Invited Review Paper / Çağrılı Derleme Makalesi
CROSS-LAYER DESIGN IN WIRELESS AD HOC AND SENSOR NETWORKS

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ABSTRACT

This article explains a new paradigm in networking called cross-layer design (CLD), which differs from conventional layered protocol architecture. With CLD, parameters of one layer can be used in optimization of another layer, and interactions among layers are permitted. Two examples of CLD approaches used in mobile ad hoc networks (MANETS) are provided to illustrate the effectiveness of CLD. The first example is using the energy level and consumption parameters depended on transmission range (Physical layer) in the packet routing (Network layer). The second example is including link stability information in network routing. Even though CLD offers benefits, there are challenges as well. These challenges are outlined here.
Keywords: Wireless networks, cross-layer design, wireless networks, mobile ad hoc networks.

TELSİZ HABERLEŞMELİ ANINDA KURULABİLEN VE SENSÖR AĞLARI ÇAPRAZ-YÜZEY DİZAYNI

ÖZET

Bu makale yeni yöntem olarak öne çıkan telsiz haberleşmeli ağlarda çapraz yüzey dizaynın (ÇYD) farklılıklarını anlatacağız. ÇYD diğer geleneksel ağ protokollerinden farklı olarak ara yüzeyler arasında bilgi alışverişi yapılmasını sağlar. Böylece, bir yüzeyin kullandığı parametreler diğer yüzeyde kullanılabilir, bununla daha verimli bir sistem kurulabilir. ÇYD'nin yararlı olduğu iki örneği ÇYD'nin efektif olduğunu göstermek için burada sunacağız. Birinci örnek de, ÇYD ağdaki enerji tüketimini aza indirmek için iletişim uzaklığını ayarlayan mekanizma ile paket yolu bulma yöntemlerinde kullandık ve verimi arttırdık. Diğer örnek de ise haketli kullanıcıların hızlarını paket yolu bulma yöntemlerinde kullandık, bu yöntem bize daha kararlı paket yolları bulunmasını sağladı ve ağın verimliği arttı. ÇYD'nin başarılı olmasına rağmen, çeşitli sorunları da beraberinde getirir. Bu sorunları da burada açıklayacağız.
Anahtar Sözcükler: Telsiz haberleşme ağları, çapraz-arayüzlü dizayn, haketli ve anında kurulan ağlar.

1. INTRODUCTION

In the last decade, several transformations took place in wireless networks. First, wireless networks were forced to transfer more data than voice with increasing internet use in the mobile devices. That is why research and development to increase link capacity of wireless networks was accelerated to accommodate high data rates, which lead to several key innovations like space time codes (STC), multiple input multiple output (MIMO) systems (i.e., multiple transmitter and

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multiple receiver antennas) [1], iterative decoding techniques in forward error correction coding [2], and user cooperation diversity [3, 4]. With those innovations, wireless communication links can now provide few megabits per second in a wide area networks like the third generation (3G) cellular networks [5] to several hundred megabits per second like IEEE 802.11 networks (i.e., WLAN) [6]. The second transformation in wireless networks happens in the network architecture; the early wireless networks (the first and the second generation cellular communication systems) were centrally controlled, where base stations manage access, mobility and other important aspects of the network. Networks like WLAN have distributed network architecture (also known as ad hoc networks) that gained popularity because of flexible user access, easy installation and configuration, and relatively larger bandwidth per user. All of those decrease the cost of network operation for the system providers and transferred bit per second for the users.

While these transformations are taking place in wireless networks, the architecture of the network, based on Transport Control Protocol and Internet Protocol (TCP/IP) or Open System Interconnection (OSI) reference models [7], was developed for wired networks. Both TCP/IP and OSI use layered network architectures, where networking tasks divided into subtasks to optimize the networking problems. This model is called layered networking architecture model, and subtasks are layers of the model. The layers solve and optimize different networking problems independently from each others. But these optimizations were made for wired networks in which the problems in the link rarely occur and users are largely stationary. Wireless users are mobile while using the network. This mobility changes properties of wireless links, like signal strength and transmission bit rate. Another problem that is inherent with the mobility is changing network topology where connections to the neighbouring nodes and routes alter constantly. Link and topology changes put strains on the layered network architecture and break down independency among layered protocols. For example, transport layer is unaware if the packets are not acknowledged because of link failure, topology change, or congestion in the network. The last one, congestion, is the most probable cause of this problem in wired networks, and the transport layer is designed to treat this problem. When acknowledgement packets arrive late to the transport layer because of problems other than congestion, the performance of the transport layer suffers. This low performance of TCP/IP in the wireless networks was measured in [8]. This study showed that the independency of the layered architecture breaks down in wireless networks and new approach in network protocol design must be introduced for wireless networks. This new approach is called cross-layer design (CLD). CLD is considered necessary for wireless networks [9, 10, 11].

In this paper, we review and provide details in CLD approaches. Particularly CLD approaches in mobile ad hoc routing problems. The following section will briefly explain CLD in mobile ad hoc networks (MANETs). The third and forth sections will provide CLD approaches in MANETs routing, and challenges in CLD. The last section will provide conclusions and future directions for CLD.

2. CROSS-LAYER DESIGN IN WIRELESS NETWORKS

TCP/IP (i.e. Internet) reference model as well as CLD is illustrated in Figure 1. In this figure, the shaded section illustrates the traditional layering approach used in the Internet. In the Internet layering, each layer performs certain tasks, and protocols optimize their operations independently from protocols of other layer. The only interaction occurs between the adjacent layers by passing the protocol data units (PDUs) through the service access points (SAP). For example, an application layer protocol, such as email, ftp and http, prepares its data and transfers it to the transport layer. While transferring the data, the application layer protocol only identifies which the transport layer protocol will be used, for example if the data
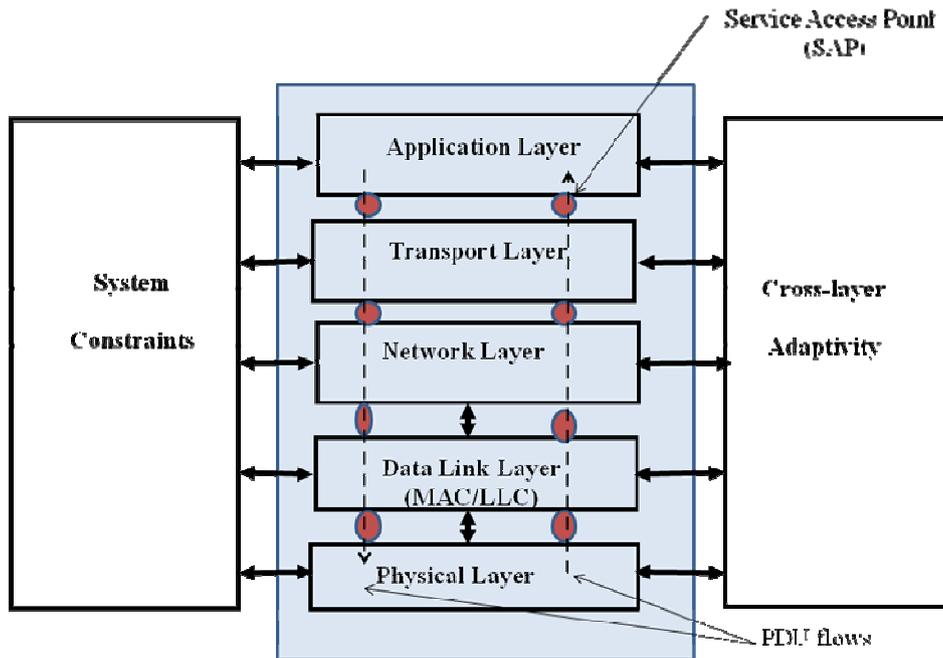
Figure 1. TCP/IP layers (shaded area), and integration of CLD with TCP/IP

need reliable transmission, then TCP will be used, or if the data do not need reliable transmission (i.e., tolerate loss), then User Data Protocol (UDP) is used. However in CLD, a parameter in one of the layers can be used in the optimization of another layer. For example, Alonso et. al. [12] proposed a CLD between physical layer (PHY) and medium access control (MAC) layer to improve spectrum efficiency of a code division multiple access (CDMA) system, where transmission rate in the PHY is adapted based on number of users and their transmission power levels at the MAC layer. Local congestion information in the MAC layer is utilized in the network layer routing protocols [13]. In that, the contention window parameter in MAC layer, needed for collision avoidance mechanism in the MAC, is utilized to construct routes. In that, nodes whose contention window parameter is lower have higher probability in participating routing than nodes with higher contention window parameter. In this CLD approach, the overal delay efficiency of the network benefits from the CLD as well [14]. Selecting an energy efficient route using CLD approaches significantly improved time that the network was operational for a given energy level. A unified CLD approach was proposed for WSNs to improve energy efficiency [15], where MAC congestion avoidance was utilized for energy efficiency in WSNs. A CLD approach between MAC and PHY layers for WiMAX systems is proposed in [16]. The WiMAX's MAC layer schedules users access based on their signal-to-noise ratio (SNR) (i.e., channel state information) where users with better channel state (better signal to noise ratio) transmit with better transmission rates and occupy the channel shorter amount of time. That proposition improved system throughput 25 to 60 percent. Quality of service (QoS) parameters in wireless networks were improved with CLD approaches [17], such as the performance of voice over Internet protocol (VoIP) [18]. Stine in [19] strongly advocates CLD approaches for wireless networks, some of the CLD approaches for wireless networks are outlined in [10].

One of the most effective implementation of CLD will be in MANETs and WSNs because these two networks are designed to have self configuration and organization properties

and do not need infrastructure. Those properties can only be accomplished when nodes act as a router as well as an ordinary node. That is why applying CLD with routing protocols improve the network efficiency significantly in routing, energy conversion, and other network performances.

3. COMBINING CLD WITH ROUTE DISCOVERY PROTOCOLS IN MANETs

In MANETs' routing, two primary routing mechanisms are used: (1) proactive and (2) reactive. Nodes in proactive routing constantly share and update their routing information and keep their routing tables fresh. This constant routing updates consume significant network resources both energy and bandwidth. Reactive routing differs from proactive routing how it discovers routes. Reactive routing initiates a route discovery algorithm when a route is needed. This conserves precious resources in the MANET and WSN. CLD can be very effective with reactive routing protocols for further increase the efficiency and optimize the system performances.

In reactive routing protocols, when a source has a packet for an arbitrary destination, it searches its routing table to find a route to this destination. If there is no route for the destination, the source initiates a route discovery mechanism. The route discovery mechanism starts by broadcasting a route request packet (RREQ). Neighbouring nodes around the source broadcast this RREQ and their neighbours rebroadcast the packets to their neighbours. This process continues until all the nodes in the network receive and process the RREQ. When the destination node receives this RREQ, it discovers that the source node has a packet for itself and replies to the RREQs by another packet called route reply packets (RREPs). The RREP can be rebroadcasted or sent back through the path that the RREQs followed to reach the destination. The destination can receive more than one RREQ, since there can be more than one path from source to destination. Whether the destination replies to all these different requests or not depends on the particular routing algorithm, but this does not change the general structure of the route discovery mechanism.
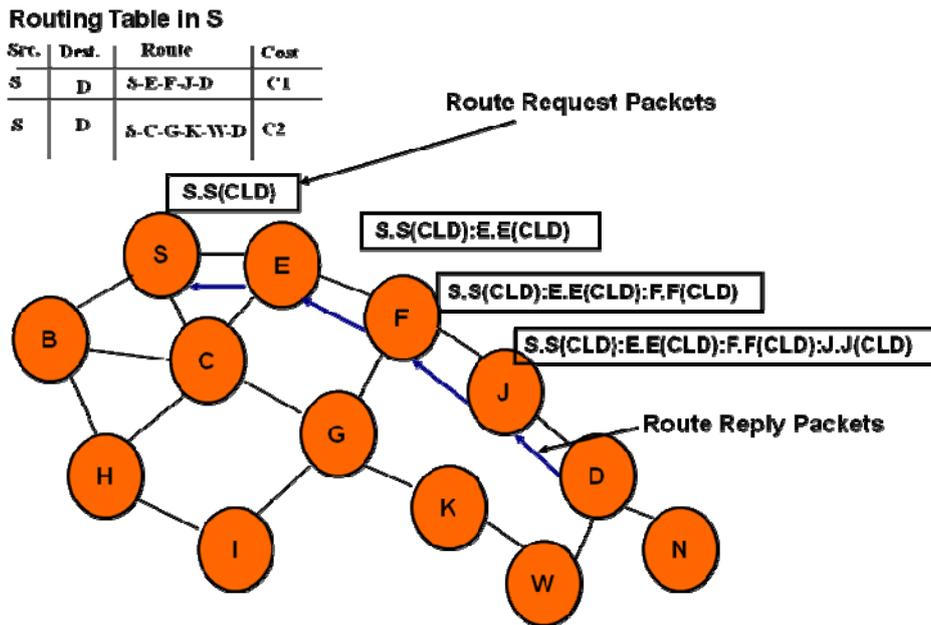

Figure 2. Route discovery mechanism in DSR with CLD, and routing table for S.

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Route discovery mechanism provides an excellent platform for CLD approaches in MANETs. The CLD parameters can be distributed with RREQs and RREPs. Also the changing conditions of the nodes can be updated at each RREQ broadcast. The route discovery mechanism with CLD is illustrated in Figure 2. The CLD parameters are inserted in the RREQ at each node before they are broadcasted. In the figure, route discovery mechanism used in Dynamic Source Routing (DSR) [10] is particularly illustrated, where S denotes the source node, and D denotes the destination node. Each RREQ packet along the route S-E-F-J-D is shown. In the original DSR, the nodes only inserts their node identification numbers in the RREQs but in the CLD approach, they both insert their identification numbers and their CLD parameter, such that the network or other nodes make use of this parameter in the CLD. Distributing parameters used in CLD within the route discovery mechanism is tested in several different CLD approaches. Next we will present two of these approaches.

a) Minimum Energy Dynamic Source Routing

One of the CLD approaches is to provide minimum energy routing in the wireless networks. In this routing strategy, the metric is how many packets a route can deliver before one of the nodes in this route ceases its operation because of battery exhaustion. In order to find maximum number of packets that can be transferred by this route, each node calculates how many packets it can transmit to the next hop with a power control mechanism before it depletes its energy, and inserts this number in RREQ. The destination node finds the minimum of these maximums and returns this value to the source with RREP. If there is more than one route from source to destination, then the source selects the route that can transfer the maximum number of packets by using the values that came with RREPs. This approach has two benefits. One of them is overall energy consumption of the network is reduced by transmit power control, and the other one is that the network is operational longer by selecting routes, which last longer. More details in this approach can be obtained from [14]. With this modification, 60 percent energy efficiency can be achieved.

b) Link Expiration Time Approach

Another CLD approach that utilizes the RREQ to disseminate CLD parameter is in vehicular networks [21]. One of the major problems in mobile networks is link failures or breakages. If the nodes estimate how long a link will be available, then the routing protocol can select a route that lasts longer. This improves throughput of the network. In this approach, CLD parameter is link expiration time (LET) of the link. LET is calculated using the transmission range of the nodes and relative speeds of the transmitting and receiving nodes. LET is an indication of link stability. Routing protocol that utilizes the LET values finds a route that can be more stable. Route discovery mechanism is modified to carry LET values. Another modification was done how nodes react to route discovery messages (i.e., RREQs). The area around a source is classified into three regions based on the transmission range and relative speeds. These transmission regions are undesirable coverage area, reliable area and unreliable coverage area. These regions are illustrated in Figure 3. Nodes in the undesirable coverage area are too close to the source node. When those nodes are used, the network needs too many links between the source and destination.
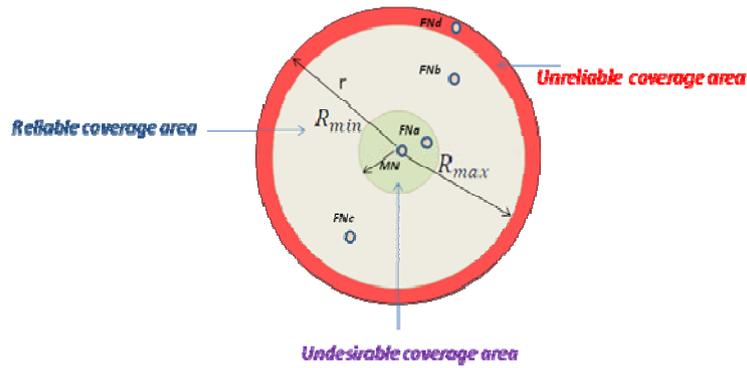
Figure 3. Coverage areas in the CLD approach in routing of MANETs.

Nodes in the unreliable coverage area are close to the edge of the transmission range, and they can be out of the range with high probability. This increases probability of the link failure, and any route that utilizes such links can be broken sooner. Because of these, the nodes in the reliable region will forward any RREQ and nodes in the other regions refrain from rebroadcasting of RREQ to avoid routes that include them. With these provisions, using LET and coverage regions in packet routing, which is a CLD approach, improved the routing performance. The CLD approach was tested with ad hoc on demand routing protocol [22]. The packet delivery ratio of the network with AODV-CLD routing did not drop below 95 percent, while packet delivery ratio of other schemes dropped significantly. Coverage area approach with AODV (AODV-RCA) achieved 90 percent delivery ratio, and conventional AODV had only 78 percent delivery ratio when there 14 hops between source and destination.
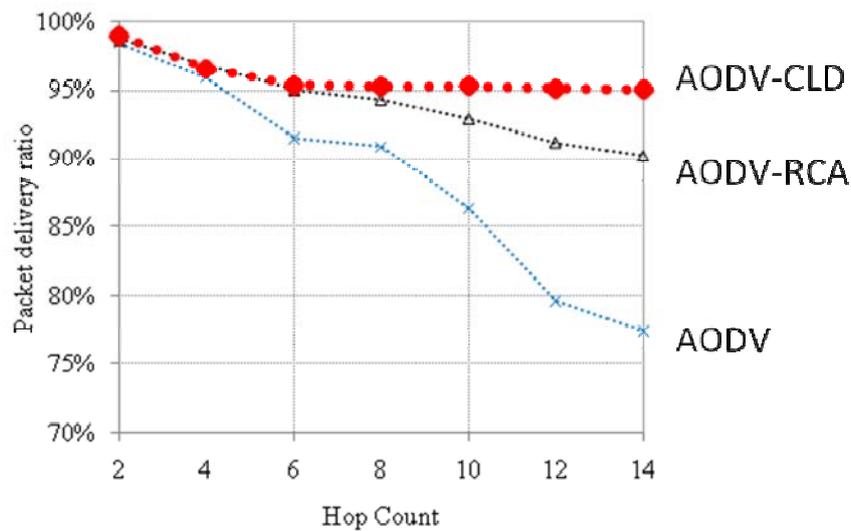

Figure 4. Packet delivery ratios vs. average number of links in a route (hop count)

4. CHALLENGES IN CLD

Although CLD is shown to be effective in wide range of scenarios, the CLD approaches have challenges. There is no unified approach for CLDs and each solution is unique for a specific problem. In addition to this, integration of network layers creates network protocol stack that is hard to manage and can be even unstable [23]. Timing of the optimization parameters in different layers has different scales. For example, fading in PHY occurs in microseconds, but routing decisions are made in milliseconds and using instantaneous channel state information in routing will be deteriorating [9]. Another challenge, how heterogeneous networks (networks with different user architectures like some wireless and some wired) utilize CLD approaches. When nodes in the network have heterogeneous architectures, they have different protocol layers, and CLD parameter that tunes one of the architecture can affect the other adversely. That is why CLD needs to be transparent to the other network architectures in the network. CLD may also face problems in standardization process, where including many CLD approaches can be difficult in a meaningful standard.

5. CONCLUSIONS

This article provided glimpse of what CLD can offer to wireless networks, particularly for MANETs and WSNs. Simulation studies and proposals of CLD approaches are abounded in the literature. There are opponents of CLD as well. But for wireless networks and communication systems CLD approaches that encapsulate Physical-Data link-Network layers are widely accepted. Here we presented two case studies. One of them is CLD approach for energy efficiency, and the other for routing stability. With such benefits, CLD will be the tool to use to meet ever increasing demand for high data rates in wireless networks.

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