Cross-Layering in Mobile Ad Hoc Network Design

To overcome network performance problems, the MobileMan cross-layer design lets protocols that belong to different layers cooperate in sharing network-status information while still maintaining the layers' separation at the design level.

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Mobile ad hoc network (manet) researchers face a major challenge: achieving full functionality with good performance while linking the new technology to the rest of the Internet. The IETF Manet Working Group addresses the latter issue by proposing a view that manets are an evolution of the Internet. The worldwide success of the Internet, mainly determined by a layered architecture, has promoted the adoption of a similar solution for manets. However, a strict layered design is not flexible enough to cope with the dynamics of manet environments, and will thus prevent performance optimizations.[1]

To what extent, then, must developers modify the pure layered approach by introducing stricter cooperation among protocols belonging to different layers? At one end, some solutions based on layer triggers use strict layering to maintain compatibility and solve interdependencies between protocols. A full cross-layer design represents the other extreme.

TRIGGERS VERSUS CROSS-LAYERING

Layer triggers—predefined signals to notify events such as data delivery failures between protocols—have been used extensively in both wired and wireless networks. Examples include

- the Explicit Congestion Notification mechanism, which intermediate routers use to notify the transmission control protocol layer about congestion; and
- L2 triggers, added between the link and Internet protocol layer to efficiently detect changes in the wireless links' status.

A full cross-layer design, on the other hand, introduces stackwide layer interdependencies to optimize overall network performance. In cross-layering, protocols use the state information flowing throughout the stack to adapt their behavior accordingly. For example, given current channel and network conditions, the physical layer can adapt rate, power, and coding to meet application requirements. Although the literature shows the advantages of this approach, previous work focused only on specific problems—such as data accessibility—and looked at the joint design of two to three layers only, such as the physical, media access control (MAC), and routing layers.[2]

In the ongoing cross-layer versus legacy-layer architecture debate, the ad hoc research community recognizes that cross-layering can provide significant performance benefits, but also observes that a layered design provides a key element in the Internet's success and proliferation.[3] Strict layering guarantees controlled interaction among layers because developing and maintaining single layers takes place independently of the rest of the stack.

On the other hand, an unbridled cross-layer design can produce spaghetti-like code that is impossible to maintain efficiently because every modification must be propagated across all protocols. Further, cross-layer designs can produce unintended interactions among protocols, such as adaptation loops, that result in performance degradation.

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MOBILEMAN

We believe that developers must adopt a careful cross-layer design to overcome potential manet performance problems. Our approach introduces inside the layered architecture the possibility that protocols belonging to different layers can cooperate by sharing network-status information while still maintaining separation between the layers in protocol design.

The MobileMan project's primary aim is to exploit a manet protocol stack's full cross-layer design (http://cnd.iit.cnr.it/mobileMAN). We are not aware of an existing reference architecture that accomplishes this goal. MobileMan still implements protocols inside each layer, but offers the advantages of

- allowing for full compatibility with standards, as it does not modify each layer's core functions;
- providing a robust upgrade environment, which allows the addition or removal of protocols belonging to different layers from the stack without modifying the operations at the other layers; and
- maintaining the benefits of a modular architecture.

This reference architecture exploits the advantages of a full cross-layer design while still satisfying the layer-separation principle.

Figure 1 shows that some network functions, such as energy management, security, and cooperation, are cross-layer by nature. MobileMan seeks to extend cross-layering to all network functions through data sharing. The architecture presents a core component, *Network Status*, that functions as a repository for information that network protocols throughout the stack collect. Each protocol can access the Network Status to share its data with other protocols. This avoids duplicating efforts to collect internal state information and leads to a more efficient system design.

MobileMan achieves layer separation by standardizing access to the Network Status. This implies defining the way protocols can read and write the data from it. Interactions between protocols and the Network Status are placed beside normal-layer behavior, allowing optimization without compromising the expected normal functioning. Replacing a network-status-oriented protocol with its legacy counterpart will therefore let the whole stack keep working properly, although at the cost of penalizing functional optimizations.

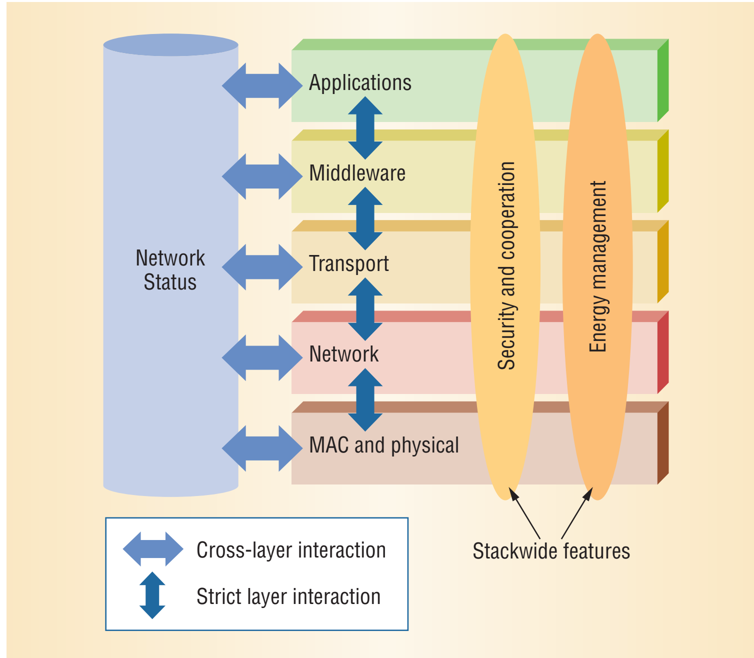

Figure 1. MobileMan architecture. Some network functions, such as energy management and security and cooperation, are cross-layer by nature. MobileMan seeks to extend cross-layering to all network functions through data sharing.

For example, using the legacy TCP implies that cross-layer optimizations will not occur at this layer and that the transport protocol will not provide any information to the Network Status component. However, the overall protocol stack will still operate correctly, although with degraded performance.

Performance gains

We believe that the MobileMan reference architecture offers the following performance advantages in ad hoc network design:

- *Cross-layer optimization for all network functions.* Cross-layering is a must for functions such as energy management, but provides benefits for all network functions.
- *Improved local and global adaptation.* Developers can use MobileMan to adapt the system to highly variable ad hoc network conditions and to better control system performance. For example, developers can exploit a cross-layering design to perform both local and global adaptations to network congestion. Specifically, the MAC layer reacts locally to congestion by exponential back-off. When congestion is high, this response is insufficient, requiring dual-option compensation: Either the forwarding mechanism can reroute traffic to avoid the bottleneck or, if alternate routes do not exist, the optimization can use transport protocol mechanisms to freeze traffic transmissions.
- *Full context awareness at all layers.* Developers can design protocols to be aware of the Network Status, energy level, and other factors. Cross-layering facilitates achieving context awareness at higher layers—such as

The MobileMan project is researching a physical implementation of an enhanced IEEE 802.11 wireless technology.

middleware and application layers.

- *Reduced overhead.* Collecting Network Status information avoids data duplication at different layers.

Protocol redesign

The only way to gain these benefits, however, is to redesign protocols. To fully exploit cross-layering and measure its impact on ad hoc network performance, developers are currently redesigning the full protocol stack even when they can still integrate legacy protocols to form a mixed architecture. MobileMan introduces the following modifications at each layer.

Wi-Fi. The MobileMan project uses IEEE 802.11 as its reference technology. The project is conducting ongoing research into a physical implementation of an enhanced IEEE 802.11 wireless technology[4] to fix performance problems. Specifically, by exploiting interactions between Wi-Fi and the network layer, through data sharing, MobileMan enhances the 802.11 MAC as follows:

- *Enhanced back-off.* Research shows that the binary exponential back-off scheme performs inadequately in ad hoc networks by causing channel underutilization and unfair sharing.[5] To fix these problems, the MobileMan project is working on an enhanced card, which implements the asymptotically optimal back-off algorithm, extending the standard protocol to achieve a theoretical optimum performance.[6] In addition, MobileMan can fix problems stemming from exposed and hidden station phenomena by exploiting Network Status information collected at the MAC and network layers. Taking into consideration that a large physical-carrier sensing range[7] causes nodes within two to three hops to conflict with each other when accessing the shared channel, the MAC layer exploits the topology information that the routing protocol provides to achieve fair channel scheduling.
- *Routing performed at the MAC layer.* By exploiting at the MAC layer the topology information collected by the routing protocol layer, we are developing an efficient packet-forwarding scheme inside the MAC card.[2]

Routing and forwarding. MobileMan considers routing according to the cross-layering principle, so that other layers also can use routing data. A proactive protocol meets this requirement because it collects topology information even when it is not required to perform packet forwarding. The protocol uses this apparently unnecessary information to facilitate other layers' tasks. Indeed, the MobileMan project is investigating the use of a link-state protocol[8] in which a node propagates link-state information to other nodes in the network, limiting flooding of updates in space and time to reach scalability.

The primary consequence of such a link-state routing protocol is a hazy, node-centered knowledge of network topology. A node has a precise knowledge of the neighborhood that nodes two to three hops away from it form. As the distance from this node increases, the neighborhood data becomes less precise. This knowledge can be used to implement multipath reliable forwarding mechanisms[9] to deliver data over existing paths, provided by routing, according to performance and reliability criteria that a performability index summarizes.

A performability estimator classifies the reliability, performance, and cooperation along used routes and computes the performability index for each route. This index summarizes path behavior, taking into account factors such as congestion, link quality, and selfish nodes—all of which can influence system performance. Every time a node sends a packet to a destination, the protocol updates the performability index for the relative route, according to the delivery outcome. The outcome can be inferred by looking at transport ACKs notified through the Network Status. The forwarding function uses the performability index to select among alternative paths to achieve traffic load balancing.

Transport protocol. This protocol seeks mainly to provide the upper layers with a reliable and connection-oriented service. It minimizes useless data retransmissions by analyzing and reacting appropriately to different events occurring at lower layers, such as route failures, route changes, and congestions.[10] The efficient implementation of a reliable transport protocol in ad hoc networks requires strict cooperation with lower layers.[11] Therefore, the MobileMan transport protocol exploits information reported by the routing and Wi-Fi layers in the Network Status component.

Middleware. The middleware layer generally provides abstractions that hide complex details from application programmers. In a manet environment, this trend must be reversed to provide context awareness.[12] In MobileMan, the Network Status contains the network context, which provides context awareness in the cross-layer architecture. For example, we are currently investigating how ad hoc networks could efficiently implement peer-to-peer routing substrates to exploit the information that the Network Status exports. By directly using the topology information the routing protocol collects, a peer-to-peer substrate can locally identify which peers are participating in a specified service, reducing the overhead of building overlay structures.

The MobileMan cross-layer architecture promotes stricter local interaction among protocols in a manet node. The Network Status uniformly manages the cross-layer interaction, and respects the principle of dividing functionalities and responsibilities in layers. This approach aims to optimize overall network performance by increasing local interaction among protocols, decreasing remote communications, and consequently saving network bandwidth. Engineering the Network Status component presents the greatest challenge. This component should be general enough to represent a vertical layer whose changes do not affect the overall system. ■

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