A Utility-based Framework for Performance and Energy-aware Convergence in 5G Heterogeneous Network Environments

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***Abstract*—The integration of a broadcast oriented RAN architecture into a convergent framework for heterogeneous networks offers two major contributions. On the one hand, it presents an interesting solution to satisfy the exponential growth of the mobile video data traffic, and on the other hand, it is also identified as a promising key technology, that can contribute to improve the energy efficiency of 5G networks. This work proposes a novel Convergent Architecture for Broadcast, Broadband and Cellular services (CABS). This architecture is complemented with the Performance and Energy-aware Access (PEC) network selection algorithm. This joint solution offers a balanced trade-off between the user perceived QoS and the network energy efficiency in challenging heterogeneous scenarios. Furthermore, this approach guarantees the broadcast service continuity in harsh environments, and therefore, is helpful in one of the most critical scenarios for broadcasting industry: mobile and indoor reception. The proposed solution was modelled and tested in Network Simulator version 3 (NS-3), in which among other updates, a first version of an ATSC 3.0 model was introduced.**

***Index Terms*—5G, ATSC 3.0, converge, energy, heterogeneous networks, LTE, mobile TV, utility-function, WLAN**

I. Introduction

ABOUT fifteen years ago, when Gustafsson and Jonsson introduced the *Always Best Connected (ABC)* vision [1], they have already envisaged a heterogeneous scenario with a plethora of independent Radio Access Technologies (RAT) working together, where users were always connected to the optimum delivery platform. They identified four main actors involved in any convergence scenario: users, different technologies access operators, network service providers and application service providers. A similar vision was shared by the ITU [2] in the recommendation *Optimally Connected, Anywhere, Anytime* (ITU-R M.1645). This report defined the framework and objectives for the systems beyond IMT-2000. It was proposed, for instance, to increase the system capacity and Quality of Service (QoS) by exploiting the network heterogeneity with a better usage of radio resources. In [3], a tutorial of the network selection problem for heterogeneous environments was presented, including insights of the basic stages involved in network ranking. These seminal works were mainly focused on broadband and cellular technologies, where with the dawn of the Digital Terrestrial Television (DTT) other approaches had also considered the broadcast services as key actors for the heterogeneous environments [4], [5], [6]. Fig. 1 illustrates a heterogeneous urban scenario, including a DTT network.

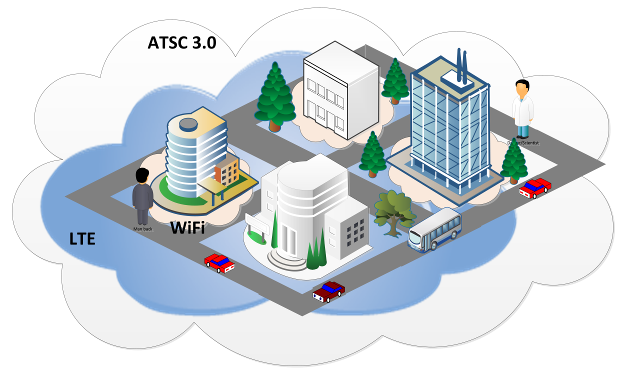


Fig. 1. PEC deployment scenario.

More recently, the development of the fifth generation (5G) of wireless communications, has brought the integration of different radio access technologies into the focus of the research community once again. By definition [7], 5G should support a wide range of verticals gathered in three main use cases: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and ultra-reliable and low-latency communications (URLLC). Theses use cases were defined with very different cost efficiency and functional requirements [8]. Technologies like software-defined networking (SDN) and network functions virtualization (NFV) provide the enablers and the flexibility to deal with the challenge of creating multiple logical networks [9]. In fact, in the 5G framework, the cooperation of different networks is covered under the multi-connectivity (Mco) concept, where users can be connected via multiple communication links to any system architecture. In [10], for instance, a converged architecture is presented to support multi-connectivity with joint traffic steering, aggregation, switching, splitting and packet duplication for multiple RATs. This approach can also be the key to improve the reliability of the data transfer on URLLCs [11] or to increase the throughput on the video delivery for eMBB [12].

In the meantime, the report published in [13] indicates that the volume of video traffic (i.e. streaming, real-time applications, TV on-demand, etc.) over the Internet will reach the 82% of the total traffic by 2020, while the number of mobile devices continuous to growth. One of the components of this video volume correspond to the one-to-many linear services, where the transmitter conveys the same content to large audiences. In the Long Term Evolution (LTE) standard, the broadcast concept has been covered by the multicast capabilities offered by the Evolved Multimedia Broadcast Multicast Services (eMBMS) since Release 9. Even if further enhancements were included in Release 14 [14], this approach is not as efficient as traditional DTT broadcasting when large areas of population have to be covered with High Power High Tower (HPHT) architectures [15], [16]. On the other hand, the physical layer of the latest DTT standard, namely ATSC 3.0 [17], is more spectrum efficient than 5G NR for a signal antenna port due to the implementation of longer LDPC codes and Non-Uniform constellations [18], [19]. Apart form that, ATSC 3.0 offers an interesting additional advantage when compared with previous DTT standards. It is the only broadcast standard fully based on IP, which makes it more compatible with cellular and broadband networks in heterogeneous network scenarios [17].

Nevertheless, to the best of authors' knowledge there has not been any architecture proposal that includes ATSC 3.0 in a convergence context, which also considers 5G network broadband wireless and cellular technologies in order to support broadcast-oriented services. This paper introduces a novel convergent architecture to enable seamless connectivity and multimedia delivery in a heterogeneous network environment, which relies on cooperation between broadcast, broadband and cellular networks. In the proposed **Convergent Architecture for Broadcast Services (CABS)**, the different individual networks, powered by diverse technologies, complement each other and through seamless integration provide a common communications infrastructure for high performance services to heterogeneous receivers. In the CABS architectural context, this paper also proposes the **Performance and Energy-aware Access network selection solution (PEC)**, a user-centric approach to provide performance-awareness and energy efficiency to various multimedia wireless services to mobile receivers in challenging environments. PEC extends the classic energy-aware network selection by considering network energy consumption and operational costs (OPEX) and allows for a reliable quality assessment, which is fundamental for market success. The proposed solution has been tested in the Network Simulator 3 (NS-3) software, in which, alongside models for cellular and wireless broadband networking, for the first time **a model of a full IP-based DTT broadcast standard, ATSC 3.0, was included and used**. The results show how PEC, built on top of the CABS architecture proposal, outperforms the non-convergent solutions.

II. Related Work

A. Cellular and Broadcast Convergence

The convergence between the broadcast and cellular networks has drawn the attention of researchers and main actors involved in media and entertainment industry for some time now. The scarce wireless bandwidth and increasing demands of the user expectations have put the cooperation of different networks under the spotlight on a recurring basis. Table I summarises the main references.

In [4], for instance, a hybrid system composed by DVB-T [35] and GPRS was proposed to enable interactive broadcast services. The authors claimed that broadcast oriented services would be offered more efficiently through a DTT system, such as DVB-T. The coupling was performed by an external IP-backbone network, where the GSM interacting channel defined within DVB [36] was the key for the success of the proposed architecture. In this first approach, the IP packets were directly encapsulated in the MPEG-2 transport stream using the Multi Protocol Encapsulation Method (MPE), standardized within DVB. The coupling was done either at application or transport/network layers. At that time, the size of the DVB-T receivers and the power consumption were considered critical factors for the success of hybrid terminals. In [5] and [20], the authors proposed a cooperation between DVB-T and the Universal Mobile Telecommunication System (UMTS). The main objective was to combine the broadcast delivery of rich multimedia content with a more personalized unicast transmission. In this case, the additional content could be obtained either via broadcast IP or via mobile IP network, depending on the number of users subscribed to a particular content. On the other hand, another important goal of the proposal was to guarantee a seamless and wireless interactive connection to various multimedia converging services for mobile receivers. Later, the authors extended the cooperation framework to include broadband wireless services (802.11b) and have defined an interactive DVB network with two parts: a broadcast channel and an interaction channel (unicast/broadband) [6].

Gardikis *et al.* [21] suggested that the previously defined interactive scenarios could be more efficiently deployed with the use of the technology proposed by DVB-H [37] in combination with existing cellular and broadband technologies. Afterwards, in [23] DVB-H and UMTS were proposed to jointly deliver and support multimedia applications. In this particular study, the unicast data of the Internet Service Provider (ISP) for the interactive return channel was played out into the broadcast channel using a data carousel. What is more, they introduced for the first time a cost-function between the transport and application layer to select the optimum network. The main objective of this function was to offload the interactive network when required, while the network decision was transparent to the user. In the MING-T project, a new multi-standard convergence model was presented. The authors proposed integration of DVB-H and the Chinese digital terrestrial standard DTMB, with UMTS and WLAN [22], [26]. In this case, the main goal was to research, develop, prototype and validate an architecture that could provide seamless access for converged cellular, broadcast and broadband networks. The authors presented a common middleware framework that provided a unified interface to the upper application layers. In particular, each Radio Access Network (RAN) was connected to the common IP backbone through its own gateway, and eventually, this backbone was connected to the Internet. They also defined a convergence sublayer, which was in charge of the handover between different networks and encapsulation of IP packets. Other interesting approaches for the convergence of first generation broadcasting standards and cellular networks can be found in [24], [25], [27].

Ilsen *et al.* proposed a convergence scenario (TOoL+) including a second generation DTT standard for the first time, namely DVB-T2 [38]. Their main objective was to extend

TABLE I
BROADCAST, BROADBAND AND CELLULAR CONVERGENCE IN THE LITERATURE.

DTT Standard	Cellular/Broadband Standard	References	Service Scenarios
DVB-T	GPRS /UMTS	[4], [6], [5], [20]	- Enable interactive broadcast services. - Broadcast based media-on-demand. - Enriched mobile interactive television. - Seamless and wireless interactive connection to various multimedia converging services. - User service-centered applications with rich multimedia content. - Broadcast service continuity using mobile telco network. - Push/Catching of web content. - Emergency Systems.
	WLAN (802.11b)	[6], [21]	
DVB-H	GPRS/UMTS	[21] [22] [23] [24]	
	WLAN (802.11b)	[21] [22] [25]	
DTMB	GPRS/UMTS	[22] [26]	
	WLAN (802.11b)	[22] [27]	
DVB-T2	LTE-A	[28] [29] [30] [31]	
NGH	LTE-A	[32]	
ATSC 3.0	LTE-A	[33]	
5G	WLAN, LTE	[34] [12]	

the Long Term Evolution (LTE) mobile networks service area by an HTHP infrastructure with a much larger coverage area per transmitter. They introduced a slightly modified version of LTE-A, which takes advantage of the Future Extension Frames (FEF) defined in DVB-T2 for the joint transmission of classical broadcast streams and the TOoL+ service within the same RF channel. Several performance results, including field trials, were presented in [28], [29] and [30]. In [31], a similar idea was pursued. The authors argued in favor of a broadband-broadcast cooperation through the concept of a common physical layer, providing a cooperation framework for broadcast and cellular services. In particular, a common physical layer based on the 3GPP LTE eMBMS and DVB-T2 standards was presented. Finally, in [32] the benefits, both in service and coverage extension, of planing cooperative DVB-NGH/LTE networks were presented. Nevertheless, the relevant definition of a common cooperation infrastructure was not comprehensively addressed.

More recently, the emergence of ATSC 3.0 [39], which has been designed to be all-IP based, has presented an opportunity for new convergence scenarios. In [40], for instance, the ATSC 3.0 Dynamic Adaptive Streaming over HTTP (DASH) performance over LTE eMBMS is studied. Lee *et al.* presented a cooperation framework for ATSC 3.0 and LTE-A to deliver high-quality and reliable contents with a Scalable High Efficiency Video Coding (SHVC) scheme. In this case, the receiver was able to select the best network according to the network signal strength or the Signal-to-Noise-Ratio (SNR) [33]. The work also presented the first results of the trials carried out in Jeju Island (Korea).

Eventually, Ordanchenko *et al.* [12] studied the convergence concept from a multi-connectivity point of view, where the receiver supports simultaneous connectivity and aggregation across different technologies [34]. The main objective of the project was to design a dynamically adaptable 5G network to seamlessly switch between different modes and networks.

B. Energy-Aware Network Selection

The impact of Information and Communication Technology (ICT) in the energy world consumption continuous to growth [41], and therefore, the management of the power savings in the 5G era presents also strong motivation for the researchers. The energy management in the heterogeneous environments

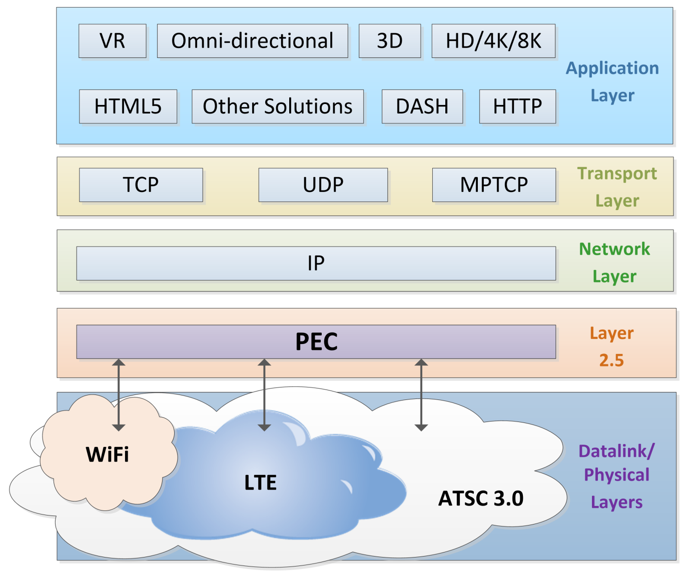


Fig. 2. Performance-Energy-aware Convergence (PEC) Framework

can be addressed with different approaches, such as improving the video coding and video delivery technology [42] - [43], focusing on the operation modes [44] or selecting the most efficient RANs [45]. The latter is one of the principles leading the proposed PEC architecture. This subsection covers the most recent works dealing with network access solutions for heterogeneous networks, with particular focus on algorithms that consider energy, operational costs and performance awareness jointly.

Trestian *et al.* [45] defined an architecture, where the optimum RAN was selected based on the network conditions, monetary cost of each service, the user equipment energy consumption and the user preferences. The estimated user energy consumption for the real time application was computed following the work presented in [46]. The authors compare their results with the work covered in [47], where the energy and costs per service were also critical parameters, and they obtained an energy consumption reduction up to the 28%. Desogus *et al.* [48] presented a similar approach with a solution that considered the received signal strength and the cost-per-user among other parameters, but they did not include any energy consumption metric.

Petander *et al.* [49] proposed an energy-aware handover algorithm based on energy consumption measurements. They

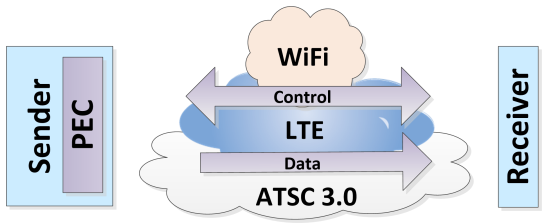


Fig. 3. PEC Framework - Dual Communication Channel Principle.

also proved that the energy consumption for UMTS bulk data transfer over the cellular network could be several hundred times higher than that of the broadband network. Huang *et al.* [50] studied the network energy consumption of 4G with data traces obtained during more than five months, and then, they compared the results with 3G and WLAN networks. The results show that the 4G network is less efficient than WiFi from an energy consumption point of view. On the other hand, in [51] the network cost and the user interface cards are again considered within the decision algorithm. The network cost and energy awareness are also included in [52], where due to the fact that the available sources of information from different networks are qualitatively interpreted, the network selection method incorporates the fuzzy logic.

More recently, Scopelliti *et al.* [53] introduced an energy-quality utility-based adaptive solution for dense networks, but only LTE cells were considered. On the other hand, the network selection criterion in [54], [55] is extended considering the network reputation, but leaving energy efficiency outside the main decision criterion. Eventually, some works focused on the energy efficient multi-connectivity for ultra-dense 5G heterogeneous networks there had also been published [56].

Despite the amount of research performed in terms of energy-aware network selection strategies, not much effort has been placed on considering the impact of energy and performance from a network operation perspective. In addition, there has not been any work that has considered inclusion of a fully based IP broadcast technology such as ATSC 3.0 in the architecture for heterogeneous network services. This research gap provides the motivation to propose the Convergent Architecture for Broadcast Services (CABS) and Performance and Energy-aware Access (PEC) network selection algorithm to exploit efficiently the resources of convergent broadcast, cellular and broadband wireless scenarios. These contributions will be described in details next.

III. CABS Architecture

This paper proposes CABS as the convergent architecture for broadcast services. CABS bridges the gap between cellular communications, broadband wireless networking and broadcast network technologies enabling a wide range of rich media broadcast services to be supported at high quality levels. Fig 2 illustrates CABS, indicating its layer-based major components. At the lowest network layers (i.e. Physical and Datalink), CABS relies on the support from the best network solutions among three network options. WiFi solutions such as IEEE 802.11ac and IEEE 802.11ax, cellular standards such as LTE and LTE-Advanced, and state-of-the-art broadcast technologies including ATSC 3.0 and DVB T2 power CABS. Complementing these lowest network layer technologies, there is a need for an additional mechanism at layer 2.5 and the proposed PEC acts as an overarching solution, enabling performance and energy-aware technology convergence. PEC provides support for an all IP communication at layer 3, solution which was embraced widely lately. Classic protocols such as the reliable TCP or unreliable UDP or innovative protocols which support multi-stream (SCTP), multi-path (MPTCP) or flexible congestion control-based (DCCP) data transmission can be employed at transport layer. The CABS architecture supports a wide range of services, including broadcast rich media services such as Virtual Reality (VR), omnidirectional (360°) video, HD/4K/8K on top of HTML5, MPEG DASH, HTTP or proprietary application layer protocols.

IV. PEC System Model

As already mentioned, in the context of CABS architecture, PEC was introduced to provide a bridge between diverse lower network layer communication technologies and enable transparent network convergence. Fig. 3 illustrates the proposed PEC deployment in a sender-receiver setup and in the presence of the three network technologies: cellular, wireless broadband and broadcast. A dual communication channel enables *communication control* to be established and maintained over one of these technologies, whereas *data* transmission can be performed over a different channel. PEC enables selection of the data channel which is most efficient in terms of energy and performance for the rich media service supported.

On the multi-link receiver side, in order for the CABS architecture to be attainable, the user equipment must have a common middleware that provides a unified interface to the upper layers and support for simultaneous connectivity with the different networks. This middleware reroutes the data packets according to the control information received by the sender and performs switching from one network to another. Therefore, it can be stated that PEC is a user service-centered algorithm that has been designed to offer a trade-off between the network energy/cost efficiency on one hand and performance, including QoS metrics such as throughput, and delay, on the other hand.

In order to add clarification, we consider a scenario where different broadband and cellular networks have been deployed in an urban environment within a broadcasting coverage footprint, as illustrated in Fig.1. The set $U = \{u_1, ..., u_n\}$ is defined as the vector containing the n users in this scenario. The set of all different heterogeneous networks is formalised in $H = \{H_1, ..., H_h\}$, where $H = M \cup F \cup W$, where $M = \{M_1, ..., M_m\}$, $F = \{F_1, ..., F_f\}$ and $W = \{W_1, ..., W_w\}$ are the sets of available broadcast (e.g. ATSC 3.0/DVB), cellular (e.g. LTE/LTE-A), and WiFi (e.g. IEEE 802.11ac) networks, respectively. Each multi-link receiver u_i collects measurements from all the accessible networks, which it is able to sense, and creates the following set of candidate networks $C_{u_i} = \{C_{1,u_i}, ..., C_{c,u_i}\}$, where $C_{u_i} \subseteq H$. The network selection is accomplished through computation of an overall utility function Φ that takes into account the different network conditions and assesses the overall network benefit in terms of energy-performance balance.

A. Overall Utility Function

The overall utility function has been defined based on individual utility function components according to the Additive Logarithm Weighted (ALoW) method [57], which exploits the mathematical properties of the logarithms. Any overall utility function component whose cost is close to 0 has a larger impact on the overall utility than that of other components. The formula from Eq. (1) describes the proposed overall utility function Φ_j defined for the j^{th} network.

$$\begin{aligned}\Phi_j = w_q \cdot ln(\phi_{q_j}) + w_{eff} \cdot ln(\phi_{eff_j}) \\ + w_{PSR} \cdot ln(\phi_{PSR_j}) + w_{del} \cdot ln(\phi_{del_j})\end{aligned} \tag{1}$$

The overall utility function components ϕ_{q_j}, ϕ_{eff_j}, ϕ_{PSR_j} and ϕ_{del_j} are utility functions defined for video service quality, network energy consumption, packet success rate and delay, respectively. Finally, w_q, w_{eff}, w_{PSR} and w_{del} are the weights for the considered overall utility function component. These weight factors enable control of the importance of the associated parameter in the eventual decision algorithm.

$$w_q + w_{eff} + w_{PSR} + w_{del} = 1 \tag{2}$$

Next, the utility functions associated with the overall function components are described in details.

1) Video Quality (ϕ_{q_j}): A zone-based quality sigmoid utility function is used to map the throughput to user satisfaction. This sigmoid function, first introduced in [58], is presented in Eq. (3). The function is dimensionless and ranges from 0 to 1. Eq. (3) is calculated based on the following parameters: ρ_{min} is the minimum throughput required to deliver an acceptable quality. ρ_{req} is the required throughput to maintain an adequate quality level for the multimedia service, and ρ_{max} is the maximum value of the throughput above which no noticeable improvement of user perceived quality is noted. The shape of the utility function is determined by the parameters α and β. For instance, in this paper α and β values of 1.64 bps^{-1} and 0.86 bps were used, respectively.

$$\phi_{q_j} = \begin{cases} 0, & \text{for } \rho \leq \rho_{min} \\ 1 - exp(\dfrac{-\alpha \cdot \rho^2}{\beta + \rho}), & \text{if } \rho_{min} < \rho \leq \rho_{max} \\ 1, & \text{otherwise.} \end{cases} \tag{3}$$

2) Efficiency (ϕ_{eff_j}): In this work, the energy/cost efficiency for delivering broadcast services has been focused on from a network perspective. The utility function is defined mainly based on the results published in [15], [59] and [16]. Brugger *et al.* present several metrics to compare cellular and broadcast networks in terms of frequency efficiency and Operational Expenditure (OPEX) cost basis. The authors have developed the *layer spectrum efficiency* metric, whose value is given by the ratio of spectral efficiency (SE) to the reuse blocking factor (RBF). They also present the approximate network cost values associated to different broadcast and cellular networks, taking into account the number of transmitters required to cover a particular area. For instance, the authors offered the number of equivalent LTE stations (ISD=2 km) required to cover an area with radius of 25 km of a single broadcast High Power High Tower (HPHT) transmitter. Based on these numbers, this work introduces the following network efficiency (NE) metric:

$$NE = \frac{SE}{RBF \cdot N_{Tx} \cdot C_{Tx}} \tag{4}$$

SE is the spectral efficiency of the physical layer, RBF is the frequency reuse factor, N_{Tx} is the number of transmitters and C_{Tx} is the approximate cost of a transmitter. The latter should include several aspects, such as power consumption, housing or maintenance. The number of transmitters per square kilometer is dependent on the real propagation scenario; nevertheless, the examples given by the authors in [15] [59] provide a fair ground for comparison purposes. Moreover, the results are in line with the results published in [16]. Although not straightforward, as it has not a real broadcast mode, the numbers for the WiFi network have been extrapolated from [50]. The utility function is illustrated in Fig. 4 and presented in Eq. (5) [57].

$$\phi_{eff_j} = \begin{cases} 0, & \text{for } NE \leq NE_{min} \\ \dfrac{NE_{max} - NE}{NE_{max} - NE_{min}}, & \text{if } NE_{min} < NE \leq NE_{max} \\ 1, & \text{otherwise.} \end{cases} \tag{5}$$

NE_{max} = 1.05 bps/Hz/€ and NE_{min}= 0.19 bps/Hz/€ are the maximum and the minimum network efficiency values. NE_{max} was obtained for an optimal network, where a single HPHT transmitter can cover the whole coverage area (of radius 25 km) with a spectrum efficiency of 4.2 bps/Hz, a frequency reuse-factor of 4 and an approximate cost of 1 million Euro. On the other hand, NE_{min} was obtained for the worst case scenario, where almost 570 transmitters are required (ISD=2 km) with a spectrum efficiency of 3 bps/Hz, a reuse-factor of 1.1 and an average cost per transmitter of €25000 [59]. The utility function follows the principle of "the higher the better", due to the importance of the efficiency, both in monetary and power consumption related terms, for the current technologies. This means that for high values of NE, the utility function will be high, whereas for low NE values, the utility will be small.

3) PSR (ϕ_{PSR_j}): Another important metric that can be measured in the network is the Packet Success Rate (PSR). This metric gives an idea of the actual load of the current network and the difficulties encountered to satisfy the expected QoS levels. In this case, the utility function is calculated as in Eq. (6).

$$\phi_{PSR_j} = 1 - \frac{LossPackets}{TotalPackets} \tag{6}$$

4) Delay (ϕ_{del_j}): The packet end-to-end delay also reflects the actual network load and can be employed to predict future

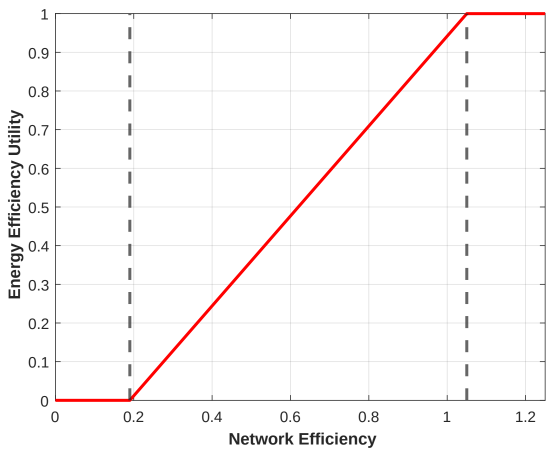


Fig. 4. Network energy efficiency based utility function.

bottlenecks in the network. The mathematical definition of this utility function is given in Eq. (7).

$$\phi_{del} = \begin{cases} 1, & \text{for } t < T_{min} \\ \dfrac{T_{max} - t}{T_{max} - T_{min}}, & \text{if } T_{min} < t < T_{max} \\ 0, & \text{otherwise.} \end{cases} \quad (7)$$

T_{min} is the minimum delay of the network and T_{max} is the maximum network delay tolerable by an end user.

B. PEC Network Selection Algorithm

In the literature, the IP protocol has been always considered to be the key element to enable convergence of broadcasting, broadband and cellular network solutions. Currently, the network convergence is a hot topic again due to the fact that recently ATSC 3.0 has been rolled out as the first IP based DTT standard in the market. In this context, PEC proposes an energy-aware network selection solution based on the networks statistics. PEC targets improvement of the QoS for the broadcast services in current scenarios. The following network selection algorithm is executed in an iterative manner and works as follows:

- Step 1 (Sensing Phase). During the sensing phase, at every τ seconds each UE (u_i), collects measurements from all the available networks. Next, each receiver creates vectors $X_j^{u_i}$ for each network j containing p items representing relevant statistical information, as shown in Eq.(8). The UE sends this collected information to the server through the control channel.

$$X_j^{u_i} = \{x_{j,1}^{u_i}, x_{j,2}^{u_i}, ..., x_{j,p}^{u_i}\} \quad (8)$$

- Step 2 (Evaluation Phase). First of all, based on the statistical information received in the sensing phase, the server calculates the utility functions defined in Section IV Eq. (3)-(7) and defines vector $R_j^{u_i}$ for each network j as follows:

$$R_j^{u_i} = \{\phi_{q_j}^{u_i}, \phi_{eff_j}^{u_i}, \phi_{PLR_j}^{u_i}, \phi_{del_j}^{u_i}\} \quad (9)$$

Next, the sender applies Eq. (1) to obtain the performance and energy-aware overall utility function score for each network and creates the vector T^{u_i}. This is sorted in descending order according to the highest $\Phi_j^{u_i}$ values, where 1 and a are the indexes of the networks with the highest and the lowest values of the PEC overall utility function, respectively.

$$T^{u_i} = \begin{bmatrix} \Phi_1^{u_i} \\ \Phi_2^{u_i} \\ \dots \\ \Phi_a^{u_i} \end{bmatrix} \quad (10)$$

- Step 3 (Network Selection). The network selection phase should consider several aspects prior to the decision based on the scores computed in Step 2. The stability, for instance, is a critical aspect in order to avoid the ping-pong effect on the network selection. Therefore a delay-based solution is employed in this proof of concept algorithm, requiring consistent indication that the new network is beneficial before the selection is made. The computational complexity is also another facet that must be taken into account, and finally, the closeness to optimality is equally very important. In this case, due to the generic approach of this study, the network selection has been simplified always picking the network with the highest score. However, any other approach is valid and is expected to produce good results (e.g. machine learning, fuzzy logic, reputation, etc.).

V. Simulation Testing Environment and Deployment Scenarios

This section presents the setup where the CABS architecture and the PEC algorithm have been jointly evaluated. The proposed solution has been built on the Network Simulator 3 (NS-3) [60]. The latest version provides support for different protocols (UDP, TCP, etc.) and a wide range of radio access technologies (802.11ac, LTE, WIMAX, etc.). Nevertheless, it does not support ATSC 3.0 or any other DTT standard. In this work a first simplified model of the ATSC 3.0 has been designed and validated. This module includes all the Modulation and Coding (MoDCoD) schemes available at the physical layer.

The ATSC 3.0 error model is based on the link abstraction technique designed for the OFDM modulation in the NS-3 WiFi module. The frequency selective nature of the channel has not been simulated taking into account the notion of the single effective SNR (Γ_{eff}) presented in [61]. In this case, a series of look-up tables are stored, where the actual Packet Error Rate (PER) values of the different MoDCoDs are mapped together with the actual Signal-to-Noise (SNR) values of the whole RF channel. The PHY tables have been obtained with a fully compliant end-to-end physical layer simulation platform built in MATLAB. Finally, other configuration parameters, such as the bandwidth or the guard interval are also included. The ATSC Link-Layer Protocol (ALP) protocol has been abstracted and simplified, as for this performance evaluation it will have a negligible impact.

TABLE II
HETEROGENEOUS NETWORKS MAIN PARAMETERS FOR THE SIMULATION ENVIRONMENT

Attribute	Broadcast Network	Cellular Network	WLAN Network
Technologies	ATSC 3.0	LTE	802.11 ac
$f_c(MHz)$	600 MHz	1800 MHz	5100 MHz
Number of Tx	1	2	2
Transmission Power	76 dBm	40 dBm	16 dBm
Transmission Height	150 m	30 m	3 m
Bandwidth	6 MHz	20 MHz	40 MHz
Transmission Power	SISO	MIMO (2x2)	MIMO (2x2)
Propagation Model	Hybrid (Indoor/Outdoor)	Hybrid (Indoor/Outdoor)	Hybrid (Indoor/Outdoor)
Video Data Rate	3.5 Mbps (H.264)		

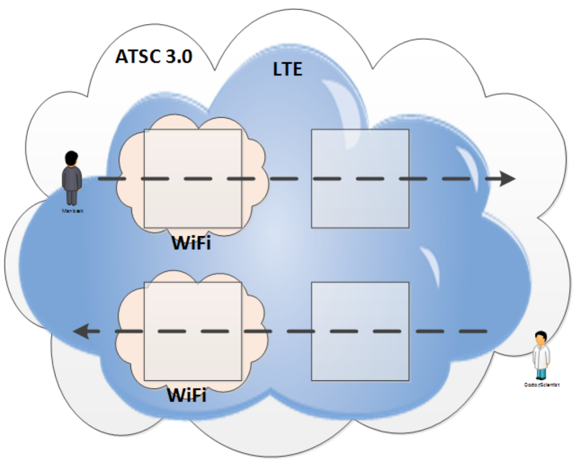
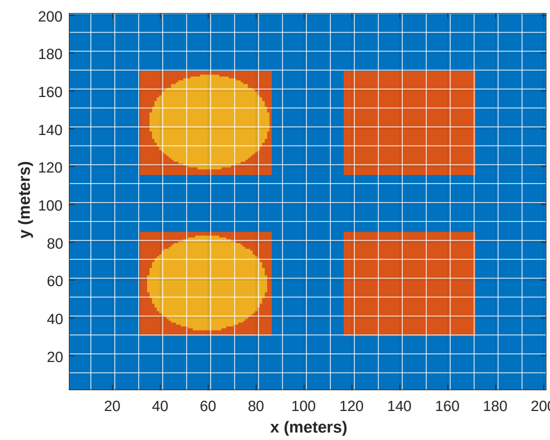


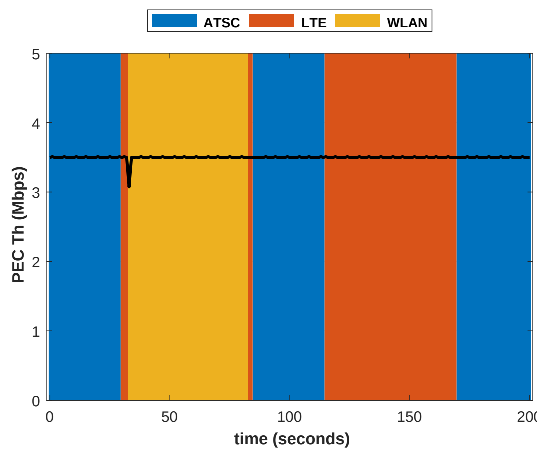
Fig. 5. Testing Scenarios for the proposed PEC architecture.

Regarding the transmission modes in the 802.11ac networks, the ideal rate control algorithm has been defined, where the best mode is always selected according to previous detected SNR values. On the other hand, the LTE network rate control relies on the Adaptive Modulation and Coding (AMC) model described in [62] and the Proportional Fair (PF) Scheduler. In the case of ATSC 3.0, there is no uplink channel, and therefore, a fixed MoDCoD (QPSK, Cr=13/15) has been selected. This data rate is enough to guarantee the required 3.5 Mbps service using a 40 % of the airtime, while the rest of the capacity can be allocated to offer a UHD service within the same RF channel. The rest of the main parameters of the simulations can be found in Table II.

As it has been detailed in Section II, there are several use cases that can benefit from the CABS architecture presented in this work. In this case, the seamless mobility for the mobile receiver that could transfer across different RAT without any intervention in the most efficient manner is the targeted case. The proposed testing scenario is illustrated in Fig. 5. The receiver performance is evaluated over a square grid covering an extension of 40000 square meters that includes four different buildings with a size of 55x55 meters and a distance between buildings of 30 meters (a wide street). The ATSC 3.0 based HPHT transmitter is located 40 km away from the city center and the eNodeBs are 200 m apart from building and 500 meters apart from each other. The only two buildings with wireless broadband support (i.e. WiFi) are located at



(a) The selected optimal network by the PEC algorithm.



(b) PEC performance over an individual path for one user.

Fig. 6. Single user PEC performance analysis.

the left half of the scenario. As expected, ATSC 3.0 can not be received inside buildings due to the high wall attenuation ($\sim$ 15 dB).

VI. RESULTS AND DISCUSSION

A. Single User Performance Analysis

In the first case, a single user walks with a mobile receiver through the grid at a constant speed of 1 m/s from the West to the East. The user direction is periodically modified to guarantee that all the pixels (1x1 m cells) are covered.

Fig. 6 (a) depicts the selected optimal network for each position: ATSC 3.0 (blue), LTE/5G (red) and WiFi (yellow). The first important outcome is that even if the HPHT broadcast transmission is the most efficient delivery method for outdoors, it does not guarantee the required throughput for indoor scenarios for a handheld receiver. In consequence, the algorithm always selects cellular (and WiFi networks, when available) for handheld indoor reception. Fig. 6 (b) plots the performance of the same user, but in this case traveling from position A (0,60) to position B (200,60) with a speed of 1 m/s during a 200 seconds time span. The black line indicates the throughput of the multi-link receiver measured at every second, and the background colour, the network delivering the service. The PEC algorithm selects always the most efficient available network and maintains a throughput value close to 3.5 Mbps. Even if the cellular networks are always available for the outdoor cases, the user is always served by ATSC 3.0 due to its network efficiency. On the other hand, inside the building, the receiver is always served by the broadband network if possible in order to offload the cellular network traffic. It must be also noted that in Fig. 6(b), a slight drop is observed at the start of the WLAN region (t=30s). This is due to the fact that the PEC selection algorithm prioritizes WLAN network due to its better efficiency in this context when compared with LTE networks even if the real throughput is a bit lower.

B. Multiple User Performance Analysis

In the second case, the same geographical scenario has been employed to study the performance for a group of three users walking together in a predefined direction through the whole grid with a constant speed of 1 m/s. The granularity is also one square meter. The obtained results have been summarized in Table III. The second and third columns collect the statistics of the throughput per user for each RAN assuming that they were connected during the whole simulation time. In the last column, we are including the actual network connectivity, which indicates the percentage of the time that a particular network has been selected by the PEC algorithm. The ATSC 3.0 and 802.11 ac networks offer the worst mean throughput and the highest standard deviation as their coverage does not cover the whole study area. However, the cellular network offers the highest throughput and the smallest deviation as it has a 100% coverage. This condition, of course, would not be fullfilled if the whole city coverage was analysed. Even though, the most interesting results are the ones offered by PEC, which guarantees an optimum mean throughput with a minor standard deviation (close to ideal case), while it uses always the most efficient network. In fact, it is connected to the DTT network more than a 65% of the time.

In a second step, the multi-user analysis has been generalized. In this case, a variable group of people randomly moving across the grid with a random velocity has been studied. The number of users ranges from 3 to 20 and the length of each simulation is about 3 minutes. In this case, only one of the eNodeBs has been switched on in order to reduce the computational complexity of the simulations. Nonetheless, this single transmitter is enough to cover the whole grid. Each UE has a random direction with a speed value between 0.5 m/s to 1.5 m/s. In this case, the results have been presented in terms of the aggregate data rate (ADR) (See Fig. 7). It is assumed that the user is either connected only to one of the technologies 100 % of the time or it implements the PEC algorithm, which always selects the best one. The vertical axis represents the ADR in Mbps, while the horizontal axis indicates the number of users. It is important to note that the PEC ADR (purple line) matches LTE/5G (red line) and increases in a linear basis with the number of UEs, which actually represents the ideal case when a single RAN covers the whole grid and the UE is always connected. However, it must be noticed that PEC will select always the network with the highest efficiency as it will be discussed in the next subsection. Finally, when the number of users increase the distance between ATSC (blue), 802.11 ac (yellow) and PEC (red) increases. The main reason is that the former ones have important coverage holes in the studied area where they can not offer the required service by themselves.

TABLE III
THROUGHPUT ANALYSIS PER USER

Network	Throughput (Mbps)		Network Connectivity (%)
	$Mean$	$Std.Dev.$	
ATSC 3.0	2.404	1.565	% 68.63
LTE	3.497	0.059	% 21.07
802.11 ac	0.349	1.007	% 10.30
PEC	3.483	0.174	% 100

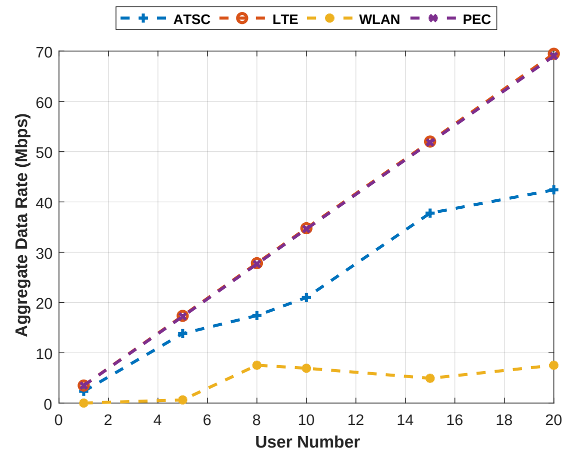


Fig. 7. Aggregate data rate of the heterogeneous network per user number.

C. Energy/Cost Efficiency Analysis

In a third step, the energy/cost efficiency has been analyzed. First of all, in Fig. 8 the network efficiency (NE) of a single user traveling across the same path previously defined is depicted using the metric defined in Eq. (4). The background colours depict the network to which is connected the UE at each second and the black line represents the network efficiency. As expected, the NE value changes together with the selected network and this is one of the key performance

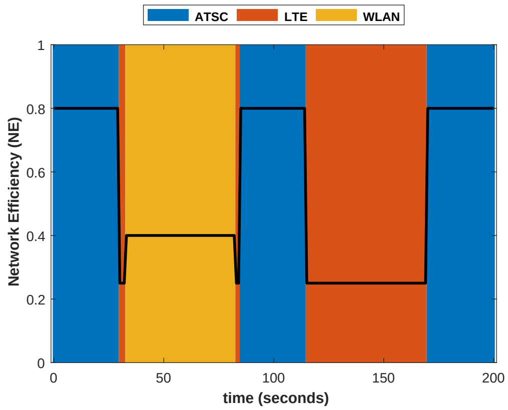


Fig. 8. Network efficiency (NE) of the UE and the selected network.

TABLE IV
NETWORK EFFICIENCY IN A MULTI USER SCENARIO

	ATSC 3.0		LTE		WLAN		Total
	%	NE	%	NE	%	NE	NE
Case 1	100	0.8	0	0.25	0	0.4	0.8
Case 2	0	0.8	100	0.25	0	0.4	0.25
Case 3	0	0.8	0	0.25	100	0.4	0.4
PEC	73.05	0.8	17.50	0.25	9.45	0.4	0.75

indicators of the proposed solution. Even if the LTE network is available 100% of the time, the PEC algorithm chooses the ATSC 3.0 RAN when possible, as it is more efficient from an energy/cost point of view. The same rule applies when the 802.11 ac network is available. In a similar way, the network efficiency has also been studied for the multiple-user case. In particular, the most complete case when 20 users are randomly moving is analysed. The results are gathered in Table IV. The first three rows (Cases 1 to 3) show the scenarios where the user is connected to a single network during the whole simulation time, whereas the last one shows the PEC results where the most efficient network is always selected. Each network has a column indicating the percentage of the connection time and the related NE of the network. The last column shows the averaged network efficiency. The numbers shows that the proposed PEC algorithm NE approaches the cost/efficiency golden value set up by ATSC 3.0, as it selects the most efficient network when available.

VII. CONCLUSION

The exponential demand for the video content over mobile networks, the different requirements defined for the verticals within the 5G framework and the awareness of the importance of the network energy consumption in 5G, have put the converge of heterogeneous networks under the spotlight of the research community once again. In addition, the standardization of a fully based IP broadcast standard, namely ATSC 3.0, has recently brought another important player into the market. In order to address those issues, this work proposes a novel convergent architecture for broadcast, broadband and cellular services (CABS) along with the Performance and Energy-aware Access (PEC) network selection algorithm. The latter is a user service centered solution that guarantees the seamless connectivity to the most efficient network, whereas the user perceived quality is maintained at high level. The proposed architecture has been tested via simulations using a Network Simulation (NS-3) model, which includes a DTT standard modeled for the first time. The PEC algorithm has been evaluated in three demanding scenarios; it has been demonstrated that PEC offers a good balance between QoS (Table III) and energy consumption awareness (Table IV) in all of them. The results also show that by employing the proposed solution, a nearly constant throughput was maintained during user mobility in a heterogeneous network environment and the network efficiency was substantially improved.

ACKNOWLEDGMENT

Gabriel-Miro Muntean acknowledges the Science Foundation Ireland grant 13/RC/2094 to Lero - the Irish Software Research Centre (http://www.lero.ie). In addition, this work was also supported by the Basque Government (Grant IT1234-19) and by the Spanish Government Grant RTI2018-099162-B-I00 (MCIU/AEI/FEDER, UE).

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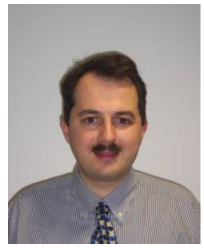

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