QoS Adaptation Control in Virtual Circuit Switched Mobile Networks

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***Abstract*— This paper highlights the issues behind QoS adaptation in virtual circuit-based mobile networks. We explain the need for end-to-end adaptation and reveal how such adaptation occurs during mobile handoffs. The instability and sensitivity problems occurring as a result of frequent handoffs and QoS adaptation are explained and related to control theory. We provide some control approaches that we believe can ensure stability in the network under such circumstances. It is important that future broadband wireless networks must be able to offer network services and QoS assurance without causing network instability. This paper, therefore, reveals possible approaches to be considered in the design of future broadband wireless systems. Unlike other similar work on QoS adaptation, we do not aim to control the level/rate of a value, but the decision to adapt, that is the timing of it, using control theoretical techniques.**

I. INTRODUCTION

The (r)evolution in computer networking is dramatically changing the way people learn and interact, the way companies operate, and almost every other aspect of personal, professional and business activity. One major paradigm shift is mobile computing. Mobile computing is a broad concept that has the general idea of enabling users to use wireless devices to access applications and services anywhere and without constraints in time or form.

The issue at the core of mobile wireless systems is that of creating an appropriate wireless infrastructure that can handle Quality-of-Service (QoS) in an integrated and seamless fashion. The technical challenge is that the resulting interconnected network is not homogeneous; it is a collection of heterogeneous components and sub-systems. Integration is beneficial to the users, through the support of diverse and multiradio terminals, but it creates problems to the network providers in maintaining QoS in the network.

One of the methods traditionally used for providing hard guarantees in wired networks is the use of packet switching technologies like ATM and MPLS. Both technologies differ from other networking technologies in that they have the mechanisms to provide hard guarantees by reserving related resources throughout the routing path. Hence, they have the ability to provision and control the QoS in the network based on user requirements.

In this work we consider the case of VC-based mobile networks, such as Wireless ATM (WATM) and Mobile MPLS (MMPLS), which extend the virtual circuits into the radio access part of a mobile network architecture. Several investigations have been focused on connection, location and handoff management for WATM and MMPLS. However, little attention has been devoted to understanding the issues behind QoS support in VC-based mobile networks. The underlying impact of dynamics associated with QoS adaptation in these environments even less well understood.

Providing QoS guarantees in wireless mobile networks is agreeably difficult. Mobile terminals can often experience an occasional decrease in the quality of their connections (high error rates) due to physical layer impairments. Impairments are introduced in mobile wireless networks not only by the propagation characteristics of the signal, but also by mobility events [1]. As mobile nodes roam (handoff) freely inside the coverage area of the network, they may encounter different bandwidth availability in different cells.

Unlike hop-by-hop networks, a VC-based mobile connection is a concatenation of wired and wireless links. Providing QoS by using techniques borrowed from packet switched networks, is still not a straightforward solution [2] [3]. To support real-time mobile multimedia services, QoS conformance during mobile connection setup is necessary. As a result, call admission control (CAC) needs to be performed at both the core switches and the mobile nodes.

If the strict QoS conformance philosophy usually found in circuit switched networks is followed here, then ongoing calls may be forced to terminate, or new calls may be rejected during call admission when a mobile migrates from its current wireless cell to another with a different availability of network resources. If there is an associated service level agreement for the dropped (or blocked calls) the operator/provider will certainly be in violation. Clearly, this is not a desirable behavior.

On the other hand, if a path or call setup is not governed by strict guarantees, but there is some flexibility on the part of the mobile application, then calls will continue to receive service, albeit different (and probably lower). This technique is called QoS adaptation.

QoS adaptation is, therefore, the dynamic matching of the application requirements and the network capabilities to overcome problems caused by mobility and the wireless medium and to accommodate user or application changing requirements.

QoS adaptation can be enforced by different parts of the network (end-systems, switches, etc.) and can be performed by different layers in the protocol structure, not necessarily in the same way or at the same time. The research issue is then how to control application flexibility and QoS changes both at the network ends and the network core.

In the integrated mobile broadband network, fixed and wireless segments will co-exist. From the user's point of view, the network should behave as if there are no differences between the segments. To make heterogeneous components work together is relatively easy so long as standards are set and obeyed. However, there is no way to reassure the customer that QoS will be maintained (a *sensitivity* issue), and that network services will be reliable and available (a *stability* issue).

In this paper, we highlight the choices that need to be made in the design of a QoS adaptation framework for virtual circuit-switched mobile networks networks. We present work that has been done towards this goal and we address many of the outstanding issues which arise in the development of such a system, including: (i) re-negotiating QoS after mobility events, (ii) handling QoS inconsistencies after mobility events, (iii) understanding the system dynamics in terms of transient and steady state response and, (iv) relating sensitivity and stability issues in adaptation, with modern control and network theory.

Section II provides background on virtual circuit switched mobile networks. Section III explains the issues of QoS adaptation in mobile networks . Section IV links the QoS adaptation strategies with control theory and Section V presents the conclusions and future work stemming from this study.

II. VIRTUAL CIRCUIT MOBILE NETWORKS

All-IP is the concept of moving the cellular wireless network architecture from the current circuit-based concept to a packet-based architecture utilizing IP protocols and technology where possible. According to [4], there are four main reasons for this design choice. First, an IP-aware RAN can give better support to IP applications. IP is the basis for packetized data, voice and signaling, making the use of IP based protocols and technology desirable to be utilized wherever possible. Second, an IP infrastructure is widely available, reducing the cost of deployment. Third, IP-style engineering is faster and cheaper. Fourth, by constructing networks based on IP technology, seamless connections can exist between 2G, 3G, 4G, WLANs, Bluetooth, and other access networks. This future internet can be called the ”Mobile Internet” [5].

Given the tremendous increase in the use of wireless devices to access the Internet and multimedia services, concerns related to providing and maintaining specific service levels arise. It is therefore reasonable to consider an extension of MPLS into the mobile domain. More specifically, MPLS adds several advantages to an IP-based RAN including faster table lookup, less control overhead, and the ability to be applied over networks using any Layer 2 switching. This proves to be very desirable in the multi-radio access architectures considered for future wireless networks.

We believe that the requirements of an IP-based radio access network (RAN) can be met when a fast switching transport, such as MPLS, is combined with mobility protocols, creating virtual circuit-based mobile networks [6], [7]. The use of MPLS in Radio access networks has been also examined in [8] and [9].

The basic network topology considered for this research work is a Hierarchical Radio Access Network (RAN) as shown in Figure 1.

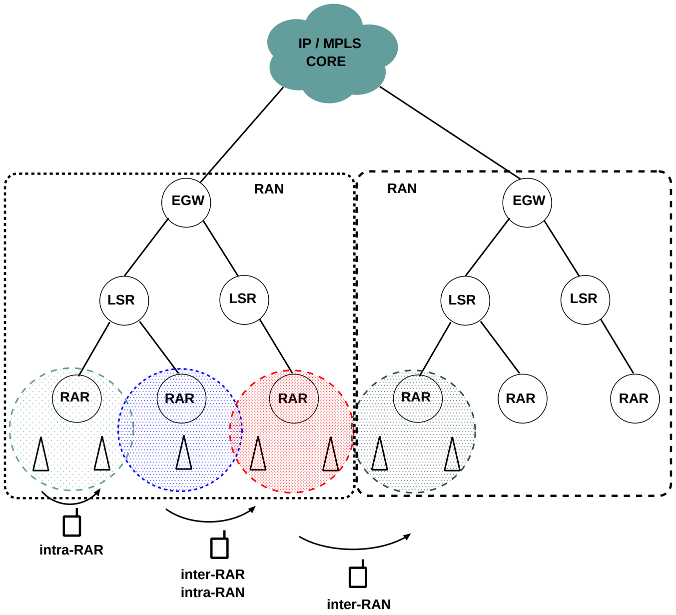


Fig. 1. Virtual Circuit radio access network

The RAN consists of at least three layers of label switched routers (LSRs). The edge components of the architecture are the radio access routers (RAR), which are the first IP aware devices of the network seen from the mobile terminal. One, or more, base stations (BS) are attached to a RAR (or integrated into it) and provide the physical radio link to the mobile node (MN). Several RARs are interconnected to one or more Edge Gateways, which in turn provide access to outer (backbone) networks including other RANs. The RARs and the EGWs are linked through a network of MPLS-capable routers.

Mobile nodes are connected to the RARs through base stations using IP. The connection from the RAR to the correspondent node (either mobile or fixed) is done using MPLS. Any handoffs that occur between base stations under the same RAR are called intra-RAR handoffs and those occurring between base stations that are connected to different edge switches are called inter-RAR handoffs. In the same way, handoffs within the RAN are called intra-RAN handoffs and handoffs between RANs are called inter-RAN handoffs.

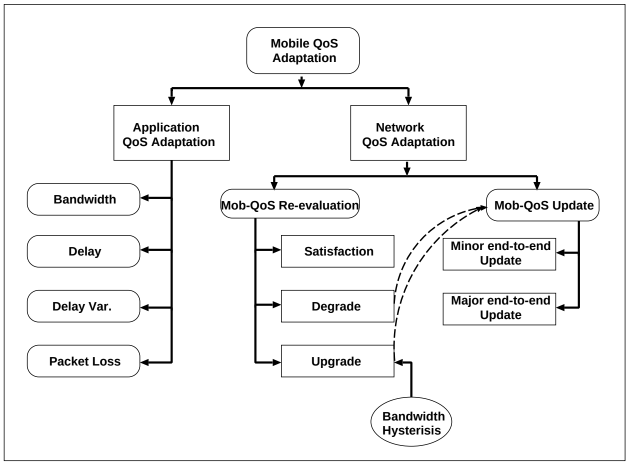


Fig. 2. The components of the mobile QoS adaptation framework

III. QoS ADAPTATION FRAMEWORK

Following the research of end-to-end QoS provisioning for multimedia wireless networks, we utilize the comprehensive mobile QoS framework for IP-based wireless networks described in [10].

The overall adaptation process engages both the undergoing application and the network. On one hand, the application must be involved as it has to adapt to changes in the available QoS while on the other hand, the network has to adapt to the alterations made to the QoS requirements of the supported applications. From the network point of view, the adaptation process includes procedures for QoS upgrade, downgrade and satisfaction. The framework is illustrated in Figure 2.

From the application point of view, the adaptation process involves aspects such as bandwidth, delay, delay variation and packet loss adjustments triggered by mobility events in the network. To this direction, the concept of ”bandwidth window” is introduced. This approach enables application adaptability to variations in the available network bandwidth during mobile host’s migration between wireless cells. Such an adaptation process is possible only when the application under question is able to operate with acceptable performance over a range of bandwidth without being forced to terminate.

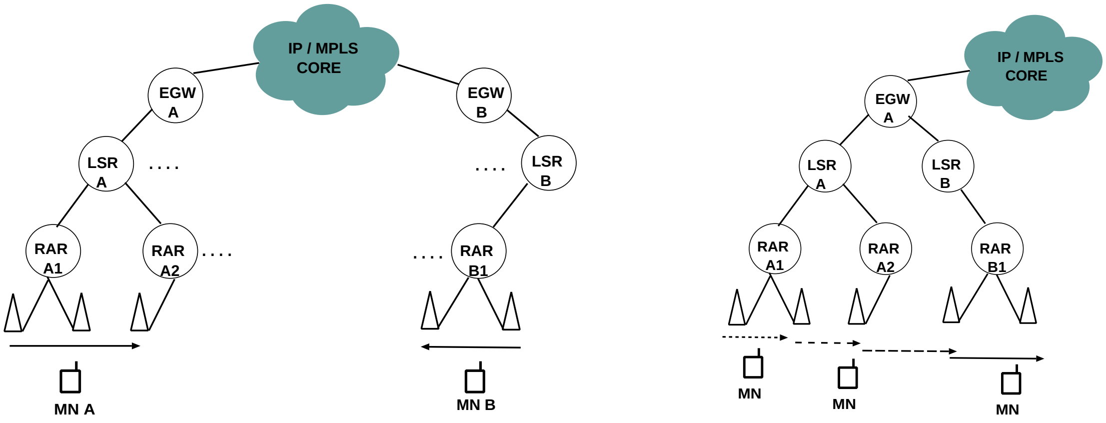
It has been shown widely in the literature that several applications, such as video, can scale down their QoS requirements without being forced to terminate. The reduction could refer to a different frame rate, picture resolution size, color depth, etc. [11] [12]. It has also been shown that hierarchical encoding and variable compression techniques can also support bandwidth adaptation [13]. In addition to bandwidth adaptation, there are situations where delay adaptation is also possible even for delay-sensitive applications such as multimedia, provided that the delay values are within certain limits [13]. Variations of delay due to longer resultant paths after handoffs can be resolved, to some extent, by content buffering prior to usage by the application. A trade-off hence exists between greater roaming capabilities and lower experienced quality by the terminal user. Although quality degradation is clearly not desired, it should be considered as the only alternative to the even more undesirable event of forced call termination.

Network QoS adaptation involves the phases of re-evaluation and update. Re-evaluation occurs during host migration across wireless cells in addition to the handoff procedures to govern the decision of Mob-QoS upgrade, downgrade or satisfaction. The update process is then necessarily invoked to resolve any inconsistencies that might arise in the network after a handoff.

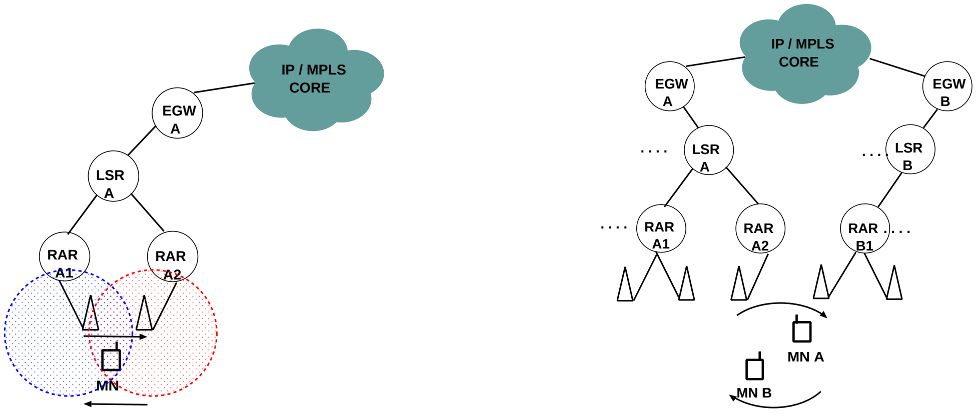
QoS Satisfaction If during a new call request or a handoff process, the network is capable of supporting the QoS requirements both in the wireless and backbone segments, then the handoff process can be completed without any need for adaptation. This situation can be considered as the optimum scenario.

QoS Downgrade If during a new call request or a handoff process, the network is not capable of supporting the QoS requirements of the application, QoS degradation must be performed to avoid call termination. Considering that the update process is performed during every handoff event, the resulting signaling overhead is likely to be substantial. Therefore, two different strategies are proposed. The ”Minor QoS degradation update strategy” is a simplistic and fast approach which takes advantage of intra-RAR handoffs (as explained in Section II) by adjusting resource reservations only over the wireless links. However, the drawback of this approach is that reservations over the wired links remain unchanged consequently leading to an inefficient state of under-utilization. On the other hand, the ”Major QoS degradation update strategy” involves end-to-end resource allocation adjustment and is invoked post to inter-RAR handoff events. The facts that during inter-RAR handoffs a significant portion of the path is modified and this type of handoffs is less frequent constitute the execution of this update strategy necessary in spite of the signaling overhead it entails.

In the case of hierarchical architectures which employ more layers of routers in the same domain, the minor update can be modified to include the RAN and not the RAR, which means



(a) Simultaneous handoffs (b) Fast handoffs



(c) Ping-Pong handoffs (d) Alternate handoffs

Fig. 3. Mobility-induced race conditions

it can extend up to the local or regional router

QoS Upgrade Although the main goal targeted by the introduction of the QoS adaptation framework is to minimize the probability of forced call termination and/or blocking due to insufficient resources, the event of QoS upgrade is also introduced in order to better exploit resource abundance when this is available. However, a limiting factor called ”bandwidth upgrade hysteresis” is considered even if the possibility of upgrade exists. This factor is considered in order to prevent unnecessary invocations of the upgrade process when no significant improvement will be made to justify the overhead caused by the upgrade process. In contrast to the QoS downgrade case, an end-to-end update process is required in the event of QoS upgrade for both types of handoffs since extra resource allocation should be performed to support the increased service quality received by the mobile host.

IV. QOS ADAPTATION CONTROL

The operation of the QoS adaptation framework explained in Section III includes procedures which, if not configured correctly, may initiate unexpected and unwanted behavior in the system. For example, a protocol may produce excessive QoS related signalling traffic (sensitivity), resulting in network congestion and instability.

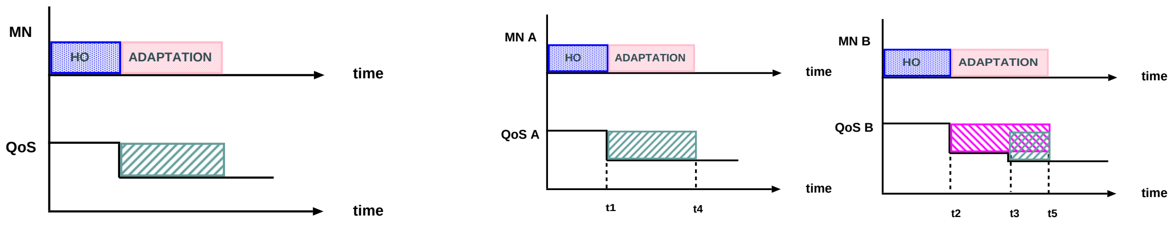
A. Stability and Sensitivity

In this section we explore the issues of of *stability* and *sensitivity* in the context of QoS adaptation in VC-based mobile networks.

1) Sensitivity: We define sensitivity as the degree of change that is considered significant enough to initiate an end-to-end QoS adaptation. It is also defined as the amount of punishment -in terms of frequency of disturbances- a system can accept without loosing stability.

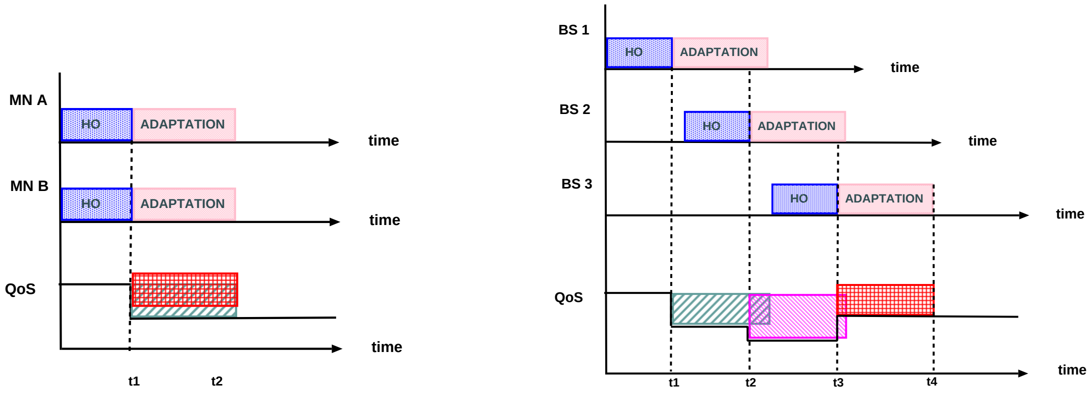
In section III we have encountered the idea of using a minimum value of bandwidth change (hysteresis) before deciding whether to upgrade. This simple control avoids excessive upgrades and limits the control signaling in the network. Sensitivity to responses from the network can also create instability. If periodic feedback is used to obtain the network status and the feedback frequency is high, the framework may end up creating unnecessary events.

2) Stability: We define stability as the ability to steer the system (network and application) to a NEW steady state after a disturbance has occurred.



(a) Steady State

(b) Transient Oscillation



(c) Continuous Oscillation

(d) Continuous Oscillation

Fig. 4. System Response during Race Conditions

Instability can be caused by a number of factors, such as:

- Over-sensitive framework. A highly sensitive QoS adaptation protocol will result in an oscillating response from the system, until the call is finally dropped or until there exists no mobility. Under this factor we can consider problems which have to do with the formula used to compute the rates (Control Law), the correct estimation of available resources and the problem of the incorrect value of addition or subtraction for an upgrade or downgrade. In the first case, the network is driven into unwanted ranges. In the second the system is constantly overshooting or undershooting, and in the third it might take more iterations to reach the goal.
- Feedback Latencies. Delays in the forward and backward channel must be incorporated into the control system. The flow control of the system must be able to provide correct information to a mobile host at the appropriate intervals. Otherwise, a lost or delayed feedback cell will create an ”information gap”, making it difficult for the framework to make decisions. If we base our system operation on periodic feedback, then varying delay will introduce errors.
- Misbehaving Components and Network errors. Problems in this area might come internally from the network and are usually transient in nature.
- Overlapping of events. The most interesting aspect of instability and sensitivity is caused not by normal mobility conditions (unless they are too numerous), but rather from mobility which causes *race conditions*. A race condition is caused by *uncoordinated* moves by one or more mobiles involved in a connection.
  Examples of such mobility events are illustrated in Figure 3 and are:
  - Simultaneous handovers
  - Fast handovers
  - Ping-pong handovers
  - Alternate handovers

B. System Response

The concept of stability must therefore be understood from a dynamic perspective where we must distinguish between (a) Steady State, (b) Transient Oscillations, and (c) Continuous Oscillations.

1) Steady State: Resource reservation during mobile connection establishment is regarded to have a steady state characteristic once the demanded QoS is satisfied. This corresponds to a step-wise response of the system. This behavior is illustrated in Figure 4(a). The QoS is considered to be affected after the handoff (HO) completes. The grey shaded rectangle on the QoS line illustrates the actual QoS will settle to the steady state value after the whole adaptation process is complete and the application(s) have made the necessary adjustments.

2) Transient Oscillation: Transient oscillations during QoS adaptation are undesirable since they cause a series of signalling traffic surge in the network. These transients should be damped by imposing certain constraints into the system, such that the resulting degree of sensitivity is sufficient to minimize the oscillation, while at the same time, provide a reasonable response so that the user can benefit from the available QoS. This degree of sensitivity is definitely related to the traffic carried by each call. A case of transient oscillation is illustrated in Figure 4(b). Suppose two mobile nodes MN A and MN B, which have a connection between them and initiate a handoff and adaptation simultaneously (or almost simultaneously). Depending on the condition of the network at each end, there is a great possibility that the update request from one node (in this case MN A) will reach the other side first, before the corresponding message from MN B reaches MN A. This means that each node will consider that the other has received its request and that the incoming message was the reply (which may be different than the initial request). Each mobile node will then adjust the related application and continue, until there is a new mobility event, or a trigger from the application with the lowest QoS.

3) Continuous Oscillation: In addition to transient oscillations, there can be cases of continuous oscillation and this can occur for both inter- and intra-RAR handoffs. This is particularly true for mobile-to-mobile connections. This phenomenon is explained better with the use of the examples illustrated in Figures 4(c) & 4(d).

The first type can arise if the mobile node switches between adjacent base stations in a ping-pong fashion. This behavior can happen either by the physical movement of the node, or because the node is at the border between the two cells and the signal is experiencing short-term disturbances.

The second is more evident when a mobile node moves to an adjacent cell before completing the previous adaptation function. In this case the oscillation will stop when the movement stops, or when the call is dropped.

C. Control System

Undoubtedly, there are numerous other conditions that can cause oscillation problems like the above. Since it is difficult to explicitly provide solutions for all the different combinations, we believe that a more abstract approach based on control theory may be more appropriate. Figure 5 conceptually illustrates the roles of user, application, network and adaptation in a QoS adaptation framework. This model encompasses all the parts that were discussed in the previous sections.

If we concentrate on the Adaptation Control block and its inputs and outputs the result is a much smaller control system. Figure 6 reveals that the problem is reduced to a closed loop system between the adaptation control and the network.

A possible configuration of the system is with a PID compensator for the controller in order to get fast rise (proportional), reduced steady state (integral) and minimized transient (derivative). The adaptor can utilize an integrator to help it slowly reach the value *r'*. The PID compensator has also been used in [14] for the control of application tasks.

Obviously this is a very simplistic model and does not correspond to the realities of a computer network, which is an integrated, distributed, non-linear and time-varying system. These attributes do not preclude the application of control theory into a network system. In [15] a water-level monitor model is used to illustrate that discrete decision making can be performed over continuously varying parameters. Figure 7 illustrates the controller of Figure 6, but with delays in both the forward and backward paths. If the delays can be estimated correctly, then a Smith predictor can be used with good results. In such a case, the system will be stable if the open-loop plant is stable. A similar approach has been taken by Cavendish in [16], where an integrator was used as the plant and a Smith predictor as the controller in system with time delays in ABR rate control.

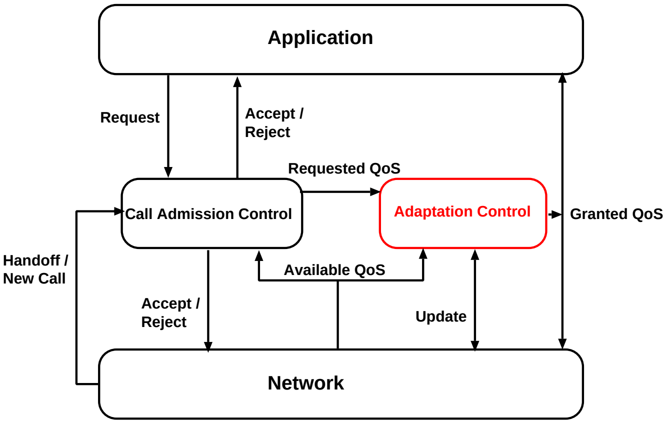


Fig. 5. Call admission control and adaptation control

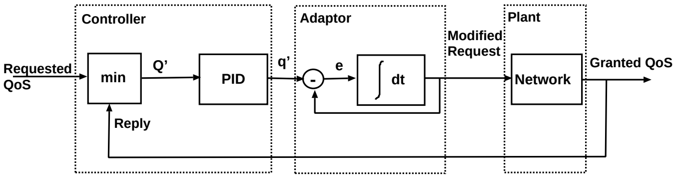


Fig. 6. QoS adaptation closed-loop control

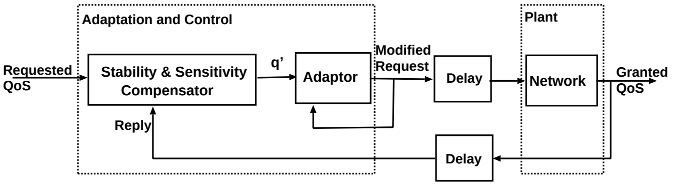


Fig. 7. QoS adaptation control with delays

Another approach for handling the non-linearities of such systems is by using adaptive control [17]. Adaptive Control is used in situations for which a design model cannot be developed with any reasonable degree of confidence. (Usually not pure engineering systems, like biological, chemical, economic). Adaptive control makes the control law adapt to it's own behavior. The adaptation is done in two ways. The first assumes that a design model is available, but the parameters of the model are not known. The second assumes that no design model is available but it is known how the closed loop system is required to behave. We find the second approach, called Model Reference Adaptive Control (MRAC), to be more relevant to the purposes of this study. Figure 8 illustrates the adaptive control structure for the QoS adaptation framework.

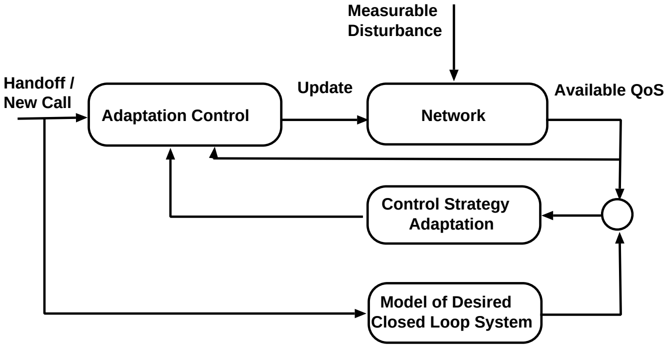


Fig. 8. Adaptive control model

The closed loop system on top is essentially what we have seen in Figure 6. The adaptive model proceeds to add a Control Strategy Adaptation module and a Closed Loop System Model. The reference input is applied to both the real closed loop system and the ideal model (in our case the ideal model is assumed to have unity gain, i.e., we want the output to be equal to the reference). If the performance error between the two is zero, the closed loop is operating as desired and it is left alone. If an error exists, it becomes the input to the Control Strategy Adaptation module that adjusts a vector of parameters that can change the behavior of the QoS adaptation control. Hopefully the change in the QoS adaptation control will create an input to the network that diminishes the error. The authors in [18] also make use of adaptive feed-forward and adaptive feedback to compensate for disturbances in congestion control for ATM networks.

D. Preliminary Results on QoS Adaptation

We have performed preliminary simulations on a simplistic QoS adaptation model without considering sensitivity and stability issues. The model incorporates both network and application adaptation. Based on the simulation results we have verified the concept of adaptation in two types of mobile networks. In [10] we examine a random topology network carrying mostly telephony traffic (low data rates). In [19] we have implemented a UMTS network (hierarchical structure) and we defined three distinct operation environments: (a) a business city center, (b) an office environment, and (c) an urban environment. The three differ on the number of users per cell and the types of calls the handle. in all cases, the adaptation framework resulted in lower Call Blocking and Call Dropping probabilities, while keeping the calls connected for a longer time. We are now in the process of investigating specifically, the race conditions explained in the previous section.

V. CONCLUSION

This work enhances QoS support and more importantly, the reliability, availability and performance of future broadband wireless network systems. It promotes the understanding of the underlying dynamics associated with QoS adaptation, which are paramount to building high performance and reliable wireless broadband systems.

More specifically, in this paper we have highlighted the issues and the choices that need to be made in the design of a QoS adaptation framework in virtual circuit-based mobile networks.

We have explained the need for end-to-end adaptation and examined briefly how such adaptation occurs during mobile handoffs. In addition we defined the concepts of sensitivity and stability in the context of QoS adaptation and we illustrated how simple protocol actions, such as introducing hysteresis can reduce sensitivity and aid in the stability of a system. We have identified the major causes of instability and we concentrated on examples of mobility events which cause race conditions. We illustrated these race conditions in detail and we have related them with possible system responses such as transient or continuous oscillations.

Finally we have made an effort to relate the sensitivity and stability issues in adaptation, with modern control and network theory. We modeled the system under examination using control theoretical techniques and have provided possible approaches to be considered in the design of future broadband wireless systems. We propose a location for the controller and a sample control model.

We approached this problem by breaking the system down to smaller parts, up to the point that we have created a closed loop control system. We will pursue the creation of a system model that can be either used in connection with adaptive control techniques to extract an advanced model or used as the core of an adaptive control system.

Unlike other similar work on QoS adaptation, we do not aim to control the level/rate of a QoS value, but the decision to adapt, that is the timing of it, using control theoretical techniques.

Given the benefits already realized by an adaptation framework without formal control functions, we expect the system performance to increase once we implement and simulate the proposed techniques.

VI. ACKNOWLEDGEMENTS

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