A communication architecture to access data services through GSM

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Abstract: In this paper we present a communication architecture for accessing TCP/IP networks (mainly Internet) through GSM. We exploit the existing and widely used TCP/IP communication architecture, but also consider the specific features of wireless links and GSM networks. Our proposal is based in the indirect model of client/server interaction, where an intermediate element acts as a bridge between GSM and the rest of the data network. This intermediary provides enhanced functionality, improving the performance of standard TCP/IP applications in a mobile environment, maintaining the protocols in server machines, and requiring mimimum changes in the mobile clients. Those changes are basically the installation of a simple transport protocol. GSM operators are not required to change their network infrastructure in order to implement the architecture, even in the case of networks offering the new high-speed services for data transmission in GSM (GPRS and HSCSD).

Keywords: GSM, indirect model, mobile computing, Internet access.

1. Introduction

The convergence of developments in mobile communications and personal computing are creating new ways of accessing information, creating the concept of nomadic user: that one who moves along with a portable computer and requests access to information services from wherever he or she happens to be. Different technologies are being developed to support the new services that will arise in the different scenarios of mobile computing, ranging from a single wireless LAN to a heterogeneous system such as UMTS. These services will offer universal connectivity and service integration. Among several possible scenarios, the one we are interested in consists of three main components: (a) a fixed data communication network, where servers are located (typically Internet), (b) a mass of portable computers where the clients are located, requesting access to the servers from changing locations, and (c) a wireless access to the fixed network through a cellular telephone system. We will focus on the GSM [1] (Global System for Mobile Communications) technology for the wireless access network, as it currently forms one of the most comprehensive mobile telephone systems, thus being able to provide access to data services to a crowd of nomadic users. The integration of DECT cordless telephone systems and satellite services with GSM guarantees that this situation will be maintained in the future.

The main advantages of using cellular telephone networks for data access are:

1. Those networks already exist, and are increasingly familiar to the user; data transmission becomes just another facility of the mobile phone.
2. They are able to provide ubiquitous access to information.
3. Mobility issues are managed by the network.

On the other hand, the characteristics of cellular telephone networks are quite different from those of wired links. Cellular links have high latency with long, variable delays, a low and variable throughput, and are prone to sudden disconnection. That is why, in practice, applications used over cellular and wired networks are still different: wireless links create problems for existing applications, which are designed for fast and reliable connections. The success is restricted to off-line applications requiring a much reduced bandwidth, like electronic mail or SMS (short messages). These are, though, just ‘minimum services’, and not what the user would expect from the network.

In this paper we propose a framework to provide the functionality required to run standard Internet applications using a cellular system (GSM) as the access network, with an acceptable performance level. It is organized as follows. First, we introduce the current and future use of the pan-European GSM system for data transmission, and the main problems that arise when used as a platform for TCP/IP-based applications. Next, we give a brief overview of the indirect model of client-server interaction, as it is the core of our proposal. A description of the proposed communication architecture is given in Section 4. Finally, Section 5 summarizes related works regarding other approaches to this problem.

2. GSM data service

GSM is a pan-European standard for digital cellular telephone communications, widely available in Europe and rapidly expanding throughout the rest of the world. Although specifications are well defined, it has taken some time for GSM data transmission to be widely used, mainly because of the required infrastructure investment. For some time, data transmission was just a secondary target of cellular networks. However, currently GSM data services are already implemented and available in most European countries. By the year 2000, it is estimated that half the information over GSM could be data [2].

Nowadays, GSM supports circuit-switched connections, with a single error-correcting link per handset. The nominal transfer rate is 9.6 Kb/s, far from the 33.6 Kb/s of the wired telephone network (in fair conditions). Besides, actual sustainable transfer rates are even lower: slightly over 7 Kb/s for bulk data transfer over a good quality GSM link [3]. Using an all-digital connection from GSM to ISDN, and data compression, the data rate goes up to 40 Kb/s, with the additional advantage of reduced connection set-up times. This all-digital technology is a significant development, but for some considerable time, most traffic will continue to be handled by the PSTN.

In order to achieve even higher speeds, new parts of the GSM standard are being developed. HSCSD (High Speed Circuit-Switched Data) will boost user capacity up to 64 Kb/s, when using all the eight TDMA time slots of the 200 kHz GSM carrier to provide a single data circuit [4]. Another new possibility for GSM data transmission, which will be especially useful for high-bandwidth traffic, is GPRS (General Packet Radio Services) [5], a packet-switching technology well suited to the highly bursty nature of most data applications. It will also use multislot techniques, handling rates from 14 Kb/s (using just one TDMA slot) up to 115 Kb/s (8 TDMA slots). In packet-mode connections, users will not have to wait for the handset to dial and the connection to be established, as they do with a circuit-switched call. The main benefit of these approaches is that they are designed for the existing GSM infrastructure, so there is no need for operators to change their entire network to implement them. Anyway, it will take years to finish the standards for HSCSD and GPRS, more years until operators offer these services to their users, and even more years until offering it at a reasonable price (using two slots for data transmission means using the bandwidth necessary for two phone connections, so price will be doubled).

2.1 Internet access using GSM

Figure 1 gives an overview of the use of a GSM network to access Internet. A PC-Card that emulates a modem connects the computer to the handset, so that modem-based software can be used. The GSM data provider has a modem pool located in the MSC (Mobile Switching Center), the unit designed to interface between GSM and fixed networks: PSTN, ISDN, X.25, etc. In the figure, we have just considered the connection to PSTN, as it is the more used way to access an Internet Service Provider. Three different networks are traversed in the way from mobile client to fixed server (and vice-versa): GSM (digital, circuit switched), PSTN (analog, circuit switched) and Internet (digital, packet switched).

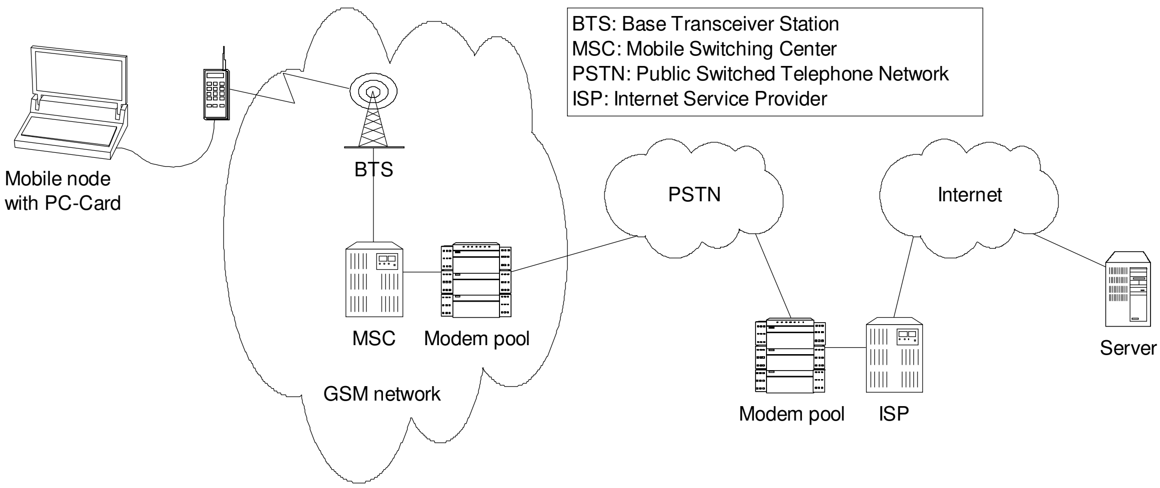

Fig. 1. Conventional access to Internet through GSM networks

In this arrangement, the only "new" step is the first one. GSM specifies almost the same services of the ISDN. In particular, GSM specifies two modes of asynchronous bearer service: transparent and non-transparent. The first one is derived from the V.110 ISDN specification: constant available throughput and fixed transmission delay. The bit error rate on the radio link, within normal coverage, is assumed not to exceed the level of 10^{-3} at the line speed of 9.600 b/s and after mere forward-error correction. The non-transparent mode is implemented using the Radio Link Protocol (RLP), a member of the HDLC family. RLP includes error correction mechanisms, using selective retransmissions, which reduce the average bit-error rate down to 10^{-8} [6]. The price to pay is an increase in latency while throughput and transmission delays become variable, remarkably so under poor conditions of the air link.

Figure 2 shows the protocol architecture used for this access. RLP is used between the mobile node and the MSC (assuming, as it is common practice, that the non-transparent GSM data service is chosen) and a standard modem to modem protocol (V.34/V42) between the MSC and the ISP. On top of those two connections, the Point-to-Point Protocol (PPP) provides a link between the mobile node and the ISP. Alternatively, when the IP address of the client is not dynamically assigned by the ISP, the Serial Line IP (SLIP), or its compressing version CSLIP, can be used instead of PPP. The rest of the protocols are the standard in TCP/IP networks.

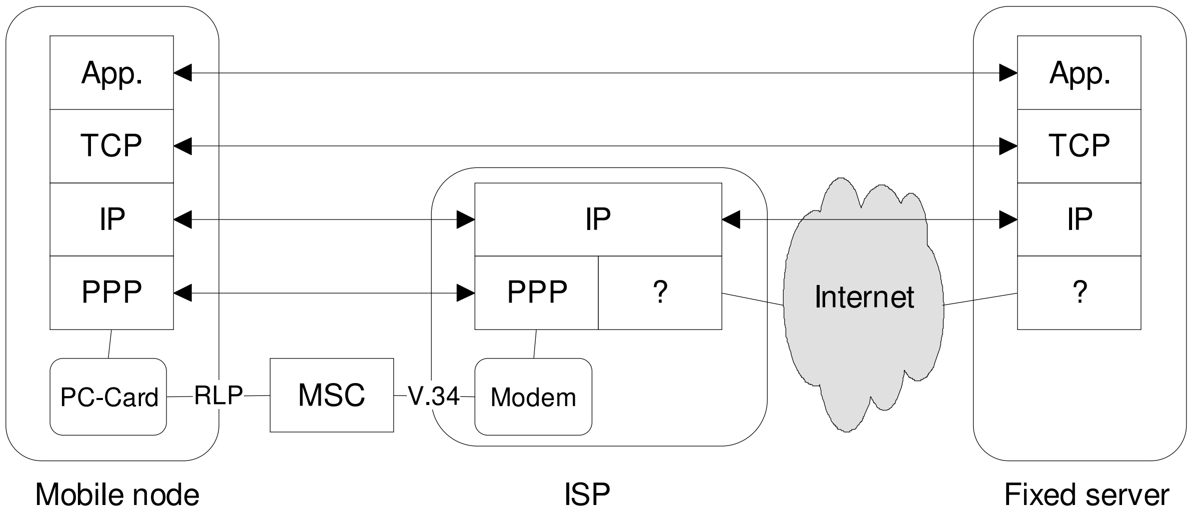

Fig. 2. Protocol architecture of a conventional connection to Internet through GSM

2.2 Mobility management

Mobility management in cellular networks covers two aspects:

- Location update and call routing, to enable the system to know the current location of a powered-on mobile station so that incoming calls can be routed to it.
- Handover (or handoff), when a call is completed, to maintain the connection with a roaming mobile station. An ongoing call is switched to a different channel or cell.

Location update, and subsequent call routing, uses the MSC and two databases: the Home Location Register (HLR) and the Visitor Location Register (VLR). The HLR contains the actualized position of every mobile user in the network. The VLR contains information about every mobile station present in a particular location area. Typically, there is a VLR per MSC: the group of cells under control of a MSC defines a VLR location area. When a mobile station moves to a new location area, it must announce itself to the network by means of a location update message sent to the new MSC. The mobile is registered in the VLR and a message is sent to the subscriber's HLR to update the location information.

2.3 TCP/IP applications over GSM

Several researchers have identified problems at the transport layer that arise in wireless networks [7][8]. Those problems are due to some design premises of TCP: it was intended for relatively fast and reliable fixed networks, and not for unstable, wireless networks. For this reason, some of the algorithms used in TCP to deal with congestion and packet losses are inappropriate in a wireless environment. In fact, these mechanisms result in unnecessary waste of capacity, and, at the same time, inefficient use of the (scarce) available bandwidth.

Regarding error control, TCP can easily make unnecessary retransmissions due to the higher error rate of the radio link, compared to a wired one. TCP timers are triggered by delays caused by RLP retransmissions, confusing them with packet losses. When the delay is high, it can even be confused with a TCP connection loss, forcing the application to make an expensive reconnection. The problem is just the same with physical disconnection of the circuit-switched wireless link.

TCP's congestion control strategies are also the origin of problems. TCP implementations assume that packet losses (followed by retransmissions) have to be interpreted as a congestion symptom, thus the action to take is to reduce the transmission window (slow start) and to double the retransmission timeout value (Karn's algorithm). These measures work fine when actually the reason of the retransmission was congestion, but lead to poor performance if the problem was just a longer delay at the RLP link.

Another problem of classic TCP over cellular networks is the large amount of redundant control information in the segment headers, which wastes a good deal of the available bandwidth. Some techniques are already available to reduce the amount of control information in TCP headers sent through SLIP (CSLIP) or PPP.

3. The indirect model

During the last years, it has been argued whether mobility should or not be transparent to applications. One approach is to cope with mobility at the operating system level, developing new protocols or adapting already existing ones. That is the objective of many proposals for mobility in the IP environment [9][10], which make possible the delivering of datagrams to a mobile station wherever its location happens to be. In theory, usual transport protocols can be used on top of mobile IP to communicate the mobile station with servers located in the fixed network. In practice, as we have seen in the previous section, serious problems of performance arise with such a configuration.

Alternatively, a non-transparent policy leads to developing and installing new applications and transport protocols for the mobile environment. Interoperability problems with existing applications make undesirable such an approach. This is the context where the indirect model of client/server interaction appears [11]. This model allows improving the performance of standard TCP/IP implementations in a mobile environment, maintaining the protocols in server machines, and with minimum changes in those used by the mobile clients.

The main idea of the indirect model is simple: whenever two different environments, such as wired and unwired, are involved in a client/server connection, split the connection in two parts, one per environment. An intermediate system is located between the two connections, participates in both of them, and manages each one in a different way, suitable for its characteristics. The intermediate element looks as a server to the mobile client, and as a client to the fixed server, so the classical client/server model becomes a client/intermediary/server model. A datagram traveling from client to server (or vice versa) will traverse some layers in the protocol stack of the intermediary before being forwarded to its destination. The number of layers above the network layer traversed at the intermediary depends on the nature of the application.

The applicability of the model can be exploited at any layer, but its benefits are specially appreciated at the transport [12] and application layers. At the transport layer, connections are break in two; in the wireless side an adapted transport protocol controls the connection between mobile and intermediary, and in the fixed side classic TCP can be used to connect the intermediary and the server. The end to end semantics of TCP is lost [13], but the performance problems described before can be solved. At the application layer, the purpose of the intermediary is to provide a mechanism for interposing application specific programs, called filters, in the middle of client/server connections. Filters may drop, delay or transform data moving to and from the mobile host, performing ad-hoc optimizations. From this point of view, the intermediate system becomes a proxy system for the client-server interaction.

4. Proposed communications architecture

The proposed design pursues the following targets:

- Compatibility with TCP/IP protocols, making client mobility transparent to the common TCP/IP user.
- To establish a framework for the development of new applications, or the adaptation of existing ones, for the mobile environment.
- To improve the quality of the data service perceived by the user, improving the throughput of network protocols. The quality of service should be close to that achievable from wired telephone networks.
- Scalability to allow the use of new services and the increment of demand that accompany the spreading of GSM networks.
- GSM operators should not be required to change their network infrastructure in order to implement the architecture, even when the new GSM standards for high-speed data service (GPRS and HSCSD) are available.

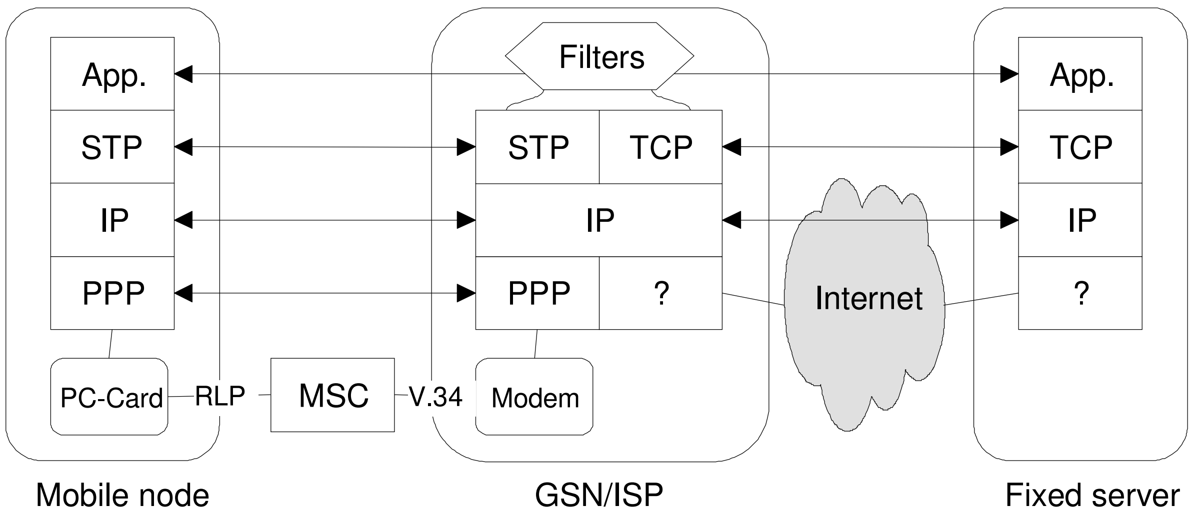

Fig. 3. Protocol architecture with an intermediary located at the GSN

Our proposal consists of an indirect architecture, with client-server communications divided in two parts. The first one, controlled by special network protocols adapted for the wireless environment, traverses the GSM network. The other one completes the connection, using conventional TCP/IP protocols. In the middle of both parts is the intermediary, known as GSN (Gateway Support Node) using GPRS conventions. There will be one or more GSNs in the GSM network, and the user will be connected by a circuit-switched connection to one of them (it will be this way until GPRS is available). The rest of the communication, from the GSN to the server, uses packet switching. Therefore, in this proposal the intermediary is not located in the border between the wireless and wired environments (as it is usual in indirect proposals for mobile computing) but in the border between circuit and packet switching environments (when GSM data services are circuit switched) or, more generally, between the GSM network and the Internet. It is possible conceive both client and server located in mobile nodes, but that is just a particular case in the general architecture, more related to theory than to real situations. The number of GSNs to install in a particular network depends on the demand of the Internet service at that network, and on the topology of the network, in the same way that it works today for the number and distribution of the modem pools for GSM data access (Figure 1). Next, we will describe, using a bottom-up approach, the different layers in the architecture for all the constituting entities, shown in Figure 3.

4.1 Network access

Taking Figure 2 as the reference point, no changes are proposed at the lowest layers: PPP and RLP protocols are used to access the GSN. The main difference is that in this arrangement, the GSN also acts as an Internet Service Provider, thus simplifying the user access to the Internet and increasing the value added by the GSM operator. However, this is just an option. Alternative ones are to locate the GSN and ISP in the MSC (avoiding the use of the PSTN), or to distribute all the functions (MSC, GSN and ISP) along separate elements, with the last one outside the GSM network. The configuration use is a question to be decided by the operator; one of our tasks is to evaluate their relative advantages and problems.

In the future, GPRS and HSCSD services will be available, and then convenience of using PPP as the link layer protocol for the mobile-MSC connection will need to be reconsidered.

4.2 Mobility management

The mobility management procedures described in Section 2 are enough to cope with the common scenario of a mobile client who establishes a connection with a fixed server. First, the client will connect with its ISP and obtain a dynamic IP address. Then, IP datagrams will flow through the circuit switched connection (or will be packet switched using GPRS) to and from the mobile client. The maintenance of that connection is guaranteed by the GSM handover mechanism.

In the case of a user who wants to access the Internet using a fixed IP address, the above solution is not appropriate. It could be the case of a station roaming out from its wireless local area network, or a server situated in a mobile node. In such situations incoming datagrams cannot be correctly routed through the appropriate GSN, as the destination address does not belong to the set of addresses managed by the GSN. Those datagrams will be routed to the home network of the mobile station. In those situations, it is necessary to use Mobile IP [17]. Mobile IP describes the use of a home agent and a foreign agent, which play roles similar to those of HLR and VLR in GSM. The home agent keeps track of mobile nodes whose home is in the network controlled by it, but that are currently visiting other networks. The foreign agent keeps track of all mobile users visiting a network, and contacts the mobile host's home agent to inform of its position. In our architecture, we integrate the functionality of both agents in the GSN. It would work as a home agent for those mobile users who habitually use the GSM network for Internet access, redirecting datagrams to their current position. It would also serve as a foreign agent for those users who are just visitors, registering them and informing their home agents. The main difference with HLR and VLR functionality is that these GSM registers are used for location updating and call routing into the GSM network, and mobile IP is used for dynamic routing in the other side of the GSN, this is, in the Internet.

4.3 Transport layer

In the GSM part of the connection, a new, simplified version of TCP replaces the standard TCP (to be implemented; the proposed name is STP, Simplified Transport Protocol). The basic challenge for STP is to maximize the throughput in the connection, efficiently using all the available bandwidth. The main limitation is the modest performance and irregular behavior of the wireless link, so the protocol overhead must be minimized, and the flow control mechanism must be tailored to the characteristics of the link. STP will provide communication services to client applications in the mobile node and to proxy agents controlling the execution of filters in the GSN.

The design objectives of the STP protocol are high performance, efficient recovering from expected and unexpected disconnections, and tolerance to delay fluctuations. The indirect model allows us to implement the required functionality as a simple, optimized point to point protocol. The combination of STP and TCP in both sides of the GSN constitutes an implementation of indirect TCP. When a client requests to open a transport layer connection, through a standard interface (BSD sockets, TLI), it is intercepted in the mobile by the STP entity, who requests a STP connection with the proxy agent in the intermediary. Once this STP connection is available, a proxy transport entity at the GSN will request to open the second part of the connection, to communicate with the server, using standard TCP. This entity will take care of disconnections and delays, sending the appropriate segments to the server to maintain the stability of its TCP connection, or temporarily closing that connection if necessary. In the GSM side, STP should introduce minimum protocol overhead, decreasing the size of headers to only a few bytes, reducing connection establishment and release overhead, and reducing traffic over the wireless link using acknowledgments sparingly. The use of compression in STP to reduce the volume of transmitted data could be considered, but it does not look an interesting option, as compression can be used for the GSM data service, and application specific compression (performed by an application layer filter) would be more effective.

A good design of the proxy transport entity is crucial to avoid TCP's limitations in wireless environments described in Section 2. It has to fool the server endpoint with probably false ACK's when the delays in the GSM section are too long, in order to avoid instability in retransmission timers, congestion window shrinking, and even unilateral disconnection from the server. Besides, it has to control the state of a TCP connection before an announced (from the mobile side) temporal disconnection, in order to be able to restart it in an effective way. The introduction of all these features break the TCP end to end semantics but, in our opinion, preserving it creates more trouble than benefit in a wireless environment.

4.4 Proxy layer

The use of the indirect model at the application layer means to interpose application specific programs, called filters, in the middle of client-server connections, running in the GSN. These filters, and its management, is what we call the proxy layer.

There can be general purpose filters (those that are supposed to perform well for any application) and specific filters (specifically designed for a particular application). In fact, the transport entity running at the GSN can be seen as a general purpose filter; it is just a question of naming. Actions that filters could perform include selective dropping of superfluous header information (e.g., in e-mail), delay data for later pickup (e.g., POP mail), re-segmentation of data, reducing "frivolous" traffic addressed to the mobile host (e.g., replying ICMP echo requests). All of these advantages can be achieved without the use of intermediaries, but in most cases client, server or both would have to be changed. In an indirect architecture like this, changes are few and just in the client, not in the server.

Filter management can be performed by the client, or by the proxy layer of the intermediary. In the first case, there must be an application layer interaction between the mobile computer and the GSN in order to activate the suitable filter. With the second option, this interaction disappears, allowing the proxy layer in the intermediary to decide, autonomously, which filters to apply to every application. It is a point of discussion which approach is best, as both have advantages. The first approach can be the one of choice if we want mobility awareness at the application layer. The second one simplifies the interaction through GSM, which is the critical step of the connection, and minimizes the changes in the protocol architecture of the mobile nodes. Nobody but the mobile client knows when a planned disconnection is going to happen, but nobody knows better than the GSM network what is the situation of their links and, hence, which filters are convenient for every situation.. Our architecture proposal considers both approaches: a protocol for application layer interaction between client and proxy will be defined for filter management, but it is an optional feature for applications. If they want to take part in that management, a service is available, but the server is perfectly able to work alone.

4.5 Adapted protocols

The action of filters is not the only manifestation of the indirect model at the application layer of the architecture. It can support the option of mobility awareness to applications (i.e. non-transparency), allowing the use of modified application protocols in the client-proxy connection, always maintaining standard protocols in the proxy-server side. The WWW is an application where this approach suits particularly well. Several efforts are devoted to the development of simplified versions of HTTP protocol [14] that would be used by specific clients (for example, a personal digital assistant) when connecting to specific proxy servers running in the GSN.

5. Related work

A number of systems based in the indirect model of interaction have been designed and implemented. In [15] the indirection is applied at the transport layer, where mobility is facilitated with *mobile sockets*, a paradigm in which the socket connections used by the proxy follow the mobile station as it roams the network. We think that such an approach is not so useful in a wide area environment, as GSM, where is not frequent to move from one GSN area to another one while a connection is open.

The M-RPC service proposed in [16] enhances the standard RPC model by adding support for dynamic sever binding, reliable transport over a wireless link, optimizations to reduce mobile host interaction, and partial support for disconnected operation. This work is an extension of a previous one [15] that focused on the transport layer. The limitation of this work is that M-RPC has RPC calls as the only purpose. It can be seen as a particular case of proxying in our architecture.

The Mowgli Project [17] proposes the insertion of a mobility aware layer into the standard UNIX socket interface. Socket connections are broken into two separate links, one between the mobile host and a proxy somewhere within the wired infrastructure, and another between the proxy and a fixed host. Extra functionality in the proxy supports an enhanced socket model for the mobile host that includes quality of service, fault tolerance, and proxy control. This enhanced socket model, the Mowgli sockets, is the main contribution of the Mowgli project. It is backward compatible with the BSD socket interface, and allows future applications to be mobile aware, in the same manner as we propose adapted protocols for the mobile-proxy communication when that awareness is desired. The Mowgli approach involves several layers of communication, from link layer to application layer. The link protocol as well as the standard TCP/IP core protocols are replaced in the wireless link. Applications in the mobile node do not access directly the transport service, but work through an agent who cooperates with the proxy in the intermediary to perform socket operations.

The work described in [18] improves TCP performance in wireless environments without violating TCP's end to end semantics. TCP modifications implemented at the base stations allow to cache TCP segments destined for the mobile host, performing local retransmissions when a packet loss is detected. It is not very useful in the non-transparent version of GSM data transmission, where RLP deals with information losses. In GSM, the main problem is not packet loss, but long, variable delays due to RLP retransmissions.

In [19], an approach similar to our indirect architecture is presented. However, this work is focused on adaptation to heterogeneous network environments, giving a poor performance in a homogeneous environment. It is considered that mobile hosts may move unpredictably through areas whose networks have very different speed, cost, security, and loss rate. This is not the scenario we have considered. Filtering is applied to application, transport, and network protocols, in a segregated filtering model: application layer filtering is performed by a *High Level Proxy*, while filtering of low level protocols is performed by a *Low Level Proxy*.. The indirection is applied to protocols as a better alternative than rewriting applications. A notable difference with our approach is the use of an augmented Mobile IP protocol in order to guarantee that all traffic moving to and from the mobile host will pass through the intermediary. We have not that problem, as using a GSM network for access guarantees that all that traffic will pass through the GSN.

6. Conclusions

We have presented a communication architecture that pursues efficient Internet access from a GSM cellular telephone network. It retains the TCP/IP architecture unmodified at the existing hosts in the fixed network, so that neither current network applications nor protocol software on fixed hosts need to be modified. This is made possible by the use of the indirect model of client/server interaction, which breaks the client/server communication in two separate parts: client-intermediate and intermediate-server. The intermediate element has been placed in the frontier between GSM and Internet.

Special attention has been paid to the performance of standard TCP/IP applications, which dramatically decreases when the access is made through a wireless network. To improve it we have proposed to substitute the standard TCP protocol with a simplified one in the mobile-intermediate part of the connection, which minimizes the traffic over that link. The action of this protocol, combined with the transport layer functionality of the proxy situated in the intermediate, will prevent the decrease of TCP performance in the fixed part of the communication. Currently we are working in the design and implementation of that protocol. A main objective of that work is to guarantee an easy integration in the most commonly used environments for Internet access, not requiring the installation of a new version of the operating system in the client machine.

Another way to improve the quality of service perceived by the user is the application of the indirect model at the application layer of the architecture as well, by means of filters running in the intermediary. That is what we have called the proxy layer of the architecture, transparent for servers, and optionally transparent for clients. Besides, the architecture is able to support the option of mobility awareness to applications, so that future developments of modified application protocols can be used in the critical mobile-proxy connection.

References

[1] M. Rahnema. *Overview of the GSM System and Protocol Architecture*. IEEE Communications Magazine, 31(4) pp. 92-100, April 1993.

[2] B. Emmerson, D. Greetham. *GSM´s extraordinary growth.* Byte Magazine, March 1996.

[3] T. Alanko, M. Kojo, H. Laamanen, M. Liljeberg, M. Moilanen, K. Raatikainen. *Measured Performance of data transmission over cellular telephone networks.* Computer Communications Review, 24(1994)5.
[4] ETSI. *High Speed Circuit Switched Data (HSCSD) - Stage 1*, GSM specification 02.34, April 1997.
[5] ETSI. *GPRS; Service description*, GSM specification 02.60, Version 5.1.0. January 1998.
[6] ETSI. *Quality of service*, GSM specification 02.08, Version 3.0.0., March 1990.
[7] H. Balakrishnan, S.Seshan, R.H. Katz. *A comparison of mechanism for improving TCP performance over wireless links* . SIGCOMM 96, August1996
[8] R. Caceres, L. Iftode. *Improving the performance or reliable transport protocols in mobile computing environments.* IEEE JSAC Special Issue on Mobile Computing Networks, 1994.
[9] J. Ioannidis, D. Duchamp, G.Q. Maguire. *IP-based protocols for mobile internetworking*. SIGCOMM, 1991.
[10] Mobile-IP Working Group of the IETF. *IP Mobility Support*. Internet Draft, 1995.
[11] B.R. Badrinath, A. Bakre, T. Imielinski, R. Marantz. *Handling mobile clients: A case for indirect interaction*. In 4th Workshop on Workstations Operating Systems, 1993.
[12] A. Bakre, B.R. Badrinath. *I-TCP: Indirect TCP for mobile hosts*. Rutgers University DCS-TR-314, 1994.
[13] B. Zenel, D. Duchamp. *General Purpose Proxies: solved and unsolved problems.* HO-TOS IV, 1997.
[14] M. Liljeberg, H. Helin, M. Kojo, K. Raatkainen. *Enhanced services for WWW in mobile WAN environment*. Proceedings of the IEEE Global Internet 1996 Conference, London, England, November 20-21, 1996.
[15] A. Bakre, B.R. Badrinath. *Handoff and system support for Indirect TCP/IP.* Proc. Second Symposium on Mobile and Location-Independent Computing. USENIX, April 1994.
[16] A. Bakre, B.R. Badrinath. *M-RPC: A remote procedure call service for mobile clients.* Proc. First Annual International Conference on Mobile Computing and Networking. ACM, November 1995.
[17] M. Kojo, T. Alanko, M. Liljeberg, K. Raatkainen. *Enhanced communications services for mobile TCP/IP networking.* University of Helsinki, Department of Computer Science, Series of publications C, No C-1995-15, Apri1995.
[18] E. Amir, H. Balakrishnan, S. Seshan, R. H. Katz. *Efficient TCP over networks with Wireless Links.* First Annual International Conference on Mobile Computing and Networking. ACM, November 1995. infopad.eecs.berkeley.edu/infopad-ftp/papers/1995/ efficient_wireless_tcp.hotos95/hotos.ps.gz
[19] B. Zenel, D. Duchamp. *A General Purpose Proxy Filtering Mechanism Applied to the Mobile Environment*, MOBICOM97, Budapest Hungary 1997.