Abstract—The 7-layer OSI architecture is the most important model for teaching computer networking. However, the various computer networking teaching sources contain much disagreement, if not outright argument, about which OSI layer describes the respective protocols used in today’s networks. If the academic claim is true that the OSI model completely describes computer networking, a consensus should be possible on where any network protocol is located in this model. Such consensus has not been achieved – Is there something wrong with the procedure of mapping network protocols to layers of the OSI model?

This paper attempts to shed light on the issue by claiming that there are indeed three different sets of criteria for deciding which OSI layer governs what protocol. It describes them, shows how their amalgamation leads to consistency problems, and offers an outline of what OSI layer placement of common protocols suggest if they are being followed consistently. It further considers the distinction between network protocols and network management protocols, refuting its ability to solve the problem. It concludes by recommending to consistently stick to one set of placement criteria.

Index terms—layering, network modeling, OSI, TCP/IP

1 Introduction

The International Standards Organisation’s (ISO) Open Systems Interconnection (OSI) model today is the single most important model for teaching computer networking. It is both universal and clearly defined, two properties that, academically, give it a clear advantage over the more sketchily laid down and protocol-specific TCP/IP counterpart.

It structures the process of information exchange over computer networks and, in its role as a model of the real process, simplifies discourse about design, implementation and deployment of complex internetworking solutions.

The seven layers of the OSI model describe the tasks to be solved to build a functional internetwork in a modular way [14]. Much similar, although not OSI-based, is the practical implementation of computer networking today: Several protocols together provide the functionality of “the network”, each being responsible for a restricted number of tasks.

Consequently, if ISO’s OSI reference framework really is a model of computer networks it should be able to describe the interdependence of prevailing protocols within its seven layers. But while there is agreement that every network protocol fits somewhere into the OSI model it is sometimes not clear exactly where it fits.

The reason for the difficulty populating the OSI model with today’s common-use network protocols emanates mainly from the situation that most of them are part of, or related to, the protocol stack of TCP/IP. From the standards formulation in the respective Request for Comment (RFC) it is sometimes made explicit which TCP/IP layer is responsible for a given protocol [2] [3], but layering with respect to the OSI model often remains unclear.

Furthermore, IETF protocol designers are least concerned about allocation to OSI layers and indeed do not intend to follow the principles of OSI layering, i.e. the complete independence of lower layers from upper layers and the concept of the sole reason for the existence of layer n – 1 being support for layer n, c.f. [9].

Possibly as a result of this uncertainty, computer networking text books seldom explicitly thematize this issue. Instead, the claim that a certain protocol is on a particular layer of either model is often hidden in the general structure of the text (the table of contents) and does not receive further coverage [cf. e.g. 12]. Various sites on the World Wide Web however do discuss the topic. As those sources (this paper uses [13] and [1] as two examples of thousands of pages in this area) are much easier available than printed material, the necessity arises to discuss the merits of their claims because tertiary education in computer networking is heavily affected by web sites explaining “how it really works".
1.1 Some contested protocols

Wikipedia\(^1\) discussion pages\(^2\) on the subject area provide some insight into the thoughts of contributors with different professional and educational background, all of whom claim to have some authority on the matter. These discussions\(^3\) reveal the following main points of disagreement:

1. Whether routing protocols should be on OSI layer 3 because they facilitate end-to-end IP delivery, or on other layers depending on what functionalities they use,

2. Whether protocols should be placed on the highest OSI layer they contribute to, or on the lowest (e.g. in the cases of DHCP and HTTP),

3. Whether the exercise of OSI-layering protocols that have been designed independent of OSI has any merit at all.

Also on more formal platforms authors disagree about certain protocols. A Cisco white paper on TCP/IP technology places Address Resolution Protocol (ARP) on OSI layer 2 [10, p.2], Forouzan on layer 3 [6, p.43]. Even its location in the TCP/IP model seems not to be entirely obvious; the Cisco CCNA Discovery curriculum (version 4.0, module 2, chapter 7.2.1.2) stacks it between Internet and Link layer.\(^3\)

1.2 Relationship of the TCP/IP and OSI Reference Models

As with the layer placement of particular protocols, the relationship between TCP/IP and OSI reference models is not often made explicit in standard networking texts. Few of them go as far as suggesting certain TCP/IP protocols to belong to a particular OSI layer as in [11, chapter 1]. Most do, however, offer a model comparison that is often depicted as in figure 1: This graphic suggests protocol location to be a surjective function from OSI onto the TCP/IP model. It particularly:

- restricts the placement of Link-layer TCP/IP protocols to OSI layers 1 and 2,
- maps Transport-layer TCP/IP protocols to OSI layer 4, and Internet-layer TCP/IP protocols to OSI layer 3, and
- restricts the placement of Application-layer TCP/IP protocols to OSI layers 5 to 7.

Fig. 1: A juxtaposition of the OSI model (left) and the TCP/IP model (right) as suggested e.g. in [6] and [12]

This relationship can be criticised. While a detailed reasoning in this regard is beyond the scope of this article [see 8, for a thorough discussion], one example shall be given to pinpoint the problem: For the OSI model, the responsibility of the Network Layer lies in the provision of end-to-end delivery of datagrams, in contrast to next-hop delivery which is the responsibility of the Data Link layer [14, p.430]. On the other hand, the TCP/IP model sees its Internet layer as the virtual network interface [7, p.8], something that clearly includes next-hop delivery. (The disagreement about ARP is based on this difference).

The relation between the two reference models is therefore not a function at all, and figure 1 is an oversimplification.

1.3 Layering Considered Harmful?

RfC 3439 [9] contains a section titled “Layering Considered Harmful”, a paragraph sometimes quoted to sketch the seemingly ultimate impossibility to decide on OSI layers for common protocols [1] [13].

Claims like these stem from a misunderstanding about the purpose of RfC 3439: It uses a completely different definition of layering and does not say anything at all about network models as such. It particularly does not reference RfC 1122 nor RfC 1123, the two documents defining the TCP/IP layers. What has indeed been considered harmful by the authors is the over-diversification of the protocol landscape.

To a certain degree RfC 3439 repudiates the necessity to design IEEE protocols in a way reconcilable with the OSI framework: Artificial separation of responsibilities by layers – OSI or TCP/IP – is to be avoided if it does nothing to improve implementation. This observation ought to be kept in mind when performing any TCP/IP-to-OSI mapping but it should never be used as a critique of the IEEE standardisation process. It is the obligation of the scientists to prove that a model is a useful abstraction of the real-life process; to argue the other way round is unrealistic.

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\(^1\)http://en.wikipedia.org

\(^2\)It should be emphasized that the reference here is to the discussion pages of the articles, typically batches of comments that as a matter of netiquette are not extensively edited. This is in contrast to the articles themselves that might change to better or worse within a matter of minutes.

\(^3\)For consistency in this paper the OSI layers 2 and 3 are called “Data Link” and “Network” layer while the TCP/IP layers 1 and 2 are called “Link” and “Internet” layer, respectively.
1.4 Network Protocols vs Network Management Protocols

To avoid some of the issues regarding layer mapping it has been suggested to distinguish network protocols from network management protocols [13] or core protocols from supporting protocols, [6, p.43], arguing that the management protocols do not carry user data and are therefore to be regarded as necessary overhead to “real” networking communication. The rationale behind this suggestion might have been that it is foremost the management protocols that seem to evade OSI classification, and not so much the protocols that actually transfer user data.

With this distinction one can apply different strategies of OSI-layering, one for the “genuine” and one for the management protocols, e.g. by basing the classification of “normal” protocols on functionality but placing the management protocols into the layer they actually manage. However, difficulties seem to begin, rather than end, at this classification:

1. The distinction itself is not easy to do: Whether TCP transmits user data or not depends on its current payload: if it is an HTTP request it does, if it is a BGP update it doesn’t.
2. The term “user data” lacks satisfactory precision: Is there any user data transmitted by Samba? Does a user-initiated traceroute constitute user data or not?
3. The distinction fails for multi-layer protocol stacks like VoIP or ATM, as they will typically contain both management and user data protocols.
4. The layering instructions for management protocols is just as opaque as before: for instance, which layer is managed by DHCP? By NTP?

In conclusion, the following picture develops: Applying a narrow definition of “user data”, the genuine protocols in IP networks are simply the core protocols from the TCP/IP protocol stack: TCP, UDP, IP, and some clear cases on link and application layer. All other protocols are management protocols. The instruction to sort them into layers “by what they manage” therefore simply reverts to the layering instruction that will below be called the conceptual approach, to matching the protocol’s and the layer’s responsibilities.

2 Three General Approaches

Investigating the reasons given for particular placements of protocols into layers of the OSI model, at least three major classes of arguments seem to prevail:

1. Functional approach: What data does this protocol send? Conclude the placement of the protocol from the payload of its data units.
2. Operational approach: On what functionality does this protocol rely? Place the protocol dependent on the services it uses.
3. Conceptual approach: What is the responsibility of this protocol? Decide the placement of the protocol by determining its contribution to network connectivity.

Of course these different approaches can lead to different results, and mixing them to populate one and the same network model leads to the described difficulties. But just as mixing the three strategies yields undesired, even haphazard, results, the effect of consistently using one method for layering might equally surprise. The following sections describe the three notions in detail.

2.1 The Functional Approach

The functional approach makes the assertion that for any PDU, if the payload is on layer n of the TCP/IP model, the PDU itself belongs to layer n − 1.

“From the IETF perspective, the payload defines layering.” [13]

Howard C. Berkowitz, IETF engineer and author

The appeal of this principle is that it directly follows the TCP/IP design approach with regards to encapsulation by arguing e.g that any PDU that has a TCP segment as payload must be on the Internet layer.

For the core TCP/IP protocols this is entirely correct: The payload of any transport layer segment is application data, the payload of a packet is a segment, the payload of a frame is a packet. But two questions remain unanswered by the functional approach:

1. How can this principle be applied to layers of the OSI model? As outlined in section 1.2 the mapping between OSI and TCP/IP is not entirely trivial.
2. What should be done with protocols that do not encapsulate any upper-layer PDU (the management protocols as characterised in section 1.4)?

There is no satisfying answer to question 1. If the network is operated by the TCP/IP protocol stack, peer-to-peer information that would belong to OSI layers 1, 5, and 6 is included in the encapsulation process on layers 2 and 7, respectively. As such the layers under the functional approach would be defined by the encapsulation process. This happens only four times, and OSI layers 1, 5, and 6 would necessarily remain empty.

There are two possible solutions to the problem in question 2. One is to place all management protocols on the highest layer because they do not fulfill the requirements to be placed anywhere else. This mapping would lead to a layer mapping as shown in figure 2.
Another attempt would be to investigate those management protocols separately and not to decide their placement at this stage.

Both these possible solutions have disadvantages. The first possibility leads to a counter-intuitive protocol placement where most functionalities are concentrated on OSI layer 7, the second one reduces the entire approach to a solution dependent on other approaches to answer “the interesting” questions. Indeed, answer 2 would decide layer placement only for all trivial cases.

2.2 The Operational Approach

There are several versions of this approach. In its most general form, the operational approach makes the assertion that no protocol \( x \) may be placed below a protocol \( y \), if \( x \) relies on \( y \) to operate. More restrictive characterisations are:

1. If a protocol uses functionality on layers \( n_1, n_2, \ldots, n_m \in N \)
   it belongs to layer \( k = \max\{N\} \).
2. If a protocol uses functionality on layers \( n_1, n_2, \ldots, n_m \in N \)
   it belongs to a layer \( k > \max\{N\} \).

This is the opposite of the functional approach – it concentrates not on the payload but the encapsulation of a PDU. The operational approach enforces a layer mapping as outlined in figure 3. The appeal of this approach is that it best maps the design intentions of the OSI model: to assemble a framework of responsibilities that together define and accomplish a general, common functionality. It also fits best into the model character of OSI as it offers some explanation behind layer placement as opposed to just a technical criterion. Furthermore it does not require the additional bypass of referring to TCP/IP layering first, and OSI layering second. It thus is not susceptible to the problems outlined in section 1.2.

This approach is the hardest to follow as the high-level purpose of networking protocols is rarely well documented, and if it is it often happens years after the protocols have been standardized.\(^4\) Furthermore, as protocol designers are not bound by the OSI layer definitions, not every protocol might strictly fit one layer – as RFC 1925 humorously puts it:

“It is always possible to aglutenate [sic] multiple separate problems into a single complex interdependent solution.” \(^4\)

R. Callon, RFC 1925, Fundamental Networking Truth #5

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\(^4\)For the Internet protocol suite see e.g. \(^5\) which was published 15 years after the first protocol proposals.
whatsoever on OSI layers 4 to 6, and DHCP as laid out in [14]; completely left out. This defies the OSI layering principles it might still seem strange that certain layers are composite and not simply singular protocol and not a stack.

While this is in itself not a problem – many protocols are actually protocol stacks and cover multiple layers – it might still seem strange that certain layers are completely left out. This defies the OSI layering principles as laid out in [14]; DHCP certainly has no responsibility whatsoever on OSI layers 4 to 6, and DHCP is clearly a singular protocol and not a stack.

It must be reiterated that the IETF refutes these principles (cf. section 1.3). The perceived conceptual weakness therefore is inherent to the IETF protocols, not to their mapping to the OSI model. Still the question remains where to place protocols whose functionalities span multiple OSI layers, an exhaustive discussion of which is considered beyond the scope of this article.

The rigorous attempt to solve this challenge might be to put them to every layer they contribute to in terms of functionality, because the solution that may seem obvious and desirable: to place protocols on their main layer of contribution, will necessarily introduce new ambiguity.

The pragmatic attempt might be to place such protocols into a layer of choice depending on the main focus of the point to be made. OSI layering is, as stated before, mainly an academic exercise. If for example the aim is to explain how Data Link Layer connectivity is “lifted” to the Network Layer with automatic address allocation it makes sense to place DHCP on OSI layer 3 (as done in figure 4). If on the other hand the automation of network configuration tasks is focused on, DHCP acts much like an application providing the necessary parameters, and could be placed on OSI layer 7.

2.4 Evaluation and Conclusion

The functional approach is either not an independent solution to the problem, or it decides only trivial cases and enforces a distinction into network protocols and management protocols (cf. section 1.4), a strategy that in turn invokes the conceptual approach (cf. 2.3). The functional approach therefore must be rejected as a strategy to map TCP/IP protocols to layers of the OSI model.

What remains are the two independent strategies, the operational approach (layer to reliance) and the conceptual approach (layer to responsibility). Although the assumption underlying current OSI layering practice – that the TCP/IP layer predetermines the OSI layer – lacks foundation, both have their merits and lead to an acceptable layer population that avoids ambiguity in the variable of interest.

Problems arise when both methods are combined: To argue that BGP must be above OSI layer 4 for its reliance on TCP (operational approach) and then to place it on layer 7 because it has no responsibilities on layers 5 and 6 (conceptual approach) lacks rigor because the conceptual approach would place any routing protocol on OSI layer 3, not 7, in the first place. Alternatively, to place ARP and DHCP both on layer 3 because of ARP’s implementation over the link layer (operational approach) and DHCP’s main role (provide IP addresses, conceptual approach) is methodologically inferior.

The operational approach leads to uncommon and counter-intuitive protocol placement (cf. 2.2). The conceptual approach differs slightly from common practice and is the hardest to apply because its criterion is harder to formalise. Using this approach, placement of every networking protocol on one singular OSI layer is hardly possible, given the design goals of IETF [9]. It has two advantages, though: it is the closest to the definition of the OSI model, and the one generally applicable throughout the protocol landscape.

From a teaching perspective a method that underscores the model properties (simplification, structuring, and explanation) of OSI could be suited best, and the conceptual approach could therefore be preferred over other attempts. Other standpoints might of course merit a different choice.

References


**Peter Gallert** (born 1971) holds a Magister degree in logic, theory of science, communication studies and media science from University of Leipzig, Germany. He has been working as Senior Lecturer: Information Technology at Polytechnic of Namibia in Windhoek since his emigration to Namibia in 2000. He is currently working on a quality of service implementation for meshed overlay networks in cooperation with the University of Cape Town.