# Simulation Study of the Spectral Capacity Requirements of Switched Digital Broadcast

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***Abstract*— Switched Digital Broadcast (*SDB*) is a new method of distributing video programming. Compared with traditional broadcast methods, it reduces spectrum requirements by taking advantage of the fact that not all program channels are being viewed by subscribers at the same time. The actual spectrum savings depends on human TV watching behavior, the popularity of delivered TV programs, streaming bit-rate composition and subscriber group size. We have developed a simulation model of an *SDB* system that allows us to explore the impact of these factors, in particular subscriber's channel flipping behavior, on the capacity requirement. Our subscriber viewing model ranges from intense, correlated channel flipping behavior to minimal flipping behavior representing *DVR* usage. Our results suggest that frequent channel flipping has little effect on the spectrum requirements under normal viewing assumptions.**

***Keywords; Multimedia Applications, VoD, High Definition Audio/Video Networking, Video Switched Broadcast, Capacity Planning, Traffic Modeling & Characteristics.***

## 1. Introduction

Switched Digital Broadcast (*SDB*) is a new method of distributing video programming. It differs from traditional broadcasting in the sense that only programs that are being actively watched by subscribers are broadcasted. Because only a fraction of the channels are ever watched at the same time, a video provider can offer more "virtual channels" than actual program channels and benefit from the statistical gains achieved through over-provisioning. For example, in a cable system with a 750 MHz plant, a traditional broadcast service can broadcast about 250 programs using a mix of analog and digital services. If all services are digital, the provider could offer 700 programs. *SDB* allows the provider to potentially offer more than 1000 programs.

Because *SDB* is an emerging technology (currently being deployed by cable operators), there are no engineering guidelines available (as far as we know) that can help a provider understand the relationship between subscriber viewing behavior and capacity requirements. This relationship, unfortunately, is complicated as it is driven by many factors including service group size, popularity of the programs, and individual viewing behaviors. We are aware of two previous relevant studies that have examined this issue. In [7], based on empirical data obtained from two *SDB* field trials, the authors showed that the relationship between total programs and the number of programs viewed concurrently can be modeled with a *Zipf* distribution [10]. Cable Television Laboratories, Inc has also performed a theoretical analysis to address the capacity requirement issue [9]. Building upon the latter effort, this paper presents a simulation model that captures human TV watching behaviors. Using the model, we investigate capacity requirements and system design issues surrounding *SDB*. One focus of this analysis is to determine the impact of subscriber's channel flipping behavior on *SDB* systems.

The rest of the paper is arranged as follows. Section 2 discusses the methodologies of how we model TV watching behavior and TV channel ranking. Section 3 talks about the simulation engine. Section 4 presents a validation of the simulation model using analytic models that we have developed in prior work [9]. Section 5 presents the results of our analysis based on the *SDB* simulation model. Finally Section 6 presents the conclusions and future work.

## 2. Statistical Model of Switched Broadcast

*SDB* delivers selected programs to a group of subscribers only when they request them. Compared with traditional broadcast method, *SDB* reduces spectrum capacity on the *QAM*-modulator pool by taking advantage of the fact that not all program channels are being viewed by subscribers at the same time. In an *SDB* system, the process starts when a subscriber changes a TV channel or turns on the TV. At that moment, the Switched Broadcast Client (*SBC*) application on the Set-top Box (*STB*) sends a channel request message upstream to the Switched Broadcast Manager (*SBM*). The *SBM* receives this message and compares the request with the available downstream resources. If a downstream resource is available, and if the program channel requested is not present on the system already, the downstream video connection is started. Channel selection for subsequent viewers of the same program follows a similar sequence, but in this case the *SBM* simply needs to return the appropriate tuning information to the *STB*. When a subscriber selects a switched broadcast program, he is also leaving another previously switched broadcast program. Therefore, the channel request message also contains information about which program the *STB* is leaving. The *SBM* uses this information to track the number of users watching a particular program. If the number of users watching a program reaches zero, the *SBM* can reallocate this downstream resource for another program request. Detailed information of *SDB* systems can be found in [7].

### *2.1. Modeling TV Watching Behavior*

Modeling of TV watching behavior must incorporate several factors, including program popularity, duration of the program, frequency of commercial breaks, and many others [8]. Previous studies have found that subscribers tend to rely on three main mechanisms when looking for TV programs: channel surfing, electronic Program Guide (*EPG*) or printed programs [2]. The third approach is arguably considered obsolete.

We propose the following viewing behaviors.

- ***Model 1***: A subscriber is in one of two states. Either the subscriber is interested in a program and watches it for a relatively large amount of time, which we call the *watching state*, or the subscriber is searching for a program and is channel flipping, which we call the *flipping state*.
- ***Model 2***: A subscriber is in one of two states. Either the subscriber is interested in a program and watches it to completion or the subscriber is searching for a program using a TV guide. This behavior differs from ***Model 1*** in that the level of channel flipping is significantly lower.
- ***Model 3***: The subscriber is a Digital Video Recorder (*DVR*) that records specific programs to completion. This model effectively has just a *watching state* as no channel changes are performed.

We use a two-state discrete model [6] to capture all three viewing behaviors. In one state, the *flipping state,* subscribers switch from channel-to-channel to get an overview of the TV programs which are currently running. In the other state, the *watching state*, subscribers settle on a TV program and watch the program for some amount of time. TV programs are probabilistically selected based on their popularity rating. The length of the *watching state* tends to correspond to the time interval between commercial breaks. In ***Model 1***, subscribers in the *flipping state* choose TV channels in an up-down sequential mode. TV channel flipping in ***Model 1*** is not considered a pure random process. Each of the channels selected in this state are watched for a very short period of time. In ***Model 2***, subscribers in the *flipping state* select the next channel by selecting the program from the TV guide. The subscriber will either move to the *watching state* or use the guide to select another channel after a short amount of time. The two states will alternate between each other, representing the normal behavior of watching and surfing TV programs, the latter likely to happen during commercial breaks. Using results from previous research [1] [2], we define the transition probabilities of the mentioned states using two exponential random variables with means of 12 minutes and 10 seconds respectively. 12 minutes corresponds to the average program "run time" between commercial breaks and 10 seconds corresponds to the average time a TV program is viewed in the *flipping state*. The total number of TV channels "flipped" while in *flipping state* has been modeled as an exponential random variable with an average of 6 channels flipped as suggested in [2]. To accommodate ***Model 2***, fewer channels are flipped and the viewing time is increased during *flipping state*. There is no published data to help us select reasonable transition probabilities for this model. Therefore we limit our analysis to the ***Model 1*** and ***Model 3*** viewing behaviors.

The simulation model will consist of a number of independent subscribers, each configured to behave using ***Model 1*** or ***Model 3.*** In addition, we can optionally add correlation between subscribers by synchronizing their transitions to the *flipping state*. This is based on evidence that the timing of commercial breaks from different channels is correlated and that viewers tend to flip during these commercial breaks [8]. The analysis presented in this paper includes the impact of this correlation on *SDB* systems.

### *2.2. Modeling TV Channels Popularity*

Previous research [7] has suggested that the popularity of TV channels follows a *Power Law* distribution, also referred to as a *Zipf* distribution [10]. Suppose we rank order all the program channels from the most popular to the least popular. The *Power Law* distribution implies that high-ranked occurrences are extremely common, whereas low-ranked instances are extremely rare. The *Power Law* probability distribution is defined in equation (1).

$$P_i = c\frac{i^{-\alpha}}{\left(\sum_{i=1}^{N} i^{-\alpha}\right)} \quad (1)$$

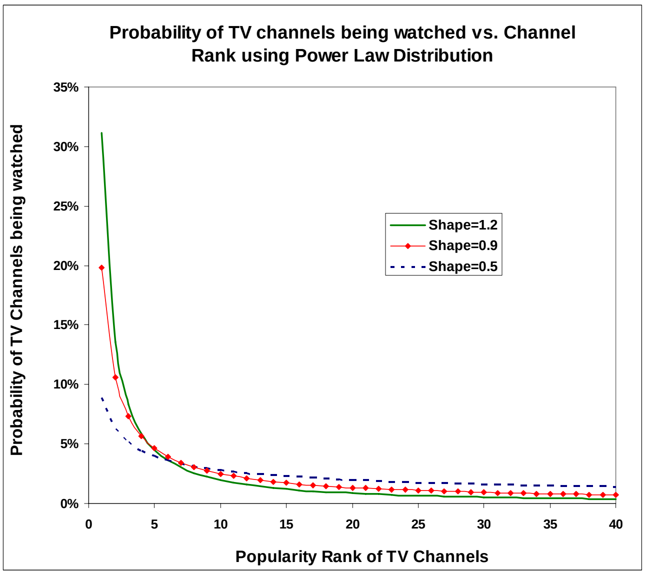


Figure 1. Probability Distribution for Different *Shape* (α) Values.

$P_i$ represents the share of the *ith* ranked program in the order ranked by popularity, *N* is the number of programs to be ranked, and *C* is a scaling factor. The $\alpha$ parameter, also called the shape, controls the concentration of high-ranked programs over the rest. Figure 1 illustrates how TV-channel popularity can be modeled using the Power Law. In this particular example, *N* has been chosen to be 40, *C* is 1, and three values of $\alpha$ have been selected {0.5,0.9,1.2}. Studies show that typical values of $\alpha$ for TV-channel popularity is in the range [0.5,0.95] for normal event days, although it can reach a value greater than 2 for special event days [7]. As can be seen from Figure 1, the number of most popular channels tends to increase for large $\alpha$ values. The tail of the distribution is used to set the maximum peak usage. The blocking probability depends not only on the popularity of the TV program channels but also on the total number of channels offered. If the set of subscribers has access to a large number of TV channels, it is likely that collectively they will watch only a small percentage of them at any given time. This principle is fundamental to the success of *SDB*.

## 3. Simulation of Switched Broadcast

A simulation model was developed to estimate the spectrum requirements for an *SDB* video service under various usage scenarios. The model mimics a pool of 256-*QAM* modulators designed for a service group. A typical 256-*QAM* modulated channel over a specified 6MHz RF channel provides 37.5Mbps of capacity [4][5].

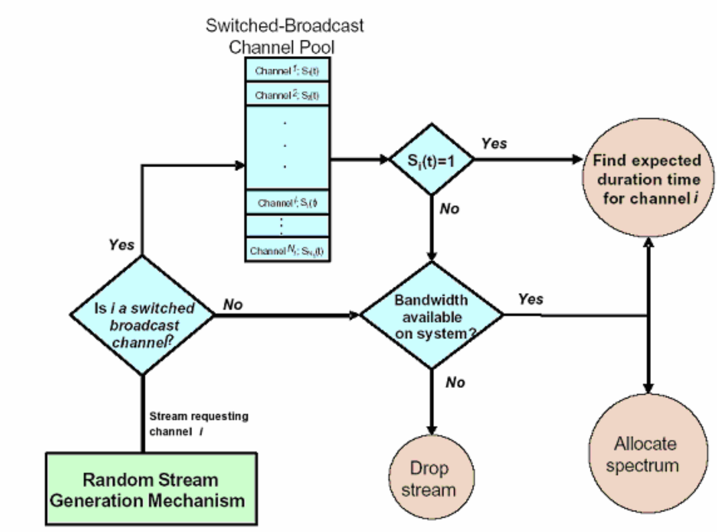


Figure 2. Architecture of the simulation model.

Incoming stream requests from subscribers arrive at the *SBM* asking to view one of the *N* TV channels provided by the cable operator. We assume requests are either *SD* or *HD* streams encoded at constant bit rates, which consume 3.75Mbps and 12.5Mbps, respectively. In our model, the request could select content from the *SDB* system, the traditional broadcast system, or from an integrated Video-on-Demand (*VoD*) system. The *N* TV channels (which do not include the *VoD* content) are aligned along the rating curve as explained in Section 2.2, $N_1$ of them are delivered using *SDB* service and $N_2$ using traditional broadcast, such that $N_1+N_2 = N$.

After the request is received, it is compared against the pool of currently viewed *SDB* TV channels. Actions are taken if a new *QAM*-modulator is needed. The maximum number of *SDB* TV channels viewed is calculated depending on various usage scenarios at any given time, and consequently the maximum spectrum requirement is accordingly obtained. The simulation model has been merged with a *VoD* simulation model that we implemented and studied in prior work [4][5]. The outcome of this merge provides a broader model capable of estimating the spectrum requirement and blocking probability for a mixture of *VoD* and *SDB* traffic under various usage patterns and system scenarios. The architecture of the simulation model is represented in Figure 2. We summarize the various modules in the following lines.

***Random stream generation mechanism:*** In Section 2.1 the TV-usage behavior for an individual user has been modeled as a two-stage alternating process. The TV-usage behavior of all active users in the system is then obtained by stacking streams from each individual user along the time horizon. This mechanism generates a train of stream requests, each of them requesting any of the *N* available TV channels.

***Mechanisms for stream request multiplexing and capacity allocation:*** We define $S_t(i)$ to represent the binary state of a switched broadcast TV program channel *i* at time *t*. At any given time, channel *i* is considered alive (i.e., $S_t(i)=1$), if at least one viewer is watching it at time *t*. Otherwise it is considered dead (i.e., $S_t(i)=0$). The expected on-time duration at time *t* of channel *i* is denoted as $T_t(i)$. This depends on the maximum watching time of all the viewers viewing it at time *t*. When a stream request, *a*, arrives at the *SBM* at time *t*, its arrival time is compared with the release time of all the streams previously accepted by the system. The release time of an accepted stream, *b*, requesting to view TV channel *i* is represented as follows,

$$release\_time_{i,b} = arrival\_time_{i,b} + \mu_{i,b} \qquad (2)$$

The $\mu_{i,b}$ term is the duration time of stream *b*. All streams in the *QAM*-modulator pool at this moment with release time smaller than the arrival time of the new incoming stream are then released, thus freeing their occupied capacity. After all the stale streams have been released, the TV channel request *i*, requested by stream *a*, is compared with the switched broadcast TV channels currently being delivered to the service group. If $S_t(i)=0$, a new stream will be requested and sent to the subscriber only if the available *QAM*-modulator pool capacity can handle this request. If successful, channel *i* state will change to $S_t(i)=1$ and $T_t(i)=release\_time_{i,a}$. When the

| Category | Assumptions |
|---|---|
| System | Pool of 256-*QAM* Modulators for delivery of video streams (6 Mhz/37.5 Mbps of bandwidth each).<br>Effective number of users set by a configurable group size and usage percentage.<br>*SDB* channels = 77, traditional channels =51.<br>Stream bit rate as *SD*=3.75Mbps, *HD*= 12.5Mbps. |
| Watching Behavior | Average time a channel in the watching stage is viewed =12 min.<br>Average number of channels flipped during flipping stage =6.<br>Average time a channel in the flipping stage is viewed =10 sec.<br>5% of viewers are *DVR* users; Average *DVR* watching stage duration = 30 min. |

Table 1. System and TV watching behavior assumptions

request arrives at the SBM, if $S_t(i)=1$, no resource allocation needs to be taken. However in this situation $T_t(i)$ has to be updated as shown in equation (3) below:

$$release\_time_{i,b} = arrival\_time_{i,b} + \mu_{i,b} \tag{3}$$

The terms $release\_time_{i,b}$ and $release\_time_{i,a}$ represent the release time of two streams, *a* and *b*, respectively, both of which requested to view TV channel *i*. In this case it is considered that stream *a* arrived at time *t* and stream *b* arrived before *a*. Note that it is possible that more viewers are watching channel *i* at time *t*, thus $release\_time_{i,b}$ represents the maximum release time of all stream watching channel *i* before *a* arrives. This process has been implemented in the simulation engine. As a result, at any given time *t* the model is able to calculate the spectrum utilized, $r(t)$, as shown in equation (4).

$$r(t) = (SD\_spectrum)\sum_{i=1}^{N_{SD}} S_t^{SD}(i) + (HD\_spectrum)\sum_{j=1}^{N_{HD}} S_t^{HD}(j) \tag{4}$$

$N_{SD}$ and $N_{HD}$ represent the number of *SDB* standard definition (*SD*) and high definition (*HD*) channels, respectively, the two terms sum to $N_1$. $S_t^{SD}(i)$ and $S_t^{HD}(j)$ represent the state of the *SD* and *HD SDB* channels, respectively, at time *t*. $SD\_spectrum$ and $HD\_spectrum$ represent the spectrum in MHz occupied by a *SD* and *HD* channel respectively. The maximum spectrum required for the system, *R*, is obtained as follows $R = MAX\{r(t_0), r(t_1), r(t_2)...\}$.

## 4. Model validation

We validated the simulation model by comparing results to a theoretical model [9] and to the results of a measurement study of a live *SDB* field trial [7]. Then, simulation results are presented for a range of system scenarios that depend on the streaming bit rates, the size of the service group, the mixture of *SD* and *HD* streams, and the distribution of channel popularity.

Table 1 identifies and presents the system settings [4][5], as well as the TV watching behavior modeling assumptions used in the simulation model. We use 77 SDB channels in the analysis since this is the likely number of analog channels that are planned to be digitally simulcast by cable operators. Currently these simulcast analog channels are candidates for SDB. Many analog channels are popular channels that enjoy high ranking in the Power Law function. Ideally one would like to apply SDB only to the least-popular channels, but due to compatibility requirements with one-way cable cards, the channels are currently candidates for SDB service. For simplicity, we assume these 77 channels are the most popular along the rating curve.

### *4.1. Validation of the Simulation Model*

In [9] a theoretical model was developed to find the average number of TV channels used in an *SDB* system. This measure, $E[l]$, is given in equation (5).

$$E[l] = N_1 - \sum_{i=1}^{N_1}(1-s_i)^T \tag{5}$$

*T* is the total number of concurrent TV viewers, $s_i$ is the probability that channel *i* is alive, and $N_1$ is the number of *SDB* channels available. Equations (6) and (7) show $s_i$ and $E[l]$, respectively, for an *SDB* system described in Table 1. The service group size and usage percentage chosen for this analysis are 300 and 60%, respectively. The former refers to the total number of subscribers the cable operator is offering TV services, the later refers to the percentage of them are watching TV concurrently. The average size of a VoD service group is approximately 500 set-top boxes for the majority of cable operators in North America [4]. Recent SDB services trials have targeted similar service group sizes [6].

$$s_i = \frac{i^{-\alpha}}{\sum_{i=1}^{128}\left(i^{-\alpha}\right)} \tag{6}$$

$$E[l] = 77 - \sum_{i=1}^{77}(1-s_i)^T \tag{7}$$

The results obtained using the theoretical and simulation model are presented on Figures 3, 4 and 5 for three different values of α= {0.25,0.75 and 1.25}, respectively. The figures compare the theoretical and simulation-derived average, expected, number of *SDB* TV channels. Figures 3, 4 and 5 illustrate that both models provide very similar results for small α values, however the theoretical model generates smaller results as α gets bigger. This phenomenon is caused by an underestimation of the theoretical model, where $E[l]$ is calculated based only on the channel rating curve and not on the fact that a TV channel can be selected 'by accident' while flipping channels. The theoretical model only calculates the average number of TV channels used, not the peak values. Comparisons between Figures 3, 4 and 5 were based on the averages even though peak values are more suitable for system capacity planning.

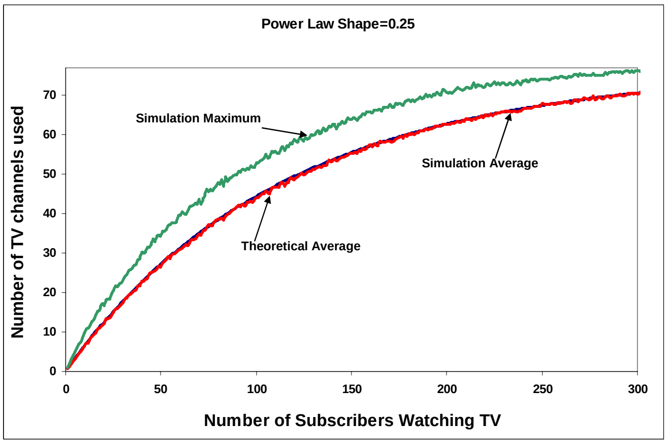


Figure 3. Comparison of simulated and theoretical models for α=0.25

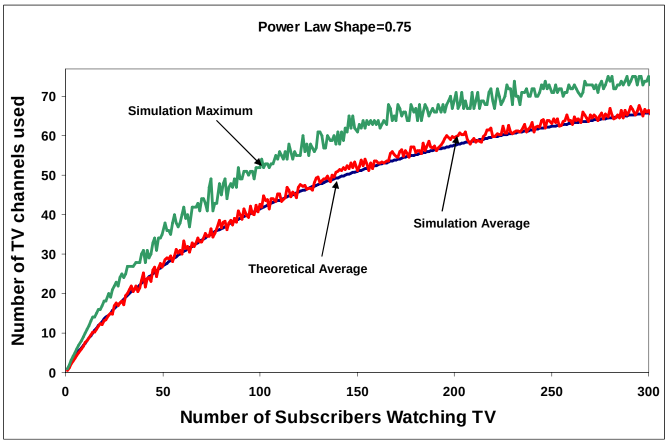


Figure 4. Comparison of simulated and theoretical models for α=0.75

Figure 6 shows the maximum number of TV *SDB* channels used as function of α and the service group size. These results were generated for realistic α and service groups size values [4][5], also it is assumed that in all the cases the concurrent peak usage is 60%. Note that Figure 6 has been separated in two regions; for α ∊ {0.5-0.95} and for α ∊ {0.95-1.7}. The first region represents standard α values that can be found in a normal day of the week or weekend. On the other hand, the second region represents α that can be found on special event days where the concentration of people watching a particular TV channel is very high. Figure 6 illustrates that the maximum required number of TV *SDB* channels decays faster when α increases on the second region of the plot than on the first region. Also it can be seen that this number increases with the group size.

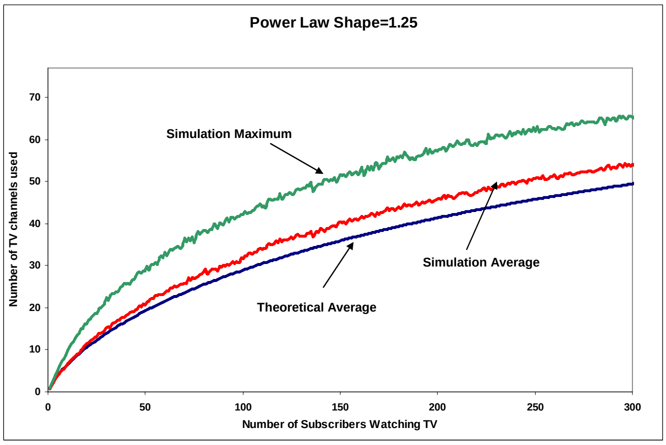


Figure 5. Comparison of simulated and theoretical models for α=1.25

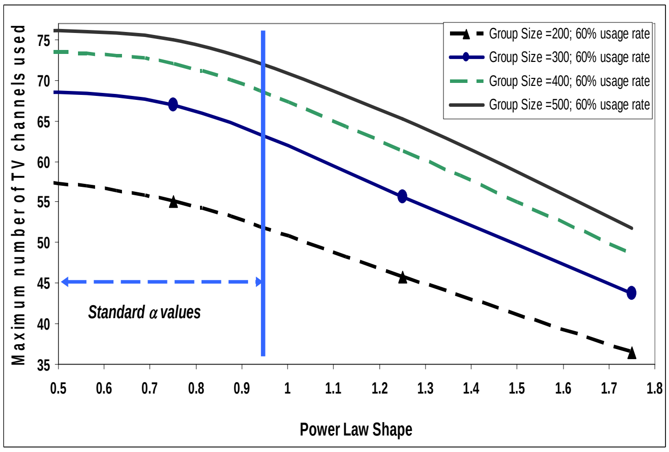


Figure 6. maximum number of TV channels used vs. α.

*SDB* field trials have been conducted recently to analyze the statistical efficiencies and operational usage of an *SDB* system [7]. The system presented in [7] is a 550 Mhz plant using Motorola set-top-boxes. In this system 89 TV channels were offered to the subscribers, 60 of them were broadcast using *SDB*. The trial was initially deployed to one node and then extended to four nodes. Each node has 1000 subscribers. From this trial the peak simultaneous channel used has been obtained for each of the four cases mentioned above. The results of the trial are compared against the results generated by the simulation model. Simulated results have been generated with the settings presented in Table 1, although the number of concurrent users has been changed, as well as the number of TV channels offered to the subscribers, matching the ones used on the trial. The $\alpha$ was set to the value of 0.85 to match what was observed in the data trial. The results of this comparison are presented on Table 2 and Figure 7. The results are similar to those of the simulator. These results also show that the difference becomes smaller as the number of nodes increases. This can be understood since when the population increases real values tend to get closer to the estimated ones.

| Number of nodes | Simultaneous viewers | Peak simultaneous channels used | |
|---|---|---|---|
| | | Real Trail | Simulated |
| 1 | 40 | 28 | 29 |
| 2 | 83 | 40 | 43 |
| 3 | 98 | 47 | 48 |
| 4 | 136 | 50 | 52 |

Table 2. Validation of simulation engine with data from field trial

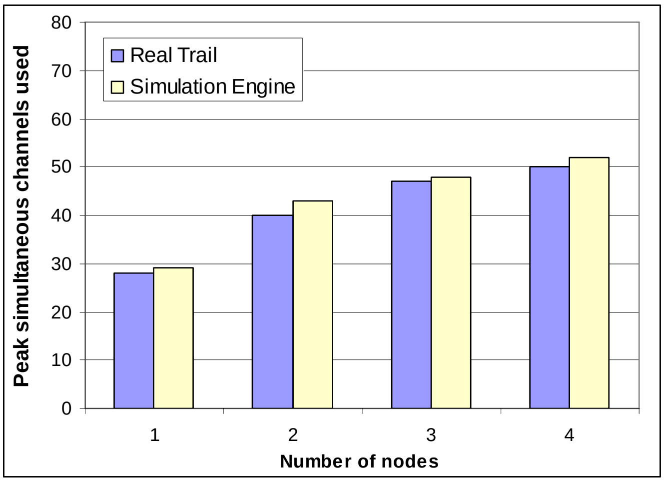


Figure 7. Validation of simulation engine with data from field trials

## 5. SIMUALTION RESULTS

### *5.1. Combining VoD with SDB Traffic*

In this subsection we analyze the pooling effect of combining *VoD* and *SDB* services on the same set of edge-*QAM* resources. Figures 8 and 9 show the *VoD* [4][5]and TV usage rates [11], respectively, on an hourly basis for the busiest day of the week, Saturday. Note that TV usage shown in Figure 9 already includes the *VoD* usage rate, since it represents the overall TV usage. Thus broadcast usage rate is obtained by subtracting the *VoD* usage rate from the total TV usage rate, and it is presented on Figure 10.

To develop a base case for comparison, we first compute the spectrum requirement when *VoD* and broadcast services are provided separately on different QAM pools, Table 1 settings have been used for this analysis. In previous work we showed that four *QAM* modulators (24 MHz) are needed to assure *VoD* stream delivery with an insignificant level of blocking for service groups of both 300 and 500 subscribers. The spectrum requirement for traditional broadcast service is a function of the number of program channels as opposed to the number of users. At a bit rate of 3.75 Mbps for *SD* service, 77 channels require a total of 8 *QAMs*, or 48 MHz of spectrum. Together, both services require a 72 MHz of spectrum.

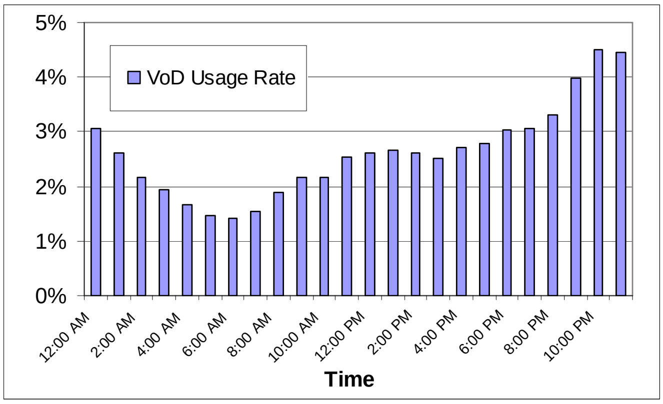


Figure 8. Hourly VoD usage rate

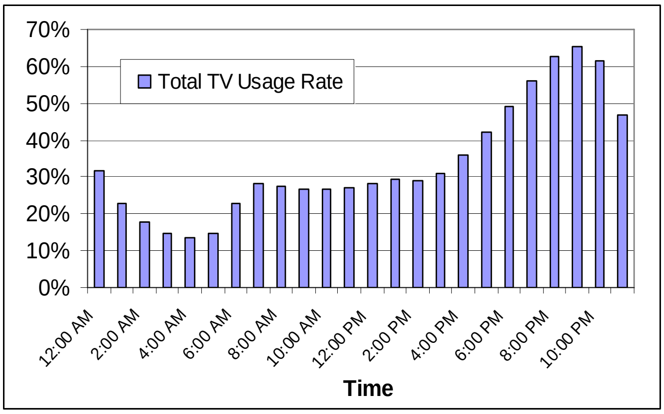


Figure 9. Hourly TV usage rate

The second step is to compute the spectrum requirement for combined *VoD* and *SDB* traffic by using our simulation model under the same system assumptions used above. The results are presented in Figure 11. Spectrum consumption varied during the day, reaching a minimum at 4 a.m., with 21 MHz of spectrum for a 300-subscriber service group and 30 MHz for a 500-subscriber service group. The maximum is reached at 10 p.m., with 47 MHz for a 300-subscriber service group and 59 MHz for a 500-subscriber service group. In these cases, 8 and 10 *QAM* modulators are then required for each service group, respectively. Instead of treating these two types of traffic separately, 24 MHz and 12 MHz of spectrum can be saved by pooling them together, respectively, for a 300-subscriber and 500-subscriber service group [4][5]. Also this saving is based on the selection of *SDB* over traditional broadcast. This represents a bandwidth savings of about 20-35%. Also note that from Figure 11 it can be seen that spectrum usage changes considerably after 3 p.m. Before 3 p.m. about 12 MHz (2 *QAM* modulators) are virtually unused by the system.

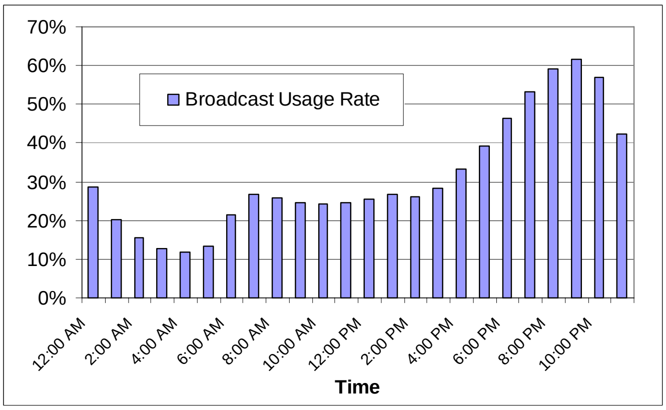


Figure 10. Expected distribution of broadcast usage on hourly basis

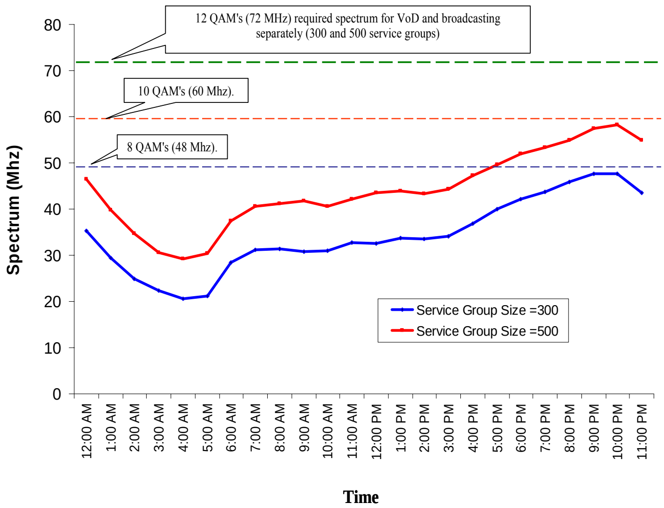


Figure 11. Spectrum requirements for combined VoD and Switched Broadcast traffic

Several reasons explain this reduction in the size of the *QAM* pool. First, multiplexing of these two types of traffic together eliminates the circumstance where spectrum can remain unused on each set of *QAM* modulators. This phenomenon occurs more often with *VoD* traffic since it occupies a comparatively small amount of spectrum and tends to leave a considerable amount of spectrum unused on the 4-*QAM* pool assigned to it during the off-peak hours. Second, *SDB* service obtains a statistical multiplexing gain when some program channels are not being watched at any time. The third reason is due to the fact that the peak-usage rate of these two stream types can occur at different times during the day, thus achieving further statistical multiplexing gain. However, we conjecture that this fact has little effect, as the peak hour for these two types of traffic are just 1 hour apart.

### *5.2. Is Channel Flipping Bad?*

This section analyzes the impact of stream duration and flipping behavior on spectrum requirements. Two extreme opposite cases are studied: short-lived streams with intensive channel flipping behavior, and long-lived streams that are closely related with *DVR* behavior. A *DVR* box is programmed to record TV programs with no channel flipping in between them. Intuition might suggest that the first case seemingly deteriorates the spectrum savings promised by *SDB* due to the frequent up-down random channel selections. On the other hand, the second case should improve the spectrum savings, as such behavior is ruled out. We investigate these two cases using the simulation model.

The *flipping stage* has been modeled assuming viewers browse TV channels in a sequential up-down random mode. It is likely that people watching the same TV program will engage in the *flipping stage* at the same time, usually during commercial breaks. There is evidence to indicate that commercial breaks of different channels are synchronized [8]. Therefore correlated flipping has been modeled by forcing a percentage of the active viewers to flip channels at the same time. The question becomes how much of the spectrum savings will be lost due to this phenomenon. Figure 12 illustrates this issue for different values of $\alpha$ using the settings as described in Table 1. The size of the service group and concurrent usage percentage chosen for this analysis are 300 and 60% respectively. The figure shows a 500 second 'snapshot' from a simulation lasting 3600 seconds.

The first peak of the curves in Figure 12 happens when all of the concurrent users were forced to engage in channel flipping behavior at the same time. After this initial "shock", randomness reduces the level of correlated flipping over time. Three important observations may be pointed out from Figure 12.

- The maximum spectrum requirement is always reached in the flipping stage and this is independent of the duration of this stage.
- As $\alpha$ increases, fewer channels are used although the relative difference between the number of channels used during flipping and watching stages increases.
- For systems with typical $\alpha$ values ranging [0.5-0.95], the results suggest that the maximum spectrum requirement is not significantly increased by correlated flipping. Further, channel-flipping increases the amount of spectrum required for *SDB* systems by less than 10% under normal viewing circumstances.

The last observation is explained by the fact that subscribers are not concentrated in any particular channel under normal cases. Thus channel flipping around any channel selected from the ranking curve also has a large likelihood of selecting another channel as popular as the previous one. For normal $\alpha$ cases, this channel's shuffle impact on the total bandwidth requirement seems to be independent of the percentage of concurrent channel flippers. In summary, Figure 12 indicates that channel-flipping behavior does not seem to have a large impact on the total bandwidth requirement, as long as $\alpha$ falls into a typical range.

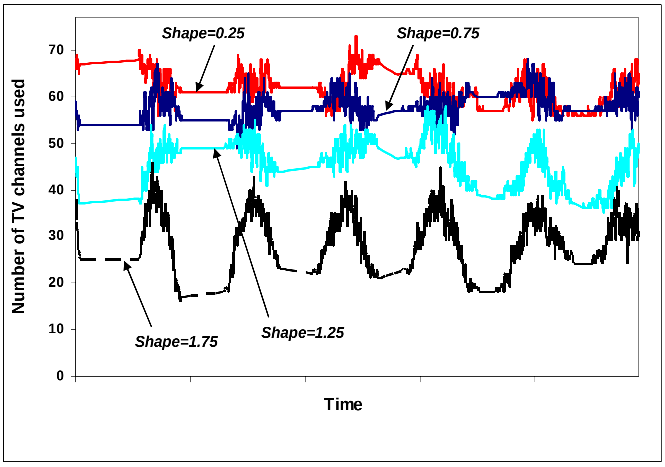


Figure 12. Impact of flipping behavior on spectrum requirements for *SDB*

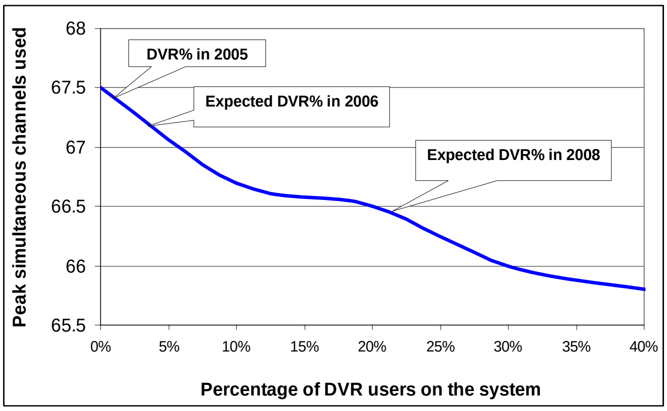


Figure 13. Peak simultaneous channels used vs. percentage of *DVR* users

Figure 13 shows the other case, where an increasing percentage of *DVR* users present in the system do not engage in channel flipping behavior at all. Figure 13 is a plot of the peak number of simultaneous channels used as a function of the percentage of *DVR* users present in the system. One may compare this plot with projections of *DVR* users [3]. The current percentage of *DVR* users (1.64%) and future *DVR* percentages (4.09% and 21.27% for end of 2006 and 2008, respectively) are marked for easy identification. As expected, the spectrum savings will increase as the *DVR*-user percentage increases, although this bandwidth reduction does not seem to be significant for the next two years. This fact also confirms a previous statement that for normal $\alpha$ ranges, peak simultaneous channel utilization does not vary too much when the percentage of concurrent flipping users increases. Therefore from this analysis, it can be concluded that the expected increment of *DVR* users in the system in the next few years should not alter the expected spectrum savings dramatically.

### *5.3. Which Channels Should be Switch Broadcasted and How Many?*

The impact of the number and popularity of *SDB* TV channels to be offered on the spectrum requirements is analyzed. Equation (8) calculates the maximum number of TV channels viewed by the service group, $M$ , as function of the available number of *SDB* ( $N_1$ ) and traditional broadcast TV channels ( $N_2$ ) offered to them.

$$M = \sum_{i=1}^{N_1} S_i + N_2 \qquad (8)$$

Where $S_i$ is the state of the *SDB* TV channel *i*. The spectrum saving is obtained primarily from the first term of equation (8). Figure 14 shows the variation of $M$ as a function of $r$ , where $r = \frac{N_1}{N_2}$ . For this analysis the setting shown in Table 1 has been used, thus $N = N_1 + N_2 = 128$ . Also group size and usage rate chosen for this analysis are 300 and 60%, respectively, and $\alpha$=0.75.

Two traces are found in Figure 14, both of them start with peak values of $r$ . The first trace selects TV channels to be *SDB*, $N_1$ , starting from the most popular ones. The second one does the same but starts from the less popular channels. From these results can be appreciated that $M$ for the second trace is always smaller than for the first one. Only at the edges of the x-axis both traces converge to the same points, this can be understood since in those cases all the channels are either *SDB* or traditional broadcasted. From Figure 14 also can be seen that $M$ gets smaller as $N_1$ gets bigger. Figure 15 shows the spectrum saving obtained using the two previous *SDB* channel selection approaches over traditional broadcast for all the 128 channels. The results suggest a significant bandwidth saving, up to 25% of the spectrum, compared with traditional broadcast. It can be seen that the second approach can provide spectrum savings up to three times bigger than the first one for values of $r \in \left\{ \frac{95}{33}, \frac{50}{78} \right\}$ .

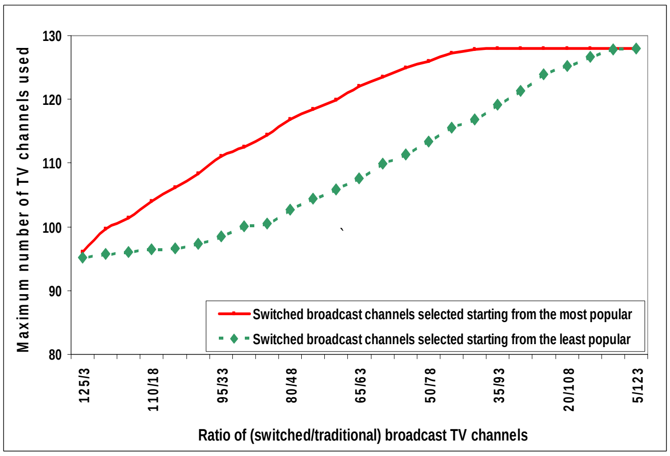


Figure 14. Maximum number of TV channels used under *SDB*

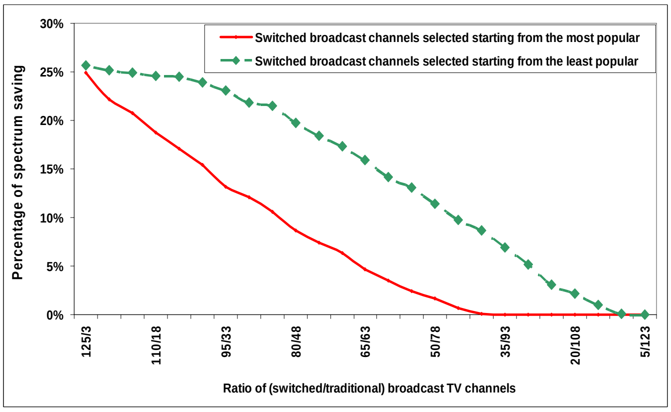


Figure 15. Percentage of spectrum saving using *SDB* over traditional broadcast

### 5.4. *Impact of Different Bit Rates Streaming for Pooled VoD and SDB traffic*

The broadcast industry is quickly moving towards High Definition (*HD*) format. This motivated us to examine the impact of offering Standard Definition (*SD*) and *HD* channels for combined *VoD* and *SDB* services. *SD* and *HD* TV channels delivered to subscribers are encoded at constant bit rates of 3.75Mbps and 12.5Mbps, respectively [4][5]. Figure 16 shows the line up of available *N* broadcast channels, *N*=128, here the most popular 77 channels have been included onto the *SDB* group. From this group the *X* most unpopular channels are encoded as *HD* and the remaining 77-*X* encoded as *SD*.

Based on simulation results, we obtained the spectrum requirements for scenarios involving both *VoD* and *SDB* using different values of *X* and different *VoD* traffic compositions. Figure 17 shows the maximum spectrum requirements obtained from the concurrent peak values of these two services. Both peaks occur at 10.pm, see Figures 8 and 10. From Figure 17 the increment on spectrum requirement for changing one or more *SDB SD* channels into a *HD* channel can be identified. This change represents an average increment of 1MHz and 1.30Mhz of spectrum requirement for a 300 and 500 service group size, respectively.

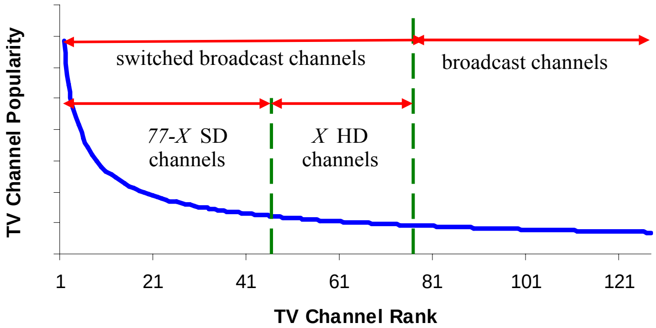


Figure 16. Encoding rate selection for TV channels based on their popularity

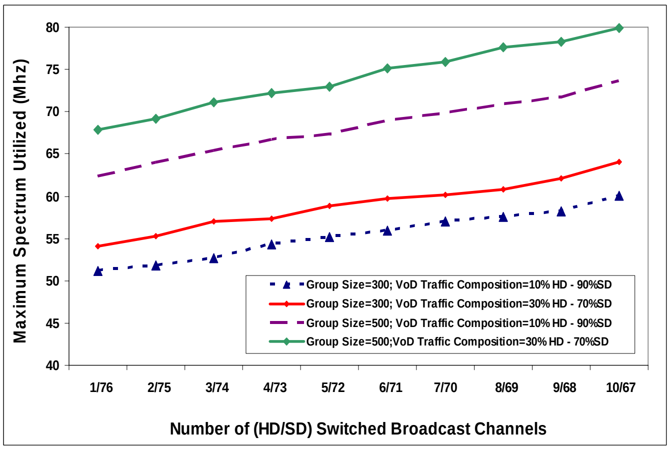


Figure 17. Spectrum requirements for variable *VoD* and *SDB* traffic composition

Replacing one *SD* channel with an *HD* channel should demand an increment of 1.4Mhz, considering that a *SD* and *HD* stream occupies 0.6 and 2Mhz, respectively, see Table 1. In contrast, Figure 17 shows that this increment changes with *X* and the group size. This result can be explained by looking at Figure 16, in this case *X* starts from the lowest portion of the switched broadcast channels rating curve. The *HD* channels switch broadcasted that are located on the lowest portion of the rating curve for this group will have smaller probability of being alive during the whole peak hour than the ones located on the highest portion of the mentioned rating curve. Thus the former will not contributed entirely to the maximum spectrum requirements of the system. Similar results can be expected when the group size increase since the probability of any TV channel being viewed during the some time of the peak hour increases.

## 6. Conclusions

This paper presented a simulation-based investigation of the capacity requirement for *SDB* systems. We demonstrated the model under a variety of usage and system scenarios. One of our main results focuses on the impact of end user's channel flipping behavior on *SDB* systems. Our results suggest that frequent channel flipping does not cause a significant increase in capacity requirement, as long as $\alpha$ falls within a normal range.

Other conclusions drawn from this analysis include:

- The efficacy of *SDB* depends strongly on the Zipf-distribution that drives subscriber's access to content. In future work we will explore the impacts when viewing behaviors in certain situations exhibit Zipf-based popularity models with shape parameters that exceed 2.
- An increase in *DVR* user percentage, which typically does not involve frequent channel flipping, does save bandwidth. However, the extent of the savings does not appear to be significant in the next few years based on market forecasts of *DVR* usage.
- The spectrum requirements for *SDB* systems are driven primarily by the number and popularity of *SDB* TV channels offered. When migrating from traditional broadcast to *SDB*, it is recommended to start from the less popular channels which will yield immediate spectrum savings.
- The benefits of combining *VoD* and *SDB* services on the same set of edge resources has shown up to 35% spectrum savings compared to deploying the services separately. The benefit is derived from the statistical multiplexing gain achieved when the services are pooled.

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