TCP over 3G links: Problems and Solutions

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Abstract

This review paper presents analytical information regarding the transfer of TCP data flows on paths towards interconnected wireless systems, with emphasis on 3G cellular networks. The focus is on protocol modifications in face of problems arising from terminal mobility and wireless transmission.

The objective of this paper is not to present an exhaustive review of the literature, but to filter out the causes of poor TCP performance in such systems and give a rationalized view of measures that can be taken against them.

1 Introduction

The proliferation of the Transmission Control Protocol (TCP) in Internet communications today incites the research community to further extend its use in mobile and wireless networks. The ultimate goal is efficient and reliable TCP flows for Internet traffic over interconnected wired and wireless paths, where the wireless path suffers from additional problems due to higher BERs (Bit Error Rates) and frequent link changes. This primarily entails the treatment of protocol issues, but also additional inter-operability in the network infrastructure.

In the large-scale mobility case, cellular networks of the 3rd generation (3G) are the most suitable candidates for support of Internet traffic, as they offer capacity for enhanced broadband data transfers, as well as improved transmission quality. They are predominantly characterized by CDMA (Code Division Multiple Access) transmission technology [1].

Figure 1 portrays the typical 3G network architecture for IP communications. The radio network controller (RNC) manages several base station (BS) transceivers and is responsible for handover operations. Packets are routed through a local switch, while a gateway switch ensures the connection to an external IP network. User profile and location information are maintained at a separate database.

Although the focus in this review is on cellular networks, many of the issues treated apply generally to wireless access systems.
2 TCP problems in 3G links

The transfer of Internet packet flows in wireless paths requires TCP to also be capable of handling transmission losses and discerning them from losses due to congestion. TCP was designed for wireline networks, where transmission losses are extremely low (BERs in the order of $10^{-10}$, and down to $10^{-12}$ for optical links). Wireless links, on the other hand, may experience much higher BERs due to interference and fading phenomena (although care is taken for loss rates not to exceed $10^{-2}$). Such random losses, if perceived as congestion, will lead to spurious timeouts or mistakenly trigger the TCP sender to reduce its congestion window and hence its sending rate unnecessarily. Problems then manifest themselves as degradation of throughput, as well as inefficiency in network link utilization. Moreover, the fact that random bit errors usually occur in short bursts leads to a higher probability of multiple packet (or segment, in initial TCP terminology) losses within one transmission window, further degenerating this behavior: bursty packet losses additionally make the system get stuck in lengthy recovery procedures (and most probably hopeless, since timeouts may occur anyhow), especially when selective or partial acknowledgements are not supported.

Problems for TCP in cellular networks also occur during the handover procedure, when a mobile moves to the coverage area of different base stations (BS). Generally, and as it will be elaborated in a later section, handovers induce temporal disconnections, buffer losses, increased latency and packet reordering. In CDMA, universal frequency reuse makes it possible to easily perform soft handoff, whereupon a mobile is connected to two or more BS. This can eliminate temporal signal loss or the need to suspend and resume the transmission of packets, which—if no notification is sent to the TCP sender—may result in buffer overflow. However, problems may still occur if soft handoff is not initiated promptly or if power control is not properly configured.

Additionally, TCP transmissions in 3G CDMA links are generally struck
by increased latency. This is due to the extensive processing required at the physical layer of these links for coding and interleaving, and to link layer processing for FEC (Forward Error Control) and link-level retransmissions. Further, since a 3G link is frequently assigned to a single host, there is a low degree of statistical multiplexing and RTT variations occur more easily.

Spurious retransmissions and timeouts may also occur because of dynamic resource sharing schemes in 3G links. Variable rate support in CDMA has the potential to offer, apart from plain multiservice traffic, dynamic resource scheduling and link utilization (e.g., the HSDPA scheme in WCDMA and HDR in cdma2000 [9, 10]). However, the temporal allocation and deallocation of resources can cause delay jitter, blocking and timeouts.

Furthermore, it is very difficult to achieve good overall TCP performance with variable rate support. Users assigned very high data rates may not reach the bandwidth-delay product, while low rate users are faced with overflow problems (there is limited memory available for the TCP/IP stack).

Link asymmetry is also an issue of concern for TCP design. Specifically, transmission rates in the downlink are usually much higher than in the uplink, particularly for the high speed HSDPA and HDR implementations. Even if this asymmetry can be tolerated by TCP’s self clocking mechanism, there is a much higher risk of buffer overflows both at the receiving and transmitting side. Ragged behavior will also evidently occur if poor transmission conditions weigh more in one direction than the other.

Finally, another handicap is that TCP/IP header compression techniques, which reduce data traffic load, do not perform properly on wireless links. Specifically, most of these schemes do not transmit the entire TCP/IP header, but only changes in consecutive headers (e.g., the RFC 1144 header compression algorithm [11]). Upon frequent TCP losses, the transmitter and receiver may fall out of synchronization, and continuously discard packets because of checksum errors.

For a more complete understanding of problematic TCP behavior, basic TCP principles should be revised ([2] or at least [3, 5, 4]). Readers can also consult the related RFC [6] or more general review papers such as [7, 8].

The improvement of TCP performance is a matter of the overall system design, protocol issues, architecture and communication of network entities, buffer management, as well as packet scheduling algorithms. Here we concentrate on the modification of the data communication protocol suite, which is the primary issue and should aim at the treatment or prevention of degenerative effects. Solutions can be loosely classified into link layer mechanisms, end-to-end TCP modifications and split-end approaches. Below is a critical view at solution approaches, rather than solution schemes. For more detailed scheme descriptions readers can refer to [7, 8] and the references therein.
3 Link layer mechanisms

A link layer is used in communication protocols to provide flow control, as well as error detection and correction. Essentially, this is the task performed by TCP. Nevertheless, the addition of a link layer operating underneath the TCP/IP stack (see Figure 2) can be very useful in wireless paths, and is adopted in 3G access systems.

![Image of data communication protocol stack with addition of link layer in 3G systems.](image_url)

Figure 2: Data communication protocol stack with addition of link layer in 3G systems. Radio access protocols provide resource control and medium access (e.g., in UMTS these are composed of RRC, MAC and PHY layer protocols).

Link layer retransmission mechanisms enable more prompt recovery from wireless losses. Their primary mission should be to reduce the packet error rate to a level that would not cause significant performance degradation at the TCP layer, which will in turn eliminate all detectable errors. In general, it would be desired to limit the packet error rate to the same level of a wireline network (below $10^{-8}$).

A link layer can also assume the role of fragmenting (and reassembling) packets into smaller segments, more suitable for transmission over a wireless link (since a smaller-sized packet leads to smaller error probability).

Currently a negative acknowledgement ARQ mechanism is specified in cdma2000 [12], while a more complex mechanism with status reports containing both received and missing packets is specified in UMTS/WCDMA [13]. Different ARQ mechanisms may further be implemented in high data rate schemes (e.g., hybrid ARQ in HSDPA [9]).

However, one must keep in mind that the link layer solution does not completely shield the TCP sender. TCP performance can still be poor for two reasons:

- retransmit timeouts caused by additional link layer delay
- out of order reception of data from the link layer, leading to unnecessary invocations of the TCP fast retransmit mechanism

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1 The Internet layer architecture is older than the OSI reference system. The final recommendation for TCP and IP was done in 1981, while the OSI reference model came out in 1983.
Both delay and out-of-order delivery can result in competing (duplicate) retransmissions from the two layers, and thus inefficient utilization of the network capacity. To cope with this, a link layer implementation should be “TCP-aware”, meaning to have the capability to view TCP headers and understand TCP semantics. Then it could be equipped with more “intelligent” functions, such as holding back duplicate acknowledgements that would trigger fast retransmissions, or control the setting of the retransmit timer at the TCP layer.

4 End-to-end TCP modifications

TCP is a connection-oriented end-to-end protocol and therefore solution approaches should primarily aim at protocol modifications at the end hosts. General protocol improvements from experimental methods are listed below.

- The use of selective acknowledgements in TCP SACK [14] or partial acknowledgements in NewReno [15] can successfully tackle multiple packet losses within a single window. Further, more accurate knowledge of the state of the system (e.g., packets in flight, pending acknowledgements) can help in the precise control of the injection of packets in the network upon heavy losses, so that the prescribed congestion window is always kept full and retransmission timeouts are avoided. Such an extension can be used supportively to the TCP SACK scheme, as is implemented in the Forward Acknowledgement algorithm [16].

- Explicit congestion or loss notification (ECN, ELN, resp. [18, 17]) can help to discriminate random losses from those due to congestion, and thus invoke congestion avoidance and control procedures only when necessary.

- Estimates regarding the amount of backlogged packets at the receiver queue or estimates of the available bandwidth (such as the schemes in TCP Vegas, Westwood and Jersey [19, 20, 21]) can assist in configuring the congestion window more properly for wireless links.

Further, we mention a list of good practices, extracted from [6], that alleviate many of the problems.

- The value of the receive window should be chosen to match the bandwidth-delay product of a 3G link (about 8-50 KB).

- The TCP timestamps option [22] allows more frequent RTT samples (instead of one RTT per window of data as in normal TCP), enabling the sender to adapt quicker to changing network conditions and avoid spurious timeouts. This can be especially useful for 3G links which experience larger RTT variations, although an additional overhead is incurred.
- The Limited Transmit algorithm [23] can extend TCP’s Fast Retransmit/Fast Recovery by sending a new segment in response to each of the first two duplicate acknowledgements received. This keeps data flowing in the system and avoids having to wait for a 3rd dupack.

- The MTU discovery procedure [24] can be implemented, which allows a sender to determine the maximum end-to-end transmission unit (PDU) supported by the link layer for a given routing path. This is useful since the default PDU fragmentation size may be too small, and a larger size can be tolerated.

- Common applications for Internet-enabled cellular mobile devices require only the transmission of a few segments’ worth of data. Therefore, it is particularly effective to have a high initial window, instead of performing slow start. An initial window of up to four segments is suitable for most applications, while it has a negligible effect on larger data transfers [25].

5 Splitting end-to-end connections

An alternative way of dealing with TCP problems in wireless links is to “isolate” the wireless portion of the path by dividing the end-to-end connection into wired and wireless connections. This is the so-called split-end approach: each connection is separate, different flow control windows can be maintained, and acknowledgements are generated for each portion separately. Further, error control mechanisms, packet sizes and timeouts can be different for each connection (Fig. 3).

![Figure 3: The split-end TCP approach](image)

This approach is reasonable in view of the distinct characteristics of wired and wireless paths and ensures that the more problematic wireless TCP behavior has the least impact on the fixed network. It is also especially convenient for cellular networks, where the mobile host is only a single hop away from the fixed network. The point of detachment should be as close to the mobile host as possible, either at the base station or radio network controller.

The isolation of the wireless link is the main advantage of a split-end approach. It also helps in faster reaction to the errors caused by mobility and
wireless transmission, since an end communication point is maintained very close to the source of these errors. We can also take advantage of this structure to simplify the protocol communication between the split end-point and the mobile host. For example, the TCP header size can be reduced by cutting down on unused options (e.g., SACK, timestamps, etc.). Additionally, if IP mobility is not implemented we can dispense with the overhead of an IP layer altogether.

However, such an approach also has several shortcomings. The need for intermediate protocol processing incurs extra delay for the packet transmissions. The approach also prerequisites the existence of large buffers at the split-end point to absorb processing and transmission delays. These two issues further raise the question of scalability, since a base station or controller may be overwhelmed if it has to serve a large number of mobile hosts with multiple network connections. Additionally, there can be a high latency during handoffs and the seamless handover procedure is obstructed. This issue is further discussed in the next section which elaborates on terminal mobility.

Finally it must be noted that split-connection approaches violate end-to-end semantics, as an acknowledgement may be delivered to the sender before the data actually reaches its destination. This is disastrous for applications that rely on TCP semantics to control traffic. However, common applications (e.g., ftp, HTTP, SMTP) do not face a problem, since they have their own application layer acknowledgements to control traffic.

6 More on host mobility

6.1 Handovers

TCP robustness to handovers depends very much on the handover procedure itself, and issues such as accurate prediction of signal strength and prompt initiation, duration (in hard handover) and signal combining (soft handover).

For hard handover\textsuperscript{2} even though care is taken from the part of the radio network controller to complete the procedure as soon as possible, a surplus of TCP problems will inevitably occur. Reasons are transmission losses, the induced latency, but also buffer overflow, since the sending and receiving of data is suspended until the handover is completed, whilst a fixed host continues to send data as the whole procedure is normally transparent to it.

In a CDMA network where soft handover\textsuperscript{3} is more easily implemented (although complexity is still an issue), errors can be kept to a minimum. However, problems may still occur if handover is not initiated promptly; it should be noted that signal fluctuations are difficult to predict and it is hard

\textsuperscript{2}Inter-frequency handover and inter-system handover are also hard handovers.

\textsuperscript{3}This is always an intra-frequency handover. More information on handovers in 3G systems can be acquired through a very educational thesis \cite{26}.
to obtain optimized handover margins. In another extent, the implementation of soft handover may not be purely advantageous, since the transmission and reception of multiple signals can burden the fixed links, especially if a mobile is connected to more than two base stations. Moreover, transmission errors may occur due to an imperfect power control mechanism during soft handover, as it is much more difficult to reach a perfect scheme in this case, while achieving the desired macrodiversity gain. Last but not least, the decision phase in CDMA soft handover suffers from additional delay, due to the need for timing synchronization of the signals from different base stations.

In split-end approaches further problems are encountered if a connection is split at the base station. Normally, all information pertaining to a TCP connection (send and receive windows, sequence numbers, retransmission status and timers, etc.) established on behalf of a mobile host must be handed over to the new BS. This shift of information burdens the network and increases the latency. This problem stipulates that it is better to split the connection at the radio network controller, as changes to different RNCs will occur much more rarely. The requirement for shift of information also brings about the inability to implement soft handover when the connection is split at the base station.

Apart from designing the procedure itself as best as possible, an extra step that can be taken to improve TCP handover performance is to freeze the retransmission timers during the handover procedure, or suppress (or suspend) the sending of duplicate acknowledgements until it is completed.

Finally, a method to eliminate handover latency in the downlink is multicasting. The basic principle is as follows: The system is informed to anticipate handoffs and multicasts data destined to the mobile host to nearby base stations in advance. Hence the goal is essentially the same as with the soft handover scheme, but the implementation is different (formation of multicast groups, etc.) and it usually operates on a larger scale (more BS are involved, which makes it more suitable for picocellular networks). There exist many schemes that propose multicasting, interested readers can for instance look up [27, 28].

6.2 IP mobility

While the radio access handover and link layer mobility are provided by the CDMA access scheme, the 3G core network needs to be able to support IP handover for unabridged connectivity to the mobile host.

Cornerstones for IP mobility support are laid with the Mobile IP scheme [29]. Mobile IP solves the problem of mobility of a node by managing the correspondence between the changing IP address of a mobile host, called the care-of address, and the home address permanently or semi-permanently assigned to the host. All packets sent to a mobile node’s home address are
tunnelled by a home agent to the current care-of address of the mobile.

Mobile IP demands the integration of mobility management entities into the core 3G architecture. However, the general problem concerning TCP/IP transfers is to resume the sending and reception of IP packets as soon as possible subsequent to a handover, with the least disruption to the transmission sequence [30]. During handoff additional latency which deteriorates TCP behavior is incurred by procedures for: 1) address resolution delay and 2) home network registration.

There exist proposed schemes that take action against the above deficiencies. Hierarchical mobile IP [31] aims to reduce the home network registration delay by implementing a hierarchical mobility management scheme, where short-range mobility is handled through a local router called mobility anchor point (MAP). When a mobile moves within a MAP domain, handover latency is greatly reduced as the binding update needs to reach the MAP only. Secondly, fast (or low-latency) handover [32] aims to reduce the address resolution delay by address pre-configuration. It involves cooperation between the old and the new access router so that the new address can be resolved and packets can start being forwarded to the new access router before the handover is executed. Finally, there also exist multicast approaches for IP mobility (e.g., [33]).

A critical note on the fast handover approach is that packet forwarding results in a lot of re-ordering at the receiver, since packets through the new access router may arrive sooner at their destination. In that case, selective TCP acknowledgement schemes are called for to assist recovery (the relatively slow and loss-neglecting recovery procedure in Reno and NewReno turns out to be insufficient and these schemes can perform worse than Tahoe, see [31]).

Clearly, one can combine the key benefits of these approaches into a new mechanism. A scheme that builds on top of the hierarchical and the fast handover approach—and also employs a multicasting function—is S-MIP (Seamless Mobile-IP [35]). This achieves fewer packet losses and more accurate handover through movement prediction, improving the overall behavior. S-MIP also keeps re-ordering problems to a minimum by maintaining different buffers for forwarded packets, which are flushed out before packets from the new access router. The integration of S-MIP mechanisms into the UMTS architecture has been proposed in [36], exhibiting superior performance.

7 A summary of major points

This review has offered an analytic presentation of performance problems and solutions related to the transfer of TCP data flows in networks including wireless paths, with emphasis on 3G cellular links. Certain major points can be highlighted.
First, TCP performance problems can be kept to a minimum by appropriate changes in the end-to-end protocol mechanisms. Especially the use of existing experimental schemes, such as selective or partial acknowledgements and explicit loss or congestion notifications greatly improve performance. But also the more accurate tracking of the state and available bandwidth of a link are important ingredients of an improved scheme.

Moreover, the addition of link level mechanisms in the “last mile” can help in faster reaction and recovery from losses and timeouts. This is requisitied and practically more helpful, since it is very difficult for end-host protocol modifications to be uniformly supported in a network. Maximization of performance is then achieved by using a TCP-aware link layer protocol. In this case however, it is important to understand how the competitive ARQ mechanisms in the TCP and link layer interact with each other to affect overall performance and how the specific parameters of each should be fine-tuned.

On what concerns the split-end approach, dividing the end-to-end connection into wired and wireless paths is reasonable and seems especially attractive in single-hop networks, but it is not strictly necessary. As was shown in [37], although an appropriate split-end scheme can perform better than the standard TCP Reno, its performance can be worse than that of an advanced end-to-end or a well-tuned TCP-aware link layer protocol.

It should also be stressed that the complete exploitation of Internet services over 3G links is not accomplished unless IP mobility is supported. Although this demands the integration of IP mobility management entities into the core 3G architecture and incurs additional TCP problems, in the long run an all-IP cellular network will provide for cost savings and ease of use.

Finally, coupled with TCP performance are issues concerning appropriately large buffer sizes to combat link asymmetry and achieve good utilization in 3G cells, and the design of fast and rate-preserving scheduling algorithms to alleviate problems occurring by the intermittent allocation of resources in such systems.

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