Future TV Content Delivery over Cellular Networks from Urban to Rural Environments

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***Abstract*—With increasing number of TV channels and growing need for on-demand services, the traditional digital terrestrial television (DTT) is becoming a less attractive way of distributing TV contents. As an alternative, we discuss a converged platform in UHF band for TV and mobile broadband provisioning based on LTE cellular technology and infrastructure, here referred to as CellTV. The requirement for CellTV is to provide a seamless TV coverage from urban to rural environments and to minimize the spectrum requirement so that the leftover can be used for mobile services. We formulate an optimal spectrum allocation problem for CellTV to distribute different TV channels with different transmission modes. Each TV channel is delivered via either unicast links or broadcast over single frequency networks (SFNs) of different modulation orders according to the location-dependent viewing demand and cellular infrastructure availability. Based on a case study of the Greater Stockholm region, we identify that CellTV requires only a small portion of the UHF band to deliver the TV contents in urban areas, thus releasing a significant amount of spectrum for mobile broadband services. Meanwhile, the spectrum requirement for CellTV is considerably higher in suburban and rural areas due to the transitions of transmission modes. We further generalize these findings to provide a guiding principle for CellTV deployment in mixed environments and also to demonstrate the flexibility advantage of CellTV in adapting to the growing diversity of TV contents.**

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

I. Introduction

A. Background

During the last decade, digital terrestrial television (DTT) has established itself as the most popular platform for TV distribution in Europe after replacing the role of analog terrestrial television. However, the future of DTT is less promising. The competition with other platforms is increasing, such as cable, satellite and internet protocol television (IPTV) via fixed broadband, while linear content is losing its dominance in the living room. The tremendous success achieved recently by over-the-top (OTT) services like Netflix and BBC iPlayer is a clear sign of the growing popularity of video-on-demand (VoD) services. They provide consumers with a choice of contents and flexibility unmatched by the DTT service. Moreover, the consumption of audio-visual content is rising rapidly on smartphones and tablets, which the DTT industry has struggled to reach without much success thus far.

Nevertheless, neither cable nor fixed broadband could be expected to replace the role of DTT and to provide universal TV coverage. Their service penetration is still limited to the urban areas in most of Europe. In particular, several major European countries, such as Spain and Italy, still have more than 90% of the households relying on DTT services [2]. Hence, a terrestrial network would be the only viable replacement.

The cellular network, after its rapid development in recent years, is considered a versatile platform for content delivery, as it can provide both good coverage and high flexibility inherited from its all-IP architecture. In fact, audio-visual contents already amount to two thirds of the total data traffic in mobile broadband (MBB) networks today [3]. Therefore, in light of the converging trends of audio-visual service in both MBB and DTT networks, the World Radio Conference 2015 (WRC-15) will discuss the possibility of progressively re-farming the UHF broadcast band (470-790 MHz[1]). One of the studied options is to allocate the re-farmed UHF band for a converged all-IP platform which is likely to utilize cellular technology and infrastructure [5]. So far the study on converged platform has been primarily regulatory driven. And there are still many challenges from the market perspective [6]. Above all, technological feasibility and gain, which is the focus of this paper, has barely been studied.

This paper considers a converged platform entirely based on cellular technology, hereafter termed as CellTV. One of the key enablers for CellTV is the evolved Multimedia Broadcast/Multicast Service (eMBMS) introduced in 3GPP Long Term Evolution (LTE) radio technology [7], allowing TV contents to be broadcasted over a single frequency network (SFN) with high spectral efficiency. Depending on the local viewing demand and existing base station (BS) density, TV content can be delivered via either unicasting or broadcasting over an SFN formed dynamically by a group of eMBMS-enabled BSs. To further improve the spectrum utilization efficiency, any spectrum in the UHF band unoccupied by CellTV could be reused by MBB services on a secondary basis. In particular, we will investigate the spectrum requirement for providing a

This paper was accepted for publication at IEEE Transactions on Wireless Communications in June 2015.

Part of this work was presented at the IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2014 [1]

[1]The Swedish government has recently announced the decision to reallocate the spectrum band between 694-790 MHz from DTT broadcasting to MBB from the year 2017 [4].

seamless CellTV service in an inhomogeneous environment with mixed morphologies.

B. Related work

Recent studies have mainly focused on analyzing requirements and capacity limits for delivering mobile TV over an OFDMA-based cellular network. In [8], the authors outline the relevance of applying a mixed broadcast/unicast solution when there is a ”long tail” of channels requested by few users. Detailed traffic analysis for delivering mobile TV over this hybrid broadcast-unicast deployment has been investigated in [9] and [10]. The implementation and cost aspects of providing mobile TV service in 3G networks are discussed in [11]. The convergence of mobile TV and MBB services in an LTE networks is presented in [12]. In [13], the authors have developed a general roadmap and analytical models for assessing the network performance using advanced features of LTE network and different deployment options. However the quality of service requirements for DTT for fixed reception is significantly higher than that of mobile TV. Furthermore, the strict coverage requirement of a DTT poses a formidable challenge for any attempt to replace it with mobile networks, although fixed TV receivers can rely on advanced antenna configurations with better performance. Consequently, the existing results on mobile TV cannot be directly applied to the study on distributing terrestrial TV service over mobile networks.

For fixed TV receptions, a ’tower-overlay’ system has been proposed in [14] using LTE technology and DTT network infrastructure. [15] presents a study on the spectrum requirement for delivering today’s over-the-air TV service via LTE eMBMS networks deployed in the urban areas of different cities in the U.S., indicating a considerable amount of spectrum could be released from the UHF broadcast band. [16] extends the study to Swedish urban and rural areas. It suggestes that a moderate amount of spectrum could be released in rural areas by unicasting less popular TV channels, instead of relying on eMBMS with large inter-site distance (ISD).

C. Contribution

The key difference between the related work and this study lies in its objective. Previous studies mainly aim at demonstrating cellular technology’s capability for mobile video delivery. This study, however, probes whether the performance of a (hypothetical) CellTV approach can be sufficient to replace the DTT network in the UHF band in a real-world scenario. Before studying detailed aspects of its implementation, we focus on assessing the spectrum requirement for providing a seamless CellTV coverage.

More specifically, we have modeled the inhomogeneous environment with varying local viewing demands and infrastructure availabilities. As we have seen in our previous work [16], different transmission modes (i.e., either unicast or broadcast and of certain modulation coding scheme (MCS)) are best suited for different morphologies. However, unlike an isolated homogenous scenario, a gradual transition from one morphology to another allows us to find out when and how to switch from one transmission mode to another. The transmission of one area would affect the spectral efficiency of its neighbor as either interference or constructive signal (if they form up an SFN). Thus, the overall spectrum requirement can only be minimized by a coordinated planning of transmissions throughout the inhomogeneous areas.

We have formulated the resource allocation issue as an optimization problem to estimate the minimal amount of required spectrum for CellTV. Its service requirements are protected through probabilistic constraints that employ long term statistics of the view demand and infrastructure availability. In addition, our analysis also takes into account of the potential interference from MBB as a result of the freed spectrum. We apply this resource allocation framework to the Greater Stockholm region as a case study. We further extend the analysis to provide generalized guidelines for CellTV deployment in an inhomogeneous environment with mixed morphologies.

The remainder of this paper is organized as follows: Section II describes the system model of CellTV. The proposed resource allocation framework for CellTV is formulated as an optimization problem in Section III. Then, Section IV presents the scenario for numerical evaluation and the main results are shown in Section V. Finally, Section VI concludes the discussion.

II. System model

A. Service Requirement

Since CellTV is intended to replace the DTT service, it should be able to deliver at least the same amount of TV channels with the same level of QoS as DTT. The TV content is defined by the numbered set of TV channels: $\mathbf{C} = \{1, \ldots, C\}$. Each TV channel has a data rate requirement ϱ^c, and a popularity rating π^c representing the average portion of the TV viewers watching channel c, $\forall c \in \mathbf{C}$.

DTT service typically has a country-wide universal coverage (e.g., it covers 99.8% of the inhabited area in Sweden). The standard QoS for DTT is defined by the service availability at the TV coverage boundary, which must be higher than 95%. In addition, since CellTV could deliver TV content via unicast mode as well, the QoS should also include a temporal service availability that was not explicitly defined in the DTT system. Therefore we set the requirement for temporal service availability at 99%, which is equivalent to a blocking probability of less than 1%. This means unicast service in CellTV has a guaranteed QoS similar to IPTV, in contrast to the best effort nature of OTT services.

B. Cellular System

The set of cellular BSs with given locations and antenna heights are defined by the numbered set $\mathbf{K} = \{1, \ldots, K\}$, $k \in \mathbf{K}$. All BSs are assumed to have the same transmit power, denoted by $\bar{p}$. Their spatial relationship is defined by the indexed sets for BS neighborship: $\mathbf{H}^m = \{\mathbf{H}_1^m, \mathbf{H}_2^m, \ldots, \mathbf{H}_K^m\}$, where $\mathbf{H}_k^m$ represents all BSs within m tiers of BS k. We assumed that all transmitters are equipped with multi-element antennas.

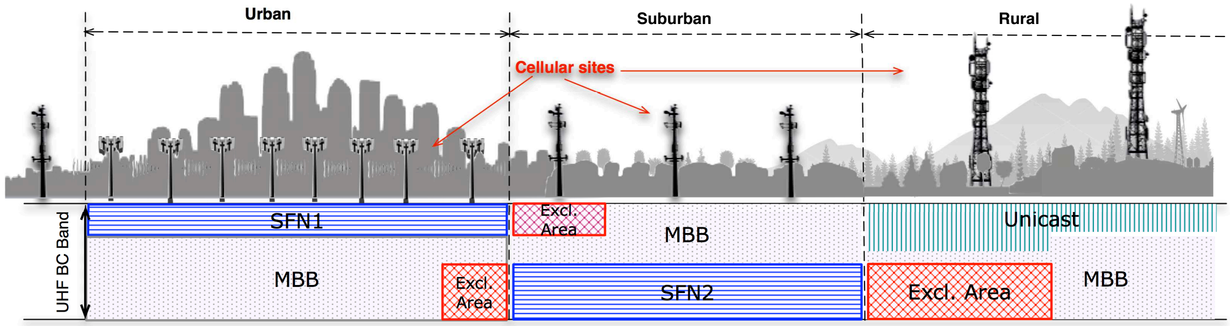

Fig. 1: Illustration of CellTV concept.

The available set of radio frequencies is denoted by $\mathbf{F} = \{1, \ldots, F\}$, $f \in \mathbf{F}$. The frequency spacing $\bar{w}$ is equivalent to one or multiple LTE subcarrier bandwidths (15 kHz each). We assume channel aggregation can group non-adjacent frequencies for transmitting the same content.

1) SFN: A group of BSs broadcasting the same TV channel on the same frequencies may form an SFN. Each SFN is defined by its frequency, modulation order and the content it carries. Each TV channel can be served by different SFNs in different areas. The set of SFNs is denoted by $\mathbf{J} = \{1, \ldots, J\}$. The set of BSs belonging to SFN j is denoted by $\mathbf{K}_j$. A single BS may be included in different SFNs operating on different frequencies. The assignment of a BS to an SFN is defined by

$$v^c_{j,k} = \begin{cases} 1, & \text{if BS } k \text{ is in SFN } j \text{ for TV channel } c; \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

Similarly, the assignment of a frequency to an SFN is given by

$$s^c_{f,j} = \begin{cases} 1, & \text{if freq. } f \text{ is used in SFN } j \text{ for TV channel } c; \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

Thus, the amount of spectrum used for broadcasting channel c at BS k is $BW^B_{c,k} = \sum_f \sum_j v^c_{j,k} s^c_{f,j} \bar{w}$.

We further assume that the first two tiers of BSs outside the coverage of each SFN should be reserved as assisting cells (BSs that are broadcasting the same content on the same frequency of the SFN, but are not considered within the service coverage). The implementation of assisting cells is essential for ensuring the SFN spectral efficiency [17], but it reduces the spectrum available for other services in these BSs. The assisting cell association is defined by

$$e^c_{j,k} = \begin{cases} v^c_{j,k'}, & k \in \mathbf{H}^2_{k'} \setminus \mathbf{K}_j; \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

It means that BS k is designated as an assisting BS to BS k' if k' belongs to an SFN (i.e., $v^c_{j,k'} = 1$) and k is within 2 tiers of k'.

2) Unicast: As opposed to the broadcasting case, the bandwidth required for unicasting is dependent on the number of TV viewers per cell. Let N^c_k denote the number of active TV viewers watching TV channel c in the coverage of BS k. N^c_k is assumed to follow Poisson distribution with the mean $\lambda^c_k = \kappa_k \pi^c \zeta_k / \xi_k$. Here κ_k is the average number of viewers per population. ζ_k and ξ_k are the population density and BS

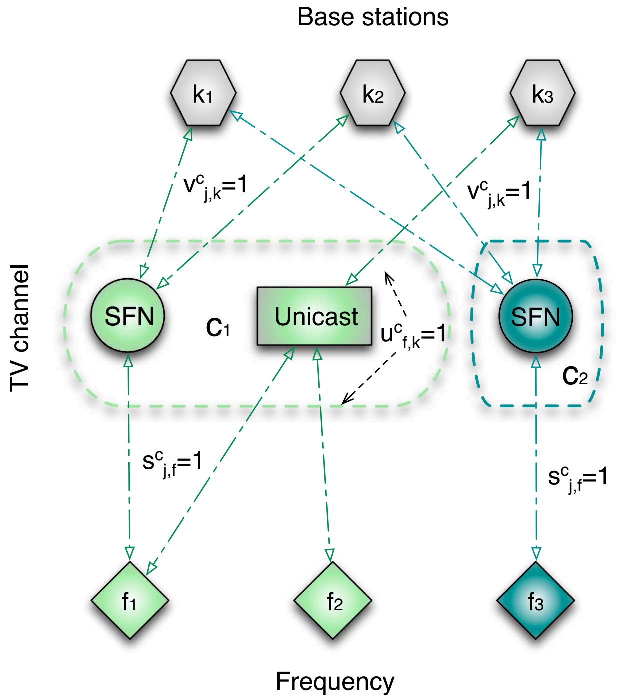

Fig. 2: Graph representation of the assignment problem.

density around BS k, respectively. Note that κ_k and π^c are long term statistics measured for each hour of the day. In this study we have assumed the peak hour value to estimate the worst-case spectrum requirement.

The frequency allocation for unicasting channel c at BS k is defined by

$$u^c_{f,k} = \begin{cases} 1, & \text{if freq. } f \text{ is used at BS } k \text{ unicasting ch. } c; \\ 0, & \text{otherwise.} \end{cases} \quad (4)$$

Thus the amount of spectrum allocated for unicasting channel c at BS k is defined as $BW^U_{c,k} = \sum_f u^c_{f,k} \bar{w}$. For simplicity, we assume multiple unicast users are served by time-division multiplex, i.e., each user have access to all spectrum allocated for unicast for a fraction of time in an alternating pattern. The active users are assumed to be distributed uniformly within the coverage area.

FIg.2 shows an example of the channel assignment and SFN association. This system consists of 3 BSs, 2 TV channels and

3 frequency bands. TV channel c_1 is broadcasted at BS k_1 and k_2 which form an SFN over frequency band f_1. The same TV channel is instead unicasted at BS k_3 over both f_1 and f_2. TV channel c_2 is broadcasted over a single SFN that includes all three BSs using frequency band f_3.

With the advancement of cellular technology, the effect of inter-cell interference can be mitigated by Multi-Cell Coordination (MCC). It is more effective for improving the signal-to-interference-and-noise-ratio (SINR) of unicasting links than broadcasting, but it also helps SFN to suppresses non-SFN interferences. The MCC gain is abstracted by a percentage of interference reduction [18].

C. Receivers

At the receiver side of the converged platform, we have assumed that the legacy TV reception antennas have been upgraded to multi-element antennas. They are deployed either indoor or outdoor on the rooftop depending on the morphology of the studied area. In broadcast, the spatial/polarization diversity gain can improve the SINR. In unicast, multiple-input and multiple-output (MIMO) can be implemented to improve the spectral efficiency through spatial multiplex gain. However, this gain can only be achieved if the correlation between the signals received at different antenna elements is sufficiently low.

Due to the multi-path fading in indoor environment, it is easier to avoid any significant spatial correlation for indoor MIMO receivers. For rooftop antenna which is typically in line-of-sight of the transmitter, a spacing of more than 2-3 meters between each antenna element is often required [19]. We assume that at least a four-element receiver antenna can be realized by installing two dual-polarized antennas with sufficient spacing in-between. To compensate any possible overestimation in the spatial diversity gain, we have also made very conservative assumptions on the antenna directivity.

III. Problem Formulation

Due to the interference from neighboring cells and the potential gain from SFN association, the transmission mode and frequency allocation at one BS may affect its neighboring BSs. Therefore, the resource allocation must be done for all BSs and TV channels together in order to minimize the overall spectrum requirement of CellTV. In particular, we define the objective function as the average spectrum requirement of CellTV per BS, weighted by the number of population in each cell. Thus, the spectrum in areas with a potentially higher demand for wireless services are given more weight. The optimization problem is formulated as follows:

$$\text{Minimize} \quad \frac{\sum_{f\in\mathbf{F}}\sum_{k\in\mathbf{K}} a_{f,k}\bar{w}\zeta_k/\xi_k}{K\sum_{k\in\mathbf{K}}\zeta_k/\xi_k}$$

Subject to:

$$\Pr\left(\sum_{f\in\mathbf{F}} u^c_{f.k}\bar{w}S_u\left(\gamma^u_{f,k}\right) \le \min\left\{\sum_{f\in\mathbf{F}} u^c_{f,k}, 1\right\} N^c_k \varrho^c\right) \le 1\%;$$

$$\Pr\left(\sum_{f\in\mathbf{F}} v^c_{j,k} s^c_{f,j}\bar{w}S_b\left(\min_{k\in\mathbf{K}_j}\gamma^b_{f,k}\right) \le v^c_{j,k}\varrho^c\right) \le 5\%;$$

$$\sum_{j\in\mathbf{J}} v^c_{j,k} + \min\left\{\sum_{f\in\mathbf{F}} u^c_{f,k}, 1\right\} = 1;$$

$$a_{f,k} = \sum_{c\in\mathbf{C}}\left[\sum_{j\in\mathbf{J}}(v^c_{j,k}+e^c_{j,k})s^c_{f,j} + u^c_{f,k}\right] \in \{0,1\};$$

$$\forall k\in\mathbf{K}, c\in\mathbf{C};$$

The decision variables, $v^c_{j,k}$, $s^c_{f,j}$ and $u^c_{f,k}$ are binary variables. $v^c_{j,k}$ represents the BS-SFN association. $s^c_{f,j}$ represents the frequency assignment for an SFN. $u^c_{f,k}$ is the frequency allocation for unicasting. In the objective function, ζ_k/ξ_k represents the number of population per BS and K is the total number of BSs.

Among the constraints, the first one defines the blocking requirement for unicast: the probability that the amount of bandwidth allocated for unicast is less than the required bandwidth should not exceeds 1%. The term '$\min\left\{\sum_{f\in\mathbf{F}} u^c_{f,k}, 1\right\}$' indicates whether TV channel c is assigned for unicast on any frequency at BS k. S_u is the spectral efficiency of the unicast link. It is a function of the unicast SINR, $\gamma^u_{f,k}$, as defined in the following subsection. Note that, the temporal variation in viewing demand is captured by the assumption that the number of active viewers follows Poisson distribution. Given the distribution of the spectral efficiency for a randomly picked unicast viewer, the blocking probability could be solved analytically by applying multi-Erlang model and following the Kaufman Roberts recursion method [20]. As long as the viewing pattern does not deviate far from the Poisson distribution assumption, the blocking probability requirement would force the algorithm to allocate sufficient amount of bandwidth to ensure the quality of service. In fact we have applied the peak hour statistics to represent the most spectrum-demanding situation in this study.

Similarly, the coverage requirement for broadcasting is signified by the second constraint. S_b is the spectral efficiency of the broadcast link. It is a function of the lowest cell-border SINR of all BSs associated to that SFN, defined by $\min_{k\in\mathbf{K}_j}\gamma^b_{f,k}$, because the MCS chosen for an SFN must be robust enough even for the worst case users. $\gamma^b_{f,k}$ is the broadcast SINR to be defined in the following subsections.

The service requirement is defined by the third constraint. It ensures that all TV channels are delivered in all BSs by either broadcasting or unicasting, without any service duplication. Finally, the spectrum usage is restricted by the last constraint, such that the same frequency could not be allocated to transmit more than one TV channel at a given BS.

Note that, if we remove the BS/SFN association decision variable from the above formulation, it reduces to a frequency assignment problem. As indicated in [21], the frequency assignment problem itself belongs to the NP complete category. A frequency allocation problem for SFNs in an homogenous environment was discussed in [22] as NP complete. Since our problem includes not only frequency allocation but also the resource allocation between unicast and broadcast of different modulation orders in an inhomogeneous world, it follows that our problem formulation is also NP complete.

In this study, the numerical results in the following section are obtained directly through exhaustive search to preserve its accuracy. We are more interested in the implications from the quantitative results rather than the solution process of the optimization problem itself. Because the primary objective of this study is to evaluate the feasibility of the converged platform in terms of the minimal spectrum requirement. This framework should be used as a dimensioning tool for network planning based on long-term statistics of the viewing demand and infrastructure availability, rather than for real time resource allocation. To achieve the latter objective, we need to either develop a heuristic algorithm to solve the optimization problem or apply approximations to simplify the formulation, which is beyond the scope of this study.

A. Unicast SINR

For a random user located at r within the coverage of BS k, its unicast SINR on frequency f is given by (5).

Here $g_k(r)$ is the pathloss from the user to BS k. θ is the MCC gain ($\theta \leq 1$) and N_0 is the noise power. The interference accounts for both broadcast transmissions from neighboring SFNs and unicast transmissions. $X_{f,k'}$ is the collision indicator. Its value equals to 1 when collision occurs on frequency f between BS k and k', and 0 otherwise. It is a Bernoulli random variable with mean value equal to the traffic load (the average portion of time-frequency resources that are occupied) at the interfering cell, $\chi_{f,k'}$. Depending on the type of interfering unicast traffic, $\chi_{f,k'}$ may take different values:

$$\chi_{f,k'} = \begin{cases} \chi^{mbb}_{f,k'}, & f,k' : a_{f,k'} = 0; \\ \chi^{u}_{f,k'}, & f,k' : u^c_{f,k'} = 1,\ \forall c \in \mathbf{C}, \end{cases} \tag{6}$$

where $\chi^{mbb}_{f,k'}$ is the MBB data traffic load and $\chi^{u}_{f,k'}$ is the CellTV unicast traffic load. Even though both are unicast traffic, we made this distinction in order to model the priority of CellTV traffic and to regulate the MBB traffic admission. According to the above definition, any frequency not allocated for CellTV service is locally accessible by MBB traffic. However, to avoid causing excessive interferences, we assume that the amount of admitted MBB traffic is proportional to the amount of available spectrum after CellTV usage, such that the MBB traffic loads on these frequencies equal to a constant.

On the other hand, the unicast traffic load, $\chi^{u}_{f,k'}$, is calculated based on the actual viewing demand. To keep the problem tractable, we assume that the differences in the traffic load and cell radius are negligible between BS k and its dominant interfering neighbors k'. Then we can obtain the CellTV unicast traffic load by solving the following fixed point equation numerically [16]: Here R_k is the radius of the cell. $\vec{X}_{f,k}$ is the collision vector made up by $X_{f,k'}$ of the interfering BSs around BS k. Assuming the users are uniformly distributed within the circular cell coverage, we can use this integral to calculate the ratio between the expected bandwidth consumption and the allocated bandwidth. This ratio converges to the expected CellTV unicast traffic load as proven in [13].

TABLE I: Spectral efficiency for SFN and unicasting [26].

	Broadcasting		Unicasting	
	Rural/Suburban	Urban	Rural/Suburban	Urban
α	0.65	0.75	$0.5 \cdot 4$	$0.6 \cdot 4$
β	$4 \cdot 4/2$	$4 \cdot 4/2$	0.5	0.5

B. Broadcast SINR

The broadcast SINR $\gamma^b_{f,k}$ is always calculated for the user located at the edge of the cell. The border SINR is defined in (8).

Here $g_{k',k}$ is the pathloss between BS k' to the user at the coverage border of BS k. $\varpi(\tau)$ is a weight function of the constructive portion of a received SFN signal defined as [23]:

$$\varpi(\tau) = \begin{cases} 0, & \tau < -T_u; \\ 1 + \frac{\tau}{T_u}, & -T_u \leq \tau < 0; \\ 1, & 0 \leq \tau < T_{CP}; \\ \frac{1-(\tau - T_{CP})}{T_u}, & T_{CP} \leq \tau < T_{CP} + T_u\ ; \\ 0, & \text{otherwise}. \end{cases} \tag{9}$$

Here $\tau = (r_i - r_o)/c$ is the propagation delay difference, with c being the speed of light. T_u is the length of the useful signal frame and T_{CP} is the length of the cyclic prefix. The interference accounts for both the self-interference from within the SFN and the external interference from other SFNs and unicast transmissions.

It should be noted that this SINR calculation may lead to optimistic results as pointed out in [24] [25]. The performance of SFN in a realistic scenario would be less homogeneous and affected by a non-ideal receiver response function. To compensate any potential overestimation of SINR performance, we have made conservative assumptions on the loss factor in the calculation of the spectral efficiency.

C. Effective Spectral Efficiency

The spectral efficiency is defined as a function of the SINR:

$$S = \alpha \log_2[(1 + \beta\gamma/\epsilon)], \tag{10}$$

where ϵ is a margin of 5 dB to account for fast fading [27]. The parameter α represents the bandwidth efficiency, determined by protocol overhead and the adjacent-channel-leakages-ratio (ACLR) requirement. It also includes the spatial multiplex gain from MIMO in unicast links. β corresponds to the SINR implementation efficiency which is mainly affected by the modulation and coding [28]. For broadcasting, β also accounts for the spatial/polarization diversity gain (see Table I). The maximum modulation order is assumed to be 512QAM.

$$\gamma^u_{f,k}(r) = \frac{u^c_{f,k}\bar{p}g_k(r)}{\sum\limits_{k'\in\mathbf{K},k'\neq k}\theta\left(\sum\limits_{c\in\mathbf{C}}\sum\limits_{j\in\mathbf{J},}(v^c_{j,k'}+e^c_{j,k'})s^c_{f,j}\bar{p}g_{k'}(r)+X_{f,k'}\bar{p}g_{k'}(r)\right)+N_0}. \tag{5}$$

$$\chi^u_{f,k} = \min\left[\int_0^{R_k}\frac{u^c_{f,k}\lambda^c_k\varrho^c\ 2r\ \mathrm{d}r}{\sum_{f\in\mathbf{F}}u^c_{f,k}\varpi R_k^2\sum_{\vec{X}_{f,k}}\left[Pr\left(\vec{X}_{f,k}|_{\chi^u_{f,k}}\right)S_u\left(\gamma^u_{f,k}\left(r,\vec{X}_{f,k}\right)\right)\right]},1\right]. \tag{7}$$

$$\gamma^b_{f,k}(R_k) = \sum_{k'\in\mathbf{K}}(v^c_{j,k'}+e^c_{j,k'})s^c_{f,j}\varpi(\tau_{k'})\bar{p}g_{k'k}\Bigg/\Bigg\{\sum_{k'\in\mathbf{K},k'\neq k}\Bigg[s^c_{f,j}(v^c_{j,k'}+e^c_{j,k'})(1-\varpi(\tau_{k'}))\bar{p}g_{k'k}+$$
$$\theta\Bigg(\sum_{c\in\mathbf{C}}\sum_{j'\in\mathbf{J},j'\neq j}s^c_{f,j'}(v^c_{j',k'}+e^c_{j',k'})\bar{p}g_{k'k}+X_{f,k'}\bar{p}g_{k'k}\Bigg)\Bigg]+N_0\Bigg\}. \tag{8}$$

TABLE II: 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 (%)	15	15	30	45	60
Propagation: Hata model variates	Urban (large city)	Urban (medium city)	Suburban	Open area	Open area
Tx antenna height (m)	15	15	30	45	90
ISD (km)	0.2 - 0.7	0.8 - 1.2	1.5 - 3	4 - 5.5	6 - 7.5
Transmission power	46dBm/20MHz/antenna				
Tx antenna type	15 dBi, 3-sectorized, 4 elements				
Rx antenna type	0dBi indoor gateway with 4 elements		9.15dBi rooftop antenna [32] with 4 elements		
Rx antenna height (m)	1.5		10		
Rx noise figure (dB)	10		7		
Wall attenuation (dB)	10		0		

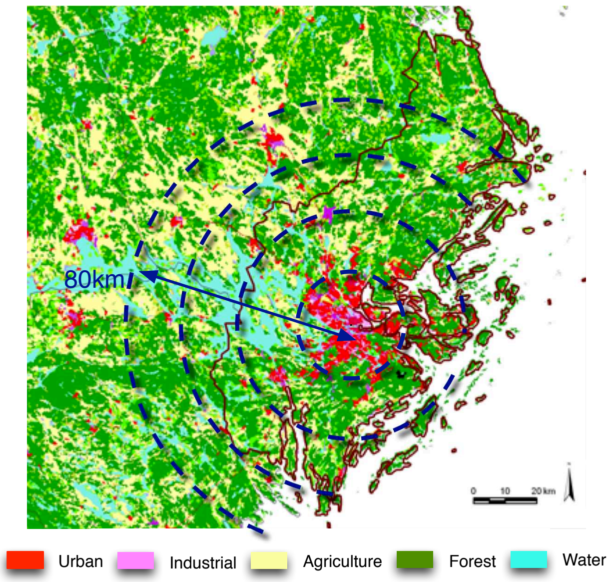

Fig. 3: Studied area in greater Stockholm region [29].

IV. Evaluation Scenario

As mentioned earlier, previous study [16] considered only two representative cases: dense urban areas and sparsely populated areas. In contrast, this study includes the whole area within an 80 km radius from Stockholm city center for the quantitative analysis. The selected area covers distinctive morphologies and has a good coverage of both DTT and mobile services. The Swedish scenario is of interest because its DTT service penetration is similar to the average level of EU member states which is around 40% [33]. Thus, implications for the general pattern of the CellTV spectrum requirement can be drawn from this case study. For countries with distinct DTT service profiles, this methodology can be directly applied to country-specific analysis.

TABLE III: 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

In our model, this circular area is divided into multiple rings. The transition from dense urban to rural area is characterized by the gradual changes in BS density, ξ, and population density, ζ, in each ring. We further assume different propagation conditions, transmitter/receiver types and over-the-air TV service penetration ratios associated with different morphologies (see Table II). We assume that the cellular network would be equipped with significantly larger backhaul

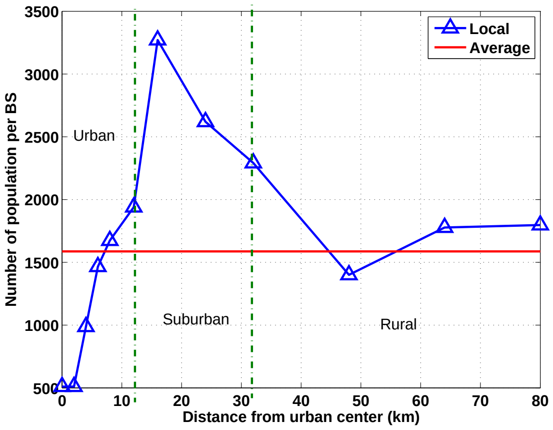

Fig. 4: Number of inhabitants per BS at different locations in the Greater Stockholm area [30], [31].

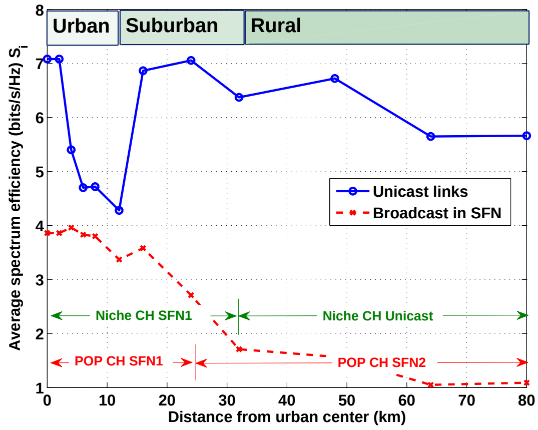

Fig. 5: Achievable local spectral efficiency of CellTV in greater Stockholm region.

capacity than it is available today to support the growing data traffic including the provisioning of audio-visual content.

It is worth noting that, while both the BS density and population density typically decline monotonously as the distance from city center increases, the ratio between these two, i.e., the population per BS, is more intricate. We found that it is the lowest in urban areas and the highest in suburban areas as shown in Fig 4. The same trend has also been identified around several other Swedish cities. This is probably because the population density is based on the residential data, but more BSs are built in the urban area to meet the peak capacity demand during working hours.

On average, we assume that each Swedish household consists of 2.1 inhabitants with two TV sets, and the average time a viewer spent on a given channel is around 30 minutes. The TV viewing ratio during the peak hour is 40%. In combination with the DTT service penetration ratio at different locations, ν_k, we can derive the average number of viewers per population as $\kappa_k = 2/2.1 \cdot 0.4 \cdot \nu_k$. We assume 60 TV channels are offered by CellTV (currently, there are 54 channels provided by DTT in the Stockholm region). Both standard definition (SD) (576i) and high definition (HD) (1080i) programs employ H.264/AVC (MPEG4) coding format. Four of these TV channels are considered as the most popular ones, representing 50% of the total viewing share. The remaining TV channels are denoted as the Niche channels with a much lower viewing share per channel. Details about different TV channels are summarized in Table III. The TV consumption pattern is based on the data from the Swedish national regulator [34]. The channel popularity is approximately divided into only two categories to keep a clear presentation of results.

The traffic load for MBB is assumed to be a constant of 0.5. We consider a three-sectorized configuration for unicasting. For broadcasting, the same contents are transmitted in all sectors over the same spectrum band.

V. Numerical Results

A. Case study: the Greater Stockholm region

As a numerical example for the proposed framework for CellTV resource allocation, we first show the results of the case study on the Greater Stockholm region. In this study, we assume an MCC gain of 6 dB and two-tier assisting cells around each SFN. The transmission modes are optimized based on the viewing demand, the local infrastructures and propagation conditions. The local achievable spectral efficiency is shown in Fig. 5.

In urban areas, the achievable spectral efficiency for unicasting is limited by the use of omnidirectional receiver antennas and high inter-site interference, while broadcasting enjoys high SFN gain from high BS density. Therefore, even though the number of viewers per BS is the lowest in urban areas, SFN is still considered as a more efficient way for distributing all the TV channels.

In suburban areas, the deployment of directional rooftop antenna provides a notable improvement on the achievable spectral efficiency for unicasting. In contrast, the SFN gain declines rapidly as the ISD increases. Nevertheless, broadcasting is still the preferred option in suburban areas because of the high number of viewers per BS. Note that both popular and niche TV channels are delivered by continuous SFNs that spans from urban to suburban areas; therefore, the actual spectral efficiencies of the SFN are limited by the suburban ISDs. While a smaller SFN that covers only the urban area may enjoy a higher spectral efficiency, the spectrum cost for adding extra assisting cells between these smaller SFNs could raise the overall spectrum requirement unnecessarily.

In rural areas, the SFN gain further diminishes and the population per BS slowly declines. Therefore, all the niche channels switch to unicast mode, whose performance is less affected by the increase in ISD. However, the popular TV channels, still holding considerable viewing demand, are instead broadcasted over a new SFN with a lower modulation order. It has continuous coverage over the rural area.

The resulting overall spectrum requirement for CellTV is

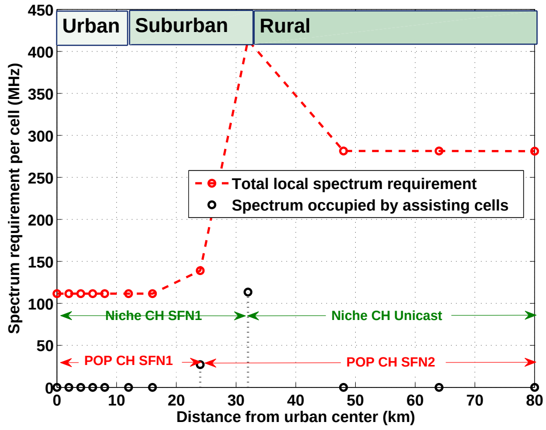

Fig. 6: Local spectrum requirement of CellTV in greater Stockholm region.

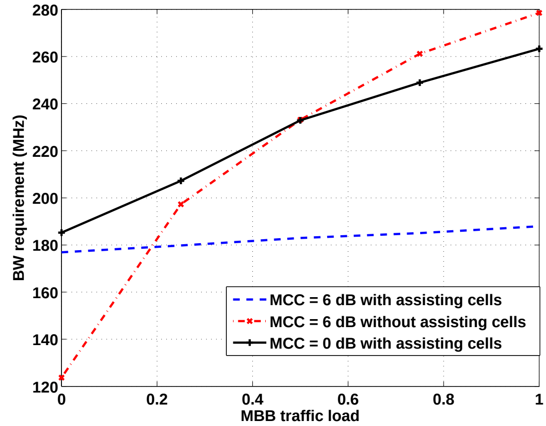

Fig. 7: Sensitivity analysis of CellTV spectrum requirement.

185 MHz and the local spectrum requirement is illustrated in Fig.6. As we can see, the amount of required spectrum in urban areas is only around 110 MHz thanks to the SFN gain. However, when the transmission modes inevitably switched at the border between suburban and rural areas, a local 'spectrum bottleneck' is created due to the combination of high spectrum requirement for unicasting and spectrum occupied by assisting cells in that area. The amount of spectrum could be released in rural areas is limited due to the relatively large number of inhabitants per BS and a higher reliance on over-the-air TV reception. The improvement in MCC could alleviate the 'spectrum bottleneck' and make unicasting in rural areas more efficient, but the general trend of spectrum requirement distribution would remain the same.

There are essentially two main causes behind the 'spectrum bottleneck' in the suburban area. First, the number of viewers per base station is larger in suburban areas. As we have seen in Fig.4, the population per base station in suburban areas is the highest in the studied region. Besides, the DTT service penetration is also higher in suburban areas than in urban areas. The second reason is the fact that urban areas and rural areas require different transmission modes to utilize the spectrum efficiently. The switching from SFN to unicast, or to another SFN with different MCS would increase the local spectrum requirement. Because part of the spectrum must be reserved for assisting cells near the border of an SFN to ensure an acceptable broadcast spectral efficiency. The optimization algorithm decides that it is the least costly in terms of the overall spectrum requirement to implement the switching in suburban areas, but this leads to an increased spectrum demand locally.

As a sensitivity study, we show the impact of MCC gain and assisting cells on the overall spectrum requirement of CellTV in Fig. 7. Apparently, both MCC and assisting cells are indispensable against MBB interference. Without either of them, the overall spectrum requirement would be considerably higher as the MBB traffic load increases. Besides, it is also worthy noting that the implementation of assisting cells is not the most spectrally efficient measure if the MBB traffic load

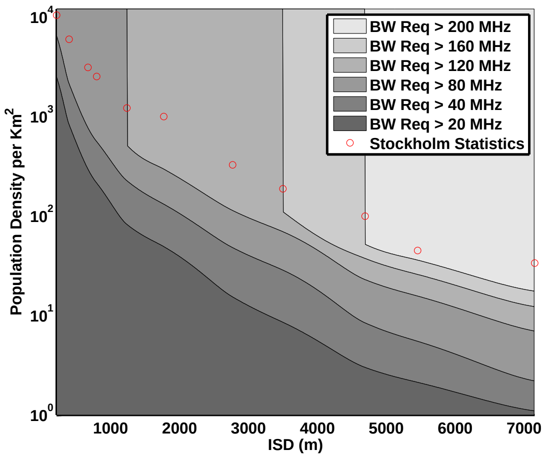

Fig. 8: Spectrum requirement of CellTV with mixed morphologies.

is low.

B. *Feasibility Analysis*

To gain a deeper insight into the performance of CellTV service in different environments, in Fig. 8 we present the feasible region of CellTV service. The contour of different grey scales shows the feasible combinations of population density and cellular infrastructure availability that can support CellTV service with certain amount of spectrum. For instance, if the amount of spectrum available is less than 40 MHz, then the converged platform can serve a population density of more than $500/\text{m}^2$ in urban areas (e.g. ISD$<$ 1000m), and a population density of less than $10/\text{m}^2$ in rural areas (e.g. ISD$>$ 5000m). Some contour have vertical outlines. It suggests that an infinite population density can be supported by broadcasting all TV channels if the ISD is sufficiently small.

Fig.9 illustrates the optimal transmission configurations corresponding to different morphologies. For instance, in the region with high population density and large ISD, all TV channels should be allocated to broadcast mode. In the middle

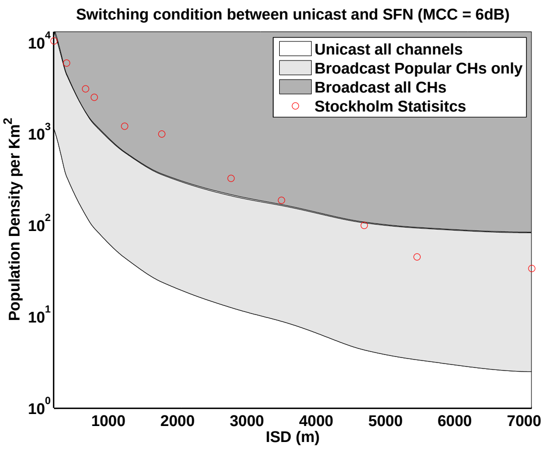

Fig. 9: Optimal transmission modes for TV content delivery with mixed morphologies.

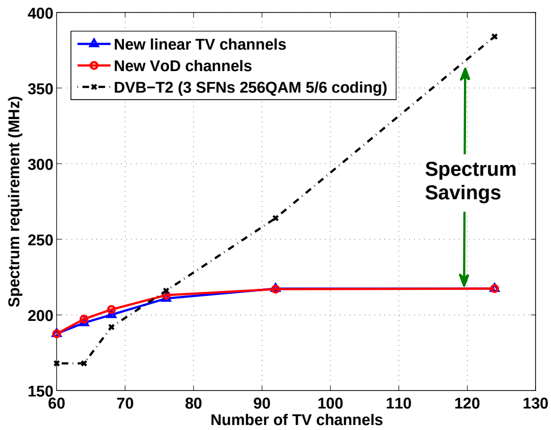

Fig. 10: Spectrum requirement for CellTV in the Greater Stockholm region with different numbers of TV channels.

part, only the popular channels are broadcasted while the niche ones are unicasted. Finally in the bottom region, all TV channels are delivered through unicast. The borders between these regions move downwards as the ISD increases. Because broadcast is more efficient to handle the increased number of viewers inside the larger cell coverage, even though the SFN gain has dropped significantly.

Another interesting observation from Fig.9 is that the spectrum requirement is more sensitive to population density than ISDs in rural areas (lower right corner) and vice versa in urban areas (upper left corner). This is due to the fact that most TV channels are delivered by unicasting in rural, as clearly indicated in Fig.9. On the other hand, as the ISD decreases and population density increases, more TV channels are delivered by broadcasting. Eventually when all TV channels are allocated for broadcasting, the spectrum requirement becomes dependent on ISDs only.

It is worth noting that the spectrum requirement illustrated in this contour plot represents the 'lower-bound' value of the spectrum requirement because it is not possible to include the spectrum cost for the switching between different transmission modes in this presentation. As such, Fig.8 should be used as an indicative mapping between the demographic conditions and the CellTV spectrum requirements. Network planners could rely on a graph similar to Fig.9 to quickly determine the resource allocation for each TV channel.

A direct example of their applications is by mapping the statistics of the Greater Stockholm region onto the contour plots. As marked by the red circles in Fig.8, the spectrum requirement for CellTV deployment in Stockholm continues to increase from less than 100 MHz in urban areas to more than 200 MHz in rural areas (the 'spectrum bottleneck' in suburban areas observed in earlier results is not reflected in this figure for reasons explained above). Fig.9 also correctly predicts that all TV channels should be broadcasted inside Stockholm city and only the niche channels are delivered by unicasting in rural Stockholm.

C. Flexibility to adapt to future changes

Fig.10 demonstrates the inherent advantage of CellTV in adapting to the growing diversity of TV content. This figure depicts the spectrum requirement of CellTV for distributing different numbers of TV channels, starting from 60 channels (as in the assumption used above) to more than 120 channels. It is assumed that the increase in the number of TV channels does not affect the total number of TV viewers, but the number of viewers per TV channel reduces as the channel number grows. Two different assumptions were made about the properties of these new TV channels. In the first case, all of them are VoD channels, i.e, they must be delivered by unicasting; the second case assumes they are traditional linear channels, and as such can be delivered by either unicasting or broadcasting.

The result shows that the difference between linear and VoD channel assumptions is relatively small, as all the TV channels start to be delivered by unicasting as the number of channels grows and the viewer number per channel declines. Consequently, the overall spectrum requirement for CellTV flattens out around 220 MHz when the number of TV channels is sufficiently large. For comparison, we also plotted the estimated spectrum requirement for DVB-T2 to broadcast the same number of linear TV channels. Note that 3 SFNs are generally regarded as the minimum to provide a national DTT coverage even with the optimal frequency planning. At least 4 SFNs would be needed if the cross border interference is considered. The advantage of CellTV is clearly illustrated by the savings in spectrum requirements.

VI. Conclusion and Future Works

In this paper, we have investigated the spectrum requirement of a converged platform for TV provisioning based on cellular technology and infrastructure, referred to as CellTV. The TV distribution in CellTV adapts the transmission mode of each TV channel to the local viewing demand and infrastructure availability. For instance, less popular TV channels are delivered via unicast in area with lower base station and viewer densities, while popular TV channels are broadcasted in area with small inter-site distance to utilize the SFN gain. But different transmissions at neighboring areas may affect each other's spectrum requirement, due to interferences and gain from SFN associations.

We have formulated the resource allocation for CellTV as an optimization problem to minimize the overall spectrum requirement for providing a seamless coverage from urban to rural areas. We have applied this framework to a case study of the Greater Stockholm region and obtained the optimal solution. It shows that the spectrum requirement for CellTV is only around 110 MHz in urban area by broadcasting all the TV channels over a continuous SFN. Most of the TV channels switch to unicast mode and a few popular ones to another SFN with a lower modulation order at the border between suburban and rural areas. As parts of the spectrum are occupied by assisting cells deployed next to the border of the SFNs protecting them from harmful interferences, this switch of transmission modes causes a spectrum shortage in the suburban area. In rural areas the spectrum requirement is less critical but still considerably higher than that in the urban area, as the number of viewers remains high in each cell but a larger inter-site distance neutralizes the benefits of SFN. Although the implementation of assisting cells next to the border of an SFN is costly in terms of the local spectrum requirement in suburban area, it is an indispensable measure to ensure an acceptable level of the SFN spectral efficiency and reduce the overall spectrum requirement. In addition, CellTV transmissions could benefit considerably from multi-cell coordination.

One interesting observation is that the spectrum bottleneck lies in the suburban area rather than in urban or rural areas which were typically assumed to be the worst-cast scenarios. One cause to this phenomena is the inherently high number of users per base station in the suburban region. Its population density is higher than the rural area but the infrastructure density is much lower than the urban area. Another critical reason is that the switch from one transmission mode in the urban area to another one suitable for rural areas happens in the suburban area, leaving a significant amount of the spectrum unavailable for any other services. In other words, the spectrum shortage in the suburban area is the result of the opposite conditions in rural and urban areas. Thus, it also highlights the importance of analyzing the complete transition from urban to rural areas, instead of an isolated study of a particular morphology.

We further extended the case study to a more generalized setting with mixed morphologies. These results provide illustrative examples for identifying the feasibility of CellTV service in various environments and the design principle that could facilitate the network planning. Lastly, we also demonstrated the advantage of CellTV in adapting to the growing diversity of TV content by comparing its spectrum requirement to that of an optimized DTT network for delivering over 120 TV channels.

In the future studies, we plan to investigate the coexistence between mobile broadband and CellTV with detailed mobile broadband traffic modeling and identify the capacity limit of such a converged platform for content delivery. We will also develop an algorithm that can solve the optimization problem in a time efficient manner, so that this framework can be implemented for real-time resource management in future CellTV deployment.

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