Cross-Layer Methods for Ad Hoc Networks

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The Open systems interconnection (OSI)model used to be a common network model for years. In the case of ad hoc networks with dynamic topology and difficult radio communications conditions, gradual departure is happening from the classical kind of OSI network model with a clear delineation of layers (physical, channel, network, transport, application) to the cross-layer approach. The layers of the network model in ad hoc networks strongly influence each other. Thus, the cross-layer approach can improve the performance of an ad hoc network by jointly developing protocols using interaction and collaborative optimization of multiple layers. The existing cross-layer methods classification is too complicated because it is based on the whole manifold of network model layer combinations, regardless of their importance.

Keywords: cross-layer methods ; ad hoc networks ; OSI

1. Introduction

An ad hoc network is a network of mobile radio nodes with no infrastructure: without gateways, access points, base stations, etc. (**Figure 1** and **Figure 2**). A classic, well-established approach to network protocols is to split protocols into OSI model layers. This is a very effective approach for wired networks with reliable communication channels where the performance of protocols of different layers does not depend on the state of other layers. In the case of a mobile ad hoc network with dynamic topology (with radio channels exposed to noise, interference, no line of sight, etc.), the insulation of layers leads to sub-optimal network operation. The use of cross-layer methods in the development of protocols of ad hoc networks allows achieving optimal performance for ad hoc networks. Here and further, cross-layer methods are considered methods with no layer isolation, intensive exchange of information between layers, and joint layer management.

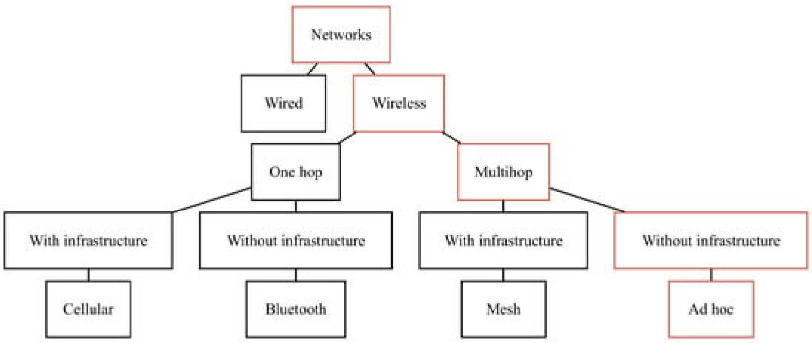

Figure 1. Network classification.

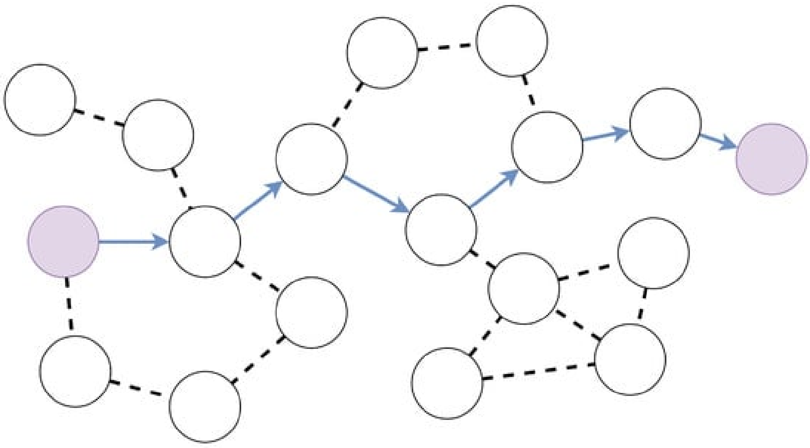

Figure 2. Ad hoc network.

Ad hoc networks have the following properties [1]:

- **Self-organization**. Nodes are organized into networks and manage the network independently and in a distributed manner without centralized intervention. Each node acts as both the user and router [1].
- **Peer network**. Nodes of ad hoc networks are equal and perform the same functions [1].
- **Limited resources**. Ad hoc networks usually consist of portable devices with low computing power, memory, and battery charge [1].
- **Network robustness**. The failure of any network node almost never affects the performance of the network as a whole, unlike the failure of the central router of classical networks [2][3].
- **Dynamic topology**. The network nodes move relative to each other. As a result, node connections and routes between nodes appear and disappear [2][3].
- **Limited constantly changing capacity of radio lines**. Radio lines are susceptible to interference from neighboring nodes, noise from outside, multipath fading, and the Doppler effect [4].
- **Shared channel resource**. The lack of dedicated channel resources (the contention of nodes over channel resources) leads to interference and packet collisions, which reduces network bandwidth [4].
- **Vulnerability to attacks**. In classical networks, all data from a single subnet passes through one powerful firewall, and an attack from outside the network is directed only to the firewall. In the ad hoc network, each node is equally vulnerable to attacks from outside [5].
- **Large amount of service data for routing**. It is necessary because of ad hoc network dynamic topology to send more (than static networks) service information about the lines state, etc., to find network routes [4].
- **Frequent network fragmentation**. Network mobility can cause the ad hoc network to be divided into isolated subnets [4].
- **Complexity of providing QoS**. The poorly predictable instability of radio lines, interference of nodes, frequent route breaks, and delay in finding a new route all make the task of providing QoS in ad hoc networks very difficult [4].

Ad hoc networks are often used in the following areas [1]:

- **Military use**. It is difficult to deploy a cellular network in a warzone, but an ad hoc network can be deployed almost instantly.
- **Rescue and search operations**. In the event of a disaster, the local infrastructure is destroyed, and in the case of search operations in sparsely populated areas, the infrastructure initially does not exist. The rapid deployment of an ad hoc network allows immediate rescue and search operations.
- **Distributed file sharing**. During a meeting, such as a conference, one can quickly deploy a network to share files and presentations.

Cross-layer methods strive to improve the performance of ad hoc networks by collaboratively developing protocols using multiple-layer interaction [6][7][8]. Compared to the layered OSI approach, the cross-layer approach allows interaction between layers, reading and changing the parameters of some other layers [9][10][11][12]. Cross-layer methods have emerged from the desire to ensure interaction and joint optimization of multiple layers [13]. For example, the physical layer can select data rate, power, and coding to meet application layer requirements. Cross-layer design is also indispensable in increasing battery lifetime (minimizing energy consumption) [14][15] and in optimizing the end-to-end latency for real-time applications [16][17], as energy consumption and latency depend on all layers.

The theoretical justification of the effectiveness of cross-layer methods is given in one of the first works on network coding [18]. Network coding is the process of using network parameter settings to meet all the data flow transmission requirements. Reference [18] shows that performing only routing by intermediate nodes results in suboptimal network performance.

Cross-layer interactions can be subdivided into two large categories [19]:

- **Provision of information**. Adjacent and disconnected layers share information through interfaces or by using a common database.

- **Layer integration**. Layer separation disappears, and all layers except maybe the application layer are merged into one.

There are two main architectures for cross-layer methods (**Figure 3**): "MobileMan" [20] and "CrossTalk" [21].

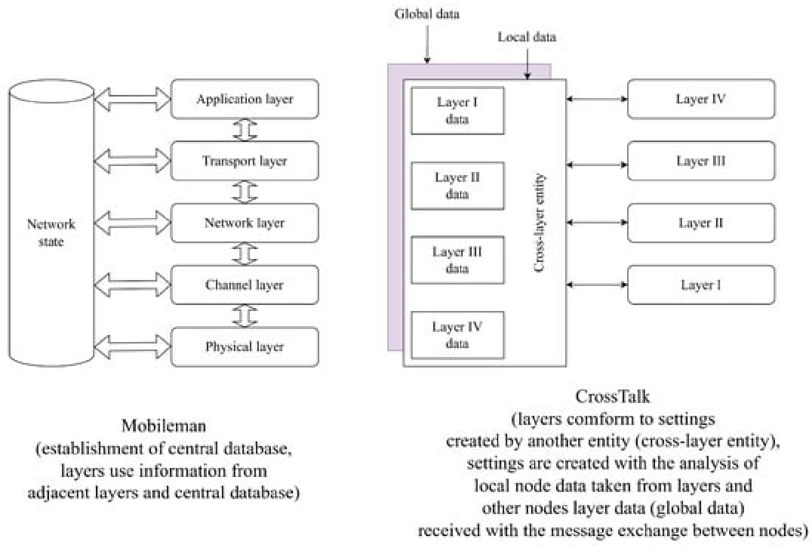

Figure 3. Two main cross-layer architectures: "MobileMan" and "Crosstalk".

The "MobileMan" architecture [20] preserves the original layer architecture (**Figure 3**). The main achievement of this architecture is the creation of a central database that collects all network state data that can be used by various layers individually. "Mobileman" is the "provision of information" kind of cross-layer interaction.

The "CrossTalk" architecture [21] introduces the notion of global network state and local node state (**Figure 3**). Global information is collected using the messages from neighboring nodes. An important difference from the "MobileMan" architecture is that in "Crosstalk", the cross-layer entity controls all layers, while in "MobileMan", the layers tune themselves separately using each other's information. "Crosstalk" is the "layer integration" kind of cross-layer interaction.

Cross-layer methods, based on the "MobileMan" and "Crosstalk" architectures, can be presented in terms of iterative optimization of multiple-layer configurations [22] to achieve QoS requirements for the data flows (**Figure 4**).

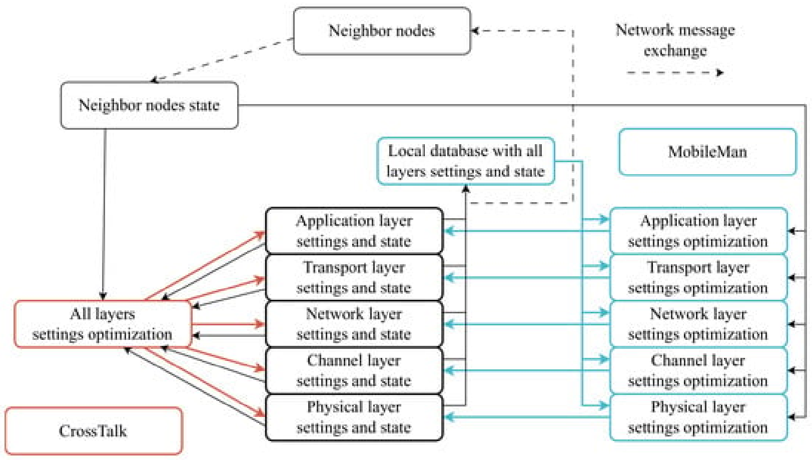

Figure 4. Cross-layer methods as the iterative optimization of multiple-layer configuration.

There are the following difficulties in developing cross-layer methods [22][23][24][25][26][27]:

- **Cross-layer method parameter selection**. One of the fundamental questions of cross-layer methods is the choice of layer parameters on the basis of which decisions about network operation are made. It is very important to consider the physical layer parameters, but it is also important to consider the application layer parameters. For example, the received signal strength indicator (RSSI) is a good indicator of signal power, but this parameter does not take into account noise and interference. The noise level is taken into account in the signal-to-noise ratio (SNR), but interference is also not included. The signal-to-interference + noise ratio (SINR) parameter is much more useful because it simultaneously takes into account the signal strength and noise. With the SNR [28], one can estimate the proximity of the nodes (i.e., the nodes are within each other's radio connection). Queue occupancy information is available at the channel layer. In addition to the above parameters, parameters that provide information about data flows are also used. As shown in [29][30], another approach is to use composite parameters obtained by combining many other parameters.

- **Layer interdependency and the complexity of independent development**. As shown in [31], cross-layer protocol design is nothing more than an OSI violation in which interlinked layers interact. The modification and improvement of a highly interconnected system is difficult. However, achieving modularity is one of the most difficult tasks in developing cross-layer methods.

- **Overly complex interaction between layers**. The flow of information between the different layers creates unforeseen relationships between layers, reducing the efficiency of the entire system. Therefore, it is necessary to choose the interaction between layers very carefully.

2. Cross-Layer Methods for Ad Hoc Networks

Srivastava et al. [31] introduced one of the first classifications for cross-layer method development approaches. The classification consists of four approaches: the creation of new interfaces between layers, the merging of adjacent layers, the development of fixed lower layers without creating new interfaces, and the holistic optimization of all layers. Ren et al. [32] approached the development of cross-layer methods by dividing them into three types: the use of event signaling between layers, the joint optimization of layer subsets, and the holistic optimization of all layers.

More recent reviews provide reviews and classifications of methods themselves. References [33][34] provide a classification of methods according to the layer combinations used in methods. Publications [23][35][36][37] focus on classifying not all cross-layer methods but cross-layer methods belonging to the same layer: cross-layer routing protocols, cross-layer transport protocols, and cross-layer applications for streaming video. Trivedi et al. [35] consider the routing protocols for vehicular ad hoc networks. The protocols are divided into two types: with the use of composite metrics from combining the physical and channel layer metrics and joint work of the network and channel layer. Awang et al. [23] deal with cross-layer routing protocols in ad hoc networks. The authors created a table with reviewed methods and what metrics and layers are used by methods. Goswami et al. [37] focus exclusively on the transport layer (the TCP protocol modifications) and the interaction of the transport layer with other layers to improve transport protocol performance. Mantzouratos et al. [36] focus on cross-layer methods that implement video streaming applications in ad hoc networks. The authors categorized methods according to the layers used in the methods. The categorization and distribution of methods by categories are the following: 1%—all except network and transport layer, 9%—use all layers (holistic approach), 40%—all layers except application layer, 50%—application layer, network and channel layer.

Every method for network control has a main goal or set of goals to achieve:

- **Line throughput**. Line throughput is the volume of successfully delivered data through the line per unit of time.

- **Energy consumption**. The less the node energy spent per successful information transmission, the more battery life, and the greater the longevity of network connectivity.

- **Line packet error rate**. Line packet error rate is inversely proportional to line throughput with regard to the line bandwidth, which is the line transmission rate.

- **Line latency**. Line latency is the sum of multiple delays: queueing delay, propagation delay, transmission delay, etc.

- **Route throughput**. Route throughput is the minimal throughput of lines inside the route.

- **Route packet error rate**. Route packet error rate is the complimentary of the lines inside route probabilities of successful packet delivery multiplication.

- **Route stability**. Route stability is how long all lines in the route remain existing and within the desired range of parameters.

- **Route latency**. Route latency is the sum of line latencies inside the route.

- **Interference**. Interference is the simultaneous transmission of multiple nodes when the total power of other nodes transmitted, except the sender, corrupts the received packets. Low interference is not harmful. High interference causes packet collisions.

- **Data overhead**. The volume of service data. The more, for example, the routing protocol sends route request packets, the lower the throughput.

The aforementioned goals are usually achievable with the intermediate goal of creating the specific method, for example, channel access method, routing protocol etc.

To this date, the practical realizations of ad hoc networks with cross-layer paradigms are almost non-existent. Some of the closest activities to practical implementations are DARPA (Defense Advanced Research Projects Agency) research [38] and different press releases and policies, such as the policy for developing ad hoc networks for automated vehicles in the European Union [39] and mesh internet in rural Africa [40]. The area of cross-layer ad hoc network control is still mostly under theoretical development. The known cross-layer method classifications, which are method-based, indicate that the development of new cross-layer methods is rather focused on the methodology itself.

2.1. One Layer

2.1.1. Physical Layer

Zorzi et al. [41] consider the problems of the development of the channel layer protocol for ad hoc networks with nodes with multiple antenna elements with MIMO technology. Network nodes are capable of forming directional antenna patterns, interference rejection, and MIMO space-time coding of signals. For single omnidirectional antennas, nodes send a transmission request packet, and the target node responds with a permission packet. All other nodes that have accepted the permission and request packet cease to use the radio channel for the time required to transfer the packet between the two nodes. If the receiving node can use a radio channel, the node allows the packet to receive. In the case of multiple antennas with independent transceivers, the node can receive multiple packets at the same time under sufficient spatial separation of senders; when transmitting packets, it can beamform in a way that reduces interference. As a result, requests for transmission packets are advisory in nature and are used to assess the needs of data streams. Therefore, the authors conclude that the interaction of physical and channel layers is necessary.

2.1.2. Channel Layer

- *Channel layer (resource reservation)*

In the works focused on the resource reservation at the channel layer, the channel layer rarely uses physical layer data, using mainly network layer data [42]. The network layer reports on the data streams passing through the nodes. On the basis of this data, the channel layer makes the decision to reserve resources. When splitting the network into clusters, route data helps to maximize the number of dedicated channels for intra-cluster communication, and in the case of a tree-like network, where nodes transmit data to a single data collector node, the route tree allows the allocation of disjoint channel resources between the previous and next link. The resource reservation by a channel layer based on the information from the network layer allows for increased network capacity, route stability, and reduced power consumption.

- *Channel layer (random access)*

In work focused on optimizing channel random access, the channel layer uses data from the physical and network layers. The physical layer evaluates the state of the channel and reports to the channel layer. If the channel state is poor, the data link layer does not transmit the packet, as the packet is likely to be corrupted, further interfering with other users. The channel layer can also indicate the physical layer at what power the packet should be transmitted, making a trade-off between the high probability of successful packet delivery and the high interference for the other users.

- *Channel layer (cooperative transmission)*

In cooperative transmission-oriented works, the channel layer interacts with the network and physical layer. Cooperative transmission is based on the fact that when the sending node sends a data packet, the packet is received not only by the receiving node but also by several other nodes (other nodes are usually called auxiliary nodes). The receiving node sends an acknowledgment packet. If the acknowledgment packet has not been sent, one of the nodes that received the data packet and whose communication channel is less attenuated sends the packet to the recipient. The difficulty of cooperative transmission is the correct formation of cooperative transmission groups and the choice of when cooperative transmission is more efficient and when cooperative transmission causes interference and is less reliable than ordinary transmission. Interaction with the physical layer in the cooperative transmission is used to obtain information about channel fading and to set signal-code structures for packet transmission from the sending node and auxiliary node. The network layer provides information about the direction of data flows. With this information, groups of nodes can be effectively selected for cooperative transmission.

2.1.3. Network Layer

- *Network layer (routing metrics)*

Cross-layer routing metrics are composite metrics based on metrics collected from multiple layers. Cross-layer routing metrics are used for existing routing protocols, turning routing protocols into cross-layer routing protocols.

Park et al. [43] propose a route reliability metric as the probability of successful packet delivery across the route. Successful packet delivery rate calculation is based on the received packets' signal-to-noise ratio from the physical layer.

- *Network layer (routing protocols)*

The single-layer routing protocol in ad hoc networks, using probing packets, can only receive information about the nodes through which the probing packet passed and the packet travel time that estimates the delay of the found route. As a result, the routing protocol can select routes by delay and hop number. Cross-layer routing protocols can use the cross-layer metrics described above or collect information from different layers.

Canales et al. [44] offer a routing protocol that uses data about free time slots from the channel layer to reduce interference. When sending a route request packet, it is checked on each hop whether it is possible to reserve non-interfering time slots on previous and next hops; if it's not possible, then the request packet is dropped.

2.1.4. Transport Layer

The transport layer is responsible for the congestion control. The transport layer protocol estimates overload by measuring the interarrival time between delivery confirmation packets or by the lack of confirmation packets. When congestion is detected, the transport layer starts transmitting packets with a lower frequency. Congestion estimation takes into account only the line buffer overload. However, packets in ad hoc networks can be lost due to line noises and packet collisions. Then, the slowdown of packet transmission by the transport layer will not affect the probability of packet loss; the transport layer will slow down to the minimum speed, underutilizing the network capacity.

Yu et al. [45] propose an adaptation of the TCP protocol to ad hoc networks. When delivery confirmation packets do not arrive, TCP believes that packets have been dropped due to line congestion rather than due to radio line noise or route disruption due to node movement, resulting in TCP slowing down the transmission speed by underutilizing the network's free capacity. To avoid this, the channel layer reports the packet loss to TCP so that the packet is retransmitted from the TCP cache of adjacent nodes. This allows TCP to avoid congestion control and use full available line capacity.

2.1.5. Application Layer

- *Application layer (overlay network)*

An overlay network is a collection of nodes and the services they provide (e.g., file sharing). An overlay network is implemented by applications. The overlay network has its own routing and neighbor discovery. However, the problem is that the overlay network topology and routes in it may not correspond to the physical network: neighboring nodes in the overlay network may be very far away from each other, and short routes in the overlay network may be very long in the underlying physical network. Therefore, cross-layer overlay networks use routing protocols to collect information about the overlay network. As a result, information about both the physical network and the overlay network is collected simultaneously, hence minimizing the amount of service information sent out by the overlay network.

Beylot et al. [46] use network layer interaction for peer-to-peer application layer protocol "Gnutella" from conventional networks, as the peer discovery task is the same as the route discovery task. As a result, application layer service data are added to the network layer service data of the routing protocol. Routing protocol route discovery success is higher than using the peer node discovery protocol of the "Gnutella" application protocol.

2.2. Multiple Layers

2.2.1. External Entity Multiple Layers Control and Optimization

External entities can control and optimize multiple layers. This approach is consistent with (inherited from) the "CrossTalk" architecture [21]. External entity control is divided into fuzzy logic-based methods and dual decomposition optimization-based methods.

- *External entity multiple layers control and optimization (fuzzy logic)*

Fuzzy logic-based cross-layer methods use a set of rules on how to transform a set of input metrics from different layers into output metrics for tuning the layers. The input metrics are converted into classes depending on how the metrics value space is partitioned into ranges. The output of the fuzzy logic-based system is the classes of metrics, which are converted into parameter values.

Xia et al. [47] propose the use of information from physical, channel, and application layers (vehicle traffic speed to account for signal fading due to the Doppler effect, average line transmission delay, probability of successful packet delivery in the line) as inputs to the fuzzy logic system. The system outputs correction factors to specify the type of modulation and error-correcting codes, transmission power, maximum number of retransmissions, and rate of packet stream creation at the application layer.

- *External entity multiple layers control and optimization (dual decomposition)*

The dual decomposition can be used to solve the problem of finding the optimal parameters of network operation. Optimization constraints are the values of data flow volumes between pairs of nodes, available signal-code constructions of transceivers and their transmission speeds, and parameters of MIMO antennas. The purpose of the optimization is to select routes and distribute flows along them, to set the transmission power, transmission rate, signal-code constructions of transmitters, parameters of MIMO space-time coding, and channel access time.

2.2.2. Independent Layers and Information Sharing

Yuen et al. [48] propose to use channel layer resource reservation packets by physical layer to estimate the channel state and send a reply so that the sender can choose appropriate signal-code construction based on channel estimation. The network layer obtains information about reserved resources and signal-code constructions from appropriate layers to choose routes.

Wu et al. [49] address the problem of allocating physical and channel layer resources to maximize throughput for multicast data streams. The result is a set of achievable trade-offs between throughput and energy efficiency. The physical layer resource is transmission speed, and the channel layer resource is time slots. The network layer translates the data flow requirements between sender and receiver into link resource requirements. The purpose of this work is to minimize line congestion and energy consumption in a bandwidth and energy-constrained environment.

3. Conclusions

The overall objectives for network control protocols are always throughput, latency, and packet error rate. These objectives remain invariant regardless of the number of layers involved in the optimization process. At the same time, these objectives can be achieved in a variety of ways. This variety is very wide, so a useful classification is needed for it. The existing surveys offer the only way to classify cross-layer ad hoc network control methods based on the involved layers. This classification is simple but not very useful because the number of the involved layers does not give us any information on the goals of the considered methods.

Most cross-layer methods use the first three layers of the OSI model. Network, channel, and physical layers form the basis of ad hoc networks. Without these layers, ad hoc networks cannot exist. Meeting the requirements for the delivery of data flows (and the possibility of delivery) depends mostly on the bottom three layers. The studies of cross-layer methods for upper layers are rare. The optimization of the application layer does not matter, as this layer creates data streams for the network to deliver. Data from the application layer should be treated as an input parameter for cross-layer methods. The transport layer is responsible for the delivery guarantee and congestion control, but the confirmation of delivery can be performed at the application layer, and congestion can be avoided by the routing protocol (network layer), which chooses paths with the least busy lines.

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