signalling mechanism for QoS, security and other important functions in IP networks. Besides the above described modules, other modules are being developed to enable the support of advanced QoS negotiation features [37]

5 QoS routing in the Internet

QoS routing in the Internet is, undoubtedly, an essential piece of future Internet functionality for supporting reliable, assured and high performance IP traffic transference, and so QoS. QoS routing is therefore relevant for both reservation-based services (i.e., IntServ and MPLS) or reservationless services (i.e., DiffServ) described in Sec. 2. QoS routing is, however, a complex problem to tackle. The first difficulty already starts with the algorithmic problem to solve. That is, QoS routing must find paths that satisfy multiple QoS requirements or constraints (e.g., latency, jitter and bandwidth). The second difficult relates to the QoS routing protocol responsible for capturing and exchanging information about network resources. In line with the motivation of this paper, this section aims on sheding some light on path selection algorithms and on aspects relating to protocols, all in the context of QoS routing.

The algorithmic problem in QoS routing is known as the Multi-Constrained (Optimal) Path (MC(O)P) routing problem [38, 39]. Briefly, the MC(O)P can be stated as follows. Given a network $G(N, E)$, where N represents the set of nodes and E the set of edges, a source node s, a destination node d, k (≥ 2) weight functions: $w_1 \rightarrow R^+, ..., w_k \rightarrow R^+$, and k constants represented by a vector $c = (c_1, ..., c_k)$, the MCP problem is to find a path p from s to d such $w_1(p) \leq c_1, ..., w_k(p) \leq c_k$, i.e. a feasible path. The MC(O)P is the problem that additionally finds a path $p = src \rightarrow v_1 \rightarrow v_2, ..., dst$, i.e., the optimal path, such there isn't any other path q such $w_1(q) < w_1(p), ..., w_k(q) < w_k(p)$.

When the QoS measures are additive, the MC(O)P problem is often interpreted as NP-hard [40]. In other words, it means that the computational-time complexity is non-polynomial. Thus, heuristics or approximation algorithms are usually used to tackle the MC(O)P. In the body of work, two instances of MC(O)P are the main focus of these heuristics. The first instance of MC(O)P is when bandwidth is one of the constraints that must be satisfied by the path computation algorithm. In this case, the MCP problem is defined as a Bandwidth Restricted Path (BRP) problem [41]. Examples of algorithm families that solve the BRP problem are the Widest-Shortest Path (WSP) and Shortest-Widest Path (SWP) algorithms [42–44]. Metric ordering is the key heuristic used by these algorithms for find BRP solutions. This heuristic requires the identification of the metric that has higher priority and the computation of the best paths according to this metric. Afterwards, it is computed the best path according to the second metric. The second instance is called Restricted Shortest Path (RSP) and is a simplification of the original MCP problem, when two additive metrics are used [40]. In this case, all the paths that satisfy the constraint associated with one of the metrics are computed and then the best path according to the second metric is selected. A widely case is the Delay-Constrained Least Cost problem (DCLC) [45].

Examples of algorithms for solving DCLC problem are the Delay Constrained Unicast Routing (DCUR) and Dual Extended Bellman-Ford (DEBF) algorithms [46].

Alternatively, one straightforward heuristic to solve MCP problems is through Metrics Combination (MC), i.e. by combining or mixing a set of QoS metric items in a single composite metric [47]. Then, existing path computation algorithms, such as Bellman-Ford or Dijkstra can be used to compute the best path. The biggest difficulty, however, is that it is unclear how we should properly combine all QoS metric items. Linear, non-linear and Lagrange relaxation compositions have been widely used in several proposals, such as the Multiconstrained Energy Function based Pre-computation Algorithm (MEFPA), the Tunable Accuracy Multiple Constraints Routing Algorithm (TAMCRA) (and its successor SAMPRA) and the LAgrange Relaxation based Aggregated Cost (LARAC) algorithm, respectively [39, 48–50].

Now we turn to the aspects relating to existing protocols. The Internet routing is handled by two different kinds of protocols each with a distinct objective. Inside of the boundary of an Autonomous System (AS) the routing of IP packets is handled by an Interior Gateway Protocol (IGP) based on shortest path, such as Open Shortest Path First (OSPF) or Intermediate System-Intermediate System (IS-IS) [51, 52]. On the other hand, to provide connectivity across ASes boundaries the de facto Exterior Gateway Protocol (EGP) - BGP (Border Gateway Protocol) - is used to exchange reachability information to blocks of IP prefixes [53]. Unfortunately, most of routing protocols have been designed without QoS (or efficiency) requirement in mind. Although best-effort routing provides good-enough service for several applications, such as e-mail or Web, it would be not sufficient for mission-critical or time-dependent applications, such as Voice over IP (VoIP), when their packets transverse congested networks.

The problem of extending routing protocols to support QoS is, however, more intricate to solve than algorithmic problem, mostly due to the potential required changes on routers. Even so, in the intra-AS level there has been significant progress and has resulted on standards, such as QoS routing Mechanisms and OSPF Extensions [43]. The biggest open problem in routing still be the expansion of QoS across AS boundaries. Since 90's IETF recognises interdomain QoS routing as the critical missing piece for distribution of QoS capabilities supported by each AS (e.g., a class or meta-class of service) [54]. In the body of work, there are a couple of IETF-drafts and proposals of QoS extensions to BGP following a similar approach [55–57]. Specifically, these works have been proposing BGP QoS attributes for routes and modifications to the BGP decision process. For instance, O. Bonaventure et al proposed an optional and non-transitive BGP QoS attribute that enables each AS to associate with routes the DiffServ PHBs (BE, AF and EF) it supports and the types and values of QoS parameters (e.g. maximum bandwidth associated to PHB) or the required QoS signalling (e.g. indication that the AS supports RSVP). Similarly, J. Cristallo et al defined an optional and transitive BGP QoS attribute, named QoS_NLRI (Network Layer Reachability Information).

Despite the scientific interest of these works, none of their proposals have turned out to be sufficiently appealing to be deployed at large scale. One clear indicator of ISPs indifference is that most of them prefer to overprovision networks rather than delivering QoS [58]. Furthermore, as these are in-band BGP mechanisms their performance is affected by most of BGP drawbacks (e.g., the well-known slow convergence or oscillatory behaviours). An additional difficult to tackle in the interdomain QoS routing is related to the need of giving more route control to users. In effect, BGP paradigm prevents any user from controlling the transit of its packets (e.g., to avoid transversing congested ASes or ASes that are filtering packet contents).

Consequently due to these difficulties, many alternative solutions are emerging to tackle the interdomain problem based on either on novel or older concepts. Not surprising is, in common, they tend to avoid any enhancements or extensions to BGP. This leads to the following open questions: How valuable are these solutions? What would be the most promising solution to be deployed at large scale? Using pure-overlays (e.g., QRON [59])? Combining overlays and BGP (e.g., OPCA [60])? Using Multihoming Intelligent Routing Control [61]? Making QoS Extensions to BGP? Or rebuilding the entire Internet routing from scratch (e.g., NIRA [62])?

6 QoS Assessment for New Generation Networks

The QoS topic in the environment of Internet services became crucial due to customer popularly and commercialisation of Internet multimedia services. Further attention to this topic was focused with emerging Internet multimedia subsystem (IMS) [63] and with on-demand multimedia content delivery.

Technically QoS has emerged from the fundamental difference between the connection oriented, circuit-switched PSTN and connectionless packet-switched networks. For the latter, resources are not explicitly allocated to individually paired hosts, instead the available network capacity is shared at each link by several connections, leading to packet losses within connections at the links' output buffers, potentially causing quality impairment at the receiving side. This approach leads naturally to view on QoS in terms of connection parameters like packet loss/delay or service availability. Such view allows us for prefect estimation of network or connection QoS, but poorly reflects the perceived quality. Besides classical QoS, perceived QoS assessment becomes increasingly important with the emergence of multimedia IP services, because it reflects a user satisfaction level which is for service provisioning the most relevant parameter.

Traditional IETF QoS assessment focuses on physical parameters like packet delay, loss or jitter, so-called Intrinsic QoS (IQ) [64]. In contrast to this approach, service quality can alternatively rated by subjective assessment. This is commonly termed Subjective or Perceived/Perceptual QoS (PQ) [64, 65] and is solely based on human perception or satisfaction regarding service usability. Determining PQ is typically carried out by surveying a set of persons, which participate in a controlled experiment [65, 66]. In contrast to this method, if there are no humans involved and PQ is computed from physical parameters, it is called Objective QoS assessment [65].

In contrast to the ITU, the IETF has not yet adopted the concept of PQ. This is rooted in the nature of the services each standard entity is concerned with. The PSTN's primary service is voice and its quality assessment is a highly subjective matter. Hence, the ITU, as the PSTN's standard body, has been concerned with PQ for more than a century. With the evolution of the Internet as the universal communication platform, however, more and more voice traffic is delivered over Internet infrastructure, henceforth calling for the same quality assessment methodology for VoIP services. Moreover, it is worth noticing that this reaches beyond Voice over IP (VoIP) services and applies to any audio and/or visual service like for instance IP Television (IPTV) or Videoconferencing. The ITU issued a few recommendations, see for example [67, 68], regarding subjective quality assessments and the proposed test methodology is suitable for perceived quality testing of Internet multimedia services. The only limitations of these recommendations is the usage scenario, because the ITU recommends for subjective audiovisual and video test PC screen. The multimedia user terminals has different size, mobility features and usage. This variety of terminals brings in new usage scenarios for the multimedia services. Moreover the usage scenario influences the human perception [69, 70] significantly. The test scenario should consider the real usage scenario, in order to avoid systematic test failure [70].

Furthermore the human visual perception of multimedia content is determined by the character of the observed sequence [71, 72]. The sequence character reflects audiovisual spatial and motion characteristics (content type, video motion features, spatial information) [70–72]. The recent trends show that the perceptual QoS is defined by set of classical QoS parameters and objective audio and video parameters. The parameter set is determined according to correlation of objective and subjective parameters [70]. For selecting the most relevant parameters while retaining as much information as possible, for such complex task are most suitable the multivariate statistical methods (i.e. Principal Component Analysis). Finally the objective parameters are mapped on subjective quality parameters (i.e. mean opinion score, willingness to pay). According to usage scenario is chosen the estimation method (analytical model, artificial neuron network, hypotheses testing or ensemble based system).

The estimation of perceptual QoS is very complex task due to multimedia service and content diversity and till now it was not proposed any universal perceptual quality estimator. On the other hand reliable estimators were proposed for certain services and usage scenarios [71–73]. Furthermore, for the estimation of perceptual QoS, multimedia content and the usage scenarios have to be taken into account in order to yield accurate ratings.

7 Net Neutrality

By this end, commonly a conclusion would round-up the paper and it wouldn't be any different if there wouldn't be another ongoing, controversial debate about the future of a QoS featuring Internet. Well, will many Internet veterans immediately say, that's nothing new at all. That's undoubtlessly true, Internet QoS has never been undisputed and will never be until its final ubiquity. But there is one point that distinguishes this debate from any in the past. Scale.

It all commenced with the final advent of real-time Internet services like Skype or YouTube, on a global scale. This, by the QoS lobby long-awaited happening, is frequently considered as the .com boom's reincarnation, meanwhile matured and based on proven sustainable business models, not at last backed up by high broadband access penetration. And exactly here is the point.

The Internet's peculiar architecture fostered the division of an unit that has been monolithic in Internet prehistory, content and its delivery infrastructure. Examples of this phenomena are AOL's, Microsoft's MSN or T-Online's failed attempts in the mid-nineties to confine subscribers to selected content hosted in their own realms. The result of this content-access division is an unequal share of total revenue between respective providers, i.e. CPs and ISPs, at least from latter's point of view.

The CEO of AT&T, E. Whitacre, first expressed this awareness some one and a half year ago. Briefly, in his point of view CPs like Google or Yahoo have to pay his company as it provides (high quality) access to their customers. This conviction has meanwhile strengthened among ISPs and finally motivated them to looby for a modification of U.S. telecommunication law to endorse their case, enforced by strict regulation. In fact, rumour tells that AT&T alone has spent 110 millions dollars by today.

Confronted by this threat, CPs see their business models endangered and launched a massive counter strike. What CPs fear is that powerful telecos like AT&T or Verizon may (ab)use their power to discriminate between traffic types, access quality or charging tolls on content, eventually turning the Internet into a two-class society, those provided ”Premium Service” and the rest. In order to prevent this, CPs, including incumbents like Microsoft, Goolge, Yahoo and Ebay, jointly invest in what is now called ”Net Neutrality”. Using equal means as deployed by their opponents, the telcos, their declared goal is to achieve exactly the opposite, a modification of U.S. telecommunication law, by then endorsing that there must be no service differentiation at all in the Internet. This essentially would exclude any QoS mechanism, enforced by regulatory means.

The implications of this battle of giants are immense. It's eithers belief that no defeat can be afforded and henceforth, both parties reveal utmost determination to achieve. In just one and a half year, for instance, Neutrality proponents, proxied by the U.S. Democrats, submitted three amendments to the U.S. Senate and House of Representatives. In this course, MP E. Markey, for example requests in [74] ”if the provider prioritises or offers enhanced quality of service to data of a particular type, (it’s its duty) to prioritise or offer enhanced quality of service to all data of that type, regardless of its origin”.

Yet neither side has succeed, mostly due to the reluctant U.S. Republicans on power. This, however, has recently changed with the result that AT&T moved its focus away from the federation towards individual states with partial success. But more scary is certainly the speed with which this matter gains scale. Vincent Cerf, nowadays on Google’s pay-roll and its primary pro Net Neutrality frontman, certainly agrees on the importance of Net Neutrality with Sir Tim Berners-Lee, but surely disagrees with his request for neutrality in Digital Right Management. In fact, frontiers in this battle are getting more and more blurred, at last indicated by the U.S. Democrate C. Gonzalez, who urged for neutrality extension regarding involved business practices.

But notwithstanding, there are certainly good reasons in favour of [75, 76] and against Net Neutrality [77]. I (Thomas Bohnert) personally agree in particular with J. Crowcroft and urge the European community, which recently set up a special commision in charge with this issue, to keep a level head. It’s just too obvious that the whole debate in the U.S. merely salvages the risk of a complex, never ending proxy war between two business engines which try to maximise profit. Most likely, the only outcome would be a heavy regulatory burden on something that is flourishing exactly because it has been free from such an evolution inhibitor, the Internet. For me, it’s deeply scary to watch lawyers, lobbyists and politicians fighting over the destination of a QoS featuring Internet and hence, over years of research and development in this area. Eventually, I call to remind that yet the Internet has never been neutral at all and free market forces are proven to be the best policy enforcement. Why should this has recently turned different for Internet ethics?

Acknowledgement

This work has been jointly supported by the EU IST Integrated Project WEIRD (WiMAX Extensions for Remote and Isolated Data Networks) and the ESF COST 290 Action. Further, the authors would like to thank Prof. Markus Rupp from Vienna University of Technology for providing further support for this research collaboration.

References

1. IEEE Higher Speed Study Group, sep 2006. http://ieee802.org/3/hssg/public/index.html. Accessed on 07.01.2007.
2. M. Nowell and G. Nicholl. *802.3 Higher Speed Study Group Objectives and Work Areas*. IEEE HSSG and CISCO, sep 2006. Accessed on 01.07.2007.
3. G. K. Cambron. The Next Generation Network And Why We’ll Never See It. *IEEE Communications Magazine*, oct 2006.
4. G. R. Bachula. Testimonly of G. R. Bachula, Vice President, Internet2 Before the United States Senate Commiteee on Comerce, Science and Transportation: Hearing on Net Neutrality. Technical report, Internet2, February 2006.
5. B. Teitelbaum and S. Shalunov. Why Premium IP Service Has Not Deployed (and Probably Never Will) . Technical report, Internet2, May 2002.
6. J. Cornu and G. Hughes. Digital Divide and Broadband Territorial Coverage. Technical report, eEurope Advisory Group, jun 2004.

7. R. Braden, D. Clark, and S. Shenker. *Integrated Services in the Internet Architecture: An Overview*. RFC 1633. IETF, jun 1994.
8. S. Blake, D. Black, M. Carlson, E. Davies, Z. Wang, and W. Weiss. *An Architecture for Differentiated Services*. RFC 2475. IETF, dec 1998.
9. R. Braden, L. Zhang, S. Berson, S. Herzog, and S. Jamin. *Resource ReSerVation Protocol RSVP*. RFC 2205. IETF, sep 1997.
10. J. Wroclawski. *The Use of RSVP with IETF Integrated Services*. RFC 2210. IETF, sep 1997.
11. S. Shenker, C. Partridge, and R. Guerin. *Specification of Guaranteed Quality of Service* . RFC 2212. IETF, September 1997.
12. J. Wroclawski. *Specification of the Controlled-Load Network Element Service* . RFC 2211. IETF, sep 1997.
13. J. Heinanen, F. Baker, W. Weiss, and J. Wroclawski. *Assured Forwarding PHB Group* . RFC 2597. IETF, June 1999.
14. B. Davie, A. Chany, F. Baker, J. C. R. Bennet, K. Benson, J. Y. Le Bedeuc, A. Chui, W. Courtney, S. Davari, V. Firoiu, C. Kalmanek, K. Ramakrishnan, and D. Stiliadis. *An Expedited Forwarding PHB (Per-Hop Behavior)*. RFC 3246. IETF, mar 2002.
15. E. Rosen, A. Viswanathan, and R. Callon. *Multiprotocol Label Switching Architecture*. RFC 3031. IETF, jan 2001.
16. D. Awduche, J. Malcolm, J. Agogbua, M. O'Dell, and J. McManus. *Requirements for Traffic Engineering Over MPLS* . IETF. IETF, September 1999.
17. D. Katz, K. Kompella, and D. Yeung. *Traffic Engineering (TE) Extensions to OSPF Version 2* . RFC 3630. IETF, sep 2003.
18. H. Smit and T. Li. *Intermediate System to Intermediate System (IS-IS) Extensions for Traffic Engineering (TE)* . RFC 3784. IETF, June 2004.
19. D. Awduche, L. Berger, D. Gan, T. Li, V. Srinivasan, and G. Swallow. *RSVP-TE: Extensions to RSVP for LSP Tunnels* . RFC 3209. IETF, dec 2001.
20. L. Andersson, P. Doolan, N. Feldman, A. Fredette, and B. Thomas. *LDP Specification*. RFC 3036. IETF, January 2001.
21. F. Le Faucheur, L. Wu, B. Davie, S. Davari, P. Vaananen, R. Krishnan, P. Cheval, and J. Heinanen. *Multi-Protocol Label Switching (MPLS) Support of Differentiated Services* . RFC 3270. IETF, may 2002.
22. C. Fraleigh, F. Tobagi, and C. Diot. Provisioning IP backbone networks to support latency sensitive traffic. In *INFOCOM 2003*, volume 1, pages 375–385. IEEE, apr 2003.
23. J. Evans and C. Filsfils. Deploying DiffServ at the network edge for tight SLAs, part 1. *IEEE Internet Computing*, pages 61–65, jan 2004.
24. J. Evans and C. Filsfils. Deploying DiffServ at the network edge for tight SLAs, part 2. *IEEE Internet Computing*, pages 61–69, mar 2004.
25. C. Hsiao-Hwa, M. Guizani, and W. Mohr. Evolution toward 4G wireless networking [Guest Editorial]. *IEEE Network Magazine*, 21(1), January 2007.
26. *Part 11: Wireless Lan Medium Access Control (MAC) And Physical Layer (PHY) Specifications*. IEEE Standard for Local and Metropolitan Area Networks. IEEE, nov 1997.
27. *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 8: Medium Access Control (MAC) Quality of Service Enhancements*. IEEE Standard for Local and Metropolitan Area Networks. IEEE, jun 2005.
28. *Media Access Control (MAC) Bridges (Revision of IEEE Std. 802.1D-1998 incorporating IEEE Std. 802.1t-2001 IEEE Std. 802.1w -2001)*. IEEE Std 802.1D-2004. IEEE, aug 2004.
29. R. Hancock, G. Karagiannis, J. Loughney, and S. Van den Bosch. *Next Steps in Signaling: Framework*. RFC 4080. IETF, jun 2005.
30. *Part 16: Air Interface for Fixed Broadband Wireless Access Systems*. IEEE Standard for Local and Metropolitan Area Networks. IEEE, jun 2004.

31. *Part 16: Air Interface for Fixed Broadband Wireless Access Systems. Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands*. IEEE Standard for Local and Metropolitan Area Networks. IEEE, jun 2005.
32. C. Eklund, R. B. Marks, S. Ponnuswamy, K. L. Stanwood, and N. J. M. van Waes. *WirelessMAN Inside the IEEE 802.16 Standard for Wireless Metropolitan Networks*. IEEE Standards Wireless Networks Series. IEEE Press, 1 edition, 2006.
33. Mobile WiMAX – Part I: A Technical Overview and Performance Evaluation. Technical report, WiMAX Forum, aug 2006.
34. L. Cordeiro, M. Curado, E. Monteiro, F. Racaru, M. Diaz, and C. Chassot. ybrid on-path off-path approach for end-to-end signaling across NSIS and non-NSIS domains (HyPath). In *2006 International Workshop Towards the QoS Internet (To-QoS'2006), affiliated with IFIP Networking2006*, Coimbra, Portugal, may 2006. Springer.
35. J. Manner, G. Karagiannis, and A. McDonald. *NSLP for Quality-of-Service Signaling*. draft-ietf-nsis-qos-nslp-12.txt. IETF, October 2006.
36. M. Stiemerling, H. Tschofenig, C. Aoun, and E. Davies. *NAT/Firewall NSIS Signaling Layer Protocol (NSLP)*. draft-ietf-nsis-nslp-natfw-13.txt. IETF, October 2006.
37. J. Zhang, E. Monteiro, P. Mendes, G. Karagiannis, and J. Andres-Colas. *InterDomain-QOSM: The NSIS QoS Model to fulfill the E2E QoS Control in the ITU-T RACF Functional Architecture*. draft-zhang-nsis-interdomain-qosm-03.txt. IETF, March 2007.
38. T. Korkmaz and M. Krunz. Multi-Constrained Optimal Path Selection. In *IEEE INFOCOM 2001*, Anchorage, Alaska, 2001.
39. H. De Neve and P. Van Mieghem. TAMCRA: A Tunable Accuracy Multiple Constraints Routing Algorithm. *Computer Communications*, 23, 2002.
40. F. Kuipers, T. Korkmaz, M. Krunz, and P. Van Mieghem. Overview of Constraint-Based Path Selection Algorithms for QoS Routing. In *IEEE Communications Magazine, special issue on IP-Oriented Quality of Service*, 2002.
41. P. Steenkiste Q. Ma. Routing Traffic with Quality-of-Service Guarantees in Integrated Services Networks. In *Workshop on Network and Operating Systems Support for Digital Audio and Video*, 1998.
42. P. Steenkiste Q. Ma. On Path Selection for Traffic with Bandwidth Guarantees. In *IEEE International Conference on Network Protocols*, Atlanta, Georgia, 1997.
43. G. Apostolopoulos, D. Williams, S. Kamat, R. Gu in, A. Orda, and T. Przygienda. QoS Routing Mechanisms and OSPF Extensions. In *Internet Engineering Task Force, Request for Comments 2676*, 1999.
44. J. Sobrinho. Algebra and algorithms for QoS path computation and hop-by-hop routing in the Internet. In *IEEE Transactions on Networking*, 2002.
45. H. Salama, D. Reeves, and Y. Viniotis. A Distributed Algorithm for Delay-constrained Unicast Routing. In *IEEE INFOCOM'97*, Japan, 1997.
46. G. Cheng and N. Ansari. A New Heuristics For Finding The Delay Constrained Least Cost Path. In *IEEE GLOBECOM 2003*, San Francisco, CA, USA, 2003.
47. A. Jttner, B. Szviatovszki, I. M s, and Z. Rajk. Lagrange Relaxation Based Method for the QoS Routing Problem. In *IEEE INFOCOM 2001*, Anchorage, Alaska, 2001.
48. Y. Cui and J. Wu. Precomputation for Multi-constrained QoS Routing in High-speed Networks. In *EEE INFOCOM 2003*, San Francisco, USA, 2003.
49. P. Mieghem and F. A. Kuipers. Concepts of Exact Quality of Service Algorithms. *IEEE/ACM Transaction on Networking*, 12(5):851–864, 2004.
50. T. Korkmaz, M. Krunz, and S. Tragoudas. An efficient algorithm for finding a path subject to two additive constraints. In *2000 ACM SIGMETRICS international conference on Measurement and modeling of computer systems table of contents*, Santa Clara, California, United States, 2000.

51. D. Oran. *OSPF Version 2, OSI IS-IS Intra-domain Routing Protocol*. RFC 1142. IETF, August 1990.
52. J. Moy. *OSPF Version 2*. RFC 2328. IETF, aug 1998.
53. Y. Rekhter, T. Li, and S. Hares. *A Border Gateway Protocol 4 (BGP-4)*. RFC 4271. IETF, dec 2006.
54. E. Crawley, R. Nair, B. Rajagopalan, and H. Sandick. *A Framework for QoS-based Routing in the Internet*. RFC 2386. IETF, dec 1998.
55. O. Bonaventure. *A Framework for QoS-based Routing in the Internet*. draft-bonaventure-bgp-qos-00.txt. IETF, 2001.
56. G. Cristallo and C. Jacquenet. An Approach to Inter-domain Traffic Engineering. In *Proceedings of XVIII World Telecommunications Congress (WTC2002)*, Paris, France, 2002.
57. G. Cristallo and C. Jacquenet. *Providing Quality of Service Indication by BGP-4 Protocol: the QOS NLRI attribute*. IETF Draft. IETF, 2002.
58. C. Filsfils and J. Evans. Engineering a multiservice IP backbone to support tigh SLA. *IEEE Computer Networks*, 40, 2002.
59. P. Mohapatra Z. Li. QRON: QoS-aware Routing in Overlay Networks. In *IEEE Journal on Selected Areas in Communications*, pages 29 – 40, 2004.
60. R. Katz S. Agarwal, C. Chuah. OPCA: Robust Interdomain Policy Routing and Traffic Control. In *The 6th International Conference on Open Architectures and Network Programming (Openarch), IEEE Communications Society*, San Francisco, California, 2003.
61. F. Guo, J. Chen, W. Li, and T. Chiueh. Experiences in Building A Multihoming Load Balancing System. In *IEEE INFOCOM 2004*, Hong Kong, 2004.
62. Xiaowei Yang. NIRA: A New Internet Routing Architecture. In *ACM SIGCOMM FDNA 2003 Workshop*, Karlsruhe, Germany, 2003.
63. P. Reichl, S. Bessler, J. Fabini, R. Pailer, A. Poropatich, N. Jordan, R. Huber, H. Weisgrab, C. Brandner, I. Gojmerac, M. Ries, and F. Wegscheider. Practical Experiences with an IMS-aware Location Service Enabler on top of an experimental open source IMS core implementation. *Journal of Mobile Multimedia*, pages 189–224, sep 2006.
64. J. Gozdecki, A. Jajszczyk, and R. Stankiewicz. Quality of service terminology in IP networks. *IEEE Communications Magazine*, 41(3):153–159, mar 2003.
65. A. Takahashit, H. Yoshino, and N. Kitawaki. Perceptual QoS Assessment Technologies for VoIP. *IEEE Communication*, 42(7):28–35, July 2004.
66. A. Watson and M. A. Sasse. Measuring Perceived Quality of Speech and Video in Multimedia Conferencing Applications. In *ACM Multimedia*, pages 55–60. ACM, October 1998.
67. ITU-T. *Subjective video quality assessment methods for multimedia application*. ITU-T Recommendation P.910. ITU-T, sep 1999.
68. ITU-T. *Methodology for the subjective assessment of the quality of television pictures*. ITU-T Recommendation BT.500. ITU-T, sep 2002.
69. O. Nemethova, M. Ries, A. Dantcheva, and S. Fikarand M. Rupp. Test Equipment of Time-Variant Subjective Perceptual Video Quality in Mobile Terminals. In *IASTED International Conference on Human Computer Interaction*, number 14-16, Phoenix, USA, nov 2005. IASTED.
70. M. Ries, O. Nemethova, and M. Rupp. Motion Based Reference-Free Quality Estimation for H.264/AVC Video Streaming. In *International Symposium on DSP and Communication Systems*, number 14-16, Sunshine Coast, Australia, dec 2005. IEEE.
71. M. Ries, O. Nemethova, and M. Rupp. Motion Based Reference-Free Quality Estimation for H.264/AVC Video Streaming. In *International Symposium on Wireless Pervasive Computing 2006*, number 14-16, San Juan, Poerto Rico, feb 2007. IEEE.
72. M. Ries, C. Crespi, O. Nemethova, and M. Rupp. Content Based Reference-Free Quality Estimation for H.264/AVC Video Streaming. In *IEEE Wireless Communication & Networking Conference*, number 14-16, Honk Kong, mar 2007. IEEE.

73. S. Winkler and F. Dufaux. Video Quality Evaluation for Mobile Applications. In *SPIE Conference on Visual Communications and Image Processing*, number 593-603, Lugano, Switzerland, jul 2003. SPIE.
74. E. Markey. *Amendment to the committee print offered Mr. Markey of Masachusetts Mr. Boucher of Virginia, Ms. Eshoo of California and Mr. Inslee of Whasington*. NET NEUTRALITY. E. Markey, apr 2006.
75. D. J. Weitzner. Twelve Billion Bargain Chips. *IEEE Internet Computing*, pages 78–81, feb 2007.
76. P. Cocherane. Net Neutrality or Suicide? *Procceding of IEEE*, 94(10), oct 2006.
77. Jon Crowcroft. Net Neutrality: The Technical Side of the Debate: A White Paper. *ACM SIGCOMM Computer Communication Review*, 37, jan 2007.