PERFORMANCE LIMITATIONS OF IEEE 802.11 NETWORKS AND POTENTIAL ENHANCEMENTS

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Abstract. The IEEE 802.11 standard is a significant milestone in the provisioning of network connectivity for mobile users. However, due to the time-variant characteristics of wireless links, interference from other devices and terminal mobility, 802.11-based WLANs suffer from performance drawbacks in relation to wired networks. This chapter surveys the performance issues related to throughput and delay in 802.11 networks and describes proposals to overcome such shortcomings.

Key words. IEEE 802.11, WLAN, Performance Evaluation, TCP over Wireless

1. Introduction. Wireless networks are becoming increasingly popular in telecommunications, especially for the provisioning of mobile access to wired network services. As a consequence, efforts have been devoted to the provisioning of reliable data delivery for a wide variety of applications over different wireless infrastructures. In wireless network, regardless of the location, users can access services available to wired-network users.

In this scenario, the IEEE 802.11 standards represent a significant milestone in the provisioning of network connectivity for mobile users. However, the 802.11 medium access control strategy and physical variability of the transmission medium leads to limitations in terms of bandwidth, latency, information loss, and mobility. Moreover, the deployment of the Transmission Control Protocol (TCP) over IEEE 802.11 networks is constrained by the low reliability of the channel, node mobility and long Round Trip Times (RTTs).

This chapter aims at providing a comprehensive analysis of the performance limitations and potential enhancements to 802.11 networks. Proposals to overcome such limitations are compared and their suitability for specific deployment scenarios is presented.

The structure of this chapter is as following: Section 2 provides an overview of the IEEE 802.11 standards and its extensions. Section 3 surveys the performance issues related to throughput and delay in 802.11 networks. Section 4 introduces existing proposals to overcome those problems. Sections 5 and 6 provide comparisons of the different solutions. Finally, Section 7 draws some conclusions.

2. The 802.11 Standards. The IEEE 802.11 Wireless Local Area Network (WLAN) standards were first adopted in 1997 and revised in 1999 [1]. It aims at "providing wireless connectivity to automatic machinery, equipment or stations that require rapid deployment, which may be portable or hand-held, or which may be mounted on moving vehicles within a local area" [1]. The IEEE 802.11 specification provides "wireless standards that specify an "over-the-air" interface between a wireless client and a base station or access point, as well as among wireless clients" [2].

Figure 2.1 presents an overview of the IEEE 802.11 protocol stack. The standards specify the Medium Access Control (MAC) sublayer, the MAC management protocol and services as well as different physical layers (PHY). A key issue is transparency.

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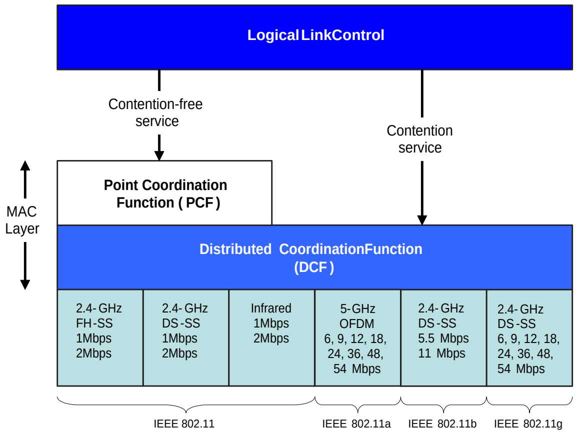

FIG. 2.1. *Overview of the IEEE 802.11 Protocol Stack.*

Above the MAC layer, 802.11 appears as any other 802.x LAN and offers similar services. The protocols are specified for communicating stations with and without the support of a specific infrastructure (Infrastructure Mode and Ad Hoc Mode, respectively). Furthermore, the standards describe the procedures for preserving privacy of user information.

The MAC protocol provides two medium access methods: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). The DCF is a contention protocol based on the Carrier Sense Multiple Access Protocol (CSMA), known as CSMA/CA, with CA standing for collision avoidance. It also uses small RTS/CTS (Request To Send / Clear To Send) packets to reserve the medium in order to avoid collisions due to problems involving a hidden terminal. The exchange of such control messages allows all the terminals within the receiving range of both the source and the destination terminals to defer transmission in order to allow successful delivery of a data frame.

Fig. 2.2 illustrates the RTS/CTS mechanism. The Network Allocation Vector, NAV, represents the duration stations sensing RTS/CTS signals which have to leave the medium idle to allow successful delivery of both a data frame and the corresponding acknowledgement. When the traffic of a station is backlogged, Request-To-Send messages are sent to notify the other stations that it wants to transmit a packet to a specific receiver. The receiver then notifies the sender that it can transmit by sending a Clear-To-Send message. No other stations transmit any packet in a period corresponding to the transmission time of the packet to be sent.

The small size of RTS/CTS control frames makes the probability of collision during their transmission lower than that of the collision of data frames, since these frames are usually larger than those involving RTS/CTS frames.

The joint usage of DCF and PCF presents obvious advantages in BSS infrastructure when the Base Station (BS) coordinates access to the wireless medium. However, experimental evidence shows that the performance of the PCF tends to be poor under certain conditions, such as during the simultaneous transmission of multimedia streams and best effort traffic [36].

The hierarchy of the IEEE 802.11 standards for wireless local area networks is presented in Fig. 2.3. Three physical layers are defined by these standards:

- Infra Red (IR), which supports bitrates of 1 or 2 Mbps;
- Frequency Hopping Spread Spectrum (FHSS), operating at 2.4 GHz, which supports bitrates of 1 or 2 Mbps;
- Direct Sequence Spread Spectrum (DSSS), operating at 2.4 GHz, which supports bitrates 1 or 2 Mbps.

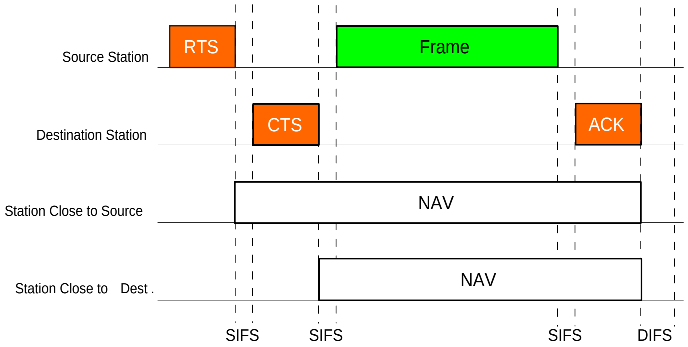

FIG. 2.2. *802.11 RTS/CTS mechanism.*

In order to improve the wireless channel capacity, physical layer extensions to the original IEEE 802.11 standard have been proposed.

The IEEE 802.11a extension adopts Orthogonal Frequency Division Multiplexing (OFDM) and works in the 5 GHz band to provide PHY data rates ranging from 6 Mbps up to 54 Mbps.

The IEEE 802.11b extension, a High Data Rate Extension, is the most frequently used nowadays. It defines requirements for the extension of the DSSS at 2.4 GHz to achieve data rates of 5.5 Mbps and 11 Mbps. An important feature of this extension is a rate shift mechanism which makes it possible for high data rate networks to slow the rate down to 1 or 2 Mbps.

The IEEE 802.11g extension is similar to the 802.11a extension and specifies a physical layer for wireless LANs in both 2.4 GHz and 5 GHz bands, with a maximum rate of 54 Mbps. Such a rate is achieved by using OFDM. This provides backward compatibility with the 802.11b extension, but is not compatible with the 802.11a extension. The drawbacks involve the complexities of implementation since the latter involves a less complex implementation. This backward compatibility in the 802.11g extension can be considered as a disadvantage, since an Access Point (AP) running at the high data rate of 802.11g will switch down to the 802.11b rate upon the logging of any 802.11b device, thus reducing the transmission rate of all other devices in a cell [41].

The IEEE 802.11e protocol is an extension of the original MAC protocol aimed at providing Quality of Service (QoS) support for a variety of multimedia services over 802.11a, 802.11b and 802.11g physical layer specifications. In this extension, classes for service differentiation are defined. It introduces certain enhancements of the basic functions of the MAC operation: Enhanced DCF (EDCA) and the Hybrid Coordination Function (HCF), which operate in Contention and Contention Free periods, respectively.

The IEEE 802.11n task group was created at the end of 2003. The purpose of

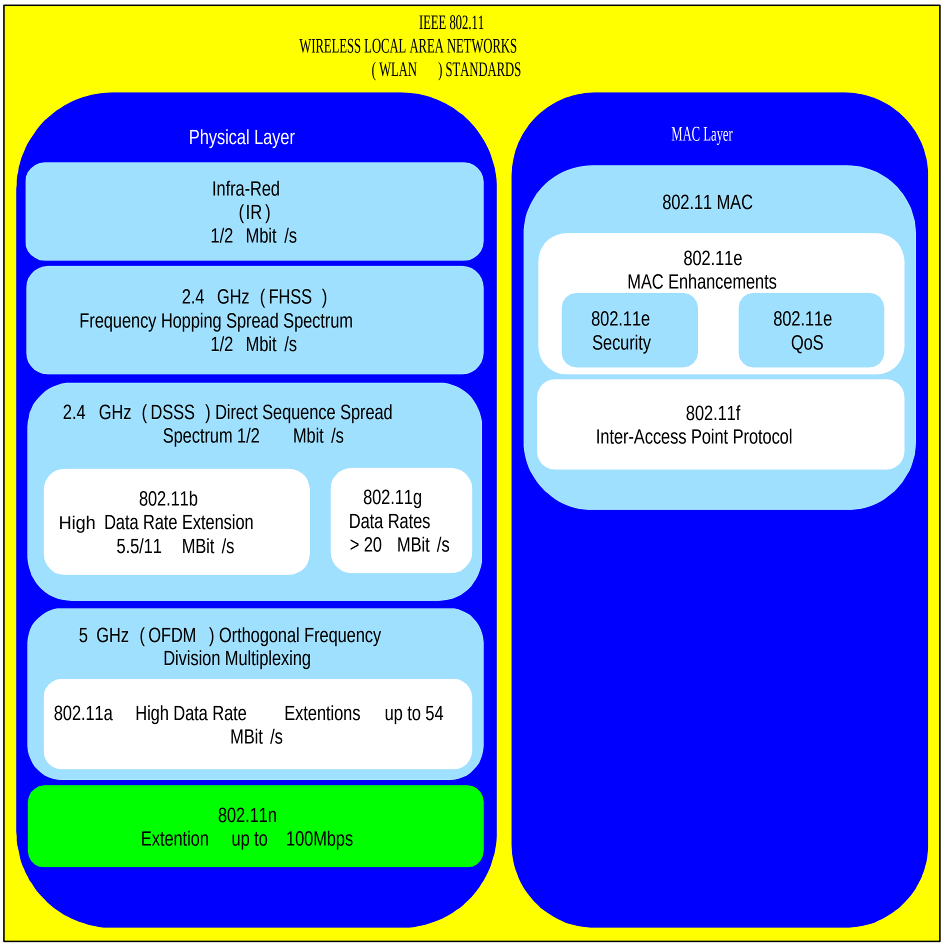

Fig. 2.3. *IEEE Wireless Local Area Network (WLAN) standards.*

this group is to develop an extension of the IEEE 802.11 standards that produces a throughput greater than 100Mbps. For this extension, throughput will be measured in the region between the 802.11 MAC and higher layers rather than at the physical layer. This measurement procedure, should reveal the real throughput available for applications. A discussion of the differences between the actual data rate available for an application and that reported by standard specifications is presented in the next section. According to the estimated schedule of the 802.11n task group the publication of the standards release is expected for October 2005.

For additional details about IEEE 802.11 extensions, the reader is referred to the website of the IEEE 802.11 Working Group [3].

3. Performance Bounds and Limitations. Although the IEEE 802.11 standards provide mobile broadband access to the Internet, it suffers significant performance limitations. This section provides an overview of these drawbacks, both from the theoretical as well as from the implementational point-of-view.

The performance of the IEEE 802.11 standards depend on both throughput and delay considerations when the CSMA/CA (with the RTS/CTS mechanism) is employed. Actually, the main goal of the proposed mechanisms is the provision of both high throughput on the wireless channel and low delay in packet delivery.

The most relevant issues are discussed next:

- *Bandwidth* – The IEEE 802.11 standards specify the rates available for data transmission at the physical layer. The total link capacity is shared by all nodes which can operate within transmission range, including hidden terminals. Since collisions dramatically decrease the throughput, it is desirable to have knowledge of the total available bandwidth. Thus, various predictive algorithms have been proposed for that [33].
  Moreover, the IEEE 802.11 standards have certain theoretical limitations, due to the MAC policy, and these cannot be eliminated by simply raising the channel capacity. In [4], these limitations, are identified as the Throughput Upper Limit (TUL) and the Delay Lower Limit (DLL).
- *Latency* – Latency in a wireless medium is greater than in a wired one. The factors that influence latency are propagation delay, overhead added by both physical layer and link layer protocols and the retransmission policy implemented at the link layer.
- *Channel losses* – Wireless channels suffer from fading caused by interference with other sources. While the Bit Error Rate (BER) varies from 10^{-6} to 10^{-8} in wired channels, it varies from 10^{-3} to 10^{-1} in wireless channels [7]. The typical scheme used to recover from losses is the link layer ARQ (Automatic Response reQuest).
- *Mobility* – The most common network setting is the infrastructured BSS connected to a fixed network via a Base Station (BS). Handoff (Switching between these BSs) require that all the information associated with user activities be transferred from BS to the next to prevent the termination of service provided to the mobile user.
- *TCP* – The problems that arise in the usage of TCP over wireless networks are due to their low reliability, as well as time-variant characteristics such as fading, shadowing, node mobility, hand-offs, limited available bandwidth and large RTTs. TCP performs poorly in such environments [10] [39] since they were originally designed for use on wired networks, which are characterized by stable links in which packet losses are mainly limited to congestion.

The IEEE 802.11 standards specify different rates for data transmission, ranging from 2 Mbps to 54 Mbps. However, a relatively large portion of the channel capacity is wasted due to the high overhead required for the transmission of data frames on the wireless channel. Each message coming from the application layer needs to be encapsulated into lower layer Protocol Data Unit (PDU) in order to be transmitted on the physical layer. Figure 3.1 provides a graphical representation of the process of packet encapsulation when TCP is used. Most overhead due to packet encapsulation is related to the PLCP Preamble, which is necessary for the synchronization of the wireless receiver. This preamble, as well as the PLCP header, are transmitted at 1 Mbps - regardless of the actual link speed. This makes it possible to operate at different speeds, since the information about the rate of the remaining portion of the PPDU is included in the PLCP header. The PLCP preamble and header always take 192 microseconds, regardless of the actual bitrate of the channel. An optional part of the 802.11 standards specifies the possibility of using a reduced, shorter preamble to decrease this overhead.

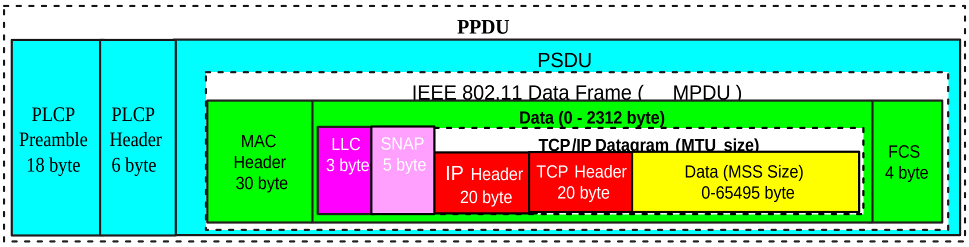

Fig. 3.1. *Packet encapsulation in TCP over 802.11 networks.[11]*
Legend:
FCS = Frame Check Sequence
MSS = Maximum Segment Size
MTU = Maximum Transmission Unit
SNAP = SubNetwork Access Protocol
LLC = Logical Link Control
MPDU = MAC Protocol Data Unit
PLCP = Physical Layer Convergence Protocol
PSDU = PLCP Service Data Unit (SDU)
PPDU = PLCP Protocol Data Unit (PLCP + MPDU)

Table 3.1
Throughput Efficiency of 802.11 with long and short PLCP Preambles.

Link speed, Mbps	Long Preamble (18 bytes)		Short preamble (9 bytes)	
	TCP Throughput, Mbps	Efficiency, %	TCP Throughput, Mbps	Efficiency, %
1	0.75	74.9	0.77	76.9
2	1.41	70.7	1.49	74.3
5.5	3.38	61.5	3.83	69.6
11	5.32	48.4	6.52	59.3

Table 3.1 displays the maximum throughput obtained under the hypotheses of non-occurence of collisions, no fragmentation and no sending of RTS/CTS frames [11] (for a frame size of 1500 bytes, which is the maximum transfer unit (MTU) commonly allowed in Ethernet networks). A high percentage of the wireless link capacity is clearly wasted in transmitting supplementary information, which recudes the bandwidth available for data transmission to a level well below the reported capacity. For the widely used IEEE 802.11b extension, which operates at a rate of 11Mbps and employs a long PLCP preamble, the throughput is reduced to less than half of the reported capacity. This value may be further decreased by exponential backoff and RTS/CTS mechanisms.

4. Available Enhancement Schemes. Various approaches have been proposed to optimize the performance of IEEE 802.11 wireless networks. These can be broadly categorized into three groups:

- *Link Layer solutions* – The principle of this approach is to solve problems locally, with the transport layer not being made aware of the characteristics of the individual links. Such protocols attempt to hide losses in the wireless link to make it appear to be a highly reliable one. Link layer solutions require no changes in existing transport layer protocols.

- *Transport Layer solutions* – The theory underlying this approach is the modification of the transport protocol in order to achieve high throughput on wireless links. Since some packets may be lost, the modified transport protocol should implement congestion control as a reaction to packet losses, moreover, other schemes should be implemented to consider the peculiarities of the wireless environment.
- *Cross-Layer solutions* – Cross-layer solutions break the principles of layering by allowing interdependence and joint development of protocols involving various differents layers of the protocol stack.

A graphical representation of this classification is presented in Fig. 4.1.

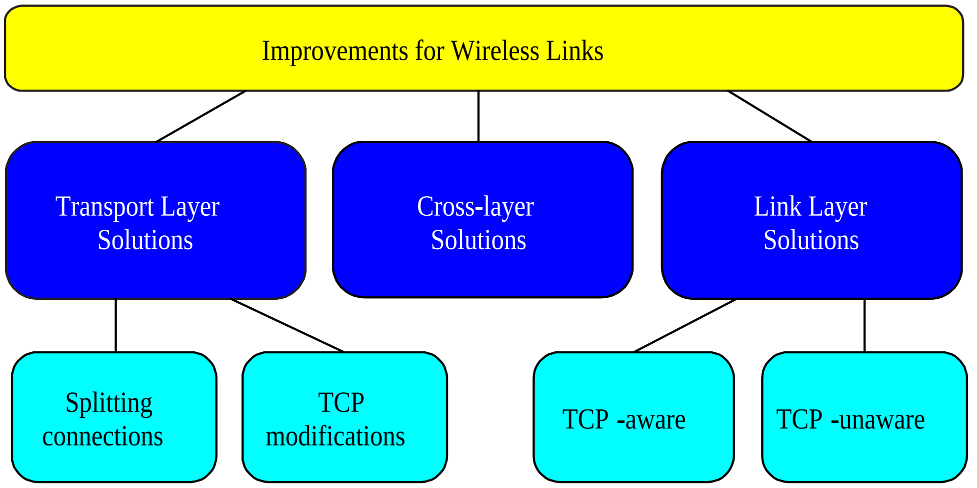

FIG. 4.1. *Graphical classification of possible improvements for 802.11 wireless networks.*

4.1. Link Layer Solutions. TCP was originally designed and optimized for wired networks and, the performance problems related to its use and involve in the nature and characteristics of the wireless medium, as such. Hence, attempts to make wireless links resemble wired ones for high-level protocols are reflected in various approaches. The proposed solutions for the link layer can be classified into two groups on the basis of the awareness of the transport layer protocol. TCP-unaware protocols optimize the link layer by hiding existing differences between the wireless medium and the transport layer so that the transport layer can operate as if it were installed in a wired network. This method does not violate the modularity of the protocol stack, however, since the necessary adaptations improve the reliability independent of higher-layer protocols. Nonetheless, this lack of awareness can affect performance under certain specific conditions. For instance, a link layer retransmission technique may trigger a considerable number of TCP time outs, greatly decreasing the throughput of TCP. TCP-aware link layer solutions attempt to prevent unnecessary changes in the behavior of the transport protocol.

4.1.1. TCP-aware Link Layer Protocols. The TCP-aware link layer protocol presents certain advantages since knowledge of the protocol operating at the transport level allows fine tuning of the performance. For instance, an approach without awareness of the transport protocol may cause local link layer retransmission of a packet, as well as duplicate acknowledgement, since retransmissions can be performed on both layers.

Snoop protocol. Snoop protocol [12] is used to handle connections in which most of the data are transferred from the Fixed Host (FH) to the Mobile Host (MH) (see Fig. 4.2). The mobile node runs a snoop protocol while snoop agents are located at the base station, which is the most common place for bridging the wired and wireless parts of a network. Snoop agents are implemented in the routing module of the protocol stack of the base station in order to allow inspection of the packet headers. These snoop agents maintain caches of TCP packets that have not yet been acknowledged by the MH. In case of duplication of FH packets, the cache is updated without sending further packets to the MH. Retransmission of cached packets is based on the reception of duplicate acknowledgements from the mobile node. Upon successful retransmission, duplicate acknowledgements are dropped at the Base Station (BS) to avoid the execution of the TCP fast retransmission mechanism.

A negative acknowledgement scheme has been added to improve the

error recovery mechanism in case most of the data are sent from the MH to the wired network. In this way, the BS keeps track of all packets lost in any window and generates negative acknowledgements to the MH. These negative acknowledgements are typically based on the Selective Acknowledgement (SACK) option of the TCP [22].

The main disadvantages of Snoop protocols [13] are:

- Required changes in the base station protocol stack, demanding base station resources;
- No consideration of packet loss and delay during handoff;
- Failure in Snoop operation for encrypted traffic when there is no access to the packet header. The only possibility for handling encrypted traffic is to have part of the TCP header unencrypted, which is not feasible according to existing IP SEC standards specifications [37].

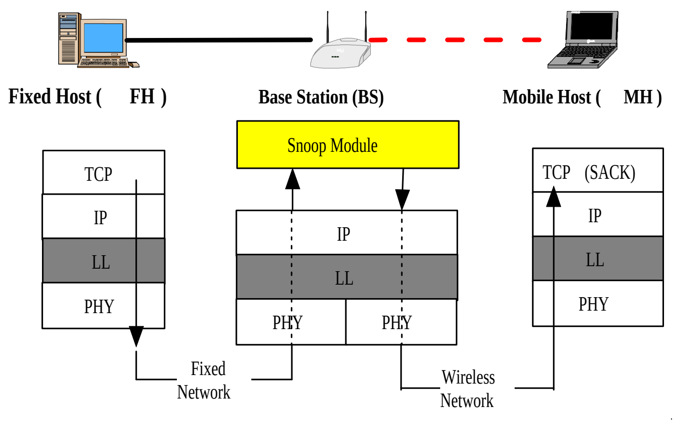

FIG. 4.2. *Snoop protocol scenario.*

WTCP. WTCP [6] performs local retransmission on the wireless link between the base station and the mobile node without the need for modification of TCP for the fixed nodes. WTCP running on a base station buffers all unacknowledged packets coming from a fixed sender, maintaining its own flow control over the wireless link.

When an arriving segment is the next expected one, it is stored in the WTCP buffer along with information about its arrival time. The sequence number of the next expected packet is then increased by the number of bytes included in the received segment. When a duplicate packet is received, it is dropped, since it has either been delivered to the wireless host or has already been buffered.

WTCP maintains the state of the information about the wireless part of the connection, such as the transmission window, sequence number of the last acknowledgement received from mobile hosts, and sequence number of the last segment sent to a mobile host.

Inaccurate Round Trip Time (RTT) estimation at the sender can lead to unnecessary retransmissions triggered by timeouts, since the sender writes the time stamp of the generation of the segment and the receiver echoes it back without any modification. If the segment is retransmitted, this RTT estimation may be affected. To avoid this, in WTCP the timestamp of the packet is incremented by the length of time the packet spent in the BS buffer. With this mechanism, the WTCP conceals the existence of wireless link errors and the difference in round trip time (RTT) from the FH sender, thus avoiding timeouts caused by local retransmissions.

WTCP does not change the basic end-to-end TCP semantics, since acknowledgements to the fixed node are generated only after a successful packet delivery to the mobile node.

4.1.2. TCP-unaware Link Layer Protocols. In early studies, enhanced link layer performance was achieved by the implementation of error correction techniques such as forward error correction (FEC) or the implementation of various Automatic Repeat ReQuest (ARQ) schemes for the retransmission of lost packets at the link layer. The combined implementation of these two techniques is considered in the AIRMAIL protocol.

AIRMAIL. Asymmetric Reliable Mobile Access In Link Layer [14] is a protocol designed for both indoor and outdoor wireless networks. The combined usage of FEC and local retransmissions provided by ARQ aims at obtaining enhanced end-to-end throughput and latency by correcting errors in an unreliable wireless channel, as well as on an end-to-end basis. The asymmetry in the design of the protocol reduces the processing load at the mobile node, since mobile terminals involve limited power and fewer computational resources than do base stations. The key idea in the asymmetric protocol design approach consists of empowering the base station with a certain degree of intelligence. The mobile terminal is required to combine several

acknowledgements into a single acknowledgement to conserve power. The BS is required to send periodic status messages, making the acknowledgement from the mobile terminal event-driven. FEC implemented in AIRMAIL incorporates three levels of channel coding with adaptive interaction. The coding overhead is adaptively changed so that bandwidth expansion from forward error correction is minimized. However, sending large packets of data through the wireless link to save power results in reduced error correction possibilities for the TCP [15].

TULIP. Transport Unaware Link Improvement Protocol [15] is designed for half-duplex radio links. The TULIP provides a reliable link for higher layer protocols. It is service-aware, i.e. it provides reliable service for TCP data traffic, although it is unreliable for UDP traffic. On the receiver side, this protocol buffers packets, passing only in-order packets to the upper-layer and thus preventing the recept of duplicate acknowledgements (by the TCP). Another important feature implemented in the TULIP is the local link layer retransmission of lost packets, which effectively prevent retransmissions over the entire path.

Delayed Duplicate Acknowledgements (DDA). DDA involve an attempt to approximate the behavior of Snoop protocols. The BS implements a local link layer retransmission scheme for packets lost on wireless links. Such retransmissions are triggered by link layer acknowledgements, rather than by the TCP-duplicated acknowledgements of the Snoop protocol scheme. As specified in [16], each TCP data packet, as well as ACKs, are encapsulated into a single link layer data packet, with its successful reception acknowledged by the link layer ACK. This ACK contains the sequence number of the link layer packet received, which is independent of the TCP sequence number. Although it maintains sequence numbers at the link layer, DDA does not attempt in-order delivery of the TCP data packets. This is differente from what happens with the Snoop protocol, for which duplicate acknowledgements are not dropped immediately but rather delayed a certain length of time. At the same time, the packet lost previously is retransmitted locally at the link layer. Upon the reception of an ACK, all delayed acknowledgements are dropped. If the retransmission is not successful and the time for which duplicate acknowledgements are delayed has expired, they will be released in the direction of the TCP sender to trigger retransmission at the TCP level. DDA provides results equivalent to those produced by the Snoop protocol, although the technique does not perform well on slow wireless links [16].

DAWL. Delayed-ACK Scheme on Wireless Link (DAWL) [17] [18] is a technique designed for the enhancement of link layer performance. It modifies the standard IEEE 802.11 MAC Stop & Wait ARQ by implementing the technique of native TCP delayed acknowledgement. The main idea is the lack of a need for immediate acknowledgement of packet receipt. DAWL assumes the existence of data in transit in the opposite direction. The possibility of encapsulating acknowledgements into data packets at the link level leads to the reduction of the traffic load in the wireless link. Moreover, DAWL implements a negative acknowledgement scheme for fast retransmission of lost packets.

Like the Delayed-ACK option of TCP, DAWL provides certain advantages in the presence of bi-directional traffic over wireless links. DAWL implementation requires a set of timers, which must be carefully tuned in order to optimize throughput, together with delay insertion for a packet delivery. Although this approach provides advantages for operation on a single-hop wireless link, it is also problematic due to the:

- Difficulty in tuning timer values in the multi-hop environment;
- The insertion of delay in packet acknowledgements;
- Increased buffer requirements at all wireless node, and
- Poor performance for links with high error rates.

4.2. Transport Layer Solutions. As mentioned above, TCP was originally designed for wired networks, where packet losses are caused mostly to network congestion, rather than errors resulting from noisy channels, handoffs and node mobility. A reduction in the congestion window is thus the TCP reaction to packet loss of any kind.

Despite the inadequacies of TCP implementation for wireless environments, changes can be avoided by adopting Link Layer solutions.

A reasonable number of solutions designed to achieve better performance through the modification of the TCP itself is available. These are logically divided into two groups according to the technique they introduce: connection splitting approach and TCP modifications.

4.2.1. Connection Splitting Solutions. In this scheme, the end-to-end TCP connection is divided into fixed and wireless parts, so that more degrees of freedom are available for the optimization of the TCP over both wired and wireless links.

The disadvantages of this solution mainly involve the attempt to perform transparent splitting (of the TCP) from the point of view of the TCP layer of the wired host. This leads to greater complexity in Base Station (BS) procedures, which is the most common and suitable place for splitting; the greater complexity involves not only the handling of hand-offs but also, prevention of end-to-end semantics of the TCP connection and, also greater software overhead caused by the TCP part of the stack involved at the intermediate point.

I-TCP. Indirect-TCP (I-TCP)[19] was one of the firt proposals for using such a connection-splitting approach. I-TCP is based on the indirect protocol model proposed in [20]. In this approach, (on the transport layer) the end-to-end connection between an FH and a mobile network is split into two separate connections: one between the FH (with regular TCP) and the Mobility Support Router (MSR), commonly the base station which serves the MH, and the other between the MSR and the MH.

The creation of two separate connections makes it possible to optimize transmission over the wireless link, concealing the loss recovery process on the wireless link from the fixed sender by implementing a modified version of TCP. The flow (control) and congestion control mechanisms used by I-TCP allow faster reactions to wireless link problems such as communication interruption and mobility.

Whenever an MH moves to another cell (or BSS), all the information associated with the entire connection is handed over to the new MSR. The fixed host is completely unaware of such indirection, although it maintains the end-to-end TCP connection alive while the mobile node moves from one cell to another.

This I-TCP approach, however, presents certain drawbacks:

- End-to-end TCP connection semantics cannot be preserved;
- Base Station addition of increased overhead for each packet;
- Decrease in complexity of the base station;
- Additional overhead during hand-offs related to connection state transfer;
- Not applicable to encrypted traffic.

METP. Mobile End Transport Protocol (METP) is a special transport protocol designed to use the connection-splitting approach on wireless links. The authors [21] propose the elimination of the TCP, as well as IP layer from the TCP/IP protocol stack of the wireless node, in order to reduce the overhead due to TCP and IP headers of the packet, as well as to their processing. The splitting point (BS) acts as a proxy for the TCP connection, providing for conversion of the packets received from the fixed network. Assuming that the wireless link is the only wireless hop within the end-to-end connection, the METP approach shifts IP datagram reception from the MH to the BS, which means that the packet passes through the IP and the Transport layer of the protocol stack of the BS. After the reception of a datagram, the BS then delivers the data to the MH by using the METP protocol, which involves a reduced packet header containing only minimal information (link source and destination addresses, port- and connection-related information).

METP provides reliable data delivery across the wireless link by introducing a special local retransmission scheme to link layer ARQ. It can also keep the overall TCP connection alive while dealing with handoffs. For this reason, all information, including states and sending and receiving windows, has to be handed over to the new

BS. The authors report a throughput enhancement of up to 37% over TCP Reno and of 23% over other approaches [21]. However, this approach also has drawbacks:

- End-to-end semantics are not preserved;
- Great increase in complexity of the BS due to increased packet processing through the BS protocol stack since it must be handled twice, once when it is received (by using the TCP/IP stack) at the fixed host and again when it is transmitted to the wireless part of the network by the METP;
- Additional overhead related to the transfer of large amount of information during handoffs.

4.2.2. TCP Modifications. TCP Modification invlolves a group of solutions which promote small changes on the behavior of TCP, such as the mechanics of acknowledgement generation used by TCP. The modifications to the TCP make it unnecessary to modify the Base Station, thus avoiding overhead in packet delivery and the increase in BS complexity. The major proposals in this framework are summarized below.

Selective acknowledgements (SACK). TCP selective acknowledgements (SACKs) is one option [22] for the efficient handling of multiple losses within a single window. The SACK acknowledgement algorithm enables the receiver to inform the TCP sender when packets are received out of order. The sender can then retransmit only those packets which have not reached the receiver. This technique is designed as an improvement of the standard cumulative ACK schemes in which retransmission is triggered by the reception of duplicate ACKs.

TCP using SACK provides a technique which performs better than standard TCP for multiple losses in a single window [10]. However, the window size must be "large enough" to take advantage of the SACK characteristics. The main drawback of this selective acknowledgement is the modification of acknowledgement procedures required at both sender and receiver.

TCP Santa Cruz. TCP Santa Cruz [23] employs the option field of the TCP header for the implementation of new congestion control and error recovery strategies. The congestion control algorithm is based on relative delays, both that between packets transmitted by a sender and that other between packets received at the receiver. This information is calculated by the TCP Santa Cruz using timestamps added to the packet at both ends, a technique originally presented in TCP Vegas [24]. An increase in the amount of information available about the TCP flow provides for more accurate RTT estimations at the sender side, while losses ACKs on their way back do not influence the forward throughput. As an acknowledgement strategy, the TCP Santa Cruz can be used to SACK. This scheme leads to an improvement in performance in relation to both TCP Reno and TCP Vegas. The main drawback is the increased complexity at the sender side.

Explicit Notification schemes. ECN (Explicit Congestion Notification) allows the sender to become aware of problems not related to congestion. Knowledge about why packets are lost on the wireless link can help senders, identify those instances where congestion avoidance is not the proper reaction when losses have occurred. Different explicit notification schemes are available, as summarized in Table 4.1 [38] and described briefly below.

Explicit Bad State Notification (EBSN) [25] notifies the sender whenever a BS is unsuccessful in delivering a packet over the wireless network. To do this, it sends an EBSN message when a message is receveid, the TCP sender restarts its timer to avoid execution of the slow start algorithm. This scheme requires minor modifications in

Table 4.1
Summary of explicit loss notification schemes.

Name	Mobile host is	Generated by	What it indicates	Carried by	Path
EBSN	destination	BS	Bad channel	New signal	To source
ELN	source	BS	loss	dupack	To source

the TCP sender code.

Explicit Loss Notification (ELN) [26] makes a sender aware of errors unrelated to congestion while have occurred on the wireless link. The Base Station monitors TCP packets in both directions. When a duplicate acknowledgement is received from the TCP receiver, the BS can encapsulate the ELN message by setting the ELN bit in the TCP acknowledgement header and forwarding it back to the sender. The sender can then choose a type of reaction based on the type of loss. ELN does not, however, provide local retransmission, so no caching is necessary. However, the required checking of all TCP headers represents an increase in complexity and additional overhead associated with each packet.

4.3. Cross-Layer Design. All of these approaches optimize a single parameter at a time, but when several different variables are to be considered they should be taken into account at the same time in order to achieve a truly optimal solution for the adaptation of a TCP developed for a wired environment to a wireless scenario.

Such joint optimization can be included in the wide range of recently-proposed solutions for optimizing wireless network design that are collectively labeled "Cross-Layer Design" [27] [28]. This approach breaks the ISO/OSI layering principles by allowing interdependence and joint design of protocols for passing from one layer to another.

ILC-TCP. The most promising approach, Interlayer Collaboration Protocol (ILC-TCP) [29], was designed to improve the performance of the TCP in wireless environments, involving long and frequent disconnections. The main modification is introduction of a State Manager (SM) in parallel with the protocol stack for gathering information about TCP, IP and Link/Physical layers, if necessary, this information can be furnished upon the request of the TCP layer. Each layer (Link/Physical or IP) periodically reports its state to the SM. If conditions are not appropriate for the flow of the TCP, the SM suggests that the TCP sender stop sending packets. When conditions have improved, the TCP can proceed with regular data delivery.

This approach tries to optimize performance in a scenario in which mobile hosts act as TCP senders. It is an end-to-end approach which requires no changes in the fixed TCP receiver.

The authors [24] report an improvement up to 25% in throughput in relation to standard TCP when disconnections and varied mobility patterns are present. However, in the absence of problems, ILC-TCP offers no improvement in TCP operation over an end-to-end connection.

ATCP. In this approach, feedback between the network and the transport layers is allowed as well as between the application and transport layers [30]. On the application level, information about priority is specified by the user and interpreted by the transport layer so that priorities can be established. This approach provides a throughput improvement of up to 40% over the Reno TCP.

LLE-TCP. Link-Layer ARQ Exploitation TCP (LLE-TCP) [31] introduces cross-layer collaboration, achieved by the utilization of link layer knowledge about successful and unsuccessful packet delivery. LLE-TCP introduces an ARQ Snoop agent in the protocol stack, and this agent keeps track of all TCP packets passing through the stack. For each TCP packet, the Snoop agent receives a message from the link layer indicating the result of delivery over the wireless medium. Whenever a packet reaches its destination, the ARQ Snoop agent at the sender side generates a TCP ACK packet for the transport layer in order to acknowledge this delivery. On the receiver side, the corresponding TCP acknowledgement is then dropped.

In summary, this technique provides the TCP layer with acknowledgements derived from local link layer acknowledgements, thus avoiding transmission of such acknowledgements over the wireless medium. Overhead can thus be reduced significantly.

The throughput achieved by this technique is strongly dependent on the size of the TCP data packets. One important advantage of this technique is that it does not lead to delay when packets are delivered over the wireless link.

The LLE-TCP does present certain drawbacks:

- Increased complexity of the sender node required for the tracing of TCP packets and generation of acknowledgement;
- Difficulty in preserving TCP end-to-end semantics in multi-hop networks.

5. Comparisons. In this section, the available proposals are compared since these proposals act at different layers, there is no one proposal that outperforms the others in all possible scenarios. The best way to compare them is to underline their differences through a comparison of their characteristics. A brief summary of the existing solutions and their advantages and disadvantages is presented in Table 5.1.

Certain features, however, are shared by all of the approaches belonging to the same group. These characteristics and their limitations are described for each of the layers.

Link Layer solutions. The main advantage of Link Layer solutions is the maintenance of end-to-end semantics, without modification of higher protocol layers. This makes it possible to leave untouched the existing implementations of the protocol stack in the various operating systems and limit the introduction of modifications to the link layer.

Most of the approaches which operate at this level rely on some intermediate point within the end-to-end connection for the introduction of performance improvements. For example, the Snoop protocol agent performs local retransmissions from a cache of monitored packets, and WTCP, although operating in a similar way introduces more accurate RTT estimations, thus preventing a reduction in TCP throughput. Both Snoop and WTCP must, however, have access to the header of TCP packets in order to function, which reduces their usefullness value if traffic is encrypted. DDA solves this problem by introducing a local retransmission scheme based solely on information transferred at the link layer; by delaying duplicate acknowledgements, it prevents the TCP source from duplication of efforts in retransmissions, since packets are produced locally at the link layer. The TCP-unaware protocols AIRMAIL and TULIP also rely on link layer retransmissions, but both also employ techniques for enhancement, the FEC for AIRMAIL and in-order delivery for TULIP.

Table 5.1
Brief summary of existing solutions (advantages and disadvantages).

Name	Advantages	Disadvantages
Link Layer solutions		
Snoop	Designed for BSS infrastructure. Performance of local retransmissions. No changes in TCP.	Modification of base station stack. No consideration of handoffs. Non-functional for encrypted traffic.
WTCP	Performance of local retransmissions. Maintenance of more accurate RTT estimation.	Greatly increased BS complexity. Mandatory maintenance state of information for TCP connections. Costly management of handoff.
AIRMAIL	MH acknowledgements combined. Event-driven MS acknowledgement. Power saving. Adaptive FEC implementation.	TCP timeout caused at high error rates.
TULIP	Provision of in-order delivery; local retransmissions. Useful on half-duplex radio links.	Can cause TCP timeout.
DDA	Provision of local retransmissions on link layer. Dupacks delayed before dropping. Performance poor on slow links. Functional for encrypted traffic.	Difficulty in choosing delay value (d). Can cause TCP timeout.
DAWL	ARQ enhancements with Delayed-ACK scheme. Performance good for one-hop, low error rate link in presence of bi-directional traffic.	Difficulty in tuning timers in multi-hop environment. Increased delay of packet delivery acknowledgement. Increased buffer requirements.
Transport Layer solutions		
I-TCP	Useful in BSS infrastructure. Connection splitting for faster reaction to loss over wireless link.	End-to-end semantics not prevented. Increased overhead from BS stack. Increased complexity of BS. Overhead for state transfer during handoffs. Not applicable in asymmetric networks.
METP	Elimination of TCP and IP layers, thus reducing header transmission overhead. Simplified headers on wireless link. Designed for BSS infrastructure.	No end-to-end prevention. Greatly increased BS complexity. Handoff handling costly.
SACK	Good Performance when window size is satisfactorily large. Selective TCP ACK scheme.	Modification of TCP acknowledgement scheme required.
TCP-SC	Modification of congestion control and error recovery mechanisms. Improved RTT calculation.	Increased complexity of TCP sender. TCP modification
EBSN	Notification of TCP sender about problems on the wireless link to prevent slow starts.	Minor modifications of TCP. BS overhead.
ELN	Notification of TCP sender about errors occurring on wireless links.	Increased complexity of TCP. BS overhead.

Name	Advantages	Disadvantages
Cross-Layer solutions		
ILC-TCP	Useful in wireless environments with frequent and long disconnections.	Additional layer added to sender protocol stack.
ATCP	Prioritization of applications from upper layers. Optimization of operation on basis of link state and RTO estimation from lower layers.	Modification of TCP, as well as other layers, for feedback.
LLE-TCP	Utilization of link layer ACK information for local generation of TCP ACK	Increased sender complexity. Not truly end-to-end.

The maintenance of information related to the connection at intermediate nodes brings an increased complexity of IR, especially when transport layer per flow support is required (Snoop and WTCP), as well as a reduction in handoff performance when a large amount of information needs to be transferred to another IR to prevent the termination of an end-to-end connection.

DAWL tries to simplify the system by introducing modifications only in the ARQ scheme at the link layer and does not consider local retransmission at the IR. This design is advantageous in case of an IR crash. When this happens, all the information stored on the IR is lost, in the other schemes, and this would likely cause the termination of the end-to-end connection.

Transport Layer solutions propose modifications to TCP in order to improve the performance on wireless links. The modifications in the transport layer can be adopted for within the entire connection (SACK) or, separated by sender or receiver (EBSN and ELN). Moreover, the modification can focus directly on the wireless link, as in connection-splitting solutions (I-TCP, METP).

The main requirement for the modification of the TCP for running on wireless links is the allowance of the separation of losses due to congestion from those related to the nature of the wireless link (increased error rate, handoffs, etc.). The connection splitting solutions (I-TCP and METP) do not preserve the end-to-end semantics of the TCP while localizing the problem of the wireless link. At the same time, they introduce an increased complexity to the IR, as in the case of Link layer solutions.

The other approaches within this group preserve the end-to-end TCP semantics. SACK modifies the retransmission scheme of TCP in order to reduce unnecessary retransmissions for non-continuous losses within a single TCP window, while TCP-SC modifies the TCP sender and receiver to improve the congestion control algorithm on the basis of relative delay information. Neither SACK nor TCP-SC require IR support and the increased complexity of the sender does not accumulate at a single point, but is rather distributed among the several nodes of the network.

The explicit notification schemes EBSN and ELN require support from an IR in order to provide information either about the state of the wireless link (EBSN) or about the type of loss to the TCP sender (ELN). The crash of an IR does not have a significant impact on the functionality of these solutions since there is no connection-related information stored at this point.

Cross-Layer solutions. All the solutions mentioned try to optimize the performance of IEEE 802.11 networks within a single link, without the support of the IR.

ILC-TCP provides the framework for TCP to obtain information about long and frequent disconnections. From the lower layers of the protocol stack. More extensive feedback is introduced by ATCP, in which the TCP obtains information not only from the lower layers, but also from the application layer, depending of the level of priority of the applications running above it. ATCP introduces a modified version of TCP mechanisms considering information gathered from lower layers, such as link state and RTO estimation.

The differences between LLE-TCP, ILC-TCP and ATCP are mostly related to the optimization approach adopted. None of these tries to preserve the E2E semantics and leave the TCP unmodified. Increased performance is in fact obtained through the local generation of TCP acknowledgements based on packet delivery information provided by the link layer.

Table 5.2 provides a more detailed comparison of the existing protocols in relation to the following parameters:

- *Protocol Layer*: Solutions at the Link layer try to localize a problem and to the optimization they perform from the Transport layer. Solutions presented at the Transport layer, which are aware of the existence of wireless link, try to optimize TCP performance for conditions typical of the wireless link. Cross-layer solutions provide for joint optimization at both levels.
- *End-to-end (E2E) semantics*: This parameter identifies whether or not a solution preserves the end-to-end semantics of the TCP. Preservation means that the reception of an acknowledgement by the TCP sender provides for the notification of successful data packet delivery to the TCP receiver throughout the entire end-to-end connection.
- *TCP modification*: This parameter indicates whether a solution requires modifications to the TCP layer of the protocol stack. Since there are numerous implementations of TCP in various operating systems from different vendors, a modification of TCP may require a huge effort. For this reason, solutions which include TCP modifications may find implementation in very limited number of cases, even if the improvement achieved is usually high.
- *Intermediate Router (IR) support*: The overwhelming majority of solutions use an intermediate point within the end-to-end connection for performance optimization, such as splitting the connection at that point, or using to notify about network conditions (ELN and EBSN). In BSS infrastructure, the Base Station commonly plays the role of an IR. The rest of the parameters are connected with the existence of an intermediate point along the transmission path.
- *Retransmit at*: The most commonly used technique for performance enhancement is the local retransmission of lost packets only on the wireless link, rather than throughout the entire end-to-end connection. The "Retransmit at" parameter indicates the point where retransmissions are performed, as well as the protocol layer in which a solution handles retransmission.
- *IR crash impact*: When a solution relies on the IR, the crash of that intermediate point can lead to the termination of the TCP connection. In some cases, there is no possibility of maintaining the data flow when state information is lost.

Table 5.2 underlines the wide range of existing solutions, the differences in functionality implemented and their impact on network design. As can be seen, there is no single solution which will perform well in all scenarios.

6. Deployment scenario. Focusing on the different scenarios for deployment of the schemes presented makes it possible to define different architectures involving IEEE 802.11 wireless technology:

Table 5.2
Comparison of existing solutions.

Scheme	E2E	TCP modification	IR support	Retransmit at	IR crash impact
Link Layer solutions					
Snoop	Present	Absent	TL/LL	BS	Limited
WTCP	Present	Absent	TL/LL	BS	Limited
AIRMAIL	Present	Absent	LL	BS	Minimal
TULIP	Present	Absent	LL	BS	Minimal
DDA	Present	Absent	LL	BS	Minimal
DAWL	Present	Absent	None	Sender	None
Transport Layer solutions					
I-TCP	Absent	Present	TL	BS	Present
METP	Absent	Present	TL	BS	Present
SACK	Present	Present	None	Sender	None
TCP-SC	Present	Present	None	Sender	None
EBSN	Present	Present	LL	Sender	None
ELN	Present	Present	TL	Sender	None
Cross-Layer solutions					
ILC-TCP	Present	Present	None	Sender	None
ATCP	Present	Present	None	Sender	None
LLE-TCP	Absent	Absent	None	Sender	None

- *single-hop wireless connections*: This scenario involves transmission between two mobile stations equipped with 802.11 wireless network cards, and by far is the simplest scenario.
  IEEE 802.11 networks rely mostly on link layer ARQ to provide the reliable delivery of packets to transport protocols. If the link layer abandons the transmission of a packet after all possible retransmissions, that packet will be transmitted by the TCP. This does not, however, lead to much of an increase in overhead, since there is only a single hop between the sender and the receiver. DAWL takes advantage of improvements derived from the use of an ARQ scheme for relatively low channel error rates in the presence of bi-directional traffic.
  The E2E solutions for the Transport layer, such as SACK and TCP-SC, improve the mechanism for TCP acknowledgement and congestion control, as well as recovery from error, and these will be reflected in performance improvements. All three solutions within the Cross-Layer area (ILC-TCP, ATCP and LLE-TCP) have been designed with this scenario in mind.
- *multi-hop scenario*: In this scenario, transmission occurs via multiple hops; there is no stationary infrastructure installed in multi-hop networks. Note that the MAC protocol specified by the IEEE 802.11 standard does not perform well in such an environment. Due to problems such as hidden nodes, exposed nodes and the unfairness of the exponential back off algorithm, this protocol "can not perform well in multi-hop networks" [32]. The analysis of existing solutions shows that the design of most proposals does not consider their operation in this scenario. In the best possible situation, only the

final hop of a multi-hop connection is taken into account. Transport layer solutions (I-TCP, METP and Explicit loss notification schemes) require the support of a IR within a connection. In a multi-hop scenario, there is no centralized point for splitting (like BS), which makes the implementation of such schemes difficult. The usage of Cross-Layer schemes is more realistic. All methods reviewed introduce modifications performed in the protocol stack of the sender node. In a multi-hop network, the LLE-TCP is introduced only during the last hop [31].

- *Wireless-cum-wired scenario*: This is a more general and diffused scenario where a network is only partially wireless (802.11-based). The sender is located on the wired part of the network, which communicates with the mobile host through the gateway (the BS, in BSS infrastructure). Almost all solutions consider this scenario in their design. Moreover, some of them (such as Snoop, and WTCP) are especially designed to enhance performance in this case. All solutions in the Transport and Cross-Layer approaches can be implemented in a wireless-cum-wired scenario.
- *WLAN-only scenario*: In this scenario, all devices belong to the same WLAN, with a single Access Point. This scenario is similar to the Wireless-cum-wired scenario described above, the sender is a mobile host which communicates with a mobile receiver through an Access Point.

7. Conclusions. Wireless networks are becoming increasingly popular due to the growing use of mobile access to network services. As a consequence, significant efforts have been devoted to providing reliable data delivery for a wide variety of applications over a variety of wireless infrastructures.

In this scenario, the IEEE 802.11 standard and its extensions have gained worldwide diffusion, providing reasonable performance with reduced infrastructure and deployment costs. However, performance bounds and limitations of 802.11 WLANs exist. This chapter has provided an overview of the various solutions available for coping with these limitations.

¿From the analysis of existing improvements to the IEEE 802.11 standards, it is clear that there is no single best solution for all deployment scenarios.

Link layer solutions work on the wireless link without affecting higher-level protocols, but they increase the complexity of the base station and require the modification of the MAC protocol on the wireless link (usually implemented in the hardware). Transport layer solutions aim at adapting the transport protocol to the characteristics of the wireless network, thus implying modification of the transport protocol in the protocol stack at both the sender and receiver ends. An alternate novel approach is represented by cross-layer solutions, which establish interdependence and collaboration between protocols in different layers of the stack.

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