IEEE P802.24
Vertical Applications Technical Advisory Group

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Abstract	
Purpose	
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1 Background and Introduction

IEEE 802 technologies are used for a wide variety of applications and markets. Although the widespread usage and overwhelming adoption as PHY and Link layer technologies for all kind of information and communication solutions, a common perception of the value and differentiation of the IEEE 802 architecture in the context of vertical markets is not established, as well as there are no clear views about the reasons why IEEE 802 would be better suited to deployments in the communication infrastructure of private enterprise, industry, and the individual user, and how does IEEE 802 compare to network architectures oriented towards service providers.

In a first stance it could be agreed that the IEEE 802 architecture enables networks that are like Ethernet: Well understood, mature, predictable, offering a “cleaner” integration of disparate technologies under the common architecture and addressing.

This white-paper is aimed to collect and spell out commonalities of IEEE 802 technologies and sets the scene in relation to other well-known communication standards of similar behavior.

2 Requirements of Vertical Applications

This section defines the characteristics of Vertical Applications that usually integrate various systems including network connectivity in order to perform specific tasks or enable use cases for their industry.

2.1 Defining “Vertical”

In the context of this white paper, Vertical Applications refers to networks that serve specific use cases in specific market segments. The network is used by the entity to enable its business processes. This is in contrast to an access network, where the network services are the product.

Vertical markets involved specific usage models:

- Industrial automation
- Building Automation
- Smart Cities
- Smart Grid / Utility
- Automotive / transportation
- Agriculture
- Connected Supply Chain
- Critical infrastructure protection and control
- Wide area gaming (including AR/VR)

There are other ways of looking at ‘Vertical’. Vertical integration is really a competition/anti-trust term, rather than a technical term. In that context it describes a technical situation that some set of functionalities that may be provided by the same company could actually in practice also be provided by different companies. So, for instance, "5G" is "vertically integrated" because it actually assumes in its technical specifications that a single commercial provider will be responsible for a whole range of different features that are not really separable. In that sense IEEE 802 technologies are not "vertically integrated" because they can be deployed by different operators of completely different networks (e.g. one leverages wired connections, while others are based on wireless connectivity). Nevertheless, IEEE 802 plays a role in vertical integration through providing the plain connectivity layer, e.g. IEEE 802.11 in IEEE 1609 vehicle-to-vehicle communications, or IEEE 802.15.4 in the SEP.

Vertical markets often require highly-engineered networks to guarantee the quality of the required communication services. Quite often vertical markets follow extended lifecycles; the vertical network is expected to remain in service for a longer time than a service-provider network. And vertical markets may have different cost models compared to usual public communication networks with some are opex averse, others are more capex averse.

3 Economic Aspects for Vertical Application Networks

IEEE 802 based networks are usually aimed to “enable creating/delivering a product” instead of “the network is the product” defined by an open standard:

- An IEEE 802 network is deployed in vertical markets, where the network is owned and operated by the user of the services.
- There are also other models than subscription that provide ancillary economic value.
  - An economy of scale can be accomplished by creating a network that can be leveraged by multiple entities. This is similar to the cloud thinking – the model of sharing the infrastructure (network) without the need for them to be independently installed and managed. A similar concept to a data center just providing computing resources, but not dealing with installing and running software for all the services needed.
  - The trend toward more virtualization is a strength of IEEE 802 because it allows the network to be better prepared for that virtualization. It provides the clean separation between the infrastructure and the service running on the infrastructure. In the IEEE 802 case, this is the layer 2 to layer 3 boundary.
  - The IEEE 802.3 Ethernet transport is the most well understood transport in existence. This is analogous to the X86 computer architecture that became the basis for the computing resources of data centers.
- IEEE 802 and unlicensed spectrum enables faster innovation
  - Many of the breakthrough innovations were not as planned
  - The story of why IEEE 802 complements everything else, and everything else (alone) is not sufficient.
- IoT is built around many specialized niches. The challenge is meeting their diverse requirements. No single standard can address all of them well. IEEE 802 provides multiple standards to address multiple IoT applications.
- The model for network management requires special attention, when the owner/operator of the network may have less expertise in network management. Guidance is desired on

how to manage and operate a private network. Usually, this is simpler because the IEEE 802 network is simpler (compared to 3GPP, for example), but the documentation is often not really mature or available. Yang modeling describes the interface, but more knowledge is needed to understand how to use the network management data that is available through the interface.

3.1.1 Modularity and Interchangeability, competition economics

A user of a vertical application may want to be able to replace parts of their vertical application network with a better, newer product when one arrives (for instance, installing a new AP when a better one is available from a different vendor). IEEE 802 products lend themselves to this form of user-empowered modularity.

Building blocks with smaller functional content and broader variation offer this flexibility to the vertical application. 3GPP 5G (or cellular networks in general) does not have this modular feature. Although many vendors of UEs can be certified to the specifications, it is much harder for the network owner to mix multiple vendors in the RAN and Core of the network.

3.1.2 Possibility of small business entities deploying small scale networks

It would be possible for a small utility or municipality with only a few employees to set up a reasonably secure Wi-Fi network at their workplace, perhaps with temporary help from a consultant if they were making sure it was really secure. But they would find it much more difficult to acquire a municipal spectrum license for LTE technologies, and install, configure, and maintain a 3GPP private network infrastructure.

IEEE 802 also enables a greater degree of scalability. A network that starts small can easily be scaled to more complexity and users as the business grows. A 3GPP access network is designed from the start for large scale, and is more difficult to apply at a small scale.

4 Key Aspects of the IEEE 802 Technologies for Vertical Applications

4.1 Layering

- IEEE 802 is a transport network
- IEEE 802 is Layer 2
- IEEE 802 provides direct and simultaneous support of IPv4 and IPv6 or pure layer 2 protocols
- IEEE 802 offers trade-off and optimizations between flexibility (L2) and scalability (L3)

4.2 Routing and Bridging

- IEEE 802 enables networks to scale with routing and bridging.
- IEEE 802 supports layer 3 protocols such as IP, which enables routing to enable IEEE 802 networks to expand to higher scale
- IEEE 802 networks can be built at smaller scale to provide more flexibility

- Smaller scale provides opportunity for real-time
- IEEE 802 standards can emulate a point to point network over a wireless point to multipoint network to enable bridging over the wireless link.
- IEEE 802 can support multiple different L3 and above protocol suites
- IEEE 802 can also offer L2 routing when appropriate (e.g. 802.15.10)
    - Note: Not an alternative to L3 routing, but there to address a different problem

4.3 Management and Control

- IEEE 802 does not provide as many means of control for a specific end device and its traffic on a path.
- There are some management facilities in some standards
- It is easier for IEEE 802 to support an "unmanaged" network, such as consumer Wi-Fi.
- 802 provides local networks that may be (but don't have to be) connected into the Internet or other networks.
- Public operator networks are focused on services for single devices, while IEEE 802 networks support and include multiple devices (networks of networks) – devices can communicate with each other as well as with other networks

5 IEEE 802 standards aimed for vertical applications

5.1 IEEE 802 Overview and Architecture

- 802-2014 - IEEE Standard for Local and Metropolitan Area Networks: Overview and Architecture
- 802c-2017 - IEEE Standard for Local and Metropolitan Area Networks:Overview and Architecture--Amendment 2: Local Medium Access Control (MAC) Address Usage
- 802d-2017 - IEEE Standard for Local and Metropolitan Area Networks:Overview and Architecture Amendment 1: Allocation of Uniform Resource Name (URN) Values in IEEE 802(R) Standards
- 802E-2020 - IEEE Recommended Practice for Privacy Considerations for IEEE 802(R) Technologies

5.2 IEEE 802.1 Bridging and Management

- 802.1AB-2016 - IEEE Standard for Local and metropolitan area networks - Station and Media Access Control Connectivity Discovery
- 802.1AC-2016/Cor 1-2018 - IEEE Standard for Local and Metropolitan Area Networks--Media Access Control (MAC) Service Definition - Corrigendum 1: Logical Link Control (LLC) Encapsulation EtherType
- 802.1AC-2016 - IEEE Standard for Local and metropolitan area networks -- Media Access Control (MAC) Service Definition

- 802.1ACct-2021 - IEEE Standard for Local and Metropolitan Area networks -- Media Access Control (MAC) Service Definition - Amendment 1: Support for IEEE Std 802.15.3
- 802.1ABcu-2021 - IEEE Standard for Local and metropolitan networks--Station and Media Access Control Connectivity Discovery Amendment 1: YANG Data Model
- 802.1ABdh-2021 - IEEE Standard for Local and metropolitan area networks-- Station and Media Access Control Connectivity Discovery Amendment 2: Support for Multiframe Protocol Data Units
- 802.1AE-2018 - IEEE Standard for Local and metropolitan area networks-Media Access Control (MAC) Security
- 802.1AE-2018/Cor 1-2020 - IEEE Standard for Local and metropolitan area networks--Media Access Control (MAC) Security Corrigendum 1: Tag Control Information Figure
- 802.1AEdk-2023 - IEEE Standard for Local and metropolitan area networks-Media Access Control (MAC) Security -- Amendment 4: MAC Privacy protection
- 802.1AR-2018 - IEEE Standard for Local and Metropolitan Area Networks - Secure Device Identity
- 802.1AS-2020 - IEEE Standard for Local and Metropolitan Area Networks--Timing and Synchronization for Time-Sensitive Applications
- 802.1AS-2020/Cor1-2021 - IEEE Standard for Local and Metropolitan Area Networks--Timing and Synchronization for Time-Sensitive Applications - Corrigendum 1: Technical and Editorial Corrections
- 802.1AX-2020 - IEEE Standard for Local and Metropolitan Area Networks--Link Aggregation
- 802.1BA-2021 - IEEE Standard for Local and metropolitan area networks-- Audio Video Bridging (AVB) Systems-- Corrigendum 1: Technical and Editorial Corrections
- 802.1CB-2017 - IEEE Standard for Local and metropolitan area networks--Frame Replication and Elimination for Reliability
- 802.1CF-2019 - IEEE Recommended Practice for Network Reference Model and Functional Description of IEEE 802(R) Access Network
- 802.1CM-2018 - IEEE Standard for Local and metropolitan area networks -- Time-Sensitive Networking for Fronthaul
- 802.1CMde-2020 - IEEE Standard for Local and metropolitan area networks -- Time-Sensitive Networking for Fronthaul - Amendment 1: Enhancements to Fronthaul Profiles to Support New Fronthaul Interface, Synchronization, and Syntonization Standards
- 802.1CS-2020 - IEEE Standard for Local and Metropolitan Area Networks--Link-local Registration Protocol
- 802.1Q-2022 - IEEE Standard for Local and Metropolitan Area Network--Bridges and Bridged Networks
- 802.1Qcz-2023 - IEEE Standard for Local and Metropolitan Area Networks--Bridges and Bridged Networks - Amendment: Congestion Isolation
- 802.1X-2020 - IEEE Standard for Local and Metropolitan Area Networks--Port-Based Network Access Control

5.3 IEEE 802.3: Ethernet

- 802.3-2022 - IEEE Standard for Ethernet
- 802.3ck-2022 - IEEE Standard for Ethernet Amendment 4: Physical Layer Specifications and Management Parameters for 100 Gb/s, 200 Gb/s, and 400 Gb/s Electrical Interfaces Based on 100 Gb/s Signaling
- 802.3cs-2022 - IEEE Standard for Ethernet Amendment 2: Physical Layers and Management Parameters for increased-reach point-to-multipoint Ethernet optical subscriber access (Super-PON)
- 802.3db-2022 - IEEE Standard for Ethernet - Amendment 3: Physical Layer Specifications and Management Parameters for 100 Gb/s, 200 Gb/s, and 400 Gb/s Operation over Optical Fiber using 100 Gb/s Signaling
- 802.3dd-2022 - IEEE Standard for Ethernet Amendment 1: Power over Data Lines of Single Pair Ethernet
- 802.3de-202 - IEEE Standard for Ethernet - Amendment 5: Enhancements to the MAC Merge and Time Synchronization Service Interface for Point-to-Point 10 Mb/s Single Pair Ethernet
- 802.3cx-2023 - IEEE Standard for Ethernet -- Amendment: Media Access Control (MAC) service interface and management parameters to support improved Precision Time Protocol (PTP) timestamping accuracy
- 802.3cy-2023 - IEEE Standard for Ethernet -- Amendment: Physical Layer Specifications and Management Parameters for greater than 10 Gb/s Electrical Automotive Ethernet
- 802.3cz-2023 - IEEE Standard for Ethernet -- Amendment: Physical Layer Specifications and Management Parameters for multi-gigabit optical Ethernet using graded-index glass optical fiber for application in the automotive environment
- 802.3.1-802.3.1-2013 - IEEE Standard for Management Information Base (MIB) Definitions for Ethernet
- 802.3.2-2019 - IEEE Standard for Ethernet - YANG Data Model Definitions

5.4 IEEE 802.11: Wireless LAN

- 802.11-2020 - IEEE Standard for Information Technology--Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks--Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications
- 802.11-2020/Cor 1-2022 - IEEE Standard for Information Technology--Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Networks--Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Corrigendum 1 -- Correct IEEE 802.11ay Assignment of Protected Announce Support bit
- 802.11ax-2021 - IEEE Standard for Information Technology--Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks--Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and

Physical Layer (PHY) Specifications Amendment 1: Enhancements for High-Efficiency WLAN

- 802.11ay-802.11ay-2021 - IEEE Standard for Information Technology--Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks--Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Enhanced Throughput for Operation in License-exempt Bands above 45 GHz
- 802.11ba-802.11ba-2021 - IEEE Standard for Information Technology--Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks--Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Wake-Up Radio Operation
- 802.11az-2022 - IEEE Standard for Information technology - Telecommunications and information exchange between systems Local and metropolitan area networks - Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 4: Enhancements for positioning
- 802.11bd-2022 - IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Next Generation V2X
- 802.11bb-2023 - IEEE Standard for Information Technology--Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks--Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications -- Amendment: Light Communications
- 802.11bc-2023 - IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications -- Amendment: Enhanced Broadcast Service

5.5 IEEE 802.15: Wireless Specialty Networks

- 802.15.3-2016 - IEEE Standard for High Data Rate Wireless Multi-Media Networks
- 802.15.3f-2017 - IEEE Standard for High Data Rate Wireless Multi-Media Networks Amendment 3: Extending the Physical Layer (PHY) Specification for Millimeter Wave to Operate from 57.0 GHz to 71 GHz
- 802.15.3d-2017 - IEEE Standard for High Data Rate Wireless Multi-Media Networks--Amendment 2: 100 Gb/s Wireless Switched Point-to-Point Physical Layer
- 802.15.3e-2017 - IEEE Standard for High Data Rate Wireless Multi-Media Networks--Amendment 1: High-Rate Close Proximity Point-to-Point Communications
- 802.15.4-2020 - IEEE Standard for Low-Rate Wireless Networks
- 802.15.4-2020/Cor 1 - IEEE Standard for Low-Rate Wireless Networks Corrigendum 1: Correction of Errors Preventing Backward Compatibility

- 802.15.4y-2021 - IEEE Standard for Low-Rate Wireless Networks Amendment 3: Advanced Encryption Standard (AES)-256 Encryption and Security Extensions
- 802.15.4w-2020 - IEEE Standard for Low-Rate Wireless Networks--Amendment 2: Low Power Wide Area Network (LPWAN) Extension to the Low-Energy Critical Infrastructure Monitoring (LECIM) Physical Layer (PHY)
- 802.15.4z-2020 - IEEE Standard for Low-Rate Wireless Networks--Amendment 1: Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques
- 802.15.4aa-2022 - IEEE Standard for Low-Rate Wireless Networks Amendment 4: Higher Data Rate Extension to IEEE 802.15.4 Smart Utility Network (SUN) Frequency Shift Keying (FSK) Physical Layer (PHY)
- 802.15.7-2018 - IEEE Standard for Local and metropolitan area networks--Part 15.7: Short-Range Optical Wireless Communications
- 802.15.8-2017 - IEEE Standard for Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Peer Aware Communications (PAC)
- 802.15.9-2021 - IEEE Standard for Transport of Key Management Protocol (KMP) Datagrams
- 802.15.10-2017 - IEEE Recommended Practice for Routing Packets in IEEE 802.15.4 Dynamically Changing Wireless Networks
- 802.15.10a-2019 - IEEE Recommended Practice for Routing Packets in IEEE 802.15.4(TM) Dynamically Changing Wireless Networks - Amendment 1: Fully Defined Use of Addressing and Route Information Currently in IEEE Std 802.15.10
- 802.15.13-2023 - IEEE Standard for Multi-Gigabit per Second Optical Wireless Communications (OWC), with Ranges up to 200 meters, for both stationary and mobile devices

5.6 IEEE 802.16: Broadband Wireless MANs

- 802.16-2017 - IEEE Standard for Air Interface for Broadband Wireless Access Systems

5.7 IEEE 802.19: Wireless Coexistence

- 802.19.1-2018 - IEEE Standard for Information technology--Telecommunications and information exchange between systems--Local and metropolitan area networks--Specific requirements--Part 19: Wireless Network Coexistence Methods
- 802.19.3-2021 - IEEE Recommended Practice for Local and Metropolitan Area Networks--Part 19: Coexistence Methods for IEEE 802.11 and IEEE 802.15.4 Based Systems Operating in the Sub-1 GHz Frequency Bands

5.8 IEEE 802.21: Media Independent Handover Services

- 802.21-2017 - IEEE Standard for Local and metropolitan area networks--Part 21: Media Independent Services Framework
- 802.21-2017/Cor 1-2017 - IEEE Standard for Local and metropolitan area networks--Part 21: Media Independent Services Framework--Corrigendum 1: Clarification of Parameter Definition in Group Session Key Derivation
- 802.21.1-2017 - IEEE Standard for Local and metropolitan area networks--Part 21.1: Media Independent Services

5.9 IEEE 802.22: Wireless Regional Area Networks

- 802.22-2019 - IEEE Standard - Information Technology-Telecommunications and information exchange between systems-Wireless Regional Area Networks-Specific requirements-Part 22: Cognitive Wireless RAN MAC and PHY specifications: Policies and Procedures for Operation in the Bands that Allow Spectrum Sharing where the Communications Devices May Opportunistically Operate in the Spectrum of Primary Service
- 802.15.22.3-2020 - IEEE Standard for Spectrum Characterization and Occupancy Sensing

TV White Space has not been widely adopted in North America because most of the “white space” spectrum has been auctioned off for commercial cellular, leaving broadcast television packed into the remaining channels. The use of CBRS has been adopted for small regional networks, despite the downsides of much shorter range due to the higher frequency band.

6 Common network model for vertical application networks

A common foundation of the network architecture for a variety of vertical applications is provided by the IEEE Std 802.1CF-2019 IEEE Recommended Practice for Network Reference Model and Functional Description of IEEE 802 Access Network.
All communication networks providing the means to connect various communication endpoints (terminals) to the same or different information servers over a shared infrastructure follow the same architectural principles. IEEE 802 technologies well support the realization of an access network, that establishes the shared infrastructure allowing to manage the connections of a wide variety of terminals through wired or wireless interfaces to their communication peers, either through bridging in the local area, or through routing by an access router in more widespread networks.

6.1 Network Reference Model

Figure 1 below shows the mapping of the IEEE 802 Network Reference Model (NRM) to usual communication network topologies. Core of the NRM is the Access Network that connects terminally either directly through bridging or forwards traffic to the access router when the communication peer is behind the same Layer 2 domain. Various control entities support the access network to provide secured and managed connectivity.

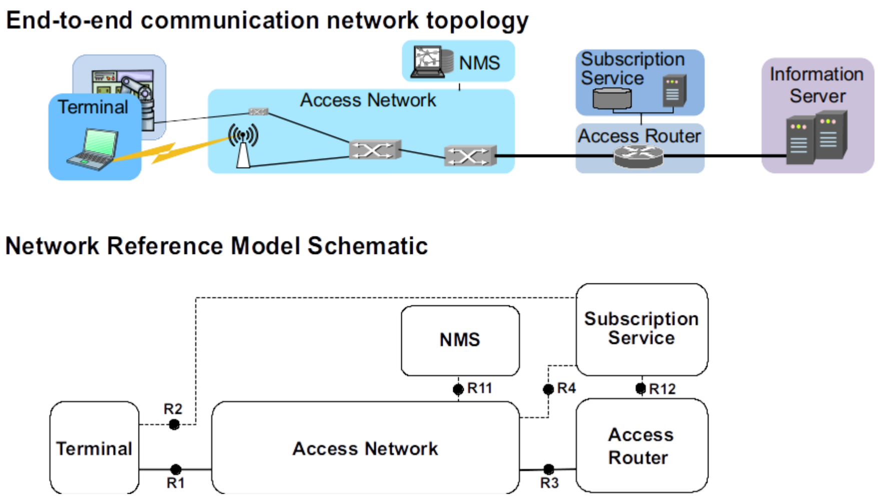


Figure 1: Network reference model design

NMS denotes the network management system that provides the functions to configure and to monitor the correct operation of the access network infrastructure. The subscription service is the control entity that deals with the communication demand of the individual terminals. It provides authentication to restrict the usage of the access network to only known terminals and provides to the access network the configuration parameters that each of the terminal expects for proper operation.

Subscription Service is a general term that can mean any function from a traditional operator subscription service to a private network’s authentication and device policy control function.

Figure 2 below further details the network reference model through exposing the internal structure of the access network as well as the terminal and access router, and through the definition of reference points labeled R1 to R12 to denote control and user data interfaces of the access network. Solid lines indicate the path of the user data, while dotted lines indicate the flow of control information. The figure also shows an additional control entity called Coordination and Information Service, which is only needed when multiple access networks dynamically share the same communication resources, like in the case of dynamic spectrum management or dynamic resource sharing of virtual and virtualized access networks.

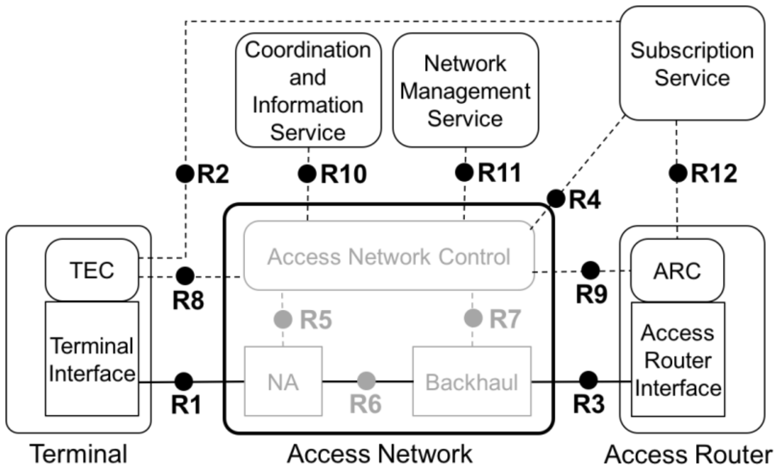


Figure 2: IEEE 802 Network Reference Model

The IEEE 802 NRM is a conceptual model allowing many different implementations to leverage the same foundation and network functions, but it is not intended as exact blueprint for the installation of a real network. Vertical applications have very specific networking requirements. To accommodate the variety of the requirements, the IEEE 802.1CF provides guidance and a common structure to build powerful networks out of the universal IEEE 802 technology building blocks.

The applicability and flexibility of the approach is demonstrated in IEEE Std 802.1CF through the mapping of the NRM to a number of deployment scenarios from a simple WLAN router, home networks, simple and more complex enterprise networks, industrial networks, public WLAN hotspots to virtualized WLAN access networks for in-building IoT services and networks for fog computing.

6.2 Generic IEEE 802 access network functional behavior

In addition to a common network reference model introduced above, the specification also provides generic functional description of the operation of an access network built through IEEE 802 technologies. Figure 3 below shows the functional phases of an access network during a session of an IEEE 802 terminal. The session begins with the terminal searching for potential access to a network and ends with either terminal or network tearing down the connectivity.

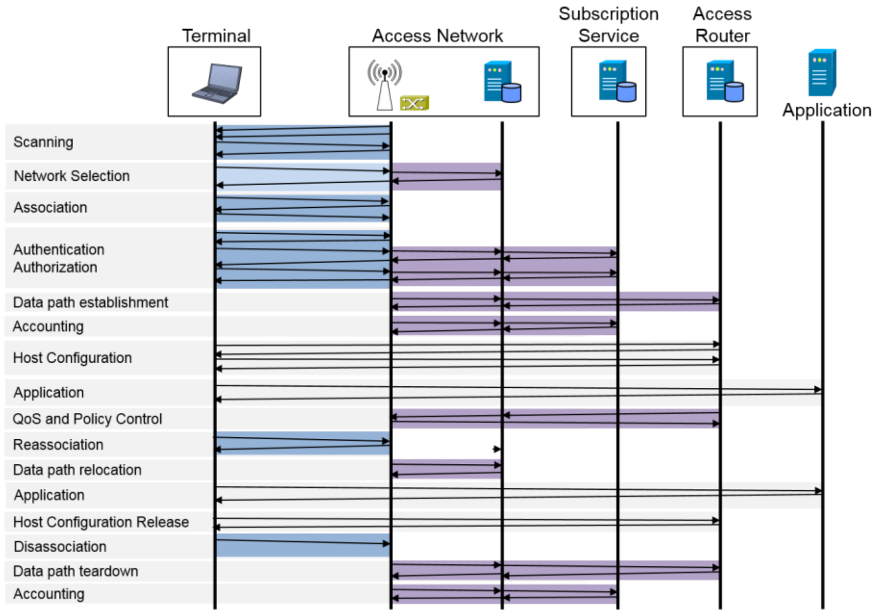


Figure 3: Lifecycle of a user session

There are many network functions invoked between the beginning and the end of a session, and the figure 3 above shows a typical example mainly aligned to the IEEE 802.11 air interface. The functional description provides a comprehensive reference of the management and control information conveyed over the reference points between the access network and external control and management entities. Such reference is not only helpful for educational purposes but also fosters commonalities in the design of the control gear of IEEE 802 access network and provides a development base towards virtualization of IEEE 802 access networks.

6.3 Network virtualization, instantiation, and slicing

While well-known models like VLANs in IEEE 802 or the network slicing solution of 3GPP provide several isolated user data planes in a common infrastructure, which can be either assigned to different services or to different tenants of the network, the network functional modeling provides the prerequisites for setting up multiple instances not only for the user data path, but also for all the control associated with a user data path. Separating not only the data paths of multiple tenants, but also all the control associated with a data path allows to address one of the main prerequisites of deployment of vertical application networks, the need for independent operational domains for each of the verticals. Virtualized IEEE 802 access networks behave exactly the same way as dedicated access networks but have the cost and scalability benefits of making use of a common infrastructure. It is the same approach that was taken through Virtual Machines (VMs) leading to the establishment of cloud computing.
Figure 4 below sketches the concept of virtualization of IEEE 802 access network. Three instances are shown based on a common infrastructure, each with its own control entities and

interfaces towards terminals and application servers reachable through the access router. As infrastructure resources can be dynamically shared among the virtualized networks, the CIS acts as control entity managing the dynamic assignment of infrastructure resources.

The virtualized access network example shown above is directing into potential network evolution beyond the current understanding of network slicing. However, the IEEE 802.1CF specification already provides the model and concepts of virtualized access networks, that can be fully build based on existing IEEE 802 protocol specifications. It is shown that realization of such powerful networking concepts with IEEE 802 technologies is a matter of implementation without the need for lengthy standardization activities. Just, let’s do it.

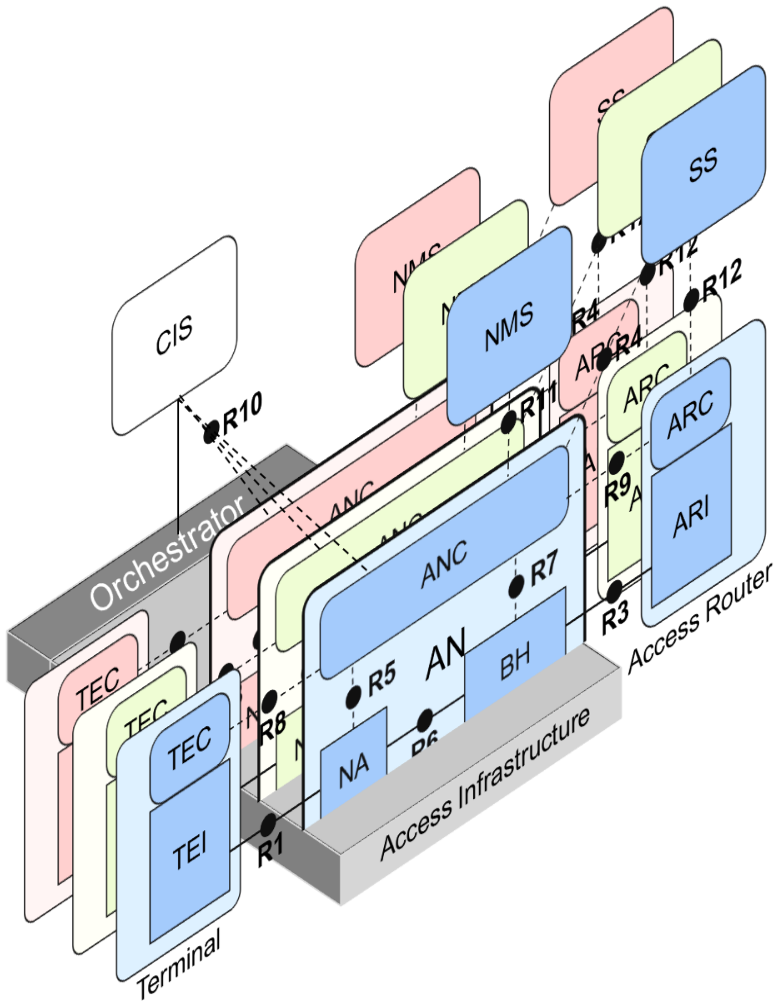


Figure 4: Multiple instances of virtualized IEEE 802 access network

7 Higher layer functions and service design in vertical application networks

IEEE 802 provides a high variety of wired and wireless solutions for the Physical and Link layer functions of communication links to serve a very wide range of requirements of applications. Each of the applications can choose out of the common IEEE 802 communication toolbox the features that fit best its particular needs without compromises or exaggerated complexities due to a common higher layer architecture.

Application specific protocol stacks for network layer, transport layer, and application layer functions have been mostly replaced through IP protocols in the past decades to leverage the huge benefits of the common IP protocol regarding flexibility, performance, availability, and cost. IEEE 802 technologies played a huge role in the transformation to IP protocols as the protocols and technologies provided excellent support for the transport of IP packets and they were able to cope with the growth of IP traffic through steady enhancements.

Therefore, usually the **Generic IP** protocol stack is used for realizing vertical applications, leveraging IPv4/IPv6 in the Network layer, TCP or UDP in the Transport layer, and well-known IP protocols like HTTP, CoAP, or MQTT in the Application layer.

However, the IEEE 802 technologies allow for more specific network solutions when special requirements or conditions arise. Legacy networking protocol stacks can be operated for transition and interoperability aside of IP protocol solutions on the same communication infrastructure. The figure below illustrates for a few examples the approaches to realize vertical application networks on top of IEEE 802 technologies.

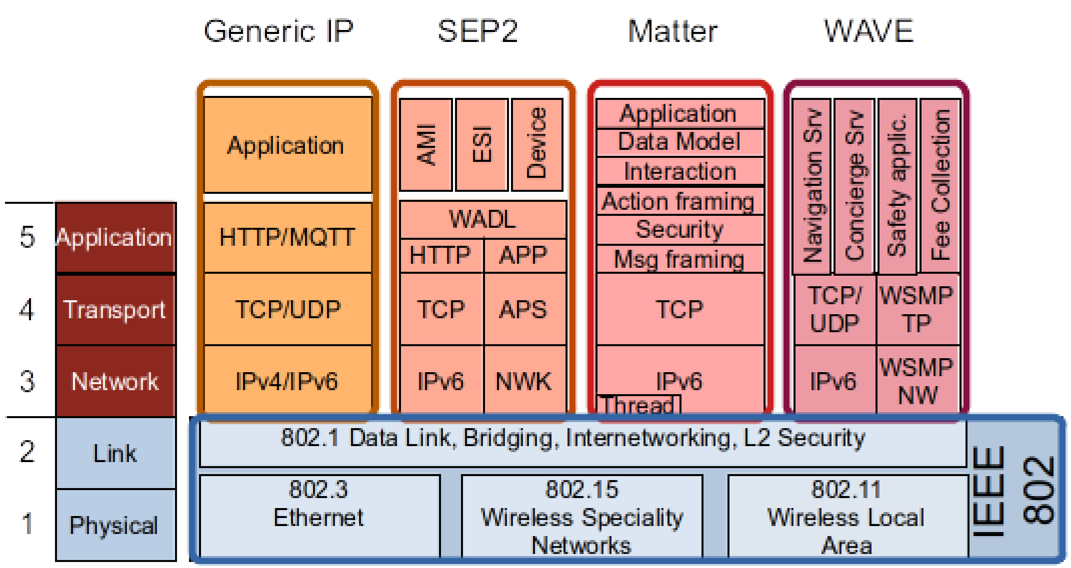


Figure 5: Examples of vertical applications based on IEEE 802 networking

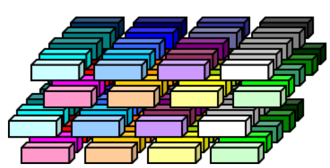
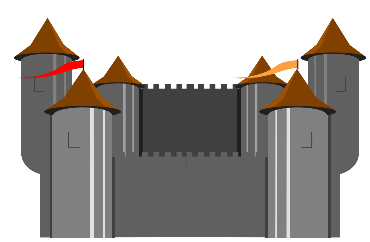
Vertical application networks often not only deploy the IP based protocol suite but leverage more specialized transport solutions.

The **Smart Energy Profile 2** (SEP 2) standard was initially specified by the ZigBee Alliance in conjunction with the HomePlug Alliance and later adopted by IEEE through IEEE 2030.5. It provides a RESTful messaging protocol for information and control for energy management in Home Area Networks for both wired and wireless networks. It can be applied on transport based on IETF IP protocols or other specialized transport protocols for particular link technologies like IEEE 802.15.4.

Matter is a smart-home connectivity standard that originated from the former Connected Home over IP (CHIP) project. It aims to provide interoperability among smart home devices and IoT platforms of different vendors and providers. Matter provides a multi-layer application protocol suite that is provided as open source for easy adoption. In addition to plain IP based connectivity over any kind of link technology it also supports Thread based connectivity over IEEE 802.15.4.

WAVE (Wireless Access in Vehicular Environments) is specified through IEEE 1609 leveraging IEEE 802.11 as wireless link technology. Various optimizations in the upper part of the Data Link layer and above were applied to cope with the particularities of a rapidly changing wireless environment. The IEEE 1609 series of specifications describes the architecture and services necessary for devices to communicate in a mobile vehicular environment. It follows the open system interconnect model and provides support for the Internet Protocol and its transport protocols. In addition, securing WAVE management messages and application messages is addressed as well as administrative functions necessary to support the core security functions.

8 The building block/stone heap and the castle – why IEEE 802 is somewhat different.

	IEEE 802	**Others e.g. 3GPP**
	Open architecture	Defined architecture
		

8.1 General paradigms

Aim	Simplicity first	Perfect solutions
Approach	Divide and conquer	Strictly hierarchical
Goal	Common solutions	Extreme optimization

	IEEE 802	Others e.g. 3GPP
Purpose	Unifying layer for network of networks	Specifically defined network structure
Scalability	Very small to large	Higher entry burden but expandable to extremely large
Spectrum	unlicensed	licensed
Ownership	Anybody	Often bound to some authorization

8.2 Provisioning (Planning and installation)

Approach	Limited size local area network	Nationwide services network
Tools	Small set of functions	Comprehensive architecture
Objectives	Link layer connectivity	End2end service delivery
Applicability	Very small to large	Higher entry burden but expandable to extremely large
Standardization	Set of individual standards	Suite of related standards
Interoperability	Layered interoperability	Service interoperability
Execution	Easy entry	Comprehensive knowledge required

8.3 Administration

Approach	Self-configuration, often distributed	Centrally controlled
Tools	Use of simple security means	Complex security architecture
Objectives	Flat-fee services	SLAs and contracts
Applicability	More choices for customization and sophisticated use cases	Better suited to standard deployments
Standardization	Limited to L1 & L2; higher layers adopted from IETF	Complete suite of specifications partly leveraging IETF protocols
Interoperability	Basic tools provided, but finally relying on peer-to-peer agreements	Fully specified
Execution	Very scalable depends on operational needs	Only full scope according to specifications

	IEEE 802	Others e.g. 3GPP

8.4 Operation

Approach	Usually over-provisioning used to avoid operational complexity and expenses	Dynamic re-adjustments of network resources to optimize operational cost
Tools	Simple means for verification of proper operation	Comprehensive monitoring
Objectives	Simplicity and automation	Full control and deep insights
Applicability	Keep bits flowing	Generate value
Standardization	Comprehensive standards for automation	Adjustable interfaces for operational excellence
Interoperability	Plug and play	Plug and configure
Execution	Switch it on and let it run	Operations center

8.5 Maintenance

Approach	Highly modular to allow for gradual replacements and enhancements	Introduce a next generation end-to-end network for the next level
Tools	Incremental enhancements	Complete replacements
Objectives	Foster and grow	Revolutionize the network
Applicability	Incremental adjustment of network capabilities	Harmonized infrastructure renewal
Standardization	Individual standards enhancements	Generational suites of standards
Interoperability	Forward and backward compatibility	Generational interworking
Execution	One piece at a time	Regular swap of complete infrastructure

8.6 Troubleshooting

Approach	It depends	Count and measure everything
Tools	Simple tools for detection and localization	Comprehensive network management suite
Objectives	Base functions for proprietary	Ensure detection of any

	IEEE 802	Others e.g. 3GPP
	solutions and common sense	malfunction and quick recovery
Applicability	Economic solutions adjusted to the needs of the use cases	Guaranteed availability of highly complex infrastructures
Standardization	Definition of managed attributes	Standardized attributes, architecture, and procedures
Interoperability	Enable basic commonality	Interoperable higher layer network management
Execution	Low barrier to entry for vertical asset owners	Unique skill-sets and workforce

9 Conclusion

The IEEE 802 family of standards provides a solid foundation of connectivity for many kinds of vertical applications. The various IEEE 802 technologies are able to address the wide variety of requirements that result from deploying networks optimized for very specific purposes.
Through modularity and interchangeability of functional building blocks, IEEE 802 networks are suited to easily scale from very small to very large infrastructures with modest to very demanding data transfer capacities fostering not only functional but also economic competition among different approaches. Nevertheless, the various solutions follow common architectures and a common network reference model to facilitate gradual improvements and to keep necessary learning curves for design, implementation, and operation relatively flat.
Even when IEEE 802 standards are providing by far the primary transport technologies for IP based communication solutions, other network protocols, as often used for optimization or interoperability in vertical applications, are supported as well and can even run in parallel with IP on the same network infrastructure.

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