An Alternative Viewpoint on the (Cross–)Layering in Wireless Networks

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Abstract

The capacity of a communication network depends on the mode in which the network is operated. The operational mode is determined by the network protocols, which are in turn built within a layered architecture. In the recent years there has been an abundance of efforts to optimize the protocols in the wireless networks through a cross–layer design, which is an approach that goes beyond the application of the strict layering. These efforts are mostly motivated by the fact that the wireless networking offers an immense multitude of possibilities for interaction among the nodes, since it possesses dynamically defined links over a shared wireless medium. In that sense, the current OSI–layering paradigm appears over–restrictive with respect to the operation modes of a wireless network. Therefore, in this paper we take an alternative view on the layering in wireless networks. Within the new layering paradigm, a communication task is decomposed into subtasks that are defined to be more general than the subtasks defined within the OSI–layering. The new layering paradigm aims to set a ground for systematic building of wireless network protocols by accounting for the operational modes that are inherent to the wireless network, such as broadcast transmissions, links with variable data rates, possibility to use cooperative diversity etc. As a bottom line, the presented alternative layering sets the stage for building cooperative protocols in the wireless networks.

I. Introduction

There is a lucid definition, attributed to J. L. Kelly, that a channel is a part of the communication system that one is “*unwilling or unable to change*” [1]. A communication network can be understood as a set of communication channels between multiple information sources/sinks and the capacity offered by those communication channels is dependent on the manner in which the network is designed and operated. There are many parameters in network topology, architecture and protocols that the network designers are able to change and thus increase the capacity. However, what the network designers have been (and are) less willing to change is the current layered architecture for building network protocols, such as the OSI–layering or the TCP/IP protocol stack. This is because, while the architectural shortcut can lead to a performance (capacity) gain, a good architecture leads to quick proliferation and that can be seen as a long–term goal of the engineering design [2].

In the recent years, there has been a growing revisionist feeling towards the current layering paradigm [3] and this has been especially evident within the wireless networking community. In the wireless networks, the notion of link cannot be rigidly defined as in the wired case, since the existence of a wireless physical communication channel between two nodes can be controlled e. g. by the transmitted power or by the applied modulation/coding scheme. Most importantly, the interactions among the network nodes in a wired network are constrained to take part over the predefined set of mutually independent links. In the wireless setting, the links are created over a shared medium and they are mutually dependent, which immensely increases the space of possible interactions among the wireless network nodes. This multitude of interactions makes the designer able to make many changes in the ways network is operated, while the foreseen performance gains bring willingness to make intervention in the layered design.

The efforts for protocol optimizations in the wireless networks have been mostly associated with the term *cross–layer optimization* or *cross–layer design* [2], [4], [5], [6]. In a strictly layered approach, there is a principle that the algorithmic design at each layer can be done in a black–box manner and in isolation from the other layers, provided that it conforms to the pre–defined interfaces towards the other layers. In a cross–layer approach, this principle is bypassed and two or more layers are designed in concert in order to optimize the overall task (service) performed by the layers. Such overall task can be e. g. optimization of the energy spent while supporting some communication flow, provision of service with some given QoS guarantees etc. For example, the flow control/retransmission at the transport layer can be designed in concert with the flow control/retransmission at the link layer in order to improve the connection throughput. Usually, in the joint design the interface between the layers in question gets enriched, such that a layer has more information about the inner operation of the other layer. For example, the routing layer may become aware of the physical–layer information about actual channel states of the wireless links towards the other nodes, such that during the route discovery the link with highest quality is selected.

The effect of the cross–layer design can be seen in the tightened inter–layer coupling and introduction of novel qualities in the interactions among the layers. This aims to capture the natural coupling that the wireless medium does for the operation of the algorithms at the different layers. Nevertheless, there can be some unforeseen interactions among the layers if caution is not exercised during the cross–layer optimization [2]. Such occurrences mostly happen due to the incompatibility between the cross–layered change and the legacy interfaces to the other layers for the wireless system in question. Therefore, a proper cross–layer optimization should be undertaken with a holistic stance, by having the effects of the inter–layer changes tamed with respect to the overall system design.

The cross–layering endeavors presented in the research literature keep the basic communication task of each layer almost unchanged from what is bing defined in the OSI–layering system[1]. For example, the communication task of the link layer is to provide a reliable transmission of data to a given destination node. Most of the current cross–layer solutions take this task as a starting fact and attempt to optimize the way in which it is performed by using information from the physical (PHY) layer and providing a more elaborate information to the upper layers. However, as we have stated above, the notion of link in a wireless network bears a dynamic semantics due to the interactions among the nodes over the shared wireless medium. Thus, it becomes natural to ask whether there are alternative task definitions for the layers, so that we can capture the richness of possible interactions among the wireless nodes. Furthermore, it has been observed [3], [7] that the original OSI–layering is inappropriate for multiaccess channels. Since a multi–hop wireless network consists of multiple interacting multiaccess channels, this further justifies the reconsideration of the layering in a wireless setting.

In this paper we make an attempt to provide an alternative viewpoint on the layering in the wireless networks. The goal is to obtain a layered framework which can encompass some wireless–specific features and operation modes, such as: link volatility, broadcast transmissions, cooperative diversity [8], etc. Therefore, we will redefine the subtasks into which a communication task in wireless network should be decomposed, which results in layers' functionalities which are different from the conventional OSI–layering.

The paper is organized as follows. In the next section we will discuss the aspects of the current OSI–layering. In Section III there is a description of the specific features of the wireless communication that are major drivers in reconsidering the layering. The layer tasks of the new layering paradigm are described in Section IV and Section V contains the discussion. Finally, Section VI concludes the paper.

II. Layering in Communication Networks

A modular system architecture is specified by components (modules) regarded as black boxes with well–defined interfaces among them. The layered architecture is a form of hierarchical

[1]We primarily refer to OSI layering since it has explicitly addressed the physical and the link layer, but the discussion is also valid for the TCP/IP protocol stack.

modularity central to the data network design [7]. Each layer can be designed and implemented in isolation as long as it conforms to the specified functionality and the interfaces towards the other layers. Note that, by adopting a particular type of layering (i.e. modular decomposition), some early restrictive decisions are made with respect to the design of all systems that will be instances of that layering. Therefore, a given layering paradigm should have a structure that is forward–compatible with respect to the features of all systems that are about to be built and optimized within that layering framework.

The high–level task of a communication network is provision of a channel for end–to–end data transmission[2]. The execution of this task (function) can be decomposed into hierarchical execution of several subtasks (subfunctions) and the decomposition of this task is reflected into the decomposition of the system into layers. The OSI–layering reflects a natural hierarchy for decomposing a high–level communication tasks over a heterogeneous network based on wired links. The seven layers of the OSI hierarchy are: physical, data link control, network, transport, session, presentation and application layer. The physical (PHY) layer should provide a virtual bit pipe between any pair of nodes joined by a physical communication channel. The Data Link Control (DLC) layer interprets a set of bits as a packet and provides reliable two–way transmission packets to the network layer. The network layer provides to the transport layer a route, which is ordered sequence of links over which a packet should be transmitted in order to reach the destination node. By using this route, the transport layer provides end–to–end data pipe to the communication flow that comes from the upper layers. In this text, the rest three layers will be abstracted into a source of communication flow.

In order to support communication over multiaccess channel, the OSI–layering had to be upgraded with a MAC sublayer [7], which provides an intermittent synchronous data pipe to the DLC layer. The standard MAC has been defined as a sublayer that enables communication among nodes that share a *single* communication channel of a local area network in which any node is capable of receiving any packet. The authors in [7] note that in such case the major functions of the network layer are accomplished in the MAC sublayer, which obviates the use of network layer in the local area networks. However, in the case of multi–hop wireless networks we need to achieve a different interplay between the networking and MAC layer function due

[2]This is not always true for wireless sensor networks and we will outline the difference in Section V

to possible existence of multiple interacting multiaccess channels.

The OSI layering decomposes the high–level communication task in a way to ensure that the provision of an end–to–end communication channel is universal with respect to *heterogeneity* in:

- Type of the information source;
- Network topology;
- Network devices.

While the universality can bring benefits with respect to heterogeneity, it can introduce a performance loss when a particular type of information source or network is considered. We can call this a "rate distortion effect of the universal architecture", in analogy to the rate distortion [9] that occurs when a continuous information source is digitalized. We can further use this analogy. Digitalization can be seen as a conversion of the data into universal format with acceptable distortion. But exactly the universality of digital transmission brought convergence of the communication services (information sources) and enormous growth of the communication engineering area. This analogy just confirms that the layered architecture is a necessity in building communication systems.

III. Some Specific Features of the Wireless Communication

In the purely wireless networks, the context for layering is different. The supportable information sources are still heterogeneous and the network topology is dynamically changed. The heterogeneity across the wireless devices can still be present, but in dominant number of studies of the wireless networks it is assumed that the devices are homogeneous regarding the structure of the network, DLC, MAC and PHY layer. For example, when considering multi–hop transmission from S to D via the node M, it is usually assumed that the link between S and M is realized with the same hardware and algorithms as the link from M to D. Such homogeneity makes a fertile ground for doing cross–layer optimization, simply because the transmissions from S to M and M to D can be jointly optimized. Clearly, the system can still be built with the OSI–layering, by optimizing the transmission over a single link and then compose two such transmissions to get a multi–hop transmission. By joint optimization, the space where the optimal solution is being sought contains the search space of the OSI–layering. Therefore, in principle, the joint optimization cannot produce worse result than OSI–layering.

A distinctive feature of the wireless transmission is that a wireless transmission from a node S, with given fixed transmit power P_T, conveys information to several nodes $M_1, M_2, \ldots$. The maximal data rate at which S can communicate with M_i is given by

$$R_i = B \log_2 \left(1 + \frac{P_T \cdot g_i}{N_0 \cdot B} \right) \quad \text{[bps]} \tag{1}$$

where B is the allocated communication bandwidth, N_0 is the noise spectral density and g_i is the attenuation of the channel from S to M_i. Since in general $g_i \neq g_j$ for two nodes M_i and M_j, then the obtainable data rates from S to M_i and M_j are different. Thus, in principle, as long as the received power is nonzero, the link between two node can convey nonzero bits per second[3]. If we assume that the attenuation occurs only due to the free–space propagation, then (1) can be turned into a relation that shows achievable data rate as a function of the distance between two nodes.

Conversely to this physical communication channel, many network–layer protocols use the unit–disc graph model to represent the link abstractions in the wireless network. In such model, if two nodes are at distance $d \leq d_0$, then they can establish link of rate R_0; if $d > d_0$, then it is considered that there is no link between those two nodes. Also, the unit–disc graph model is purely geometrical and does not account for the fading in the wireless channel. This model neglects many of the physically possible links and thus likely brings a suboptimal performance. As an intermediate variant, by using adaptive modulation and coding, the highest–speed links can be complemented with lower–rate links to the nodes with higher attenuation. Nevertheless, the example from [2] shows that these additional links do not bring performance gain straightforwardly. Namely, it is shown that if the network layer uses shortest–path routing, the overall throughput in the network decreases. This is because the routing protocol remains oblivious with respect to the variable data rates at the links and operates as if the links are defined according to the unit–disc graph model. A proper cross-layer approach would have made the routing aware of the possibility of having links with variable rates.

Another important feature is that the wireless medium is shared among the nodes. This means that a given wireless link is operating concurrently with other wireless links and the overall data rate provided by a link is dependent on its interaction with the other links. It is important to

[3] In practice this is not the case — e. g. if the received power is below some level, a synchronization is impossible to achieve.

understand that here we consider the interaction among the links as multi–faceted. For example, if two nodes S_1 and S_2 are using simultaneously the same resource to transmit information to D, then the links $S_1 - D$ and $S_2 - D$ are interfering, which is one type of interaction. To illustrate another type of interaction, consider the case when S is using M to relay data to D. Then the activity of the link $M - D$ is correlated with the activity of the link $S - M$ and this gives rise to a self–interference within the route $S - M - D$. The OSI–layering is oblivious with respect to such self–interference. Due to such dependencies among the links, the protocols for the wireless networks should be designed in a way that the end–to–end communication channels in the network are efficiently supported due to the synergistic operation of all network nodes. In other words, the protocols in the wireless networks should inevitably contain a cooperative flavor.

Finally, the changes in the wireless network topology are far more dynamic compared to the wired network. This changes may occur due to mobility, propagational changes in the wireless channel, but also application of some power–saving strategy. Namely, energy expenditure is usually a key concern in the operation of the wireless network, such that a node can temporarily suspend its activity on the wireless medium in order to save energy. Therefore, the wireless network protocols should be able to cope with such intermittent link availabilities.

IV. New Layering Paradigm for Wireless Networks

We have, so far, established two important facts:

1) The current layering paradigm for communication protocols is suited to the networks where all physical links that have non–zero capacity are utilized. We have seen that this is not the case in the wireless networks.
2) Layering is a necessity if the long–term goal is to have an architecture that stimulates proliferation.

These facts constitute a strong motivation for creating alternative layering paradigm that is more suited to the physical properties of the wireless networks.

As a starting point, we consider the case when the required communication service is provision of a reliable communication flow from a source node S to destination node D. We assume that the communication between S and D is based on wireless transmissions and this communication can involve different nodes apart from S and D. The communication subsystem that provides end–to–end reliable communication flow between S and D is termed *transport module*. The communication flow is further specified by a set of QoS parameters and these parameters are provided as an input to the transport subsystem.

Although there can be a discussion of alternative layering over the whole transport module, we will adopt a conventional transport layer, which segments the communication flow into packets and requires a virtual end–to–end link between S and D for each packet. Such virtual end–to–end link is provided by the *networking module*, which resides within the transport module. The interface between the transport layer and the networking module should be defined in a way to encompass the possible cross–layer optimization (e. g. propagation of QoS parameters, optimized flow control etc.).

Our objective is to define the subsystems (layers) within the networking module in a way that can capture the multitude of possible interactions within a system based on wireless transmissions. Therefore we decompose the operation of the networking module into four subsystem, each dedicated to a generic task:

1) Network task: Selection of a *successor set of nodes* for given destination node.
2) Data Link Control (DLC) task: Reliable transmission to the *successor set*.
3) MAC task: Determining the *set* of transmitting/receiving nodes
4) PHY task: Provision of virtual data pipes via wireless transmissions.

We have intentionally borrowed the OSI–layer terms for the names of the generic tasks. The mapping between these tasks and the functioning of the OSI–layer will be discussed for each task separately. Regarding the terminology, we will explicitly use OSI to denote the task as it is standardly defined in the OSI system. For example, “MAC task” denotes the generic task of determining the set of transmitting/receiving nodes, while “OSI–MAC task” refers to the standardly used one in the OSI system.

A. The Network Task

Consider the example on Figure 1. Let some intermediate node M_1 contain data for the destination node D. As discussed in the previous section, due to the broadcast nature of the wireless medium, a single wireless transmission from M_1 reaches several nodes, possibly including the node D. A *successor set* is a set of nodes to which M_1 should reliably transmit the packet that is destined for D. When a packet is reliably transmitted to a successor set it does not necessarily

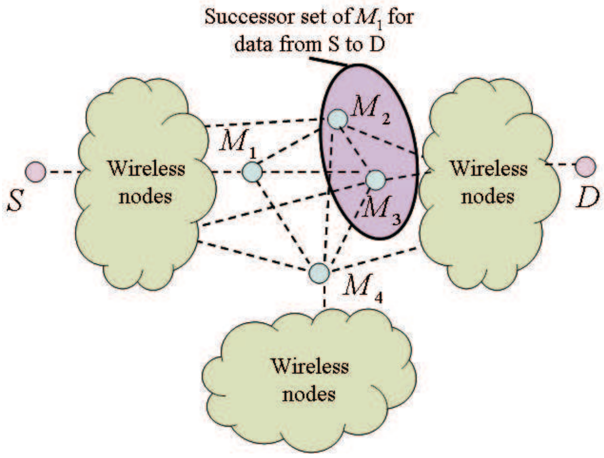

Fig. 1. Selection of a successor set for M_1 for packets from S to D.

mean that there is at least one node in the successor set that completely contains the packet from M_1. Rather, M_1 considers the packet to be *forwarded* when M_1 has acknowledgement that the union of the data contained in all the nodes in the successor set contains the packet. Within the OSI–architecture, this task can be completely settled within the network layer, but it is a generalization of the OSI–defined task, since a set of successor node is selected instead of a single successor node.

The link–by–link packet forwarding appears as a special case of the forwarding based on successor sets. By using successor sets, there is uncertainty about which nodes have exactly been involved in a forwarding of an actual packet. As it is the case for the link–by–link packet routing, the successor set of M_1 for a packet to D is represented by nodes that are preferably selected to be "closer" to the D as compared to M_1. For example, note that on Figure 1 the node M_4 is not in the successor set of M_1.

The wireless link from M_1 to a certain node M_2 is time–variant and can be unavailable due to several reasons: interference at M_2, deep fading of the link which introduces transmission errors, M_2 may apply some power–saving sleeping strategy and thus have inactive transceiver at certain times etc. Furthermore, due to the time–variant wireless channels among the nodes, at some instants forwarding via another node M_3 can be more efficient (i. e. the packet moves faster towards the destination) compared to the forwarding via M_2. The purpose of introducing successor set instead of a successor node is to equip the system with a link–layer diversity mechanism that can provide immunity with respect to such time–variant wireless links. Note that any change due to link unavaliability within the OSI framework is handled inefficiently, since activates the network layer to search alternative successor node. This is not the case with the newly defined network task, where the link selection is naturally handled at the lower layers.

B. The DLC task

In a OSI–DLC protocol, a packet is transmitted to a single node until an acknowledgement for reliable transmission is being received (or a failure is announced). Hence, the packet is physically forwarded on each link. On the other hand, when considering reliable transmission to the successor set, a *virtual forwarding* may occur. To explain this, let M_2 be in the successor set of M_1 for a packet transmitted from S to D. Let M_1 contain some data from S destined to D. Due to the previous transmissions, it is possible that the same data has been already received by M_2. Then M_1 does not need to transmit its data but it only needs to get an acknowledgement that the data has been received by M_2. In such case, M_1 does only a virtual forwarding to M_2.

We use the example on Figure 2 to illustrate the virtual forwarding. For the data from S to D, let the successor sets be defined by the following table. Note that Figure 2 does not depict all physical links, but only links that are considered via the node–successor relation. In this example,

Node	Successor set
S	M_1, M_2, M_3
M_1	M_2, M_3
M_2	M_3, D
M_3	D

TABLE I

DEFINITION OF THE SUCCESSOR SETS FOR THE EXAMPLE ON FIGURE 2

instead of using unicast links as in the link–by–link forwarding, the forwarding with successor sets relies on multicast transmissions. If the packet transmitted from S is correctly received by M_1 and M_2, then M_1 should receive acknowledgement that the packet is already in M_2, such that M_1 considers that its forwarding task for this packet is done. We can conclude that such defined DLC task should embed a form of cooperation among the links to each successor node.

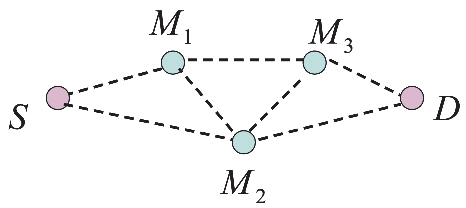

Fig. 2. Illustration of the virtual forwarding. If M_2 acknowledges the packet from S, then M_1 does not need to forward that same packet.

The actual realization of this operation is an issue that should be resolved by the MAC task. For example, being aware that M_2 is also in the successor set of S, M_1 can delay the transmission of its acknowledgement to S and attempt to listen for an acknowledgement from M_2 to S first.

Note that in performing this task, the node M_1 uses the information for its own successor set, but also the successor set of S. By looking at the intersection of these sets, M_1 concludes that it can make virtual forwarding to M_2. Hence, if we treat the sequence of successor sets to be a network–layer information, then this task contains aspects from two layers in the OSI architecture, namely the DLC layer and the network layer. In the link–by–link forwarding the virtual forwarding cannot occur, since it cannot happen that a node (S) and its successor node (M_1) have common successor node (M_2).

C. The MAC Task

The OSI–MAC layer does a task of medium reservation in order to provide an intermittent synchronous bit pipe to the DLC layer. Note that the OSI–MAC layer always reserves the medium for a single transmitting node. Also, the single destination of the reliable transmission is specified by the DLC layer.

The generic MAC task that we consider within the networking module generalizes the OSI–MAC layer task. First, the receiving node is not predefined, the successor set is passed to the MAC layer and the MAC layer has flexibility to choose the actual set of receiving nodes. Consider again the example from Figure 2. When at certain instant a packet should be forwarded from S to the successor set $\{M_1, M_2\}$, the MAC layer of S may decide to reserve the medium in order to transmit only to M_1 because e. g. it knows that currently the transceiver of M_2 is in the sleeping mode.

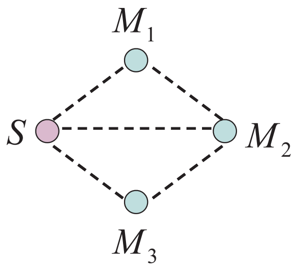

Fig. 3. The nodes S, M_1 and M_3 use cooperative diversity to transmit to M_2.

A more radical departure from the OSI–MAC layer can be seen that the MAC layer here can engage other nodes to participate in the transmission of a given packet. This situation occurs if the system applies some instance of the *cooperative diversity* [8]. In cooperative diversity, the radio transmission of the source node is assisted at the physical layer by the radio transmissions from one or more other nodes in order to ensure more efficient packet transmission. As an example on Figure 3, let M_1, M_2, but not M_3 be in the successor set of S. The MAC layer of S may reserve the medium in such a way that S, M_1 and M_3 transmit certain packet to M_2 using cooperative diversity. It is worth noting that the node M_3 is used in the transmission of the data from S to D, although the participation of this node is invisible at the network layer. Note also that the transmissions of M_1 and M_3 are invisible to the DLC layer of S and M_2.

D. The PHY Task

The OSI–PHY task is to provide a virtual bit pipe between any pair of nodes joined by a physical communication channel. Since we have seen that the notion of physical channel in a wireless setting can be quite fuzzy, we can say that the first part of the PHY task is to control the physical channel, by regulating the power and/or using the antennas to spatially tune the channel. Second, it should provide virtual bit pipe between any two nodes between which there is a physical channel of some minimal non–zero capacity. Finally, another part of the PHY task is to support relaying with Amplify and Forward (AF) or Decode and Forward (DF) [8]. For the example on Figure 3, neglect M_3 and assume that only S and M_1 are applying cooperative diversity to transmit data from S to M_2. In the AF mode, the signal that arrives at M_1 from S is not even interpreted as a sequence of bits – it is treated as a noised waveform that should be amplified and retransmitted. In the DF mode, bit (symbol) decisions are made, but the content of the decoded bit sequence may not be interpreted/repacketized, such that the forwarding remains at the PHY layer.

V. Discussion

The tasks defined by the appropriate OSI layers appear as special cases of the four generic tasks defined for the new layering paradigm. However, many of the additional functionalities offered by the new layering paradigm are possible only when the network devices are homogenous with respect to the implementation of the networking module. A main feature of this layering paradigm is that it fosters cooperation among the nodes over the shared wireless medium.

An important difference between the networking module in OSI and the newly defined networking module can be seen in the data flow within a node. Namely, in the OSI system a data that enters the node through the physical channel should go up the layers at least to the network layer (when routing is applied) or at least to the DLC layer (when bridging is applied). On the other hand, within the new layering, the data might stay at the PHY layer only (when cooperative diversity is applied) or go up to the MAC–layer. The latter case occurs with virtual forwarding — when node M_1 gets acknowledgement that its successor node M_2 has already received the data from S, the DLC layer of M_1 does not need to send acknowledgement to S.

The protocols designed according to the new layering paradigm should be backward compatible, for example with the ubiquitously present IP protocols. This issue is tackled in two different ways. First, the protocols according to the new networking module are applied within the wireless domain, while the access point can use standard protocols to connect to the wired networks. This makes the new layering paradigm appropriate for building e. g. mesh networks. Second, a protocol within the new layering paradigm can always be built in a way that, by setting the appropriate parameters, it falls back to a special case, compatible to the required OSI–like protocol.

Finally, a note on wireless sensor networks [10]. The high–level communication tasks in a wireless sensor network can be fundamentally different from provision of an end–to–end channel. For example, a sink node that collects sensor measurement may not be interested in the data of the individual sensors, but in obtaining the value of some function calculated over the sensor measurements. In such case the wireless network should actively process the data by doing data fusion. Such information–processing paradigm requires to reconsider the layering of the complete transport module according to its interactions with the application module. Thus, the layering in this case can reflect the application–specific nature of the wireless sensor networks.

VI. Conclusion

The current layering paradigm for building network communication protocols has been created in a way that naturally reflects the hierarchy in the wired networks. To a great extent, this paradigm has proven successful in wireless setting. Still, there are continuous efforts to optimize the wireless protocols through a cross–layer design, which is an approach that goes beyond the application of the strict OSI–layering. The abundance of the cross–layer design approaches poses the question whether the wireless network protocols should be built according to an alternative layering paradigm. In this paper we have first reviewed the important aspects of the current OSI layered network architecture. Some pertinent premises which make the OSI architecture natural in a wired setting are not present in a wireless setting. In this respect, perhaps the two most important features in a wireless network are: (1) the wireless link is fuzzy and dynamic compared to the wired link and (2) the shared wireless medium gives rise to multiple multiaccess channels. In order to capture the multitude of possible interactions in the wireless setting, we have introduced a novel layering paradigm. Within the new layering paradigm, a communication task is decomposed into subtasks that are defined to be more general than the subtasks defined within the OSI–layering. Therefore, the protocols built within the OSI layered architecture appear as special cases within the new paradigm. The new layering paradigm aims to set a ground for systematic building of wireless network protocols by accounting for the operational modes that are inherent to the wireless network, such as broadcast transmissions, links with variable data rates, possibility to use cooperative diversity etc. As a bottom line, the presented alternative layering sets the stage for building cooperative protocols in the wireless networks. The message of the paper is two–fold. First, the layering paradigm described here can serve as a starting point to make more concrete definitions of the layers which are here discussed at rather conceptual level. Second, using the discussion in this paper, a similar approach can be undertaken to redefine the layers in application–specific communication architectures, such as the wireless sensor networks.

VII. Acknowledgement

The author would like to thank Dr. Hiroyuki Yomo and Dr. Aleksandar Risteski for the constructive comments and suggestions.

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