Hybrid Cognitive Satellite Terrestrial Coverage
A case study for 5G deployment strategies

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Abstract. The explosion of mobile applications, wireless data traffic and their increasing integration in many aspects of everyday life has raised the need of deploying mobile networks that can support exponentially increasing wireless data traffic. In this paper, we present a Hybrid Satellite Terrestrial network, which achieves higher data rate and lower power consumption in comparison with the current LTE and LTE-Advanced cellular architectures. Furthermore, we present a feasibility study of the proposed architecture, in terms of its compliance with the technical specifications in the current standards..

Keywords: Hybrid satellite terrestrial, 5G, control and user plane separated

1 Introduction

The increasing demand for data in mobile communication networks has resulted in the need for developing sufficient and advanced network infrastructures to support higher capacity and data rate. The forecasts in [1] shows that by 2018 the mobile data traffic will be 6.3 times higher than it was in 2013. In addition to this, the global CO_2 emissions of the mobile communications sector are expected to rise to 178 Megatons in 2020 [2]. Consequently, alternative approaches in the design and operation of future mobile networks are being investigated. The concept under investigation in this paper is the separation of the control (C)-plane and the user (U)-plane in the Radio Access Network (RAN). The C-plane provides ubiquitous coverage via the macro cells at low frequency band. On the other hand, the U-plane functionality is provided by the small/data cells at a higher frequency band, such as 3.5, 5, 10 GHz, where new licensed spectrum is expected to be available for future use. The use of such bands for small cells can lead to a significant increase in capacity, since they can offer bandwidth up to 100 MHz [3]. Likewise, cross-tier interference is avoided by operating the macro and small cells on separate frequency bands, thus leading to improvement in spectral efficiency. The C-plane and U-plane are not necessarily handled by the same node and are separated. Consequently, this gives the network operators more flexibility, since the C-plane (control/macro cells) manages UEs connectivity and mobility [4]. The separated plane architecture also enables reduction in energy consumption as it leads to longer data cell sleep periods due to their on demand activation [5], [6]. Furthermore, base station (BS) cooperation in the U-plane can be done more effectively since control signalling can be performed through a separate wireless path.

In this paper, a hybrid satellite terrestrial network architecture is presented, where a satellite is deployed to provide C-plane functionality, while femtocells are deployed to provide U-plane functionality. The operating frequency band for the satellite is considered to be L-band (1-2 GHz), as proposed in Inmarsat's BGAN system [7]. Satellites have cognitive capability, i.e. real-time intelligence which can be used to maximise the utilisation of available radio resources and to improve link performance. Such intelligence includes knowledge of the location of UEs and femtocells within its coverage, which enables associating UEs to the most suitable femtocells. In general, satellites offer much wider spatial coverage compared to macro BSs. A typical satellite can offer control signalling to a whole country, thus leading to significant reduction in physical infrastructure and maintenance cost, when compared with using the latter for control signalling. The feasibility of the proposed network architecture is based on the "dual connectivity" feature, which enables the simultaneous transmission of the U-plane and the C-plane by different nodes.

The purpose of this paper is to present the hybrid architecture, and compare it with existing cellular technologies, for a variety of scenarios, as well as to examine the compliance of its simulation results with the state of the art cellular standards. The rest of the paper is organised as follows. In section 2, the definition of the hybrid satellite terrestrial network architecture is presented, by defining the functions of the network elements. Section 3 describes the techniques applied in the hybrid network to achieve an effective resource utilisation at the terrestrial and satellite parts. In section 4, the details and the assumptions of the network simulations are presented. In section 5, a performance comparison between LTE, LTE-Advanced and the Hybrid architecture is made for different scenarios. In section 6, the compliance of the performance results with the current 4G standards is investigated and the suggestions to be taken into consideration in the promising 5G cellular standards are also presented. Finally section 7 concludes this paper.

2 Network Architecture

The International Telecommunication Union (ITU) defines a "hybrid satellite terrestrial system" as the one that employs satellite and terrestrial components that are interconnected, but operate independently of each other [8]. In such systems, the satellite and terrestrial components use separate network management systems and can operate in different frequency bands. An illustration of the proposed Hybrid network is shown in Figure 1, where the UE is operating in dual mode, communicating simultaneously both with the satellite and the eNBs.

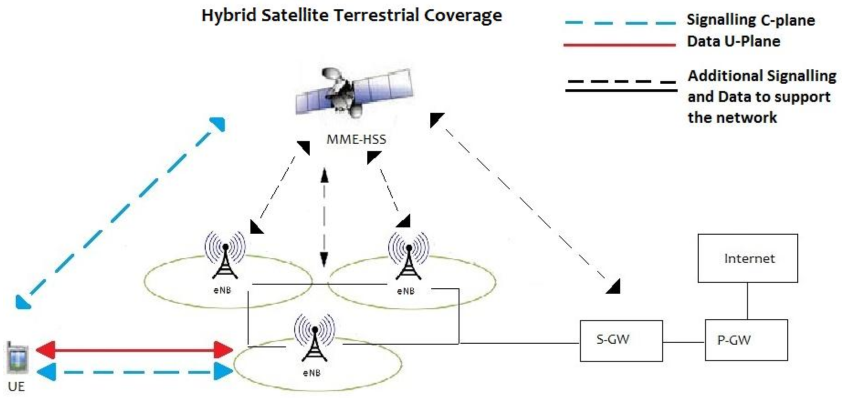

Fig. 1. Hybrid Satellite Terrestrial Architecture

From a higher level architectural point of view, as the satellite can provide coverage to the whole terrestrial network, it is used as a Home Subscriber Server (HSS) entity, carrying detailed information about the subscribers. In addition, since the satellite can communicate with the backbone network, such as the Serving Gateway (S-GW), for both data and signalling purposes, it can also serve as a Mobility Management Entity (MME), which is responsible for the mobility management of the users.

The terrestrial part of the network consists of femtocells/eNBs that are interconnected with fibre optics network. In addition, fibre optics is also used for the connections between the eNBs and the backbone network. This assumption enables reliable and fast data transfer among the terrestrial network elements, which minimises transmission errors and latency.

The reason for having two paths for the C-plane communication is that for some User Equipment (UE) activities, signalling from both the U-plane (eNB) and the C-plane (satellite) are required for successful operation. For example, power coordination and handover procedures require accurate measurement, which cannot be provided through the satellite channel due to high latency. Hence, cooperation of both data and signalling planes is essential for the smooth UE operation.

3 Resource Utilisation

The main advantage of separating the C-plane from the U-plane in cellular networks is the ability to replace part of the resources reserved for the signalling of the U-plane, with actual data. In general, the complete separation of the two planes is not possible, due to the fact that some of the C-plane functionalities have to be in the U-plane to support the reliability of the actual data transmission. In that sense, part of the Downlink Control Information (DCI) needs to occupy some of the available physical

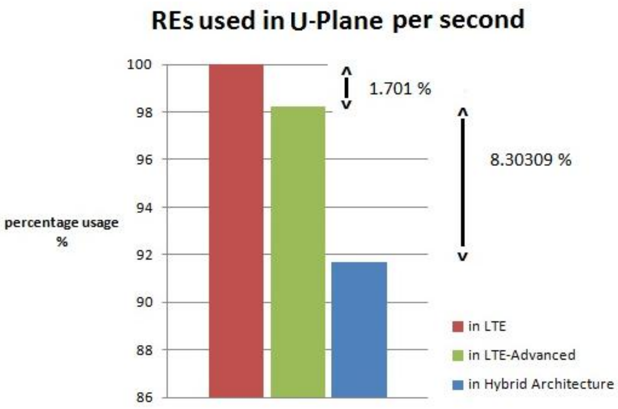

Fig. 2. Percentage usage of REs in the U-plane for the 3 architectures

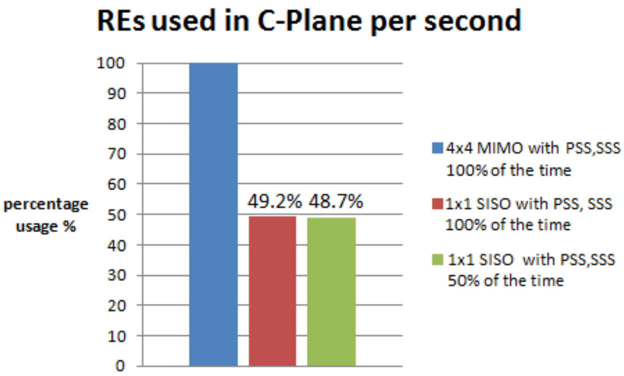

Fig. 3. Percentage usage of REs in the C-plane

resources reserved for data transmission.

The information that each physical channel needs to carry, is related to the occupied physical resources in the Orthogonal Frequency Division Multiplexing (OFDM) resource grid. These physical resources are called Resource Elements (REs).

In general, from the total available resources in an OFDM resource grid, 25% is occupied by the C-plane and 75% by the U-plane [9]. Regarding the U-plane (terrestrial) communication of the hybrid network, one of the C-plane signalling channels that must be used to support data transfer is the Physical Hybrid ARQ Indicator Channel (PHICH), which is responsible for providing ARQ acknowledgements [10]. Since the reliability of the useful data transfer is also based on a variety of upper layer protocols, it is possible to loosen the acknowledgment restrictions and reduce the resources reserved for the PHICH by a factor of 1/6 (from what was suggested in Release 8 LTE Resource Grid). By doing so, it is possible to substitute the rest 5/6 of the REs used for PHICH with actual data. In Figure 2, a comparison between the number of REs used for the U-plane in LTE, LTE-Advanced and the hybrid architecture is presented. The figure shows that about 1.7% reduction in the U-plane control signalling is achieved by separating the C-plane from the U-plane in LTE-Advanced as compared in LTE. Furthermore, the hybrid architecture can offer about 8.3% reduction in the U-plane control signalling, as compared to LTE, due to the reduction in the number of REs used for PHICH.

The following assumptions are made regarding the resources reserved for the control signalling of the C-plane in the hybrid architecture: a) Since the Reference Signals (RSs) are closely related with the number of antennas used in the system, and since the C-plane is responsible for low data rate communication, by deploying a single beam (single antenna) satellite it is possible to reduce the number of REs reserved for the RSs. b) In addition to that, since the serving satellite is used as an HSS/MME, it contains information about all the UEs. Furthermore, since the UEs communicate with the same satellite, part of the transmitted control information remains the same. Consequently, it is possible to reduce the transmission of the Primary and Secondary Synchronisation Channels (PSS and SSS) by 50% of the time. By doing so, as it can be seen in Figure 3, the resources reserved for the control information of the C-plane are further reduced thus, occupying less bandwidth on the satellite.

4 Network Simulations

In order to provide the performance results of the proposed network, a case study of providing high speed data coverage to the whole UK area was simulated in Matlab. For the calculation of the satellite's power consumption, the formula of the Friis equation was used,

$$P_t = \frac{P_r}{G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2} \tag{1}$$

considering $G_t = 10dB$ and $G_r = 1.5dB$ as the typical antenna gains of the transmitter and receiver respectively, $P_r = -80\ dBm$ for the minimum receive power, λ the wavelength, and d the distance of the satellite orbit from the earth user (36,000 km for GEO and 800 km for LEO). In addition, the same equation was used to calculate the power consumption of the terrestrial part of the network, assuming as total eNBs' power needs, the sum of power required for pure wireless transmission needs between each active eNB and its edge serving user. The assumption made for the terrestrial part was that each femtocell/eNB could serve an area with radius $R_{\text{femto}} = 10$m and each Macro BS (used for signaling in LTE-Advanced), could serve an area with radius $R_{\text{macro}} = 5$km. Moreover, for the calculation of the capacity provided per km^2 , the Shannon's capacity law was used

$$C_{per\_user} = B\log_2(1+\frac{P_r}{N_0 B + I_0}), \qquad (2)$$

where $B = 20\ MHz$ the available bandwidth per cell, $No = -174\ dBm/Hz$ the noise spectral density and I_o the interference produced by the neighboring active eNBs assuming that the requirement of having and existing line-of-sight (LOS) path between the UE and the satellite is satisfied.

5 Network Performance and Comparison Between Different Scenarios

In this section, a comparison of the proposed architecture with LTE and LTE-Advanced has been done for different scenarios. Initially, since the satellite is exclusively responsible for providing the C-plane functions, the overall performance of the hybrid network is mainly based on the selection of satellite orbit. The performance specifications of a Geostationary Earth Orbit (GEO) satellite and a Low Earth Orbit (LEO) satellite are presented in Table 1. As it can be seen, a LEO satellite constellation presents better performance in terms of power consumption and latency of signal transmission, compared with a GEO satellite. However, the latter offers wider coverage and less capital and operating expenditures (CAPEX and OPEX), which is a topic beyond the scope of this paper, since a single GEO satellite can provide coverage even to a whole continent. Furthermore, the inter-satellite handovers that occur in LEO constellations increase the C-plane complexity and may also introduce further delay in the control functionality, which are however factors that are not taken into consideration in this paper.

For purely power reduction objectives and in order to substantiate the superiority of the hybrid network, a LEO satellite constellation is assumed to be deployed for the C-plane functions. The different scenarios simulated, represent three different case studies. In i) all UEs are active and all eNBs are switched on, in ii) all UEs are active and 2 out of 25 eNBs/km^2 are cooperating to enhance local performance, and in iii) when 13 out of 25 eNBs/km^2 are considered to serve idle users and are switched off.

In the simulations, 5 UEs per eNB was considered on average and the available bandwidth was 20MHz per eNB. In addition, the coverage radius of each eNBs was considered to be 10m. The performance results regarding the U-plane capacity achieved per architecture are shown in Table 2 and are illustrated in Figure 4. As it can be seen, the hybrid architecture achieves the highest capacity in all scenarios. This is a result of the reduction in the resources reserved for the PHICH, as discussed in section III. At this point it is worthy to mention that it is impossible to switch off any of the unused or underused eNBs in LTE, because the desired “always connected” behaviour of the UEs will be interrupted.

Regarding the power consumption of the C-plane, only the performance results of LTE-A and the Hybrid architecture are presented. Power consumption of LTE is omitted due to the fact that it is a non-separated architecture, and the corresponding C and U-planes are transmitted simultaneously, by the same eNB. As a result, the power consumption of the C-plane and U-plane are the same. In Table 3, the C-plane power consumption for the separation architectures is presented. As it can be seen, for all the scenarios, the hybrid architecture consumes the least power for wireless signal transmission in terms of mW/km^2. In Table 4, the power consumption for wireless transmission purposes of the network as a whole is illustrated (C-plane and U-plane) and a comparison of the different scenarios is presented in Figure 5. As it was expected, the power consumption of a separated architecture is higher than the power consumption of a non-separated architecture. This is due to the fact that in a separated architecture, umbrella coverage network elements are set on top of the already existing network infrastructure for providing the C-plane functions and thus, their power consumption has to be added to the network's total power consumption. However, the results in scenario iii, which represents the non- peak traffic hours of the network, show that the power consumption of the hybrid network can be less, compared with both LTE-Advanced and LTE. This shows that the proposed architecture represents a strong candidate for future mobile energy efficient technologies.

Table 1. Specifications of Different Satellite Deployment Scenarios.

Satellite Orbit	**Power Consumption [mW/km^2]**	**Earth to satellite transmission dalay [ms]**	**RRC_IDLE to RRC_CONNECTED delay [ms]**
GEO at 36,000 km	119.71	120	800
LEO at 800 km	0.059116	2.6	280.8

Table 2. U-Plane Capacity per Architecture.

Technology	**U-plane capacity [Gbps/km^2]**		
	Scenario i	**Scenario ii**	**Scenario iii**
LTE	357.95	359.06	N/A
LTE-A	358.81	359.92	357.94
Hybrid	363.3	364.42	362.42

Table 3. Power Consumption of the C-Plane

C-plane	**C-plane power consumption [mW/km^2]**		
	Scenario i	**Scenario ii**	**Scenario iii**
LTE-A deploying 5km macro BSs	0.061459	0.061534	0.062457
LEO satellite (800km)	0.059116	0.059116	0.059116
GEO satellite (36,000km)	119.71	119.71	119.71

Table 4. Power Consumption of the Whole Network

Technology	**Total network's power consumption [mW/km^2]**		
	Scenario i	**Scenario ii**	**Scenario iii**
LTE	12.112	12.163	N/A
LTE-A	12.173	12.224	11.988
Hybrid with LEO satellite	12.171	12.222	11.986
Hybrid with GEO satellite	131.822	131.873	131.673

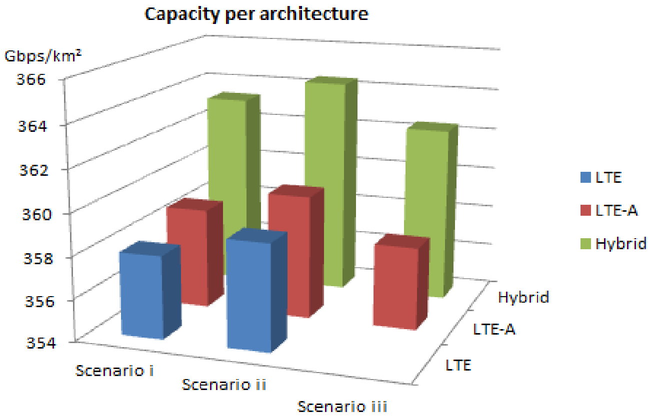

Fig. 4. Capacity per architecture

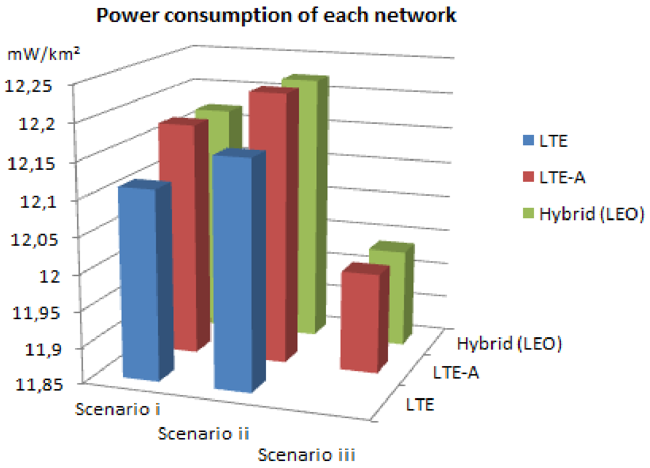

Fig. 5. Power consumption of each network

6 Compliance of the Proposed Hybrid Architecture with 4G Cellular Standards

The performance requirements for a mobile technology to be considered as 4G or beyond 4G, must comply with the requirements of the International Mobile Telecommunication (IMT) Advanced standard. These requirements suggest that the average spectral efficiency must be greater than 2.2 bits/s/Hz, and also the C-plane latency for the transmission from RRC_IDLE to RRC_CONNECTED state, must be less than 100msec [11].

Through simulating the network with the specifications described in section IV, the Hybrid network architecture achieves 2.85 bits/s/Hz, considering femtocells with 10m radius that serve on average 5 UEs per cell. Regarding the C-plane latency, as it was also discussed in Section V, the deployment of a GEO satellite results in C-plane latency of 800 ms and the deployment of LEO satellite in 280.8 ms. Of course both results are not compliant with the IMT-Advanced requirements however, they can be considered as a suggestion in the development of future cellular technologies, such as the promising 5G. In that sense, in order to allow the deployment of such technologies in future mobile standards, it is suggested to loosen the above C-plane restriction to 800 ms for GEO or 300ms for LEO satellites. It is worthy to mention, that such a delay in the states' transition, occurs due to the fact that the state of the art satellite network architectures may not be capable of processing large amounts of data (as the ones discussed in this paper), retransmitting them to the backhaul network for further process. However, extensive research is being made on advanced satellite network architectures that will be capable of high speed data processing without retransmission, fact that will enable future network architectures, as the one proposed in this paper, to be implemented offering gigabit end user services. Integrating such advanced satellite payloads in the proposed architecture, it will definitely meet the IMT-Advanced latency specifications.

In addition to the above mentioned requirements, it is also useful, to present a comparison of the hybrid network's performance regarding the LTE-Timers. The most important of them are: T300; T301 and T310, which indicate the maximum delay for a connection establishment and re-establishment request, as well as for physical layer problems. The possible values according to LTE-Advanced are within the ranges [400-8000] ms for T300 and T301, and [50-2000] ms for T310. Hence, according to the limitations in the wireless signal processing, the single return through the satellite signal transmission has an average delay of 500ms for GEO and 25 ms for LEO satellites, which fit within the LTE-Timer range. Furthermore, the values also imply that even if a transmission fails, it is possible to retransmit the desired signal before the expiration of the timer.

7 Conclusion

The proposed Hybrid Satellite Terrestrial architecture gives encouraging results towards its consideration for possible deployment in future mobile networks. The hybrid architecture, compared with state of the art technologies, gives the highest capacity per square meter and the lowest power consumption per square meter for wireless transmission purposes. Moreover, the technical specifications of the proposed architecture complies with the 4G standards. The spectral efficiency and the transmission delay meet the requirements of IMT-Advanced and the LTE-Advanced timers, respectively. The delay that occurs in the state transmission between the RRC_IDLE and the RRC_CONNECTED state, does not meet the C-plane delay requirements suggested from IMT-Advanced. However, this issue provides a design drive for satellites to minimize the latency beyond the theoretical bound as much as possible and enable such hybrid architectures to be deployed in future mobile standards.

Regarding the technical specifications of the satellite part to meet the bandwidth and data rate specifications for the transition from the current existing technologies to the suggested network architecture, there are already deployed mobile satellite systems can provide enhanced broadband capabilities and services. One of such is Inmarsat's Global Xpress system, which offers seamless worldwide coverage with advanced data rates up to 50Mbps [12]. In that sense, the UE convenience will be easier to be achieved.

As a final comment, the feasibility of the proposed architecture was based on the technical specification derived from the simulations made. Of course the issues of CAPEX and OPEX definitely play an important role for the realistic implementation of the Hybrid network, as well as for its comparison with the existing technologies. Assuming that for the U-plane, the same optical fiber network is going to be used for the interconnection among the femtocells/eNBs for each separation architecture, the investigation of the network's cost mainly focuses on the C-plane implementation. However, in case of such a study, the results have to be derived considering the whole lifecycle of the network, since by deploying a satellite, the maintenance cost of the C-plane is nowhere near the maintenance cost of the macro BSs network used in LTE-Advance.

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