Chapter 6 – NETWORK ISSUES

In the traditional approach to networking, user applications view the network as a service provider, and are not concerned with the characteristics of the network, as long as it can support the desired user traffic. This approach led to the development of layered network architectures, which facilitate modular network design and interoperability. Such approaches have distinct advantages for wired networks such as the Internet. However, they may be less appropriate for ad hoc wireless networks such as tactical networks. In this chapter the conventional approach of layered network design that is used in wired networks such as the Internet is analyzed. This is followed by a discussion of some characteristics of wireless networks that are markedly different from those of wired networks, characteristics which suggest that novel approaches are needed to provide good performance in wireless networks. Finally, it is shown how cross-layer techniques can be used to approach the design and control of ad hoc wireless networks.

A discussion of many of the major issues relating to cross-layer design in ad hoc wireless networks can be found in Goldsmith and Wicker [12].

6.1 LAYERED NETWORK DESIGN

A hierarchical, or layered, structure has traditionally been used to reduce a network's complexity. Figure 6-1 shows one commonly used abstraction of the layered protocol stack; it is similar to the seven-layer OSI reference model, except that it does not include the session layer (OSI Layer 5) or presentation layer (OSI layer 6).[1] In such an architectural design, each layer offers services to the layer above it. Thus, for example, the application layer, which represents the functionality the user would like to obtain from the network, interfaces directly only with the transport layer. It is shielded from the lower layer functions, and consequently it does not have to know how they are implemented. These lower layers are the network layer (which performs routing in multihop networks), the data link (or simply link) layer (which performs media access control, error control, etc.), and the physical layer (which supports communication over the specific medium, which may be wire, fibre, wireless, etc.). An excellent description of layered network structures is provided in the textbook by Tanenbaum [13].

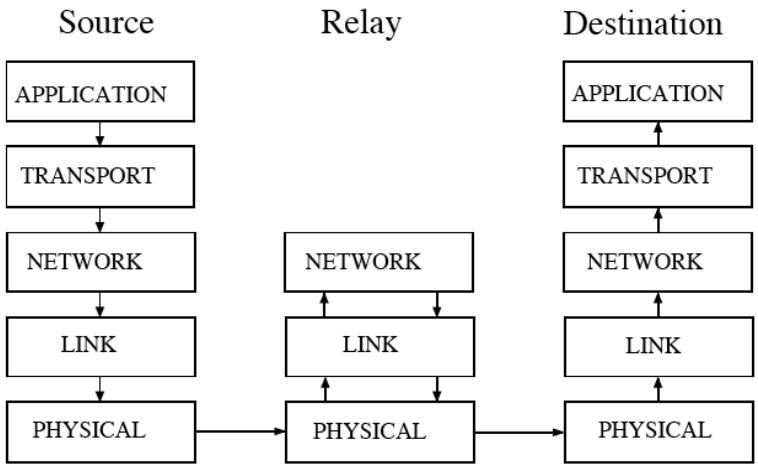


Figure 6-1: The Conventional Layered Protocol Stack.

[1] These two layers are not included in the TCP/IP protocol stack either.

Such a modular design permits the development of "open standards" that facilitate both hardware and software development. Updates to individual layers are possible without disturbing the overall network structure. Such updates may be introduced as a consequence of improved network design (e.g., improved equipment or improved algorithm design) or updated user requirements.

In the example of Figure 6-1, the network provides a service in which the application layer at the Source node communicates with the application layer at the Destination node. It does so by using the functions of the transport layer, which in turn employs the network layer, and so on down the stack. Note that the functions of relay nodes involve only the network layer and those below it.

6.2 CHARACTERISTICS OF AD HOC NETWORKS

This section identifies some key characteristics of wireless ad hoc networks that differentiate them fundamentally from wired networks, and describes how novel approaches that deviate from the rigid layered structure discussed in Section 6.1 may provide improved performance.

In addition to their obvious differences from wired networks, wireless ad hoc networks are also fundamentally different from the cellular systems and wireless local area networks (LANs) that have been developed in the commercial domain. The primary differences result from the lack of an infrastructure. For example, cellular systems have fixed base stations, which communicate among themselves using dedicated non-wireless lines; thus, the primary issues to be addressed in cellular systems involve tracking the mobile users. Otherwise, wireless cellular communication is limited to that between mobile users and base stations. In fully connected wireless LANs, since there is single-hop connectivity among all the nodes, routing is not an issue.

In ad hoc wireless networks it is possible to establish a link between any pair of nodes, provided that the signal-to-noise ratio at the receiving node is sufficiently high. Thus, unlike the case of wired networks, the set of network links and their capacities are not determined *a priori*. Factors relating to the existence of a link include:

- Distance between nodes;
- Transmitted RF power;
- Background noise;
- Data rate;
- Error-control code rate;
- Modulation scheme;
- Other-user interference; and
- Quality of service (QoS) requirements.

Thus, even when the physical locations of the nodes are fixed, many of the factors that affect network topology can be (at least partially) influenced by the actions of the network nodes. While some of the issues listed above are obvious, others may not be. For example, the interference level at a node depends not only on background noise (and possibly jamming) levels, but also on the interference caused by other nodes; thus, the mechanism used to schedule transmissions affects the interference level at nearby nodes. The specification of data rate and error-control code rate (along with the modulation scheme) affect the BER, and hence impact on whether or not the desired QoS requirement is satisfied. Perhaps more subtle is the fact that the specified QoS level

determines whether or not a link is present; reduction in the acceptable level of QoS permits the use of a link, but would be appropriate only if the user application can tolerate such a reduced QoS.

Furthermore, in ad hoc networks no distinction can be made between uplink and downlink traffic[2], thus greatly complicating the interference environment. Therefore, the wireless networking environment poses many new challenges not encountered in either wired or cellular networks.

6.2.1 Examples of Potential Cross-Layer Relationships in Tactical Ad Hoc Networks

Figure 6-2, taken from Prof. Michael Pursley's keynote presentation at the Cross-Layer workshop [14], illustrates many of the potential interactions among communication and networking functions at various layers of the protocol stack. The most obvious interactions are among the lowest three layers (physical, data link, and network). However, the impact of the higher layers is apparent as well, once the applications that must be supported are addressed.

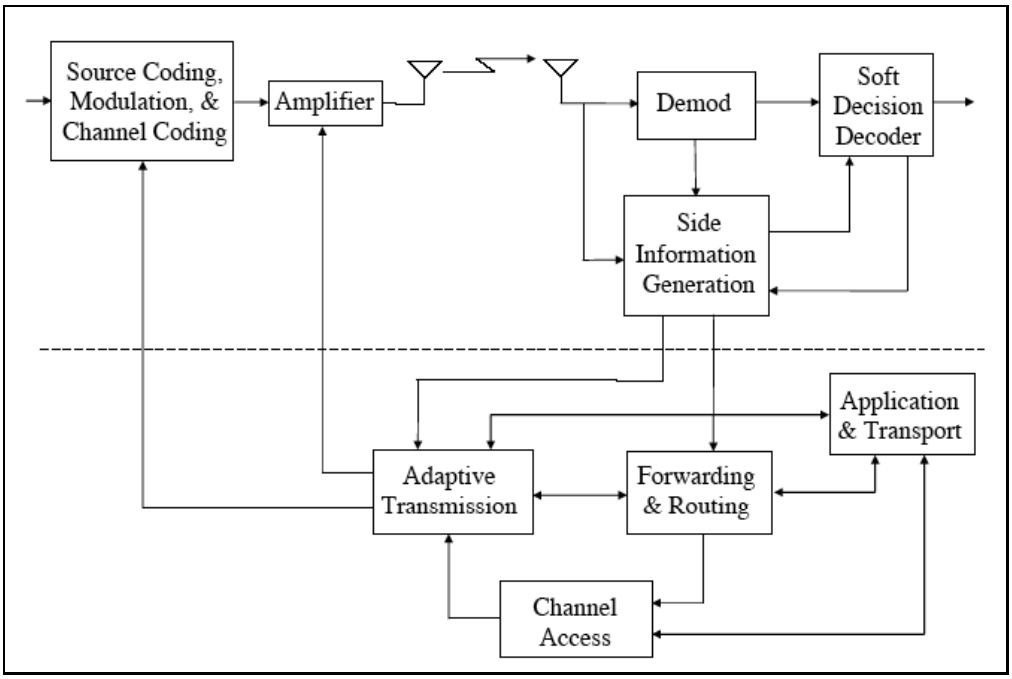


Figure 6-2: Some Protocol Interactions in Wireless Networks.

To illustrate the need for cross-layer protocols, Prof. Pursley presented the following example based on voice messaging. Voice traffic typically requires low delay to preserve its intelligibility and timeliness, but can tolerate significantly higher error rates (frame erasures) than data traffic. Moreover, voice traffic typically consists of relatively long sessions, rather than individual packets. The impact of these requirements at the various layers is summarized as follows:

[2] Cellular networks are characterized by a hierarchical structure, in which, there is an uplink between mobile users and the base station and a downlink between the base station and the mobile users. The uplink and downlink communication generally use distinct (orthogonal) channels. However, in peer-to-peer architectures such as those of ad hoc networks, a single channel is typically shared by all users, which may use multihop routes from the source node to the destination node.

- Application layer: Speech compression must match available routes and links and satisfy QoS needs (e.g., intelligible speech vs. speaker recognition).
- Network layer: Routing should emphasize the need for low delay; high-quality (low BER) routes are not needed.
- Data link layer: To accommodate a voice session, it is necessary to reserve multiple time slots on each link via the channel access (MAC) protocol. Detected packet errors may not require retransmission (because some errors can be tolerated).
- Physical layer: Code rate should adapt to link quality. Low-rate codes should be used on poor links (to avoid need for retransmissions), and high-rate codes on good links (to reduce delay). Energy conservation is secondary to need for timely delivery when considering voice traffic.

In addition to illustrating the relationships among functions at various layers, this example highlights the particular dependence on an application that involves session-based voice messaging. For example, if packet-oriented data communication were considered, it might be possible to consider the imposition of less-stringent delay requirements; however, more-stringent bit-error-rate requirements would be appropriate. Therefore, the cross-layer dependencies depend strongly on the particular application that is being supported.

When considering multimedia traffic, the various classes of traffic (e.g., voice and data) should be handled differently through the use of adaptive transmission and routing protocols, based on trade-offs such as those discussed here.

The potential benefits of cross layering are greatest in ad hoc wireless networks because of the strong interrelationships among the physical, data link, and network layers. However, some benefits may be possible in wired networks as well.

6.3 CROSS-LAYER ISSUES IN TACTICAL MILITARY NETWORKS

Some characteristics of wireless networks that distinguish them from wired networks and that suggest the potential benefits of the use of cross-layer techniques were discussed in Section 6.2.1. Several unique considerations imposed by the tactical military communications environment serve to further distinguish military ad hoc networks from both wired networks and typical commercial wireless networks. These include the following:[3]

- Tactical military equipment can support only low data rates.
- Heterogeneous equipment with different capabilities must function in the same network.
- Hostile environment (e.g., jammers, node destruction).
- Applications with very different requirements and priorities must be supported.
- Widely varying communication conditions and network topologies must be supported.
- Legacy systems must be supported while transitioning to future systems.

The authors believe that cross-layer approaches can, in fact, provide improved performance relating to at least some of these problems. For example:

[3] The two lists in this section are based largely, although not exclusively, on material from the panel discussion presentation by Prof. Andrea Goldsmith at the Cross-Layer workshop [15].

- Adaptation and diversity can provide robustness to jamming and destruction or compromise of nodes.
- Cross layering can support different requirements (e.g., voice, data) and priorities across all layers of the network protocol stack.
- Cross layering can adjust higher layer protocols to the capabilities of underlying equipment.
- Cross layering can adapt to and provide robustness against variations in the communication capabilities and network topology.
- Cross layering can allow nodes to use information obtained by one layer at a higher or lower layer as well (particularly important to permit exploitation of network status information by the application/ middleware layers).

However, it will be difficult to overcome some obstacles, such as the need to support communication with legacy systems that cannot provide the necessary degree of adaptivity. For example, new military radio systems such as the USA's Joint Tactical Radio System (JTRS) will be able to use adaptive cross-layer protocols to save energy and to improve QoS performance. However, legacy SINCGARS radios do not have the necessary degree of adaptivity to support cross-layer operation. For example, SINCGARS radios have only manual power settings, and SINCGARS ACKs do not provide the necessary physical-layer information to permit JTRS equipment to adapt intelligently in joint JTRS-SINCGARS networks. Additionally, security issues may impose significant obstacles on the exchange of some information up and down the protocol stack.

6.4 THE IMPACT OF ENERGY-RELATED CONSIDERATIONS

Energy-awareness is a crucial aspect for those ad hoc or sensor networks where the nodes are powered by batteries. For example, the batteries carried by a soldier may constitute a significant fraction of the overall load that must be carried. Therefore, means to reduce energy consumption are extremely desirable. The traditional approaches to energy reduction involve the development of energy-efficient electronics and energy-efficient modulation schemes, as well as the use of directional antennas (which focus the beam in the desired direction, thereby eliminating the transmission of energy in unnecessary directions). Additionally, energy awareness can be viewed from the networking perspective, which involves multiple layers in the protocol stack.

Two basic forms of energy-aware network operation can be considered. Under "energy-efficient" operation, the goal is to maximize the number of bits that are delivered per unit energy over a period of time. In this mode of operation, energy use may be considered as a cost (e.g., the cost of replacing the batteries). However, in some applications batteries cannot be replaced during the course of a mission. Such a situation can arise when soldiers are unable to return to base, or alternatively in the case of sensor networks. This case is known as "energy-constrained" operation.

It is important to note that energy-efficient operation does not ensure good performance in energy-constrained applications. For example, use of the most energy-efficient routes may result in premature depletion of energy at some nodes.

The issue of energy awareness (in both its energy-efficient and energy-constrained forms) crosses several layers of the protocol stack. One obvious trade-off is that of energy used for signal processing versus that used for communications. For example, signal-processing algorithms that significantly compress the data can provide benefits to overall network operation by reducing the number of bits that must be transmitted, thereby saving RF energy and reducing bandwidth requirements. However, the reduction in energy may be outweighed by the increased energy needed for data compression and decompression operations. Energy

consumed by the nodes' hardware is an especially significant component of overall energy consumption in short-range networks, where RF transmission energy is relatively low. Furthermore, the complicated nature of energy-related trade-offs is illustrated by the fact that the amount of energy consumed by hardware can be reduced by reducing the bit duration of the transmitted symbol, whereas RF energy can be reduced by doing the opposite. Therefore, trade-offs between energy and delay must be considered.

Energy may be saved by the use of sleep modes, because nodes consume energy even when they are not transmitting or receiving. However, use of such sleep modes complicates many aspects of networking, including synchronization, routing, channel access, sensing functionality, etc. Another approach to energy-aware operation involves controlling transmitted power levels, which are a key factor in determining both connectivity and interference levels. Additionally, modulation, coding, and data rate are key factors in determining whether or not a reliable link is present. Therefore, there is a need to coordinate functions at several layers of the protocol stack.

The bottom line is that the introduction of energy considerations, especially in energy-constrained operations, results in fundamental changes to the considerations that need to be addressed in ad hoc network design. Most importantly, it introduces trade-offs among performance measures such as delay, throughput, and node/ network lifetime, and necessitates tight coupling among the layers if near-optimal performance is to be obtained.

6.5 CROSS-LAYERING VS THE CONVENTIONAL LAYERED MODEL

The use of cross-layering techniques does not mean that the layered architecture should be abandoned. To the contrary, the layered architecture has worked well in the Internet, and its modular structure (see Section 6.1) provides an efficient and scalable framework for network design. Nevertheless, significant performance improvement can be expected if cross-layer techniques are implemented in ad hoc networks.

Thus, cross-layer design is not about eliminating layers, but is rather about designing across them. Wireless networks can benefit most from cross-layer design, but benefits are possible for wired networks as well. The degree of improvement that can be achieved depends strongly on the type of network. For example, sensor networks are expected to benefit more from cross layering than general mobile ad hoc networks (see Section 6.6). The research community is only beginning to understand the nature of cross-layer design, and still needs to determine where significant cross-layer gains are possible.

Despite the potential benefits of cross layering, caution is needed to avoid the possible unintended consequences of some cross-layer interactions.[4] For example, the tight coupling of layers may lead toward a tendency to develop proprietary protocols, and hence the need to redesign a new system for every application, thereby eliminating many of the benefits originally obtained by layering. In addition, tight coupling of layers may lead to "spaghetti code" in which patches are continually added to improve performance, resulting in a system that is difficult to understand and hence difficult to update to accommodate changing requirements. Furthermore, the performance of an optimally designed system may be highly sensitive to the operating point, and minor errors in system parameters or minor environmental or topological changes may result in significant performance degradation from that at the optimal operating point. Finally, there is no consensus in the research community as to whether use of cross-layer optimization would increase vulnerability to attacks by intelligent adversaries, or, to the contrary, improve network robustness against such threats. It is expected

[4] See a recent paper by Kawadia and Kumar [16] for a discussion of such issues.

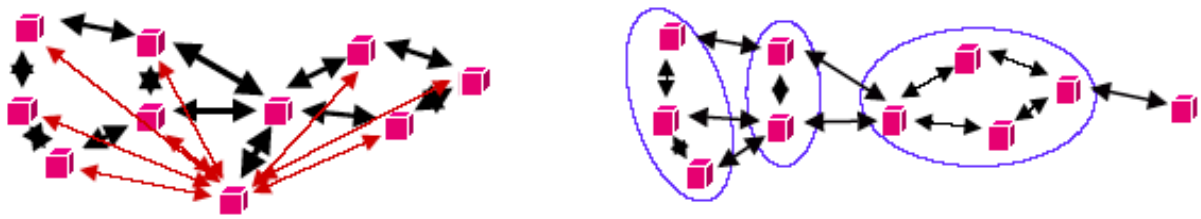
that the answer to this question will depend on the specific application and on the layers involved in the optimization.

Notwithstanding the above cautions, the authors concluded that further research and development of cross-layer techniques is important because of potential benefits that may be difficult or impossible to achieve by other means. The following list, which was adapted from [15], addresses key issues in cross-layer research and development:

- Development of the right framework for cross-layer design;
- Determination of information to be exchanged across layers, and how to use it;
- Balancing of adaptivity, diversity, and scheduling;
- Identification of the key cross-layer synergies, and which layers should be involved;
- Avoidance of unexpected interactions across layers;
- Management of cross-layer complexity; and
- Accommodation of legacy systems and protocols.

6.6 SIMILARITIES AND DIFFERENCES BETWEEN MOBILE AD HOC NETWORKS AND SENSOR NETWORKS

Wireless ad hoc networks and sensor networks are similar, in that both classes of networks are infrastructureless and use the wireless channel, as shown in Figure 6-3. In fact, in many ways sensor networks may be viewed as a special case of ad hoc networks. However, there are some significant differences between these types of networks, typical characteristics of which are summarized in Table 6-1, which was adapted from [15]. Although the Task Group's focus was ad hoc networks, rather than sensor networks, a comparison of ad hoc and sensor networks is useful in understanding the role of cross layering in ad hoc network design and control.



(a) Wireless ad hoc network (b) Wireless sensor network

Figure 6-3: Examples of Ad Hoc and Sensor Networks.

Table 6-1: Typical Characteristics of Ad Hoc Networks and Sensor Networks

Ad Hoc Networks	Sensor Networks
• Peer-to-peer with no backbone infrastructure	• Data flows to a centralized location
• Nodes typically mobile	• Nodes typically stationary
• Network size: up to tens of nodes	• Network size: hundreds or thousands of nodes
• Nodes can be well-equipped	• Nodes typically have limited capability
• Nodes generate independent information	• Node information correlated in time and space
• Can require high data rates	• Low per-node rates, but large number of nodes
• Typically support multiple applications	• Typically support a single application
• Batteries can usually be recharged or replaced	• Nodes typically energy-constrained

Although both types of networks can benefit from cross-layer design, it is felt that sensor networks stand to benefit more. One of the primary concerns in sensor networks is that nodes are typically energy-constrained, as discussed in Section 6.4. (Some examples of mobile ad hoc networks, such as those in which the nodes consist of individual soldiers, are also energy constrained because it may not be possible to replenish batteries during the course of a mission.) Therefore, it is essential that energy use be optimized across the protocol stack. Additionally, the fact that sensor networks are generally designed for one dedicated purpose (target detection, surveillance, etc.) permits a tightly coupled design in which only those functions that are necessary need to be supported. By contrast, ad hoc networks may be more constrained by existing standards and the need for interoperability, constraints which make effective cross-layer design more challenging.

6.7 SUMMARY AND CONCLUSIONS ON NETWORKING ISSUES

To fully exploit the wireless channel, some use of cross-layer techniques will likely be necessary in future wireless network applications, both in commercial and military environments. Appropriate use of cross-layer techniques would not involve the abandonment of the layered protocol structure; rather, cross layering would be used to augment the network's capability by sharing information among the layers and by jointly optimizing their performance. There appears to be considerable potential for performance improvement. Nevertheless, this field is still in its early stages of development, and the research community does not yet have sufficient insight to understand the big picture. One fundamental question, which has not yet been answered, is that of which layer interactions provide the best opportunities for performance improvement. The research community is just starting to ask the right questions, and there is now a basis for fruitful research and development.

The wireless networking environment, particularly in the case of ad hoc networks, is quite different from that of wired networks. Consequently, the properties of the physical layer play a large part in ad hoc network design and performance, and cross-layer design techniques are especially well suited for them. Although cross-layer techniques may provide some benefits in wired networks, their greatest benefits are expected to be obtained in ad hoc wireless networks and sensor networks.

Energy concerns are extremely important in ad hoc networks, and especially in sensor networks (which may be viewed as a special case of ad hoc networks). The fact that a finite quantity of energy must be shared

among all of a node's functions (e.g., transmission, reception, and signal processing) strongly links virtually all layers of the protocol stack. In fact, it may now be appropriate to consider a "hardware layer," which functions under the physical layer. The fact that sensor networks have severe constraints on energy makes them especially good candidates to benefit from cross-layer design.

Despite the potential benefits of cross-layer approaches, a degree of caution is needed in their application. For example, an obstacle to the use of cross-layer approaches is the need to accommodate legacy systems, which may not have the capabilities to implement such control functions. Additionally, excessive coordination among the layers may result in the design of special purpose systems, thereby eliminating some of the advantages of layered design. The result could be unwieldy systems that are difficult to understand, and hence difficult to update to accommodate changing requirements. Furthermore, attempts to optimize performance may result in a system that is overly sensitive to parameter values, thereby running the risk of poor performance unless all parameters are perfectly tuned (which is virtually impossible in practice).

In conclusion, further research and development of cross-layer techniques for tactical ad hoc networks should be pursued to better exploit the characteristics of the wireless communication medium. However, in doing so it is necessary to take into consideration the impact of military requirements (such as the need to support legacy systems) as well as to understand and avoid the unintended consequences that may result from attempts to optimize network functionality at several layers simultaneously.