CellTV - on the Benefit of TV Distribution over Cellular Networks: A Case Study

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Abstract

As mobile IP-access is becoming the dominant technology for providing wireless services, the demand for more spectrum for this type of access is increasing rapidly. Since IP-access can be used for all types of services, instead of a plethora of dedicated, single-service systems, there is a significant potential to make spectrum use more efficient. In this paper, the feasibility and potential benefit of replacing the current terrestrial VHF/UHF TV broadcasting system with a mobile, cellular data (IP-) network is analyzed. In the latter, cellular network, TV content would be provided as **one** of the services, here referred to as *CellTV*. In the investigation we consider typical Swedish rural and urban environments. We use different models for TV viewing patterns and cellular technologies as expected in the year 2020. Results of the quantitative analysis indicate that CellTV distribution can be beneficial if the current trend towards more specialized programming, more local contents, and more on-demand requests, continues. Mobile cellular systems, with their flexible unicast capabilities, will be an ideal platform to provide these services. However, the results also demonstrate that CellTV is not a spectrum effective replacement for terrestrial TV broadcasting with current viewing patterns (i.e. a moderate number of channels with each a high numbers of viewers). In this case, it is doubtful whether the expected spectrum savings can motivate the necessary investments in upgrading cellular sites and developing advanced TV receiver required for the success of CellTV distribution.

Index Terms

VHF/UHF TV band, Terrestrial TV broadcasting, Multimedia Broadcast/Multicast Service, Single Frequency Network, Unicast Video Streaming.

I. Introduction

Efficient use of radio spectrum is considered an essential ingredient of future mobile broadband provisioning with exploding capacity demand, in particular for IP-based mobile data. IP-access is not tied to a single service. Building a single access network, instead of the current plethora of dedicated, single-service systems ("one-trick ponies"), provides economies of scale when it comes to infrastructure deployment but also a significant potential to make more efficient use of the spectrum.

The VHF/UHF band, currently dedicated to the terrestrial TV broadcasting (i.e., 470-790 MHz) is one of the bands that have obtained special attention, primarily because of its attractive propagation characteristics. Numerous studies have been focused on investigating alternatives for enhancing the utilization of this band. One forward-looking idea is using the so-called 'TV White Space' on a secondary basis without affecting the normal terrestrial TV broadcasting service [1]. Early in 2010, the Federal Communications Commission (FCC) in the USA announced permission for unlicensed secondary devices assisted by Geo-location database to operate in the TV band [2], while the European regulators have developed their own frameworks for regulating the secondary access [3] [4]. Although these pioneering efforts led by the regulators have created high expectations for the secondary access in TV bands [5], quantitative analysis from recent studies has discovered that TV White Space is not suitable for secondary system providing wide-area coverage due to the interference constraint to primary TV receivers [6] [7]. Only short range systems with smaller interference footprint can efficiently exploit the local secondary spectrum opportunity [7].

Another, more radical, approach that is currently discussed is to re-purpose the VHF/UHF band for cellular, IP-based, systems and to distribute TV contents over this infrastructure as one of many services, and thereby effectively replace the traditional terrestrial TV network. Our expectation is that delivering TV service over cellular networks will require less spectrum than current terrestrial TV network for the same service offering and quality. At the same time this solution is more flexible and will allow other services to be provided in parallell. One of the enablers is the Multimedia Broadcast/Multicast Service (MBMS) introduced in 3GPP LTE radio technology for point-to-multipoint or multipoint-to-multipoint service over a single frequency network (SFN) [8]. Through tight time synchronization, the TV contents can be broadcasted over a SFN with high spectrum efficiency. Furthermore, additional features such as localized contents distribution and on-demand services are made possible by adopting the cellular infrastructure and as such considerably improve the flexibility of the TV service. However, as the cost of implementing such system can be considerably high, it would be difficult to motivate the investment unless significant benefit is foreseen.

The idea of distributing TV contents over cellular network originates from the domain of mobile TV systems. Previous work has mainly focused on analyzing requirements and capacity limits for delivering mobile TV over an OFDMA-based cellular network. In [9], the authors present the system architecture of MBMS in 3G networks, and outlined the relevance of applying mixed broadcast/unicast solution when there is a ”long tail” of channels requested by few users. Detailed traffic analysis for delivering mobile TV over a hybrid broadcast-unicast deployment have been investigated in [10] and [11]. The implementation and cost aspect of providing mobile TV service in 3G networks are discussed in [12]. The convergence of mobile TV service and mobile broadband network in 4G networks is presented in [13]. In [14], the authors develop a general roadmap and analytical models for assessing the network performance in terms of coverage and throughput for different deployment options using advanced features introduced in LTE (Long Term Evolution) network.

However, terrestrial TV broadcasting has a complete different service demand than mobile TV, and also has a significantly higher quality of service requirement. Current DVB-T system offers high definition (HD) TV program that requires a data rate over 7 Mbps, whereas the data rate of a typical mobile TV transmission is in the range of hundreds of Kbps. Furthermore, the strict coverage requirement of terrestrial TV poses a formidable challenge for any attempt to replace it with mobile networks. The same high quality TV programs are supposed to reach even the fixed receivers at the edge of the coverage. On the other hand, fixed TV receiver can rely on more advanced antenna configurations with considerably better performance than mobile receivers. Consequently, the existing results on mobile TV cannot be directly applied to the study on distributing terrestrial TV service over mobile network.

The concept of providing over-the-air TV service for fixed reception using a cellular LTE MBMS network begins to gain popularity in recent years. In [15], the amount of spectrum needed for delivering today's over-the-air TV service is calculated by taking different cities in the USA as reference. This work limits its focus on densely populated (urban) areas where typical inter-site-distance (ISD) of cellular networks is smaller than 2km, which ensures good performance of the MBMS network. On the other hand, larger ISD which is typical for rural areas would considerably degrades the spectral efficiency of the broadcasting network due to the long propagation delay as shown in [9], thus requiring far larger amount of spectrum to provide the same service. Therefore, it is not evident that replacing terrestrial TV service with mobile networks is feasible based on the results from urban scenarios alone. Besides, the possibility of employing unicast for less popular TV channels is not exploited in this analysis, although it may reduce the spectrum requirement as indicated by results from earlier studies.

In this paper, we aim to provide a more comprehensive assessment of the potential benefit of delivering terrestrial TV service using a cellular infrastructure. It is evaluated in terms of spectrum saving, referring to the portion of spectrum out of 470-790 MHz band that can be vacated for broadband usage. Two possible architectures of the cellular TV distribution system are investigated. One option is to deliver all TV programs over (several) SFN(s) formed by multiple cellular sites, while the other is to broadcast only the most popular TV programs and distribute the rest programs via unicast links. To properly reflect the various spectrum demand of unicast viewers in different situations, multi-Erlang model is applied to analyze the capacity and the spectrum requirement of the hybrid system. The investigation targets the year 2020 with moderate assumptions on the cellular technologies development, such as advanced MIMO and enhanced modulation/coding schemes. We based our numerical analysis on the statistics of cellular network deployments and terrestrial TV service in Sweden, which has one of the best terrestrial TV coverage as well as mobile coverage in Europe. Sweden also consists of a good mixture of sparsely populated rural areas and dense urban cities. Lastly, we study the potential impact of the predicated changes in the number of TV channels, the terrestrial TV service penetration and its consumption pattern in the coming years.

The remainder of this paper is organized as follow: Section II defines the objective of the study and describes the expected requirements for over-the-air TV service in 2020 in Sweden. The modeling of CellTV and the calculation of its spectrum requirement are explained in Section III. Then Section IV describes the representative Swedish scenarios for numerical evaluation and the major results. Finally, the main conclusion and implications are discussed in Section V.

II. Problem Formulation

The aim of this study is to quantify the required spectrum for replacing terrestrial TV network with distributing TV service over the cellular infrastructure. The potential benefit of CellTV distribution is evaluated by comparing its required spectrum to the amount of spectrum currently allocated for terrestrial TV networks.

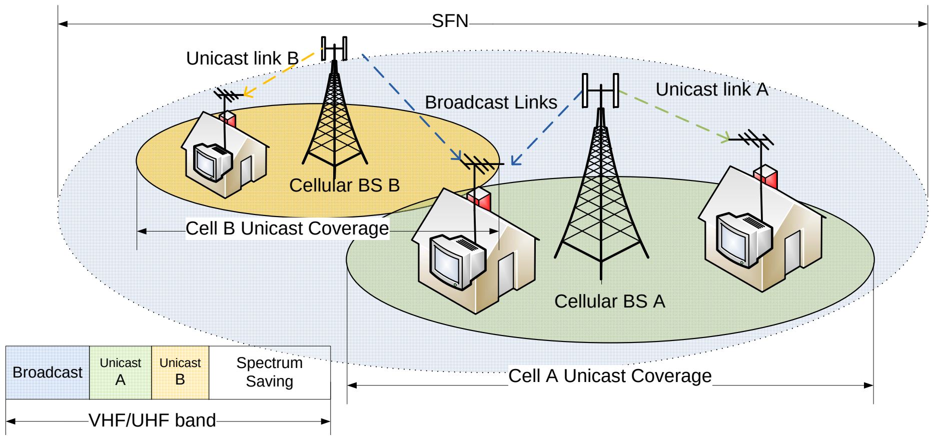

Fig. 1: Illustration of CellTV system

A. Analysis Scenarios

Sweden is chosen for our case study for its diverse geo-location types as well as its good coverage of both terrestrial TV system and mobile network. We focus the investigation on typical Swedish rural and urban environments, as they represent the possible worst-case scenarios with regard to the spectrum demand.

1) ***Rural****:* The population density in typical Swedish rural areas is very low, where most of the rural inhabitants rely on over-the-air TV reception. It is estimated that around 60% of the households in rural areas have subscription to terrestrial TV service [16]. These households are assumed to receive the TV signal through high gain rooftop antennas, which can be legacy type antennas or advanced multi-antenna units with MIMO capability that is expected to be commercially available by 2020[1]. However, as further cell site acquisition is not likely to happen in rural areas, the limited cellular infrastructure may pose a significant challenge for providing the coverage with intended data rate requirement.

[1]In rural areas with open environment large spatial separations between the antenna elements are required to limit the signal correlation from multiple antennas working in the VHF/UHF band. Therefore more than 4 antenna elements may not be practical for rooftop installation.

*2) **Urban**:* The urban area in Sweden, e.g., Stockholm, has much higher population density and also a denser cellular base station deployment. As most families in the city have cable connection, the terrestrial TV service penetration is estimated to be only 15% [17]. However, the density of terrestrial TV viewers in the city is still considerably higher than the rural area. Rooftop antenna is seldom used in apartment buildings in urban areas. Instead, we assume that indoor gateways with multiple low gain antennas are used in the urban environment.

B. Requirement for Terrestrial TV Service

*1) **Service Availability Requirement**:* In Sweden, the terrestrial TV network currently covers more than 99.8% of the inhabited area. It is required that the service availability must be higher than 95% at the TV coverage boundary, which is approximately equivalent to a service availability of 99% within the whole TV coverage area. The temporal availability is not explicitly defined in the terrestrial TV system, as the broadcast service is expected to be constantly available. However, with the introduction of unicast for TV distribution, there is a risk of temporary blocking due to fluctuations in the traffic load. Therefore, we assume that a strict requirement on temporal availability, e.g. 99.9%, should be imposed on the CellTV system in addition to the coverage requirement.

*2) **Terrestrial TV Service in 2020**:* The number of TV programs being broadcasted over the terrestrial TV network in Sweden is expected to increase slightly in 2020, reaching 60 in total, out of which 36 would be high-definition (HD) programs and 24 standard-definition (SD) programs. With advanced video coding, the data rate for an HD program is assumed to be 7.14 Mbps, and 1.83 Mbps for an SD program. For public service and commercial interest, some TV programs may have regional content that differs in each region. We assume that the division of region remains the same as that of today, i.e., at most three intersecting regions at any location within Sweden.

Furthermore, it is assumed that the terrestrial TV service penetration would remain the same in rural areas but would decline gradually in urban areas by the year 2020. The daily TV consumption pattern, however, is expected to be the same as of today: during the peak hour (8-9 pm), over 40% of the households in Sweden would be watching TV and half of them would tune to the three most popular TV programs. The dimensioning of the CellTV system is based on the peak hour traffic assumption [17].

C. Cellular TV Distribution Methods

In this study, we consider two methods for the CellTV distribution: broadcast-only or a mixture of broadcast and unicast.

*1) **Broadcast-Only**:* In this configuration, all TV programs except those with regional content are broadcasted over a large scale single frequency network (SFN) formed by a group of cellular base stations transmitting on the same frequencies. The TV programs with regional content, on the other hand, are distributed through regional SFNs each operating on a unique set of frequencies.

*2) **Hybrid of Broadcast-Unicast**:* This hybrid of broadcast-unicast distribution allows the CellTV system to broadcast only the few popular TV programs over SFNs and deliver the rest of the TV programs as typical video streaming on unicast links. In addition to the streaming of linear TV programs, the cellular unicast also enables enhanced features, such as Video-on-Demand (VoD) service.

D. Performance Metric

The key performance metric is the amount of required spectrum, BW_{req}, defined as the total amount of radio spectrum to be allocated for the CellTV system in order to provide the same level of quality of service offered by terrestrial TV networks throughout Sweden. The frequency band in question is the VHF/UHF band between 470 MHz and 790 MHz, which is assumed to be vacated by the shutdown of terrestrial TV networks.

Spectrum saving is simply defined as the difference between the amount of spectrum allocated for terrestrial TV system and the amount of spectrum required by the CellTV system.[2].

$$BW_{save} = 320 - BW_{req}(\mathrm{MHz}) \tag{1}$$

A positive value of spectrum saving indicates the potential gain for the cellular TV distribution, while a negative one may imply the infeasibility of providing the CellTV service within the VHF/UHF band allocated to terrestrial TV system.

E. Evaluation Methodology

The quantitative analysis performed in this study can be divided into two phases:

1) Selection of Representative Cases: first, specific locations that are deemed as the most problematic for cellular TV distribution are selected from Swedish rural and urban areas respectively. Then representative parameters are extracted from the real base station deployment and demographics data of the selected areas.
2) Calculation of Spectrum Requirement: based on these representative parameters, the evaluation environment is constructed with a regular (hexagonal) deployment of cellular network and uniformly distributed TV receivers. Then the required spectrum for the CellTV system for that particular setting is calculated using the analytical tools and simulation models described in Section III.

III. REQUIRED SPECTRUM FOR CELLULAR TV DISTRIBUTION

A. Broadcast-only CellTV Distribution

*1) **Spectrum Allocation for Broadcast-only**:* Multicast-broadcast over a single frequency network (MBSFN) enables multiple transmissions from multiple base stations over the same

[2] It is known that parts of the lower VHF band outside 470-790 MHz (174-230 MHz) are also used for terrestrial TV in certain areas in Sweden. These bands are not considered in this paper.

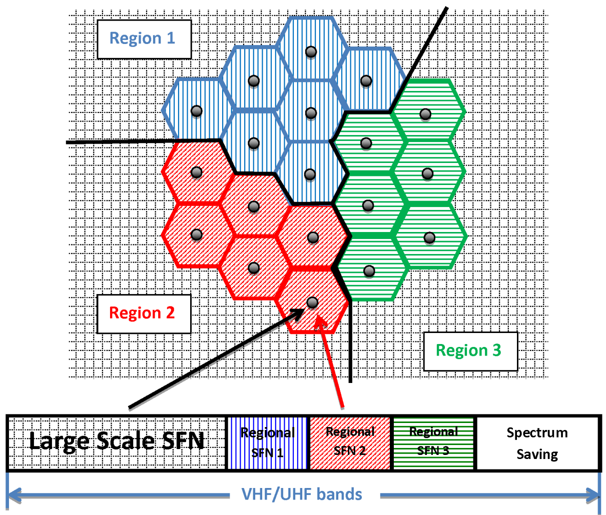

Fig. 2: Spectrum allocation of CellTV with pure broadcast

frequency channel, which is seen from the receiver as a single transmission subject to a severe multi-path propagation. Tight time synchronization of all base stations is required to overcome the effects of ISI. Due to the long data symbol duration of OFDM, LTE MBSFN considerably mitigates ISI effects when the delay spread is relative small. The propagation delay of the transmitted signals has critical impact on the performance of MBSFN. As opposed to traditional unicast transmission, portion of the transmitted signals in the MBSFN area that arrives within certain duration is considered as constructive interference or gain [18].

While the nationwide TV programs can be transmitted over a large scale SFN, the TV programs with regional content must be transmitted separately over different SFNs operating on different set of frequency channels in each geographical region. Fig. 2 illustrates the spectrum allocation for different SFNs in CellTV network.

The spectral efficiency of regional channels at the border of a regional SFN is lower than the channels belonging to the the large scale SFN because the earlier ones experiences less SFN gain. Therefore, the regional border cell has the highest spectrum requirement, representing the worst-case scenario. Denoting ESE^{R}_{min} and ESE^{L}_{min} as the effective spectral efficiency (ESE) for the SFN link at the cell border for regional channels and channels for large scale SNF, the total bandwidth required for a border cell can be calculated by,

$$BW^{B}_{req} = \frac{\eta^{L}_{HD} R_{HD} + \eta^{L}_{SD} R_{SD}}{ESE^{L}_{broad,min}} + X \frac{\eta^{R}_{HD} R_{HD} + \eta^{R}_{SD} R_{SD}}{ESE^{R}_{broad,min}}, \quad (2)$$

where η^L and η^R denote the numbers of TV programs distributed in large scale SFN and regional SFNs respectively. The subscripts HD and SD are used to distinguish between HD and SD TV programs. X is the number of intersecting regions around the studied area.

*2) **SINR for Broadcast over SFN:*** Assume that the target user is located in cell 0 at a distance r_0 from base station 0 and at distance r_i from an arbitrary base station $i \neq 0$ in cell i. The constructive portion of a received SFN signal depends on the propagation delay $\tau = (r_i - r_o)/c$, where c is the speed of light. For a given τ, the weight function of the constructive portion of a received SFN signal is [19] [20]:

$$\omega(\tau) = \begin{cases} 0, & \tau < -T_u; \\ 1 + \frac{\tau}{T_u}, & 0 \leq \tau < T_{CP}; \\ 1, & 0 \leq \tau < T_{CP}; \\ \frac{1-(\tau - T_{CP})}{T_u}, & T_{CP} \leq \tau < T_{CP} + T_u \ ; \\ 0, & \text{otherwise}, \end{cases} \quad (3)$$

where T_u is the length of the useful signal frame and T_{CP} is the length of the cyclic prefix. Due to multipath propagation, multiple copies of a signal could arrive to the receiver. Then, the weighted function should be calculated for each multipath signal. Typically OFDMA attenuates the impact of fast fading by guaranteeing that all multipath signals arrive within the cyclic prefix [14]. The raw SINR of a user in cell 0 is given as:

$$SINR_{broad} = \frac{\sum_{i=0}^{m} \frac{\omega(\tau_i)\bar{P}}{q_i}}{\sum_{i=1}^{m} \frac{(1-\omega(\tau_i))\bar{P}}{q_i} + N_0}, \quad (4)$$

where τ_i is the propagation delay, $\bar{P}$ is average power associated with base station i and q_i represents the propagation loss to the base station i, which accounts for distance-based path loss and shadowing. The total number of cells in the MBSFN area is given by m.

*3) **Effective Spectral Efficiency**:* In order to calculate the Effective Spectral Efficiency (ESE), we adopt a simplified model based on the Shannon formula. To draw a realistic link performance of future cellular system in relation to the Shannon capacity bound, we employ two parameters: bandwidth efficiency (β_{eff}) and SINR implementation efficiency (ξ_{eff}) [19]. Then, the modified Shannon capacity formula is expressed as follows:

$$ESE_{broad}(bits/s/Hz) = \beta_{eff} \log_2 [(1 + \xi_{eff} SINR_{broad})]. \tag{5}$$

Here SINR is computed when the wireless link is in deep fading, which represents 5dB loss in the raw SINR [21]. This assumption is made to account for the impact of fast fading. The parameter β_{eff} is determined by the Adjacent Channel Leakages Ratio (ACLR) requirements and protocol overheads. ξ_{eff} corresponds to the SINR which is mainly affected by the modulation[3], coding and MIMO modes. Table 1 shows the parameters and values used for calculating β_{eff} for rural and urban scenarios. Notice that for the broadcast-only case, we have neglected the gains related to dynamic beamforming due to the lack of user feedback. Therefore, we consider that ξ_{eff} for broadcast systems mainly depends on the spatial diversity gain, which is proportional to the number of transmitting and receiving antennas, M_T and M_R, respectively.

In order to provide the same coverage quality of the traditional terrestrial TV service, the CellTV network must cover all the inhabited area (households with permanent addresses) in Sweden with 99% reception probability. In other words, the bandwidth allocated for a given TV program should be sufficient to achieve the required data rate even for a user experiencing the lowest 1 percentile SINR inside the cell due to shadow fading.

[3]Maximum modulation order is assumed to be 512QAM (max 9 bps/Hz per stream)

TABLE I: BANDWIDTH EFFICIENCY FOR MBSFN AND UNICAST [21] [22]

	Rural broadcast	Urban broadcast	Rural unicast	Urban unicast
ACLR overhead	0.1	0.1	0.1	0.1
Cyclic prefix overhead	0.2	0.07	0.2	0.07
Pilot and control overhead	0.1	0.1	0.3	0.3
β_{eff}	0.65	0.75	$0.50 \cdot min(M_T, M_R)$	$0.59 \cdot min(M_T, M_R)$
ξ_{eff}	$M_T M_R/2$	$M_T M_R/2$	0.5	0.5

B. Hybrid Broadcast-Unicast CellTV Distribution

*1) **Spectrum Allocation for Hybrid Broadcast-Unicast**:* In this hybrid distribution mode, the TV programs with the largest amount of viewers are broadcasted over SFNs. In the worst-case, these TV programs are assumed to contain regional content. On the other hand, less popular TV programs are delivered via unicast link, as typical point-to-point video streaming. For these transmissions, frequency reuse of K must be applied to limit the co-channel interference from other transmissions. Fig. 3 illustrates the spectrum allocation in the hybrid broadcast-unicast system for the case of spectrum reuse three.

Assuming the amount of spectrum for unicast per cell required to achieve sufficiently low blocking probability is BW_{uni}, the total bandwidth required for the hybrid distribution is given by

$$BW_{req}^{H} = X \cdot BW_{broad} + K \cdot BW_{uni}, \tag{6}$$

where BW_{broad} is bandwidth for broadcasted channels in three regional SFNs derived by using the methodology in section III-A1. In our study, $K = 3$ is adopted for the highest effective spectrum efficiency.

*2) **Traffic Model for TV Viewing**:* As opposed to the broadcast case, the bandwidth required for unicast is dependent on the number of TV viewers per cell. Assume that the number of active

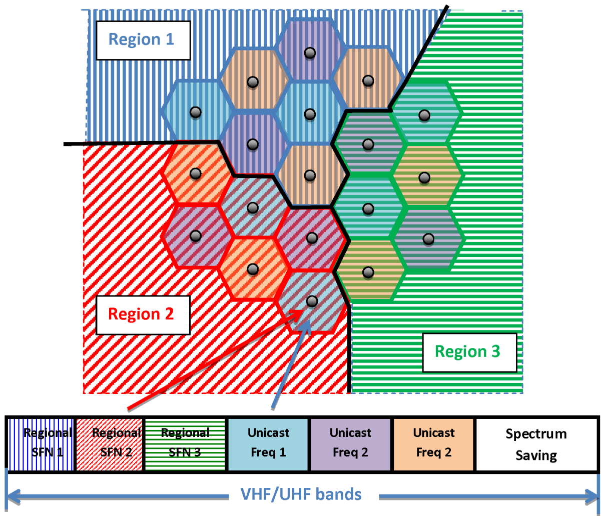

Fig. 3: Spectrum allocation for CellTV with hybrid broadcast-unicast operation

TV viewer in a cell follows a Poisson distribution, $N \in Poi(t_s, \lambda)$, with t_s being the average session length and λ the arrival rate. Based on statistics of the average ISD and population density [23] [24], the average number of active TV viewers in a cell $E\{N\}$ can be estimated by the product of the average TV viewing ratio and the number of terrestrial TV receivers within the cell coverage. Then the arrival rate of the TV viewers is given by

$$\lambda = E\{N\}/t_s. \tag{7}$$

Denote Ω as the set of TV programs delivered by CellTV (both via broadcast and unicast). An active TV viewer may select the i^{th} TV program with probability $P_i, i \in \Omega$. This selection probability can be approximated by the popularity of that TV program and $\sum_{i\in\Omega} P_i = 1$.

Within each session, the TV viewer can switch between different TV programs (either delivered by broadcast or unicast link) and spend t_c on average for each sub-session. At the end of each sub-session, the viewer may turn off the TV with probability P_e. The total session time for such system can be modeled by Coxian distribution. It follows that $P_e = t_c/t_s$. As proved in [10], the stationary distribution of the numbers of active unicast viewers is given as

$$N_{uni} \sim Poi(\rho_{uni}),\ \ \rho_{uni} = t_s \lambda \sum_{i \in \Omega_{uni}} P_i. \tag{8}$$

Here ρ is the traffic intensity. $\Omega_{uni} \subseteq \Omega$ is the set of unicast TV programs. Note that the numbers of viewers watching different sets of TV programs are in fact independent from each other, and are not affected by the sub-session duration [10].

Assume the bandwidth required for the i^{th} unicast link is b_i. If any viewers watching unicast program failed to secure the required bandwidth b_i, this cell is considered as in blocking state. The blocked viewers keep attempting to enter the desired channel until either they success or their session time out. The blocking probability is given as

$$P_{block} = Pr(\sum_{i=1}^{N_{uni}} b_i > BW_{uni}), \tag{9}$$

where BW_{uni} must be chosen such that $P_{block} \leq 0.1\%$[4].

*3) **Multi-Erlang Analysis**:* The bandwidth to be allocated for the unicast service can be obtained by testing different values in Monte Carlo simulation until the blocking requirement defined in (9) is satisfied; however, such iterative process would require extensive simulation. To reduce the computation complexity, we approach the problem with multi-Erlang analysis to solve it analytically.

To construct a multi-Erlang system, the unicast viewers in a cell are divided into K different streaming classes according to their required bandwidths, such that $b_k \geq b_i < b_{k+1}$ ($k = 1, 2, ...K$). The traffic intensity corresponding to each class is given by ρ_k. Since b_i is directly dependent on the link SINR, the streaming classes can be defined according to the SINR distribution in the cell. Assuming that the TV viewers are uniformly located inside

[4]This value is chosen to represent strict requirement on the blocking of unicast TV service, although our analysis also shows that the BW_{uni} is not very sensitive to the blocking requirement

the TV coverage, subject to uncorrelated shadow fading, the streaming class corresponds to $(k-1)\Delta\% \sim k\Delta\%$ of the SINR distribution would have the traffic intensity[5] defined as

$$\rho_k = \frac{\Delta}{100} t_s \lambda \sum_{i \in \Omega_{uni}} P_i. \tag{10}$$

To further distinguish the different rate requirements of HD and SD TV programs, each class can be divided into two subclass as

$$\rho_k^{HD/SD} = \rho_k \frac{\sum_{i \in \Omega_{uni}^{HD/SD}} P_i}{\sum_{i \in \Omega_{uni}} P_i}. \tag{11}$$

The blocking probability, which is equivalent to the portion of time in blocking state, is thus given as

$$P_{block} = Pr\{\sum_{k=1}^{K} N_k b_k > BW_{uni}\}, \tag{12}$$

where N_k is the number of active user in class ($N_k \; Poi(\rho_k)$).

The blocking probability can be obtained by following Kaufman-Roberts recursion [25] briefly illustrated below:

- Find a small unit value δ, such that $b_k \approx b'_k \delta$, $k = 1, 2, ..., K$ and $BW_{uni} \approx C\delta$ with both b'_k and C being integers.
- Define $G(c)$ that follows the recursion process given as

  $$G(c) = \frac{1}{c} \sum_{k=1}^{K} \rho_k b'_k G(c - b'_k), \tag{13}$$

  which is initialized by $G(0) = 1$, $G(c) = 0$, when $c < 0$.
- Solve $G(c)$ for $c = 1, 2...C$.
- Obtain the blocking probability as

  $$P_{block} = \sum_{k=1}^{K} \frac{\sum_{c=C-b'_k+1}^{C} G(c)}{\sum_{c=0}^{C} G(c)}. \tag{14}$$

[5]Note: all users have SINR lower than the minimum SINR requirement are considered in outage and does not contribute to the traffic in the system.

*4) **Unicast SINR:*** To obtain the unicast link SINR distribution, let us consider an arbitrary viewer at location r_i whose SINR can be expressed as

$$SINR_{uni}(r_i, X) = \frac{\bar{P}/q_0(r_i)}{\sum_{l=1}^{m'} X_l \bar{P}/q_l(r_i) + N_0} \tag{15}$$

where X is the interference collision vector conditioned on the network load x. and m' is the number of interfering base stations (sites allocated with the same spectrum for unicast). Then the spectral efficiency is derived using the same model as in the broadcast case:

$$ESE_{uni}(r_i, X)(bits/s/Hz) = \beta_{eff} \log_2 [1 + \xi_{eff} SINR(r_i, X)]. \tag{16}$$

Here, β_{eff} is modified to reflect the beamforming gain and the increased control overhead. ξ_{eff} is also changed from diversity gain to represent the MIMO implementation loss instead. The parameter settings are summarized in I.

The network load x in the system is obtained by solving the fixed point equation[6]

$$x = \min \left[(\rho_{HD} R_{HD} + \rho_{SD} R_{SD}) \cdot \int_0^R \frac{2r \text{ d}r}{R^2 \sum_X [Pr(X|_x) BW_{uni} ESE(r, X)]}, 1 \right]. \tag{17}$$

Note that the network load x is thus depending on the total bandwidth available for unicast BW_{uni} and the traffic intensity of unicast TV viewers in a cell watching either HD or SD TV programs (ρ_{HD} and ρ_{SD}).

IV. Numerical Evaluation

A. Parameter Settings

For numerical evaluation, the simulation scenarios are created based on the typical settings of Swedish rural and urban areas. The choice of Stockholm for urban scenario is straightforward. Less obvious is the selection of the rural area for investigation because Sweden contains vast area with sparse population. The most interesting scenario, which is also the worst-case for CellTV

[6]Here $ESE(r, x)$ is averaged over shadow fading.

distribution, is identified as the area with the most problematic broadband coverage according to the recent PTS report [26].

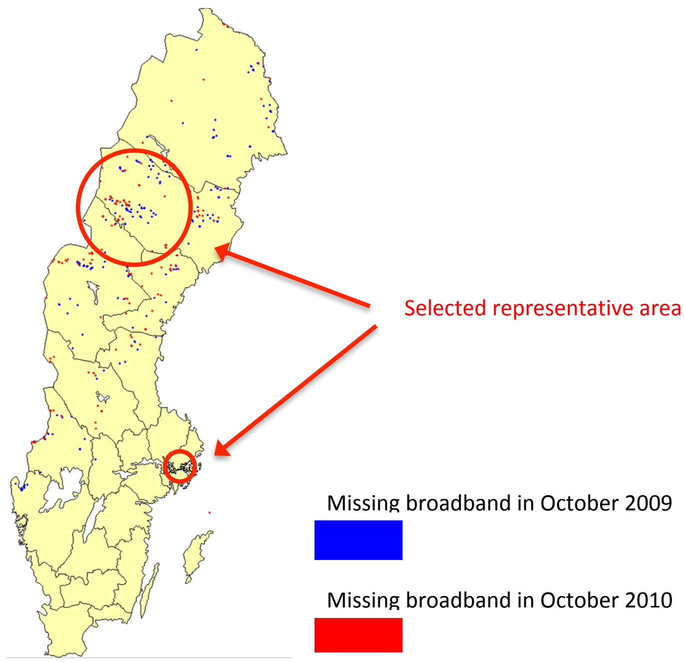

Fig. 4: Area without broadband connection and selected investigation areas [26]

Having identified the areas of investigation, we extract representative parameters from the real base station deployment and the demographics data and construct the simulation environment as a regular (uniform) hexagonal cellular deployment. The number of TV receivers in a cell is derived from the population density. On average, one Swedish household is consisted of 2.1 populations and each household possesses two TVs (Table II). Since throughout Sweden there is a maximum of three intersecting regions at any given location, only three sets of different frequency channels are needed for the regional SFNs ($X = 3$). The simulation parameters for the rural and urban scenario are summarized in Table III and Table IV, respectively[7] . For the

[7]The antenna height of 90 m for the base station is normal in rural Sweden to maximise the reach in these extremely sparsely populated areas.

TABLE II: TV SERVICE AND CONSUMPTION

Parameters	Values
Peak hour TV consumption	40% of total population
TV per household	2
Population per household	2.1
Number of HD programs	36 (in 2020)
Number of SD programs	24 (in 2020)
Data Rate requirement for one HD program	7.14Mbps
Data Rate requirement for one SD program	1.83Mbps
Number of programs with regional content in broadcast-only	3 (HD)
Number of programs delivered via broadcast in hybrid operation	3 (HD, accounts for 50% of the viewers)

hybrid operation, only the top three TV programs that account for 50% of viewing ratio are being broadcasted by regional SFNs. All other channels are delivered via unicast links in a cellular network with frequency reuse $K = 3$.

Notice that we assume the CellTV may utilize the existing GSM sites for delivering the TV service, because it provides a more homogenous coverage than the existing UMTS sites.

B. Numerical Results

1) ***Rural Scenario:*** Fig. 5 depicts the spectrum requirement for the broadcast-only CellTV system with varying ISDs in rural area. It is evident that the results are rather sensitive to the ISD. In fact, when ISD is larger than 12 km, pure CellTV broadcast with legacy antenna cannot even be accommodated within 320 MHz. This is because at such large ISD, the delay spreads of the received signal cannot be mitigated by the limited cyclic prefix and thus causing severer ISI than contributing to SFN gains.

On the contrary, the effect of ISD is less noticeable in multi-antenna cases, as their diversity gains improve SINR efficiency and as such are more resilient to lower SINR caused by ISI. How-

TABLE III: SIMULATION PARAMETERS FOR RURAL SCENARIO

Parameters	LTE Outdoor Base Station	Receiver antenna
Number of antennas	4, 8, 16	1, 4, 8, 16
Antenna gain	18dBi	8dBi (including looses)
Transmit power	43dBm/20MHz/antenna	N/A
Antenna height	90m	10m
Tilt (down)	2.5degrees	N/A
Polarization	+/- 45 cross-polarized	Horizontal polarization: ITU-R BT.419 [27]
Noise figure	N/A	7dB
Noise floor	N/A	-94dBm/20MHz
ISD range	4km - 16km	
Population density	1 inhabitants/km^2	
Terrestrial TV service penetration	60%	

TABLE IV: SIMULATION PARAMETERS FOR URBAN SCENARIO

Parameters	LTE Outdoor Base Station	Indoor gateway
Number of antennas	4, 8, 16	1, 4, 8, 16
Antenna gain	18dBi	0dBi (including looses)
Transmit power	43dBm/20MHz/antenna	N/A
Antenna height	30m	1.5m
Tilt (down)	2.5degrees	N/A
Polarization	+/- 45 cross-polarized	Vertical polarization
Noise figure	N/A	10dB
Noise floor	N/A	-91dBm/20MHz
ISD range	100m - 1500m	
Population density	5000 inhabitants/km^2	
Terrestrial TV service penetration	15%	

ever, as we mentioned earlier, even with optimistic assumption on the technology advancement in 2020, the applicability of a multi-antenna receiver with 8 or 16 uncorrelated branches is rather restricted, because of the physical limitation of the rooftop installation and the large separation distance required for uncorrelated reception in the VHF/UHF band. Therefore, a reasonable expectation of spectrum saving for pure CellTV broadcasting is in the range of 120-160 MHz, assuming a customer installation of new TV receiver antennas.

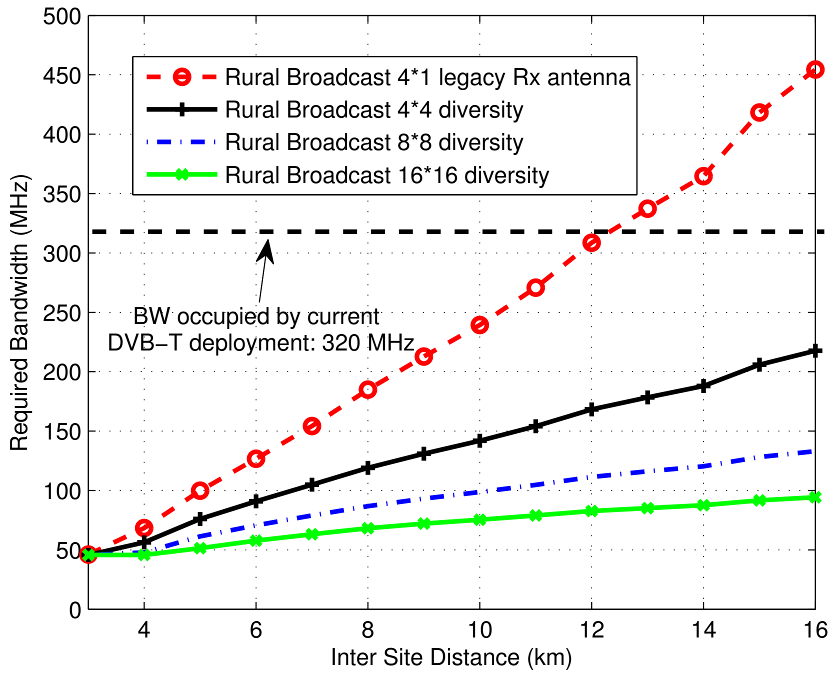

Fig. 5: Spectrum requirement for CellTV broadcast in rural environment

The spectrum requirement for hybrid CellTV broadcast-unicast operation is illustrated in Fig. 6 . Although the variation in ISD still has profound impact on the spectrum demand, the amount of required spectrum is nevertheless much lower than that of pure broadcast operation. Even with the legacy antenna, more than 200 MHz spectrum saving can be achieved at ISD of 12 km. The spectrum requirement can be further reduced by around 40% if the receiver antenna is replaced and 4x4 MIMO is implemented. In addition, we also notice that relaxing the blocking requirement does not provide much gain in spectrum saving. Thus, it is reasonable to maintain a strict requirement on the quality of service. In general, the spectral efficiencies of the unicast links are lower than that of the SFN broadcast links. However, larger spectrum saving is still achieved by the hybrid operation, thanks to the low population density. Because it is far more efficient to unicast TV programs to only a few active viewers than to broadcast all the TV programs in a large cell while most of programs are not being watched by anyone.

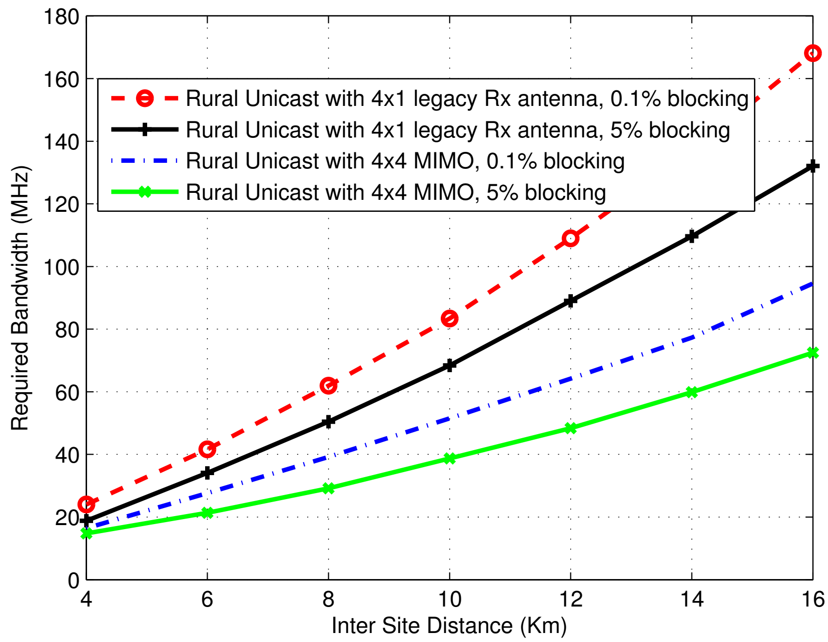

Fig. 6: Spectrum requirement for hybrid CellTV unicast-broadcast in rural environment

*2) **Urban Scenario**:* The situation in the urban environment is completely the opposite of the rural scenario. Thanks to the higher SFN gain from a much denser cellular infrastructure in the urban area, almost 200 MHz spectrum saving can be achieved even with the legacy indoor receiver antenna (Fig. 7).

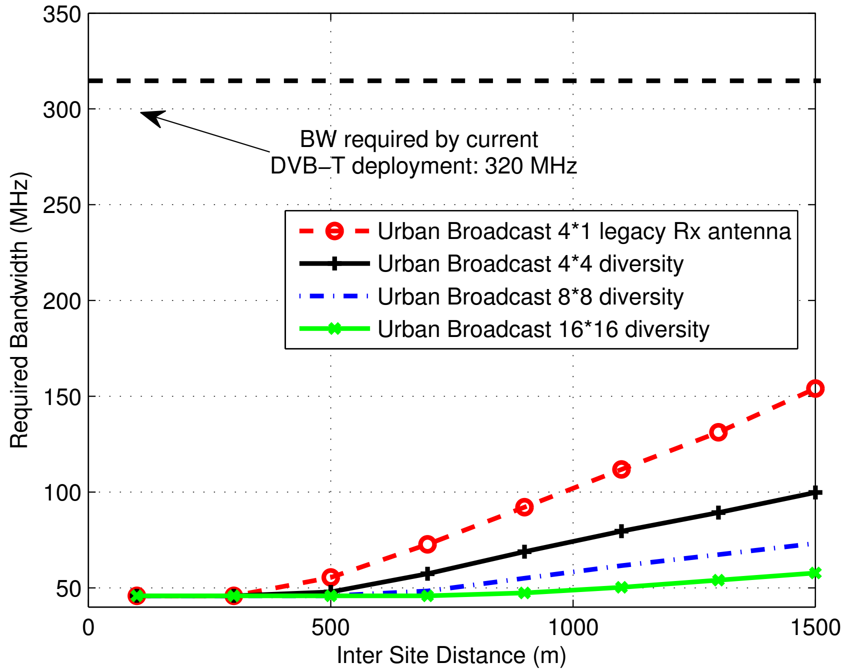

Fig. 7: Spectrum requirement for CellTV broadcast in urban environment

On the other hand, the hybrid broadcast-unicast operation may require more than 320 MHz spectrum to support the much higher unicast traffic in the densely populated urban areas. Particularly when the cell radius increases, a single cell will cover too many TV viewers for them to be supported simultaneously by the hybrid system (Fig. 8). Therefore, broadcast-only is considered as the more favorable option for CellTV delivery in urban area, if we assume the TV consumption pattern remains as it is of today.

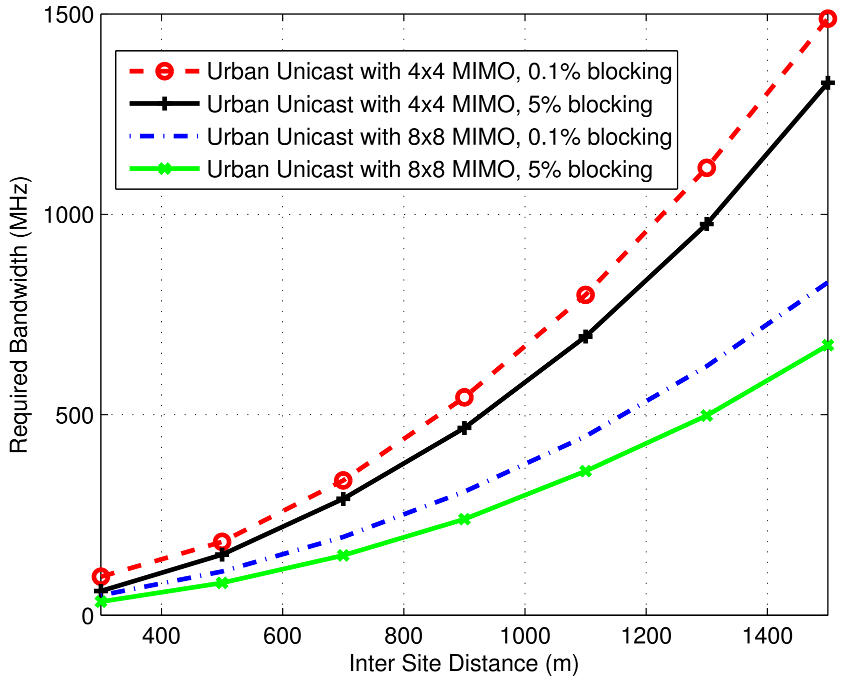

Fig. 8: Spectrum requirement for hybrid CellTV broadcast-unicast in urban environment

*3) **Impact of Shifting TV Consumption Pattern**:* It was observed that the hybrid operation is not beneficial in densely-populated urban areas. However, as the number of households with ADSL, fiber or cable access increases, it is reasonable to expect that the penetration of terrestrial TV service in urban areas will gradually decline in the future. In that case the hybrid operation with unicast capability may eventually become advantageous if the terrestrial TV penetration in urban areas reduces from 15% as estimated nowadays to lower than 3% by year 2020 (Fig. 9).

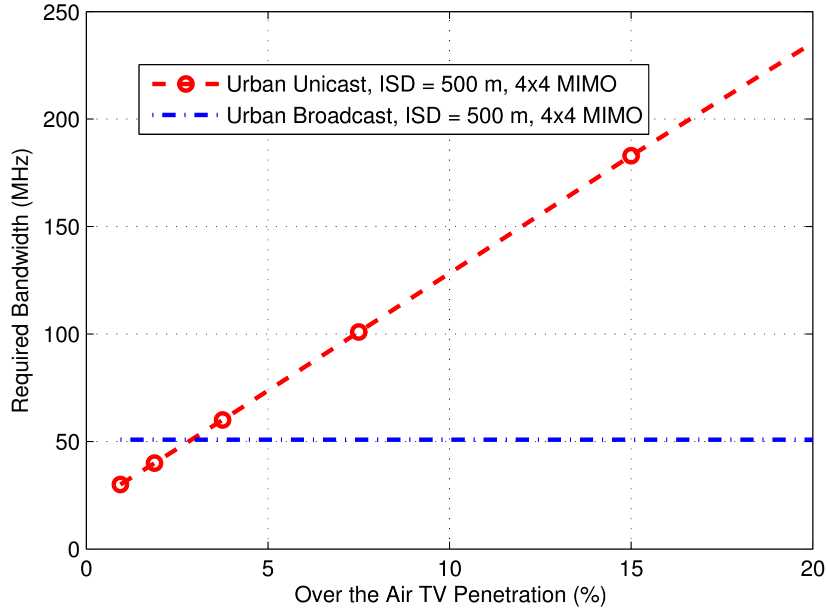

Fig. 9: Spectrum requirement for CellTV with different terrestrial TV service penetrations in urban environment

Furthermore, the video-on-demand feature enabled by the unicast also allows new TV programs or regional contents to be easily incorporated into the existing CellTV service. Since the capacity requirement for the unicast operation only depends on the number of viewers per cell, introducing new TV programs does not require any additional spectrum or frequency re-planning.

This benefit of the hybrid operation is clearly illustrated in Fig. 10. Despite its advantage in spectral efficiency in dense urban areas, SFN broadcast operation would require considerably more spectrum to accommodate the increasing number of new contents. Especially if the new TV programs contain regional content, in which case different sets of frequency channels must be used in separate SFNs. The required spectrum for broadcast-only distribution will increase drastically and become much higher than otherwise would be required for the hybrid operation.

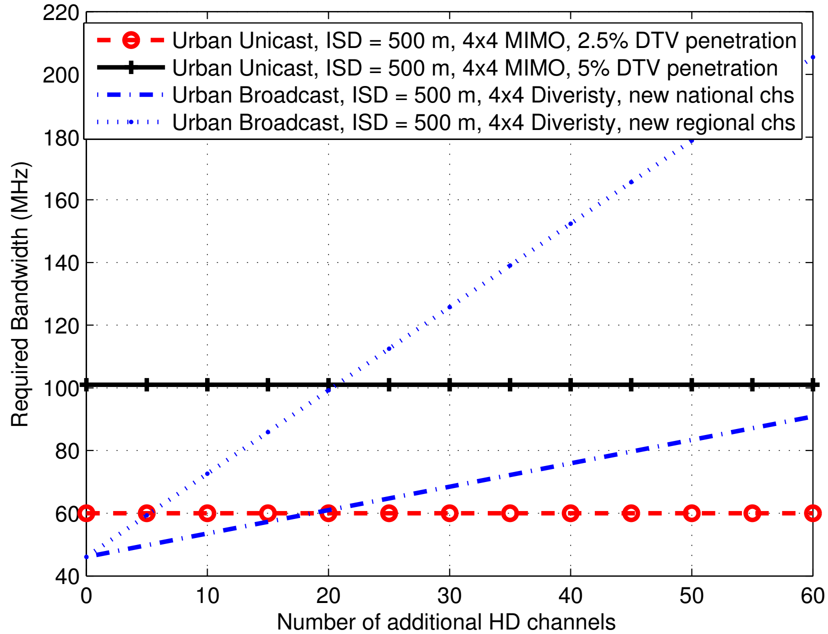

Fig. 10: Spectrum Spectrum requirement for CellTV with different number of additional TV programs in urban environment

V. Conclusion

In this paper, we have investigated the potential benefit of using cellular networks operating in 470-790 MHz as a replacement of current terrestrial TV broadcasting systems. The study targeted rural and urban Sweden in the year 2020. We have quantified the potential spectrum saving that can be achieved by this hypothetical CellTV system, using either pure broadcast over SFN or a hybrid of broadcast and unicast operations. Based on our analysis on representative Swedish rural and urban scenarios, we have reached the following major findings: First, in rural areas CellTV only provides limited benefit when the pure broadcast is considered. The spectrum saving highly depends on the performance of transceivers. The saving of 120-160 MHz is expected under reasonably optimistic assumptions about the cellular technologies with the installation of new advanced antennas at households. On the contrary, no saving at all is anticipated if some TV receivers still rely on legacy rooftop antenna.

Second, in urban areas, as opposed to the rural cases, the CellTV may bring about considerable spectrum savings of up to 250 MHz without advanced TV receivers. However, the whole spectrum has to be divided for rural and urban areas to support different spectral efficiencies. It will reduce the practically achievable spectrum saving in the urban areas.

Third, the feasibility of delivery TV service via unicast is dependent on the number of TV viewers per cell. In rural areas, introducing unicast can create additional spectrum saving of about 100 MHz since there are not many inhabitants. Unicast in densely populated areas is feasible, but may not be favorable compared to pure broadcasting unless the on-the-air TV penetration goes down to below 3%. Nonetheless, the VoD capability enabled by unicast can be regarded as strength of the CellTV.

Overall, our analysis shows that CellTV can be beneficial if the current trend towards more specialized programming, more local contents, and more on-demand requests, continues. Mobile cellular systems, with their flexible unicast capabilities, will be an ideal platform to provide these services. Our work also shows that CellTV is not effective in replacing terrestrial TV broadcasting for the current TV viewing patterns. If the change in the TV service is more modest and linear content is still the major part of the offering, then the gain would be limited. In this case it is doubtful that the expected spectrum saving can motivate the investments in both cellular sites and TV receivers.

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REFERENCES

[1] M. Nekovee, "Quantifying the Availability of TV White Spaces for Cognitive Radio Operation in the UK," *IEEE International Conference on Communications Workshops*, Jun. 2009.

[2] Federal Communications Commission, *Second Memorandum Opinion and Order-in the Matter of Unlicensed Operation in TV Broadcast Bands Et Docket No.04-186- Additional Spectrum for Unlicensed De- vices Below 900Mhz and in The 3GHz Band ET Docket No.02-380*, Sept. 2010.

[3] Ofcom, *Digital Dividend: Geolocation for Cognitive Access*, Nov. 2009.

[4] ECC Report 159, *Technical and Operational Requirements for the Possible Operation of Cognitive Radio Systems in the TV White Spaces of the Frequency Band 470-790 MHz*, Jan. 2011.

[5] K. Harrison; S.M. Mishra and A. Sahai, ”How Much TV White Space Capacity is There”,*IEEE International Symposium On Dynamic Spectrum Access Networks (DySPAN10)*, Apr. 2010.

[6] T. Dudda and T. Irnich ”Capacity of Cellular Networks Deployed in TV White Space”, *IEEE International Symposium On Dynamic Spectrum Access Networks (DySPAN12)*, Oct. 2012.

[7] L. Shi; K.W. Sung and J. Zander, ”Secondary Spectrum Access in TV- Bands with Combined Co-Channel and Adjacent Channel Interference Constraints”, *IEEE International Symposium On Dynamic Spectrum Access Networks (DySPAN12)*, Oct. 2012.

[8] *Introducation of the Multimedia Broadcast Multicast Service (MBMS) in the Radio Access Network (Rel.7 and 8)*, 3GPP TS 25.346, Dec. 2007.

[9] F. Hartung; U. Horn; J. Huschke; M. Kampmann; T. Lohmar and M. Lundevall, ”Delivery of Broadcast Services in 3G Networks,” *IEEE Transactions on Broadcasting*, vol.53, no.1, pp.188-199, Mar. 2007.

[10] D. Caterin; J. Huschke and U. Horn, ”Analytical Evaluation Of A Hybrid Broadcast-Unicast TV Offering” *IEEE Conference Vehicular Technology*, 2008.

[11] T. Lohmar and U. Horn, ”Hybrid Broadcast-Unicast Distribution of Mobile TV over 3G Networks,” *IEEE Conference on Local Computer Networks*, Florida, USA, 2006, pp. 850851.

[12] D. Gomez-Barquero; N. Cardona; A. Bria and Jens Zander, ”Affordable Mobile TV Services in Hybrid Cellular and DVB-H Systems,” *IEEE Network*, Apr. 2007.

[13] J. Huschke, ”Facilitating convergence between broadcasting and mobile services using LTE networks,” *Telecom World (ITU WT), 2011 Technical Symposium at ITU*, vol., no., pp.123-128, 24-27 Oct. 2011.

[14] L. Rong; S.E. Elayoubi and O. B. Haddada, ”Performance Evaluation of Cellular Networks Offering TV Services,” *IEEE Transactions on Vehicular Technology*, vol.60, no.2, pp.644-655, Feb. 2011.

[15] J. Huschke; J. Sachs; K. Balachandran and J. Karlsson, ”Spectrum Requirements for TV Broadcast Services Using Cellular Transmitters,” *IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, May 2011.

[16] Teracom, *Teracom Group Annual Report 2010*, retreived from http://www.teracom.se/Documents/Rapportarkiv, 2011.

[17] Post och telestyrelsen, *Data on current terrestrial TV service and deployment in Sweden*, retreived from http://www.pts.se/, 2012.

[18] L. Rong; O. B. Haddada and S.E. Elayoubi, ”Analytical Analysis of the Coverage of a MBSFN OFDMA Network,” *IEEE Global Telecommunications Conference*, Nov. 2008.

[19] P. Mogensen N. Wei, I. Z. Kovács, F. Frederiksen, A. Pokhariya, K. I. Pedersen, T. Kolding, K. Hugl, and M. Kuusela, ”LTE Capacity Compared to the Shannon Bound,” *IEEE Conference Vehicular Technology*, 2007.

[20] R. Rebhan and J. Zander, ”On the outage probability in single frequency networks for digital broadcasting,” *IEEE Transactions on Broadcasting*, vol.39, no.4, pp.395-401, Dec. 1993.

[21] F. Adachi and A. Kato, ”On Received Signal Power Distribution of Wideband Signals in a Frequency-Selective Rayleigh Fading Channel,” *IEICE Transactions on Communications*, Vol. E86-B, No. 11, 2003

[22] L. Zheng and D. Tse, ”Diversity and Multiplexing: A Fundamental Tradeoff in Multiple-Antenna Channels, *IEEE Transactions on Information Theory*, Vol. 49, No. 5, 2003.

[23] Post och telestyrelsen, *Data on current GSM and UMTS network infrastructure in Sweden*, retreived from http://www.pts.se/, 2012.

[24] Statistics Sweden, *Data on population density in Sweden*, retreived from http://www.ssd.scb.se/databaser, 2012.

[25] J. W. Roberts, ”A Service System With Heterogeneous User Requirements, in *Performance of Data Communications Systems and Their Applications*, G. Pujolle, Ed. Amsterdam, The Netherlands: North-Holland, 1981.

[26] Post och telestyrelsen, *Bredbandskartlggning (Broadband Survey) 2010-PTS-ER-2011*, retreived from http://www.pts.se/sv/Dokument/Rapporter/Internet/2011/, 2011.

[27] Directivity and Polarization Discrimination of Antennas in the Reception of Television Broadcasting, *ITU-R Recommendation BT.419-3*.