Spectrum Requirement for Cellular TV distribution in UHF Band from Urban to Rural Environment

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***Abstract*—As the number of TV-channels increases and the number of viewers per channel decreases, Terrestrial Broadcasting is becoming a less attractive way to distribute TV. In addition it does not represent a very efficient use of the UHF band (470-790 MHz). In this paper we discuss an alternative, converged platform for TV and mobile broadband provisioning based on LTE cellular technology and infrastructure, here referred to as Cell-TV. The key feature of Cell-TV is the ability to switch between a unicast mode for small viewer populations and broadcast over LTE single frequency networks (SFN) for popular content. The main advantage is that the spectrum can flexibly be shared with LTE mobile data services, effectively freeing significant parts of the UHF spectrum for these purposes. Based on a case study of the greater Stockholm area, significant potential for spectrum saving is identified in urban areas where the need for spectrum is the largest. Meanwhile, only limited spectrum savings are observed in rural areas due to the large user populations in each cell and the long inter-site distance. As most of the TV channels are broadcasted in urban areas but unicasted in rural areas, this switch of transmission modes causes considerably high spectrum demand in suburban areas.**

***Index Terms*—UHF TV band, Terrestrial TV Broadcasting, Multimedia Broadcasting/Multicast Service, Single Frequency Network, Unicast Video Streaming.**

I. Introduction

During the last decade digital terrestrial television (DTT) has established itself as the most popular platform for TV distribution in Europe. However, the future of DTT is less promising due to recent developments in audio-visual service and its consumption pattern. First, TV content is becoming increasingly diversified with more niche TV channels and video on-demand (VoD). Second, more TV contents are not only consumed through fixed TV set, but also expected to be available on different platforms. DTT as a dedicated broadcast network is ill-equipped to adapt to these changes. At the same time, the explosive growth in mobile broadband (MBB) traffic conitunes, of which two-thirds are from video streaming [1].

In light of the converging trends of audio-video service in both MBB and DTT, World Radio Conference 2015 (WRC-15) will discuss the possibility to progressively re-farm the UHF broadcast band (470-790 MHz) for a converged all-IP platform [2], which delivers both mobile data and TV content in a unified and device-agnostic way. As a system capable of utilizing spectrum efficiently for providing a plethora of wireless services, we have envisaged a converged platform based on cellular technology and infrastructure. TV content would be provided as one of the services, here referred to as *Cell-TV*. The key enabler is the evolved Multimedia Broadcast/Multicast Service (eMBMS) introduced in 3GPP Long Term Evolution (LTE) radio technology [3], allowing the TV contents to be broadcasted over a single frequency network (SFN) with high spectral efficiency. Besides, TV service can be further enhanced by unicasting niche contents and VoD.

Most of recent studies have focused on mobile TV over an OFDMA-based cellular network [4], [5]. However, the quality of service (QoS) requirement for fixed TV reception is much higher than that for mobile TV. A 'tower-overlay' system for fixed reception has been proposed in [6] using LTE technology and DTT network infrastructure. [7] presents a study on the spectrum requirement for delivering today's over-the-air TV service via LTE eMBMS networks. The results focused on the urban areas of several cities in the U.S. indicate considerable spectrum saving compared to DTT network. [8] extends the study to Swedish urban and rural areas, suggesting that moderate spectrum saving in rural area is possible by unicasting less popular TV channels instead of relying on eMBMS with large inter-site distance (ISD).

In this paper, we consider a seamless Cell-TV coverage extending from urban into rural areas, because an isolated analysis of either only urban or rural environment may underestimate the spectrum cost of switching between SFNs of different modulation orders or between broadcast and unicast. To minimize the overall spectrum requirement, a framework is proposed to adapt the transmission of each TV channel to the gradually varying infrastructure condition and viewing demand. In addition, our analysis includes the interference from MBB transmission reusing the 'freed' spectrum and its effect on the performance of Cell-TV. Based on a case study of the greater Stockholm area, we aim to provide a quantitative assessment on the potential spectrum requirement of Cell-TV and identify the key elements that affect the spectrum savings.

The remainder of this paper is organized as follows: Section II describes the Cell-TV system and the proposed framework. Then, Section III presents the studied scenario and the numerical results. Finally, conclusion and plan for future studies are discussed in Section IV.

II. System model and Problem formulation

A. Cell-TV concept

Cell-TV is assumed to replace the DTT system and operate in the 470-790 MHz band. Therefore it is expected to provide the same level of QoS as DTT network for fixed receptions:

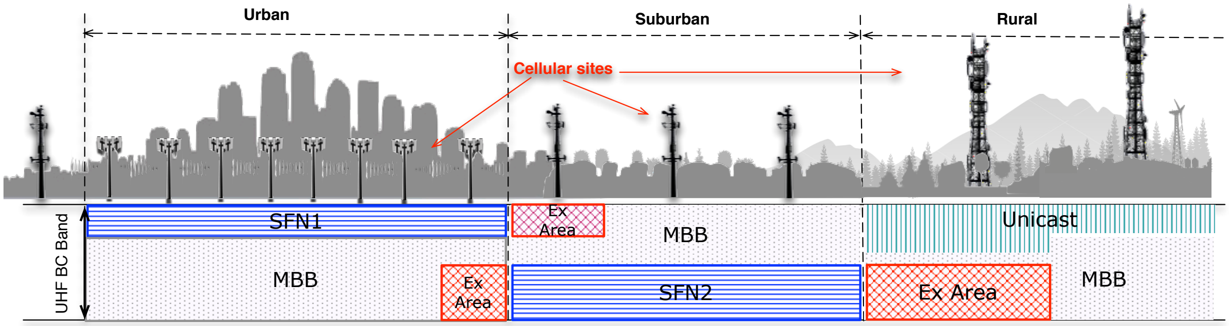

Fig. 1: System model for Cell-TV.

over 99% area coverage and less than 1% blocking. The distribution of each TV channel is determined by its local viewing demand and base station (BS) density, via either unicast or broadcast over an SFN formed dynamically by a group of eMBMS enabled BSs. Any unused spectrum are consider as spectrum saving and available for MBB transmission over the same network, as illustrated in Fig. 1. The MBB transmission and Cell-TV operation will cause interference to each other if they are using the same spectrum band in adjacent areas.

1) Exclusion Area: Since the spectral efficiency of an SFN is typically limited by the minimal SINR at its border, the frequency band of the SFN should not be reused within certain distance from the SFN border. The implementation of this 'exclusion area' is essential for limiting non-SFN interference, but it reduces the spectrum available for other services.

2) Multi-Cell Coordination (MCC): With the advancement of cellular technology, the effect of inter-cell interference can be reduced through MCC. It is more effective for improving the SINR of unicast links than broadcast, as it only suppresses non-SFN interferences. The MCC gain is defined by the percentage of interference reduction.

B. Minimizing spectrum requirement of Cell-TV

Due to the inter-cell interference and the possible implementation of exclusion area, the transmission modes of all cells involved should be jointly optimized in order to minimize the overall spectrum requirement of Cell-TV. The proposed framework for deciding the transmission modes is formulated as follow:

$$\begin{aligned} \min_{\mathbf{x}} \quad & \frac{\sum_{i\in\Pi} \zeta_i W_i^r(\mathbf{x})}{|\Pi| \sum_{i\in\Pi} \zeta_i} \\ \text{s.t.} \quad & \Pr\left(\sum_{n=1}^{N_{i,k}} \frac{(1-|x_{i,k}|)\varrho_{k(n)}}{S_u\left(\gamma_i^u(r_n)\right)} > W_{i,k}^u\right) \le 1\%,\ \forall i \in \Pi, \\ & \frac{|x_{i,k}|\varrho_k}{S_b\left(\min_{j\in\Pi_i^k}\left(\hat{\gamma}_j^b\right)\right)} \le W_{i,k}^b,\ \forall i \in \Pi. \end{aligned} \tag{1}$$

The objective function is the overall spectrum requirement of Cell-TV. The summation of spectrum requirement in each cell, W_i^r, is weighted by the number of population in each cell, ζ_i, to reflect different potential demands for spectrum. Here Π denotes the set of cells in the studied area. The design variable $\mathbf{x} = \{x_{i,k}\}$ is defined as

$$x_{i,k} = \begin{cases} -1, & \text{cell } i \text{ is inside the SFN for channel } k; \\ 1, & \text{cell } i \text{ is at the border of SFN for channel } k; \\ 0, & \text{cell } i \text{ unicast channel } k. \end{cases}$$

The spectrum requirement $W_i^r(\mathbf{x})$ as a function of $\mathbf{x}$ is given by

$$W_i^r(\mathbf{x}) = \sum_{k=1}^{K}\left(W_{i,k}^u + W_{i,k}^b + \sum_{j\in\Pi_i^e} \frac{x_{j,k}(1+x_{j,k})}{2} W_{j,k}^b\right), \tag{2}$$

where $W_{i,k}^u$ is the spectrum required to unicast channel k in cell i and $W_{i,k}^b$ is the spectrum requirement for broadcast. The last term represents the amount of spectrum vacated in the exclusion area. Π_i^e the set of cells within the exclusion distance from cell i. K denotes the number of TV channels.

The first constraint is the blocking probability requirement for unicast channels. $N_{i,k}$ is the number of active unicast viewers watching channel k in cell i. It follows poisson distribution with $\lambda_{i,k} = \kappa_i\zeta_i\pi_k$, with κ_i being the average number of viewer per population and π_k the channel popularity ratio. ϱ_k is the bit rate of channel k. $\gamma_i^u(r_n)$ is the unicast SINR for the user at location r_n and S is the corresponding spectral efficiency[1]. $W_{i,k}^u$ can be estimated analytically through multi-Erlang analysis [8], [12].

The second constraint signifies the coverage requirement of broadcast channels. Assuming cell i belongs to an SFN for channel k formed by a group of cells denoted by Π_i^k and $\hat{\gamma}_j^b$ is the lowest 1% SINR for broadcast in cell j, the spectral efficiency of the SFN is determined by the minimum $\hat{\gamma}_j^b$ among this group of cells.

III. Numerical Evaluation

A. Scenario

To apply the proposed framework to a realistic scenario, we have selected a circular area within 80 km radius from the city center of Stockholm. The selected area covers distinctive morphologies and has a good coverage of both DTT and

[1]Please refer to [8] for details on the calculations of γ and S.

TABLE I: Scenario parameters.

Morphology	Dense Urban	Urban	Suburban	Inner Rural	Outer Rural
Distance from city center (km)	0-4	4-12	12-32	32- 48	48- 80
DTT service penetration ν (%)	15	15	30	45	60
Propagation: Hata model variations	Urban (large city)	Urban (medium city)	Suburban	Open area	Open area
Tx antenna height (m)	15	15	30	45	90
Transmission power	46dBm/20MHz/antenna				
Tx antenna type	15 dBi, 3-sectorized antenna, 4 elements				
Rx antenna type	0dBi indoor gateway with 4 elements		9.15dBi rooftop antenna [14] with 4 elements		
Rx antenna height (m)	1.5		10		
Rx noise figure (dB)	10		7		
Wall attenuation (dB)	10		0		

TABLE II: TV channel types and popularity ratios.

Channel type	Popular HD	Niche HD	Niche SD
Number of channels	4	32	24
Popularity ratio π_k (%)	12.5	0.9	0.9
Bit rate ϱ_k (Mbps)	7.14	7.14	1.83

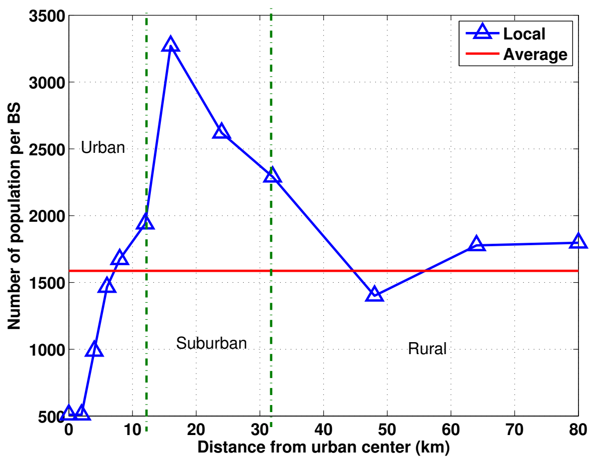

Fig. 2: Number of population per BS at different locations in greater Stockholm area [10], [11].

mobile services. The transition from dense urban to rural area is characterized by the gradual changes in propagation conditions, transmitter and receiver types[2] and over-the-air TV service penetration ν (see Table I). In addition, the BS density ξ and population per BS ζ are based on real-world statistics of the studied area. ξ declines monotonously as the distance from the city increases. The population distribution is more intricate as shown in Fig 2. The network load for MBB is assumed to be constant $\chi^{mbb} = 0.5$. We consider a three sectorized configuration for unicast. For broadcast, the same content are transmitted in all sectors over the same spectrum band.

On average, each Swedish household consists of 2.1 populations with two TV sets. The TV viewing ratio during peak hour is 40%. In combination with the DTT service penetration ratio at different locations, ν_i, we can derive the average number of viewer per population as $\kappa_i = 2/2.1 \cdot 0.4 \cdot \nu_i$. We assume

[2]For MIMO receiver, a spacing of more than 2-3 meters between each antenna element is required to avoid significant spatial correlation in rural areas with line-of-sight [13].

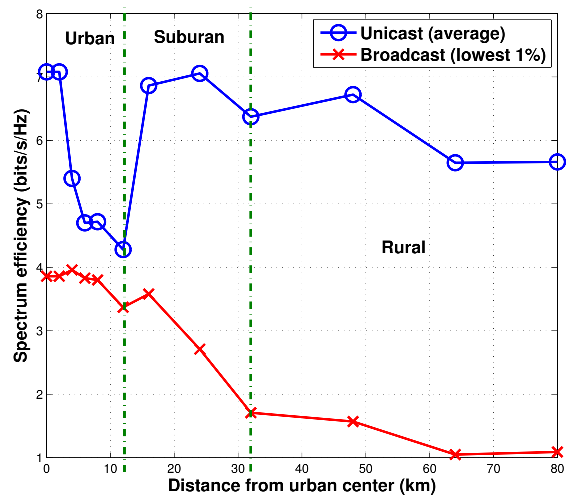

Fig. 3: Achievable local spectral efficiency (MCC = 6 dB).

60 TV channels are offered by Cell-TV, comparing to 54 channels currently provided by DTT in the Stockholm region. Both standard definition (SD) (576i) and high definition (HD) (1080i) programs employ H.264/AVC coding format. Details about different TV channels are summarized in Table II.

B. *Results*

Due to page limitation, here we show only an example of the results with a MCC gain of 6 dB and an exclusion distance of three ISDs. With this setting an overall spectrum saving of 130 MHz is obtained, in comparison with 70 MHz when MCC = 0 dB. The transmission modes of all the cells are optimized jointly based on the viewing demand as shown in Fig. 2 and the spectral efficiency achievable given the local infrastructures and propagation conditions (Fig. 3).

In the urban area, the spectral efficiency for unicast is limited by the use of omnidirectional antenna and high inter-site interference, while the SFN broadcast performance benefits from high BS density. Therefore, even though the urban area has the lowest number of population per BS, SFN is still the more efficient way to distribute all the TV channels.

In the suburban area, the deployment of directional roof antenna brings a notable improvement to the spectral efficiency for unicast. In contrast, the SFN gain starts to decline as the

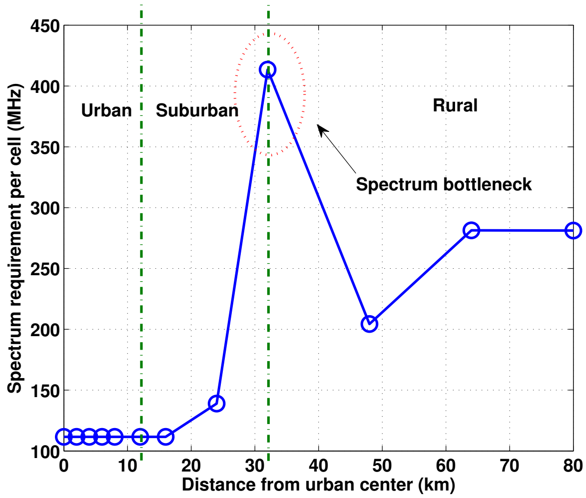

Fig. 4: Local spectrum requirement of Cell-TV system (MCC = 6 dB)

ISD increases. Nevertheless, broadcast is still the preferred option because of the highest viewing demand in suburban area. Note that both urban and suburban areas are covered by a single continuous SFN to avoid wasting spectrum in exclusion areas at the cost of a lower spectral efficiency limited by the suburban ISD.

In the rural area, the SFN gain further diminishes and the population per BS declines. Therefore all the niche channels switch to unicast, whose performance is less affected by the increase in ISD. The popular TV channels, still commanding considerable viewing demand, are broadcasted over an new SFN that covers the entire rural area with a lower modulation order.

The resulting local spectrum requirement is illustrated in Fig. 4. As we can see, there are significant spectrum savings throughout urban and most of suburban areas thanks to the SFN gain. However, when the the transmission modes inevitably switched at the border between suburban and rural areas, a local 'spectrum bottleneck' occurred due to the combination of high spectrum requirement for unicasting and spectrum access restriction in exclusion areas. The spectrum saving in rural is limited due to the relatively large number of population per BS and the higher dependence on over-the-air TV reception. Improvement in MCC could alleviate the 'spectrum bottleneck' situation and make unicast in rural area more efficient, but the overall trend in local spectrum requirement would remain the same.

IV. Conclusion and Future

In this paper, we investigate the spectrum requirement of a converged platform for TV and mobile broadband services provisioning based on cellular technology and infrastructure. We propose a framework to adapt the transmission mode of each TV channel to the local infrastructure and user demand, such that the overall spectrum requirement is minimized for providing a seamless coverage of Cell-TV service throughout urban and rural areas. Based on a case study of the greater Stockholm area, we find significant spectrum saving in urban and most of suburban areas by broadcasting all the TV channel over a continuous SFN. its coverage reaches the border between suburban and rural areas, where the popular TV channels switch to another SFN with lower modulation order and niche channels to unicast. As parts of the spectrum are restricted from reuse in the exclusion areas adjacent to the SFNs, the spectrum requirement is the most demanding in these areas. In rural areas the spectrum saving is also limited, as base station density decreases and the number of population remains high in each cell. Improvement in MCC could benefit the overall spectrum saving, but has limited affect on the pattern of local spectrum requirement.

In this initial study, we have noticed a few factors that have profound influence on the spectrum requirement of Cell-TV system. Therefore, we plan to extend the investigation to compare different population distributions and TV viewing patterns, and the tradeoff between MCC gain and exclusion distance. We will also analyze the coexistence between MBB and Cell-TV with more details to understand their capacity limits and identify the design principle for Cell-TV in an inhomogeneous environment.

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