Future Network & MobileSummit 2011 Conference Proceedings
Paul Cunningham and Miriam Cunningham (Eds)
IIMC International Information Management Corporation, 2011
ISBN:978-1-905824-25-0

FLAVIA: Towards a Generic MAC for 4G Mobile Cellular Networks

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Abstract: The future 4th generation IMT-Advanced standards for 3GPP and IEEE 802.16 are LTE-A and IEEE 802.16m, respectively. While at a detailed level IEEE 802.16m and 3GPP LTE-A seem to be significantly different, on a conceptual and functional level both technologies use similar approaches for medium access and radio resource management and are very similar at the PHY layer. In this paper, we analyse both technologies with the goal of finding common functional subsets which can be used as building blocks for a generic and extensible MAC for future mobile cellular networks. To this end, we propose a systematic categorization into services, interfaces, functions and primitives as a first step towards achieving generic architecture.

Keywords: MAC, broadband wireless access, LTE-A, IEEE 802.16m

1. Introduction

Future Broadband Wireless Access (BWA) networks are either based on the IEEE 802.16 WirelessMAN family of standards, or on the Long Term Evolution (LTE) of 3GPP. Specifically, the 4th generation (4G) mobile broadband wireless access systems, defined by the Radio sector of the International Telecommunication Union (ITU-R) as International Mobile Telecommunication-Advanced (IMT-Advanced) [1] Radio Interface Technologies (RITs), will be based on IEEE 802.16m [2], or 3GPP LTE-Advanced (Rel. 10) [3].

IEEE 802.16 and 3GPP selected Orthogonal Frequency Division Multiple Access (OFDMA) as sole radio access technology. Since both employ similar physical layer techniques a unified hardware and software platform could be developed able to support both technologies. However, both BWA standards are primarily developed according to the requirements of mobile operators and offer various specialized mechanisms on MAC layer for optimized performance of typical services like voice, video conferencing or web-browsing. Additionally, current BWA standards lack the flexibility to implement support on MAC layer for new applications or operational scenarios in a simple and well-defined manner. As an example, support for machine-to-machine (M2M) applications requires mainly modifications on MAC; in order to support these, the standard specifications have to be modified or new standard projects must be initiated.

The EU FP7 project FLAVIA [4] aims to define a modular architecture focusing mainly on the MAC layer which is on the one hand flexible enough to allow for simple implementation of novel mechanisms, and on the other hand supports advanced PHY features for high spectral efficiency. Such modular architecture would allow network equipment vendors as well as the research community to implement and test novel schemes, thus narrowing the gap between theoretical research and practical implementations. For smaller companies, the FLAVIA approach is an opportunity to reduce the entry barrier into the BWA market by developing specialized solutions.

The contribution of this work is as follows: first, we compare 3GPP LTE-A and IEEE 802.16m both from the physical layer as well as from the MAC layer perspective, with a special focus on the latter. Second, we show how an analysis on functional level of the MAC layer can leverage the development of a MAC architecture which is both *generic* (i.e. it can be used to implement both technologies) and *efficient*, in the sense that redundancy in architecture and implementation is avoided as much as possible.

2. Comparison of LTE-Advanced and IEEE 802.16m

2.1 -Physical Layer Aspects and Frame Structure

In IEEE 802.16m [5] and LTE-A [6] the OFDMA time/frequency resource grid is subdivided into physical basic resource blocks (PRBs, the IEEE 802.16m equivalent is a *slot* or *physical resource unit* – PRU) which consist of a number of subcarriers in frequency domain and several OFDM symbols in time domain. Both technologies support distributed and contiguous permutation schemes. In the first case the data is spread over the carrier bandwidth and optionally in time to achieve frequency/time diversity, reducing the probability that a whole data block is dropped due to frequency selective fading or interference. In the second case logical resource units are mapped one to one to the corresponding physical resources, allowing for exploitation of multi-user diversity by frequency-selective scheduling. However, inter-cell interference must then be mitigated by frequency partitioning or by coordination schemes.

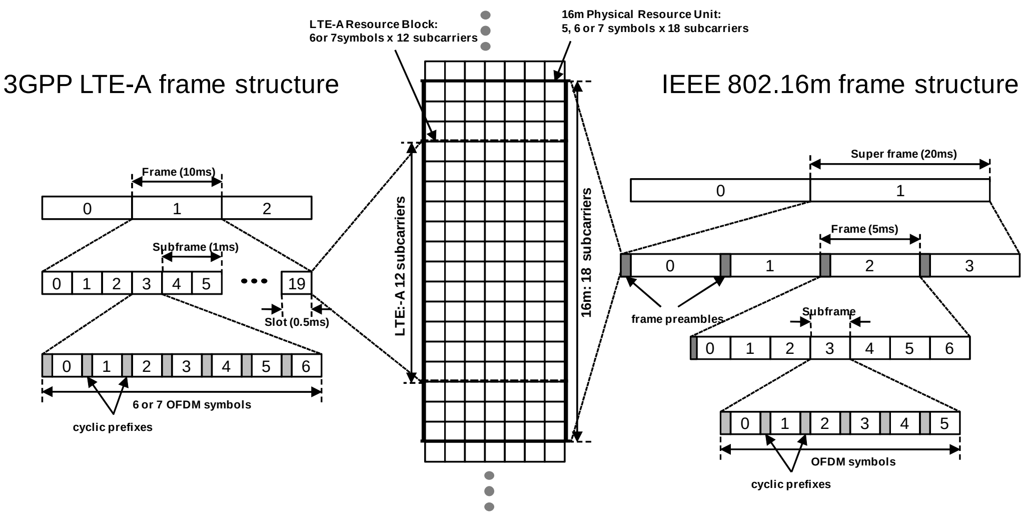

Figure 1: Comparison of LTE-A and IEEE 802.16m frame structure

The basic frame structure of both technologies is illustrated in Figure 1. As it can be seen, they are quite similar, as both comprise *frames* (with length of 10ms in LTE, 5ms in 801.16m) and *subframes* (variable length depending on the system configuration). IEEE 802.16m additionally introduces *superframes* to enable a more flexible approach for the transmission of basic system parameters like basic frame configuration, HARQ information, etc. In IEEE 802.16m, frame preambles are transmitted over the whole channel bandwidth at the beginning of each frame for synchronization purposes, while in LTE synchronization signals are placed around the center frequency every 0^{th} and 10^{th} slot. Both technologies employ reference (pilot) signals on dedicated resource elements for channel estimation and support frequency and time division multiplexing (FDD and TDD). In TDD, a configurable number of subframes are exclusively used for downlink or uplink transmissions, respectively.

Support for different MIMO techniques is essential for reaching the high IMT-A requirements. Both LTE-A and IEEE 802.16m support SU-MIMO with different feedback types, e.g. sounding-based for TDD systems, or feedback of precoding matrix indices (PMIs) for scenarios without channel reciprocity. Additionally, MU-MIMO is specified in order to increase spectral efficiency to the required level. Finally, both technologies support coordinated multipoint transmission (CoMP) or Multi-BS MIMO as it is named in 802.16m. However, this feature is not yet fully defined in both standards.

Based on this comparison, the main difference found between both technologies at this layer is that while 802.16m uses OFDMA in uplink and downlink, LTE-A uses SC-FDMA (Single-Carrier Frequency Division Multiple Access) [7] in the uplink in order to reduce the peak-over-average power ratio (PAPR).

2.2 -Functions on MAC Layer

Even though at first glance the LTE-A MAC layer might seem dramatically different than the IEEE 802.16m MAC layer, a lot of commonalities can be found between them. This is illustrated in Figure 2, where the air interface protocol stacks of LTE-A and 801.16m are compared. In both cases, a radio resource control sublayer is introduced in the control plane, denoted as Radio Resource Control (RRC) protocol in LTE-A and Radio Resource Control and Management (RRCM) functions in case of IEEE 802.16m. In the data plane, an adaptation sublayer is defined which is denoted as Convergence Sublayer (CS) in 802.16m and Packet Data Convergence Protocol (PDCP) in LTE-A. These sublayers interface to a MAC sublayer which is responsible for packet operations that are independent of the higher layers, such as fragmentation and concatenation of SDUs into MAC PDUs, transmission of MAC PDUs, QoS control, ARQ, etc. In the case of LTE-A these functions are located in two further sublayers, the Radio Link Control (RLC) protocol and MAC. IEEE 802.16m defines the MAC common part sublayer (CPS) comprising common MAC and RRCM functions.

The CS and the PDCP provide adaptation between higher-layer protocols like IP and the MAC and PHY layers of the 802.16m and LTE-A radio access, respectively. Both sublayers are responsible for IP header compression, where both technologies support Robust Header Compression (RoCH), and 802.16m additionally supports Packet Header Suppression (PHS). However, while in LTE-A the PDCP sublayer is responsible for ciphering and integrity protection (control plane only), in 802.16m these functions are part of the lower MAC sublayer. In addition, while the 802.16m CS includes utilities for classification of higher layers PDUs into MAC connections, in LTE-A the classification of higher layer PDUs into logical channels is part of the RLC sublayer.

The RRCM functions in 802.16m and the LTE-A RRC in the control plane in both technologies offer a similar wide range of radio resource controlling functionalities including (among others): broadcasting of cell information, MS cell (re-)selection, network entry, link adaptation, location tracking (for location based applications), mobility management including intra- and inter-Radio Access Technology (RAT) handover procedures, connection management, power saving schemes with long term and short term inactivity cycles with paging support, security functions, point to point radio bearers, measurements and reporting, relay functions, self organization, load balancing and multi carrier aggregation, BS-MS capabilities exchange and general error handling procedures.

802.16m's MAC sublayer has functionalities similar to the RLC and MAC sublayers in LTE-A. The RLC sublayer in LTE-A supports Transparent Mode (TM), Unacknowledged Mode (UM) and Acknowledged Mode (AM). In UM and AM modes the traffic is mapped to dedicated logical channels with in-sequence delivery and additionally ARQ support in the AM mode. With TM, traffic is mapped to broadcast and control channels without any further operations. IEEE 802.16m provides similar functions by choosing appropriate parameters for ARQ.

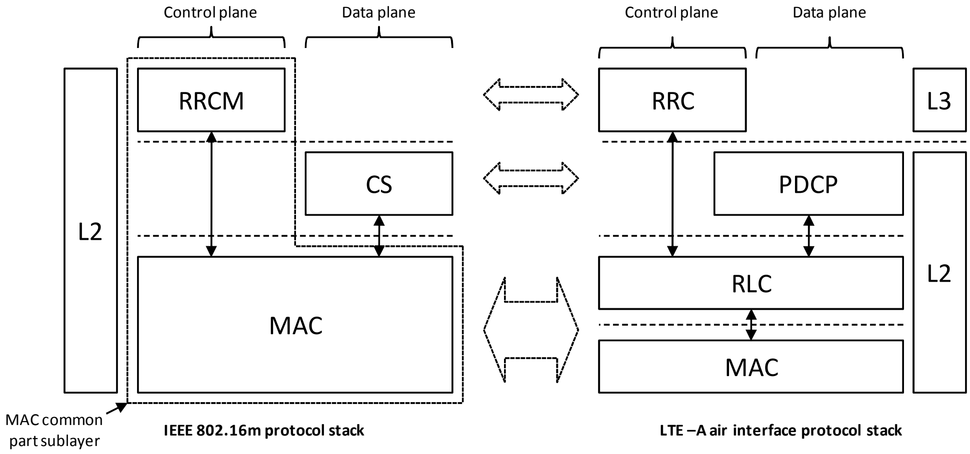

Figure 2: comparison of LTE-A and IEEE 802.16m protocol stack

MAC layers in both technologies include support of low latency HARQ for unicast data traffic, multiplexing (de-multiplexing) of MAC Service Data Units (SDUs) into MAC Packet Data Units (PDUs), random access procedures, feedback channels and power headroom reports as well as UL bandwidth requests-grant procedures. As stated above, the low level MAC functionality in IEEE 802.16m also includes encryption and integrity protection (control only) which is part of the PDCP sublayer in LTE-A.

HARQ support in both technologies includes Incremental Redundancy (IR) as mandatory mode with Chase Combining mode as a special case of IR. An adaptive asynchronous HARQ mode was adopted in the DL direction, where the modulation and coding scheme (MCS) for HARQ retransmissions may be different from the initial transmission. In the UL direction, adaptive as well as non-adaptive synchronous HARQ modes are supported in both technologies. For cell edge users having low SINR, where several HARQ retransmissions are expected for same initial transmission with a resulting significant large delay, LTE-A adopts a TTI bundling mode in which several HARQ redundancy versions are transmitted in consecutive subframes, resulting in an increased probability for correct reception by the base station.
Finally, the random access channels in LTE-A and 802.16m support contention-based and contention-free access methods for handover, bandwidth/scheduling and network (re-)entry, including definitions for contention resolution procedures.

2.3 -Radio Resource Management functions

Radio resource management is crucial for the performance of wireless networks. However, implementation details are mostly not defined in the specifications and are therefore vendor specific. Described are feedback mechanisms, and, if necessary, measurement metrics.

Exceptions are mechanisms which require the collaboration of base station and mobile station like in case of power control, and the interference mitigation section by means of fractional frequency reuse in IEEE 802.16m, which describes the frequency partitioning and partition assignments of mobile stations in quite detail.

Due to the similarity of the PHY and MAC of LTE-A and IEEE 802.16m the RRM functions and algorithms are similar for both technologies. However, different PHY procedures, control channel definitions, feedback schemes, and QoS parameters impose different constraints and requirements on the RRM algorithms.

Both technologies support uplink and downlink power control, with focus on the uplink for means of interference mitigation. For this purpose, 3GPP LTE-A defines fractional power control (FPC) which assigns terminals closer to the cell edge less power in order to avoid high interference to adjacent cells. IEEE 802.16m specifies open and closed loop uplink power control, where target SINR values can be adjusted individually for each terminal. In both technologies the base stations can exchange interference information to facilitate power control to reduce interference.

Scheduling for both technologies is conceptually identical, with schemes like proportional fair, deficit round robin, earliest deadline first, etc. Differences arise from the resource allocation and signalling mechanism. IEEE 802.16m defines MAP Information Elements (IEs), which are different from the LTE-A Downlink Control Information that is mapped on the Physical Downlink Control Channel (PDCCH). The difference in the information element enforces a different frame structure and allocation size. For example, 802.16m supports multiple allocations per user at each sub-frame, as opposed to only one allocation in LTE-A. Furthermore, IEEE 802.16m supports group resource allocations, which is not supported by LTE-A. Another example of a mechanism that requires different treatment by the scheduler is HARQ TTI bundling, which is supported only in LTE-A.

Both LTE-A and 802.16m support adaptive fractional frequency reuse schemes by means of power masking (soft frequency reuse) and inter-BS interfaces for the exchange of load- and interference-related information for dynamic interference cancelation and coordination (ICIC) [8]. The feedback control channels of both technologies differ slightly, such that RRM algorithms, although working according to the same basic principles, have to be adapted. Specifically, the algorithms are required to support the technology attributes and feedback mechanisms, such as precoding codebooks, MIMO modes, reporting periodicity patterns, and modulation and coding schemes.
Table 1 provides an overview of MAC and RRM related functions in LTE-A and IEEE 802.16m

3. Towards a generic MAC with FLAVIA

As we have seen in the previous section, on a *conceptual* level 802.16 and LTE-A have many commonalities. However, the differences in implementation are large enough to effectively prohibit a common MAC architecture until now. One of the main challenges of FLAVIA is therefore to identify common mechanisms which constitute the basic building blocks of *both* technologies, but which are not exclusively meant to deploy 802.16 or LTE-A. Such building blocks should also allow developing and implementing non-standard mechanisms and extensions to LTE and 802.16, or even designing completely new scheduled access MAC protocols.

One of the major goals of this approach is *efficiency*, at the one hand in terms of system performance by enabling innovative methods for radio resource control and virtualization, but on the other hand also for development and economical costs by providing a *common standardized architecture* in the software and logical protocol plane. Towards the PHY layer, this requires an additional abstraction interface. However, we expect that this overhead is well justified in the trade-off for the additional benefits and with the quickly increasing hardware capabilities.

Table 1: Comparison of LTE-A and IEEE 802.16m MAC and RRM related functions

Function/Technology	LTE-Advanced	IEEE 802.16m
HARQ	synchronous and asynchronous N-stop-and-wait with incremental redundancy, TTI bundling	synchronous and asynchronous N-stop-and-wait with incremental redundancy
ARQ	Sliding-window protocol with optional in-order delivery	Sliding-window protocol with optional in-order delivery
Random access	Random access channel (RACH); Contention-based and non-contention based; Uses Zadoff-Chu sequences	CDMA-based bandwidth request channel with 3- or 5-step contention mechanism and quick bandwidth request message.
QoS concept	Based on EPS radio bearers with associated QoS class index	Based on service flows mapped to specific QoS classes
Channel feedback	CQI, CSI, PMI, RI over dedicated feedback channels	CQI, CSI, PMI, RI over dedicated feedback channels
Power control	open-loop/closed-loop/fractional	open-/closed-loop
Modulation and coding	Adaptive; from QPSK to QAM 64; code rate adaptation	Adaptive; from QPSK to QAM 64; code rate adaptation
Layer 3 adaption	packet data convergence protocol (PDCP), ROHC	convergence sublayer (CS), ROHC, PHS
Interference mitigation schemes	static/adaptive soft frequency re-use, interference coordination	static/adaptive soft frequency re-use, interference coordination
MIMO support	open/closed-loop SU-MIMO (up to 8x8), closed-loop MU-MIMO with up to 4 users, 1 stream each, sounding and codebook feedback	open/closed-loop SU-MIMO (up to 8x8), open/closed-loop MU-MIMO with up to 4 users, 2 streams each, sounding, codebook and channel correlation matrix feedback
Link reliability	RLC sublayer with ARQ and support for transparent, unacknowledged and acknowledge mode	ARQ with support for in-order delivery

In order to identify the MAC building blocks, we first need to identify the *services* that all scheduled access MACs would require. With the term *service* we refer to technology-independent MAC operations that have to be implemented through technology-dependent operations. The *service* definition is technology-independent, but each service has to be implemented by means of technology-dependent mechanisms and logic operations. Note that services like data transport or scheduling are part of any scheduled access MAC, even though they can be implemented through different technologies, and therefore differently. Technology-dependent mechanisms are defined as *primitives*, which are offered by both MAC and PHY layer, and which can be possibly combined in simple or complex *functions*. Furthermore, services and functions expose *interfaces* towards other layers and services.

Note that we do not aim at re-inventing or proposing new primitives. On the contrary, the objective of FLAVIA's architecture is to utilize available primitives, thus allowing the developer to tune existing services as well as facilitating the implementation of new functions and services. Within the framework of the FLAVIA project, we are targeting a generic architecture for scheduled access wireless networks, as the one depicted in Figure 3, which is a generalization and extension of both 802.16m and LTE-A. The architecture of user equipments or the one of relay stations is similar to the one of base stations; generic MAC services are in common, but for some specific functionalities. Hence, a modular architecture design, as the one we target, allows to jointly designing different nodes, namely *entities*, with minimal effort in the development of entity-specific functionalities. For the sake of clarity, here we refer to the base station service architecture, and we point out some example to show the difference in implementing either a base station or a different entity.

As shown in Figure 3, the base station service architecture is composed of modules, each representing a service that a scheduled access technology is expected to provide in the MAC layer. Each module contains one or more functions, whose name is indicated by an “F:” prefix in the figure. For clarity of presentation, in the figure we omit most of the functions used by each service, and simply show a few relevant examples. Note that services can have common functions and use common primitives, which also means that functions can be reused when creating new services.

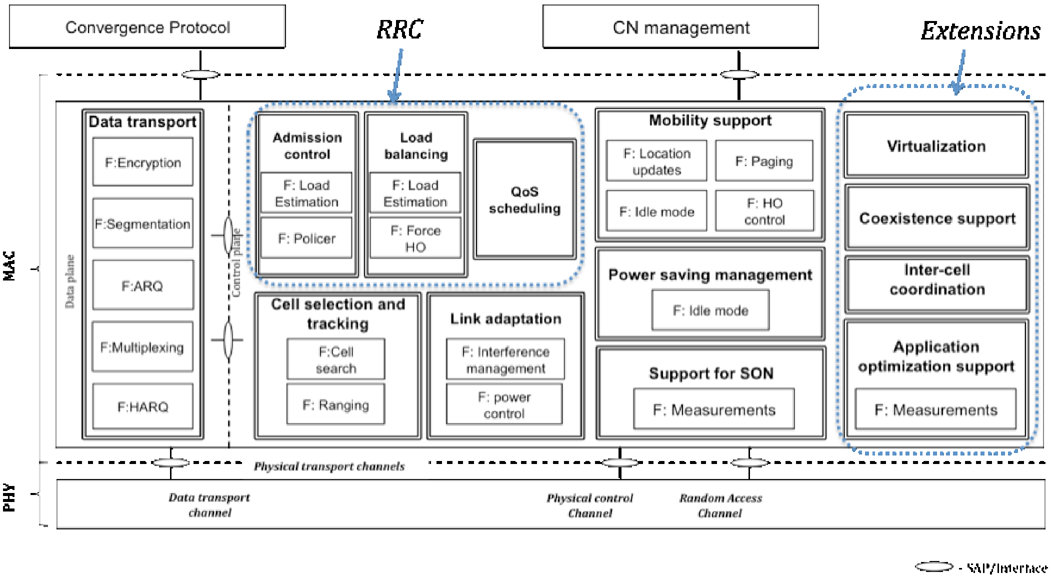

Figure 3 : High-level MAC architecture for scheduled access services

Data transport represents an example of service that is needed in each and every scheduled MAC. It provides processing and multiplexing of user or control data before sending to the physical layer. Data can be transported with protocols to increase transport reliability, like ARQ and/or HARQ. Data can be encrypted. Hence we have five functions to be implemented: security, segmentation, ARQ, HARQ, and multiplexing.

Admission control and *load balancing* are examples of services that use common functions. In fact, they both need to estimate the load and collect channel and location reports from mobile stations. However, other functions like forcing user’s handover or managing the admission control policy are specific of *load balancing* or *admission control*, respectively. It is worth noting that, *load balancing*, *admission control*, and *QoS scheduling* provides those services that are commonly denoted as RRC, as enlightened in the figure. *QoS scheduling* is the generic scheduling service, which can be implemented in a number of configurations accounting for the details of the PHY and QoS goals, if any are targeted. RRC services are an example of services that require the implementation of many functions on the base station, while only a few simple functions are required on the user equipment, e.g., a few functions to allow the UE to report about capabilities and channel status.

Link adaptation, *power saving management* and *mobility support* are other commonly adopted services, though they can be implemented in quite a different way in LTE-A and in 802.16m. For example, both LTE-A and 802.16m define adjustable activity cycles for the terminal to achieve power saving when the traffic is low. Likewise, 802.16m defines power saving activity cycles for femtocell base stations. On the one hand, the definition of the activity cycles and their parameters are quite similar in the two standards. On the other hand, the mechanism that triggers power saving cycles in LTE-A just uses an inactivity period timeout, while 802.16m standard requires a message exchange between BS and UE, with a final BS command that forces the UE to switch to power saving cycles.

The services briefly described so far are common to both 802.16m and LTE-A. However, we remark that the actual implementation of the services has to be technology-dependent, i.e. functions, primitives, and interfaces are specific for either 802.16m, LTE-A or another scheduled access technology. In the figure, the service named *Support for SON* (Self Organizing Networks) is further needed to cover future extensions of LTE-A and 802.16m that are already planned. Other services can be introduced to extend/augment the architecture, e.g. *virtualization*, *coexistence support*, *support for application optimization*, *inter-cell-coordination*, and so on. These services are particular examples targeted by the FLAVIA project, but other services could be listed here as well. In particular, the *virtualization* service is meant to run multiple instances of a base station on the same platform, possibly supporting different radio technologies. *Coexistence support* is a service needed to handle the presence of multiple overlapping cells, which do not belong to the same network, and thus they do not explicitly cooperate to harmonize the utilization of resources. *Support for application optimization* makes use of local traffic and channel statistics in order to improve the performance of running applications. Hence it has to be aware of application traffic and set MAC/PHY parameters or optimize scheduling to increase the user quality of experience for those applications. *Inter–cell coordination* includes the possibility to orchestrate the use of (cooperative) MIMO techniques and (fractional) frequency reuse schemes in an entire neighbourhood. The implementation of these extension services, as well as the implementation of basic services, mostly requires the utilization of measuring functions and control message exchange. Remarkably, MAC services do not require new primitives; they just need to use the existing ones.

4. Conclusions and Outlook

The comparison of the two major future BWA technologies, 3GPP LTE-A (Rel. 10 and beyond) and IEEE 802.16m revealed many similarities in concepts and features. On PHY layer, the differences are mostly in terms of frame structure and uplink transmission scheme. On MAC layer, at a first glance the differences seem to be larger. However, a closer look reveals that at least the core features are conceptually identical and some functions also have the same feature set. Thus, compared to the much larger differences between IEEE 802.16e and 3GPP LTE Rel. 8, the gap between future BWA technologies is becoming remarkably smaller. In this paper we have illustrated how a careful analysis of services and functions on MAC layer can help to identify commonalities between 802.16m and LTE-A, which build the foundation for a potential common, generic and flexible MAC architecture. The benefits of such an architecture would range from helping reducing implementation costs for “pure” 802.16m/LTE-A systems to facilitating the optimization and evolution of such systems by simplifying the development of future MAC layer extensions as required for instance for supporting machine-type communications or cloud services. As future work, our next step will be to conduct a detailed analysis of the required primitives at MAC and PHY layer to support the identified required services and functions.

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