A Framework for Software-Defined Digital Terrestrial Television (DTTV)

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Abstract—**Commercially viable free DTTV will depend on adoption of new technologies, some already available, that will in turn generate new business models. These technologies will permit new real and virtual channels through more efficient spectrum usage and dynamic sharing of the maximum data rate among several applications. The ongoing evolution of software-based receivers will provide the backbone for reliable reception indoors of arbitrarily formatted transmission that will not create new interference to other services.**

Index Terms—**Software defined television, orthogonal polarization sub-channels, contiguous TV channels, dynamic sharing.**

I. INTRODUCTION

With the introduction of High Definition Television (HDTV) in the U.S., TV broadcasters were promised that the high-power analog TV service would be replaced by a low-power and robust HDTV service replicating the Grade-B analog contour.

Since then it has become clear that, aside from the technical flaws inherent in the ATSC standard such as the inability to support mobile reception of HDTV, there are also flaws in the transition plan that threaten the future viability of free over-the-air (OTA) digital broadcasting in the U.S.

The flaws in the transition plan originated with the broadcasters' requirement that their analog service be replicated with reliable digital service. To that end a new propagation algorithm, together with a perfect receiver fed by a high-gain rooftop antenna, served as the theoretical model[1] that yielded the requisite replication of analog service, at least on paper, but only for analog channels above the low VHF band. The planning of future Digital Terrestrial Television (DTTV) service ignored indoor reception with settop antennas and mobile service.

It has since become clear that the propagation model, never validated, significantly over-predicts coverage[2] and that the Federal Communications Commission (FCC) planning factors, assuming a perfect receiver, significantly underestimate[3] the power required for reliable service. As for actual service planning, the assumption of a rooftop antenna no longer applies to major metropolitan areas and is incompatible with indoor and mobile DTTV reception.

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As we enter the second decade of HDTV broadcasting in the U.S., the outlook for free OTA television remains problematic. The vacated spectrum in the band now allocated for channel 2-51 (U.S.) may be assigned to unlicensed devices[4]. Without severe restriction on the available channels, and reconsidering their RF mask, these devices are expected to generate harmful interference to DTTV[5]. With the required restrictions in place, the usage of the vacated spectrum by unlicensed devices will be very inefficient unless DTTV channels in major markets are repacked into a block of contiguous channels. As will be shown in this paper, repacking the DTTV channels into a block of spectrum will be advantageous to broadcasters.

Recent advances in receiver and compression technologies and the introduction of new chips operating at a clock speed of several GHz, creates the opportunity for a gradual introduction of an advanced DTTV system. The advanced system would be capable of providing the extended and flexible DTTV service that is beyond the reach of the current ATSC standard. A general description of the proposed system was first presented[a] at the National Association of Broadcasters (NAB) Show in Las Vegas in 2005. This paper provides a detailed description of the proposed system.

This paper is divided into four Sections. Section II provides a general description of the system. The reception implementation issues are covered in Section III and the transmission implementation issues are covered in Section V. Section IV, intended to serve as a bridge between Sections III and V, covers the benefits of reallocating the DTV channels into blocks of contiguous channels.

II. GENERAL SYSTEM FEATURES

1. **Block of Spectrum:** In its preferred mode, the system would use a block of spectrum. The block is made up of contiguous channels, 6 MHz per station. A shared transmitting antenna, together with new modulation and compression protocols guarantees that if one channel is decodable then all channels will be equally and robustly received. The block of spectrum would facilitate dynamic sharing of the maximum available payload among multiple services (see APPENDIX). A block of spectrum will avoid the consequence of undesired and uncontrollable adjacent channels allocated for non-broadcast users. A block of spectrum would facilitate but is not necessary to the realization of the remaining features.

[a] Delivered at the Technology Luncheon. Text will be made available upon request. Contact www.tvantenna.tv

2. **New Sub-channels:** A block of spectrum made of two or more adjacent channels would allow for a new sub-channel to be centered between them. Using cross-polarization and advanced modulation and compression, the new sub-channels would allow for additional high-priority services such as small-screen mobile TV.
3. **Increased Number of Virtual Channels via Flexible Compression:** Initially, adding MPEG-4[b] compression will allow at least one HDTV program to be multiplexed with one standard definition television (SDTV) program on a 6 MHz channel, thus effectively doubling the number of channels. Dynamic sharing will allow for downloading of ancillary channels such as weather, stock and movies via controlled payload of regular programming. As the receiver architecture becomes software-based, the choice of compression could become channel-specific. That is, each station would be able to select the compression scheme that best fits its business plan.
4. **Expanded Service via Flexible Modulation:** The modulation of the main transmitter would depend on program content, desirable data rate for dynamic sharing and priority access to mobile TV. As is the case with compression, the implementation of a software-based receiver would also allow each station to select the modulation scheme that best fits its business plan. For example, a single frequency network (SFN) of auxiliary broadband transmitters could reuse the same block of spectrum using spread-spectrum modulation and to expand the service into the entire DMA (Direct Marketing Area) while keeping all interference at a minimum.
5. **Smart Software-based Receiver (S^2Rx) with Integrated Antenna Array:** The S^2Rx would be configured from two major assemblies: first, direct conversion from radio frequency (RF) to baseband followed by A/D converter and Digital Signal Processor (DSP). The S^2Rx will be programmable, via downloaded software, to automatically adjust to any modulation, compression and dynamic sharing protocols. Secondly, the RF front-end will be a "smart" array of small, active antennas embedded within the TV set. The array automatically adapts its pattern via polarization diversity and space diversity to maximize the signal to noise ratio (SNR) of the tuned-into TV channel.

Clearly, the S^2Rx receiver will be the critical link in the transition to the future. But the transition to full-featured software-based TV sets will be evolutionary. Once the S^2Rx receiver is widely available at a competitive price, broadcasters will be able to change modulation and compression protocols at will to maximize program delivery to mobile and fixed receivers. With open architecture, interoperability and upgrading become a matter of downloadable software.

The concept of software-based TV receivers is not new. It was first proposed in 1988[6]. However, the earlier proposal dealt only with the capability to decode transmissions based on a variety of standards. It did not encompass the smart front-end, embedded antenna array and the zero intermediate frequency (IF) proposed in this paper. Zero IF is a critical requirement for low-power and small hand-held TV.

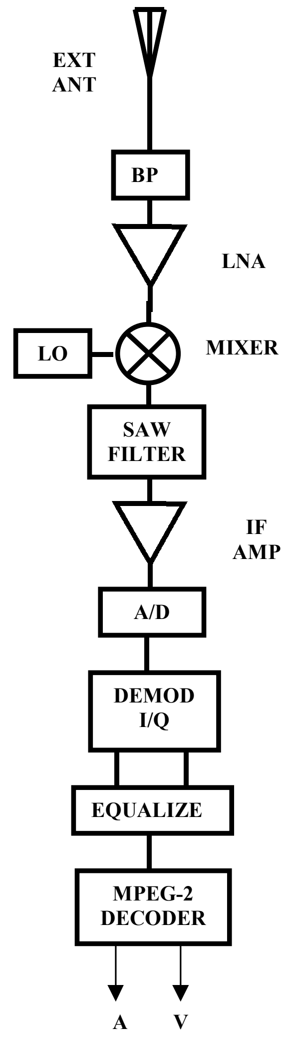

Figure 1: Current DTTV Rx

III. S^2Rx IMPLEMENTATION

Presently, most DTTV receivers are configured for single-conversion from RF to IF. The IF is first SAW (surface acoustic wave) filtered and then digitized. The digitized signal is demodulated into its I/Q components, then equalized and error corrected, followed by MPEG-2 decompression. A simplified block diagram receiver is shown in Figure 1. For

[b] In the context of this paper, MPEG-4 and Window Media Video 9 (WMV-9) have similar compression capabilities and are interchangeable. WMV-9, also known as VC-1, is the expected CODEC standard for Blue Ray DVD and HD DVD. It also requires less power during decoding, making it more attractive for hand-held devices.

clarity, AGC feedback loops and other circuits such as clock recovery and synchronization are not shown in Figure 1. Note that all of the RF/IF/Baseband processing is done in hardware and that the RF section is tethered to an external antenna.

The first step in the evolution of the S^2Rx would be the incorporation of an electronically controlled "smart" front–end integrated with an active antenna array and with a silicon tuner[7] that has an MPEG-2/MPEG-4 decoder. A simplified block diagram receiver is shown in Figure 2. The new subassemblies that provide the added capabilities are highlighted.

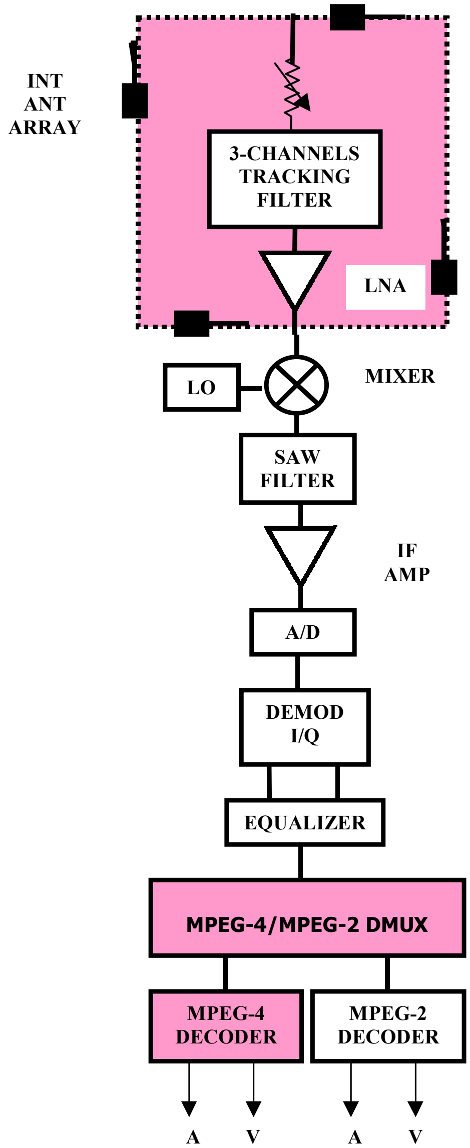

Figure 2: Step1 in S^2 Rx Evolution: Enhanced VSB "Smart" Front-end MPEG-4 Decoder

The details of the "smart" front–end were described earlier[8]. It consists of a programmable and electronically controlled steerable array made of two or four active antennas, preferably embedded in the TV set, followed by a programmable attenuator and a tracking filter whose center frequency and width are programmable. The center frequency and the bandwidth of the tracking filter would depend on the power level of the first adjacent channels and on whether the adjacent DTTV channels have agreed to spectrum sharing. The attenuator would be automatically adjusted to prevent the overload of the low-noise amplifier (LNA). The active antenna elements would steer the array pattern for maximum demodulated SNR. The active antenna elements need not be combined into a single array. They would be preset into channel-specific sub arrays for added space and polarization diversity.

The newly proposed revision of the ATSC VSB standard[c] will support the latest compression technology, as well as other claimed enhancements[d]. Each field of the ATSC VSB standard consists of 313 Data Segments (DS), made up of six groups of interleaved DS plus one Field Synch segment. These Interleaved groups can be independent of each other in their organization. Each of the six interleaved DS could have a different compression format. By associating each coded segment with a proper ID, the enhanced VSB standard could simultaneously support MPEG-2 and MPEG-4 compression of multiplexed data streams. Since MPEG-4 compression is known to require less than ½ the data rate than MPEG-2 compression for the same picture quality, at least one HDTV together with at least two SDTV data streams can coexist within the 6 MHz. Indeed, an MPEG-2/MPEG-4 decoder chipset is already commercially available.

The second step in the evolution of the S^2Rx is to replace all the hardware from the MPEG decoders through the demodulator with Digital Signal Processor (DSP) driven by downloadable software.

The concept of software-defined DTTV is not new[9]. Instructions for building rudimentary software-based radio and DTTV sets together with free software are already available through the GNU project[e]. Figure 3 shows a block diagram of the S^2Rx with software-driven DSP, up to and including the demodulator. Software-defined receivers will give each broadcaster a menu to choose the compression and eventually

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[c] Also known as A-VSB (A for Advanced) it was found in laboratory tests to be backward compatible with ATSC receivers. A formal proposal for revision of the A/53 standard was submitted to the ATSC on November 30, 2005.
[d] Improved reception under dynamic multipath and simple synchronization of distributed transmitters in a single-frequency network.
[e] http://comsec.com/wiki?UniversalSoftwareRadioPeripheral

the modulation format best suited for the application being aired, while maintaining at least one data stream for "legacy" receivers. The assumption made here is that the FCC will eventually permit added modulation and compression formats that do not create additional interference and are in the public's interest.

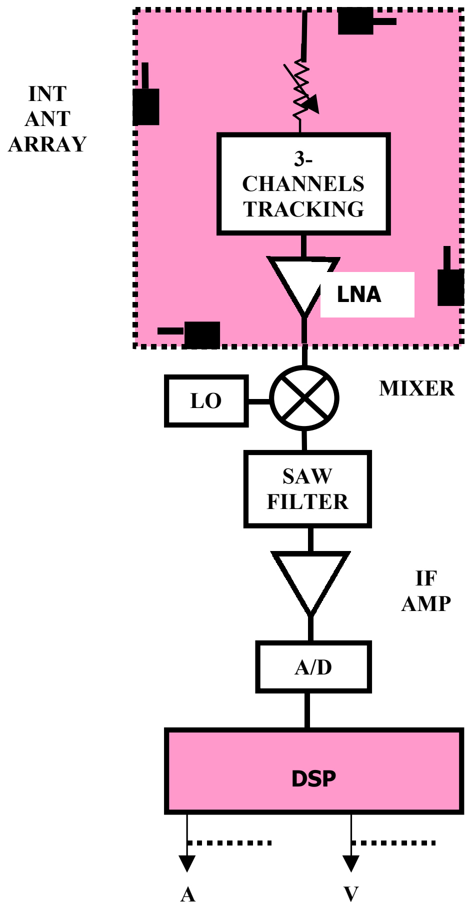

Figure 3: Step 2 in S^2 Rx Evolution: Baseband DSP

Implementation of the second step would require a high-speed processor (or parallel processors) to perform the filtering, demodulation, equalization and decoding using downloaded software. Digitized IF is already implemented in the latest DTTV receivers and high-speed processors are commercially available. Therefore the second step could be implemented in the foreseeable future.

The third step in the evolution of the S^2Rx would be to replace the traditional mixer with direct conversion from RF to baseband. The importance of ZIF (zero frequency or "dc" IF) for delivering digital television to hand-held devices cannot be overemphasized because ZIF is key to reducing power consumption and the physical size of a hand-held set. With zero IF the signal is centered on dc, which can be offset by several sources, including a local oscillator leak reflected back by an impedance mismatch, resulting in self-mixing and dc offset. The dc offset, unless corrected, reduces the dynamic range of the A/D converter. The traditional product mixer cannot be used to convert the VSB (or SSB) modulated RF directly into baseband because the lower adjacent channel will fold into the desired channel[10]. An ideal IQ (complex) demodulator together with a DSP could resolve the desired baseband[11] but an ideal and wideband IQ demodulator would be difficult to implement and it would be subject to the "dc offset" produced by imbalances within the IQ demodulator.

In order to implement ZIF for VSB signals the traditional product mixer can be replaced by a passive 6-port[12] or by a 5-ports[13] ZIF converter. The linear multiport technology, originally invented for vector analyzer measurements, derives the I/Q components from the output power levels caused by induced phase shifts relative to the phase of the local oscillator. The advantages of the ZIF multiport device are wideband, lower power local oscillator, no intermodulation distortion and no generation of new, unwanted frequencies. The disadvantages are that at least three A/D converters are required for the 5-port device, and that the device's scattering coefficients must be known and stored in a memory whose size may be too large for hand-held TV operating in the VHF/UHF bands. Replacing the traditional mixer with a passive ZIF converter would eliminate the major source of undesired power in the desired channel and in all adjacent channels. A passive and wideband ZIF converter will open the door to future options such as spread spectrum modulation over several contiguous 6 MHz channels.

The fourth step in the evolution of the S^2Rx would be to eliminate the direct conversion to ZIF and perform A/D conversion of the RF directly following the LNA. At this time this step may be regarded as an ideal. However, recent advances have demonstrated the first 5GHz delta-sigma 14 bits A/D converter (see ref. 11). The projected dynamic range, depending on bandwidth, varies from 55 dB to 100 dB. What seemed unreachable only a few years ago now seems feasible in the foreseeable future.

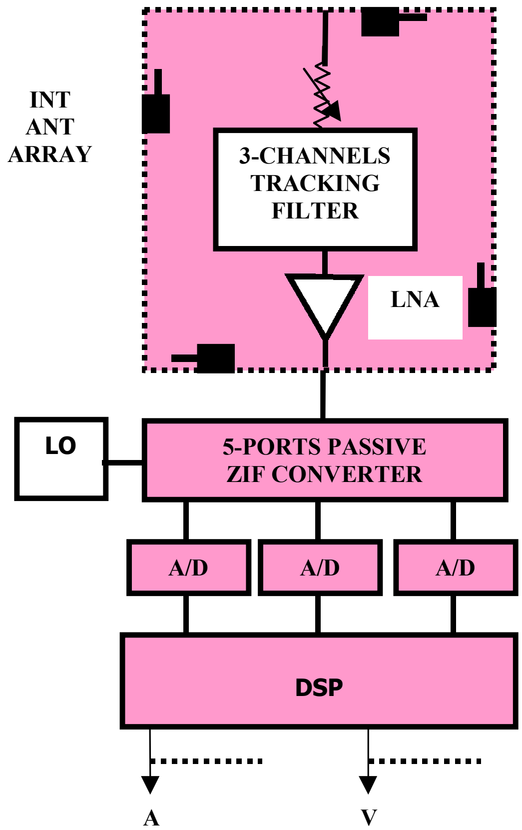

Figure 4: Step 3 in S^2 Rx Evolution: Direct Conversion (ZIF) to Baseband

IV. CONTIGUOUS CHANNELS

After the transition to digital television is complete the vacated television spectrum will probably be assigned in whole or in parts to other than free television broadcasting. The consequences of the reallocation of the newly available spectrum cannot be ascertained at this time. One clear consequence that can be ascertained is that DTTV channels will be either repacked into contiguous channels with guard bands or face undesired adjacent and cochannel interference, probably from unlicensed devices.

Providing for a contiguous TV channel block in each major market is the only known way to completely avoid interference from the proposed new services to licensed DTV stations and simultaneously new benefits to DTV broadcasters.

In most US markets the block of contiguous channels will not exceed 72 MHz. This bandwidth would allow for multiplexing all channels on one UHF or Hi-VHF (U.S. channels 7-13) antenna. For medium power stations, all channels could be multiplexed at low levels followed by a common power amplifier. Broadband, solid-state transmitters with output power > 10 kW are available.

Several benefits, apart from significantly reduced capital and operating costs would accrue from contiguous channel operation. Because the combined bandwidth of the contiguous channels would be relatively narrow, transmission from a common antenna will provide a "receive one channel, receive all channels" experience for all. Since all transmissions would originate from one shared antenna, consumers' antenna orientation will be channel-independent. By equalizing the transmitted power level of all channels[14] and by the use of a "smart" front-end at the receiver[5] the reception will be more robust and interference-free, much like cable television.

Another advantage to using contiguous channels by TV broadcasting would be the potential insertion of new sub-channels for the purpose of increasing the useable bandwidth. As shown in Figure 5, each new sub-channel would be inserted centrally between two adjacent channels and transmitted in the vertical polarization plane, while the main channels will be transmitted in the horizontal polarization plane. Vertical would be essential to the maintenance of adequate SNR margin of the sub-channel SNR. The smart antenna shown in Figures 2-4 is capable of polarization discrimination. The method of combining the odd/even sub-channels S7-S13 with the odd/even main 7-13 channels at the transmitter is a subject of the next section.

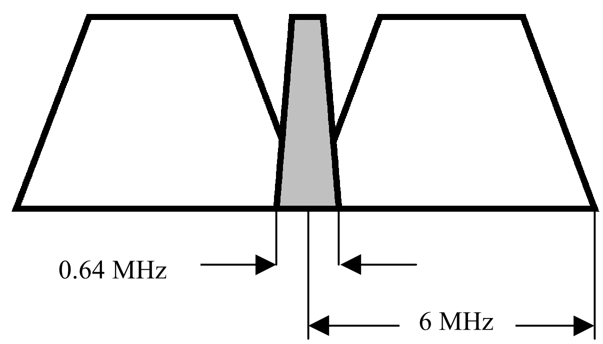

Figure 5: Power Spectral Density of Added Sub-channel with Total Power 9.4 dB below Main Channel

The modulation and data compression of the sub-channel would be optimized for the service intended. The modulation and compression need not be N-VSB or MPEG-n. A sub-channel data rate of at least 3 Mbits/sec, enough for a small-screen mobile TV, may be possible. With equal levels of the two spectral densities shown in Figure 5, the raw signal to interference ratio (SIR) is obtained by dividing the integrated power of the channel and sub-channel by the integrated power of the overlapped spectra in each channel. It is 5.1 dB for the sub-channel and 14.5 dB for the main channel. The improvement in SIR margin due to cross-polarization is estimated at an additional 15 dB[15]. Therefore, with the sub-channel peak power being 9.4 dB below the main channel's peak power, the estimated SNR would be approximately 30 dB in the main channel and 20 dB in the sub-channel. Additional SIR margin in the sub-channel could be attained by increasing its effective radiated power ERP. Increasing the ERP of the sub-channel up to that of the main channel (+9.4 dB) may be possible without causing adverse cochannel and adjacent channel interference in neighboring markets.

Another application of the sub-channel could be to help reduce carrier recovery and synchronization time of both main and sub-channels.

Channels 7-13 are ideally suited for contiguous channel operation. Heavy man-made and sky noise that plague channels 2-6 do not victimize them and they are more suitable for mobile operation than UHF channels because the Doppler shift is lower at longer wavelengths. There are other benefits to channels 7-13 such as a lesser need to adjust "dumb" settop antennas and lower capital and operating cost. The only problem associated with the choice of channels 7-13 is antenna size. The antenna size can be reduced to between 12" and 18" and still function efficiently, but it is still too large for hand-held devices. More likely than not, efficient TV service to hand-held devices will be relegated to frequencies above 1 GHz.

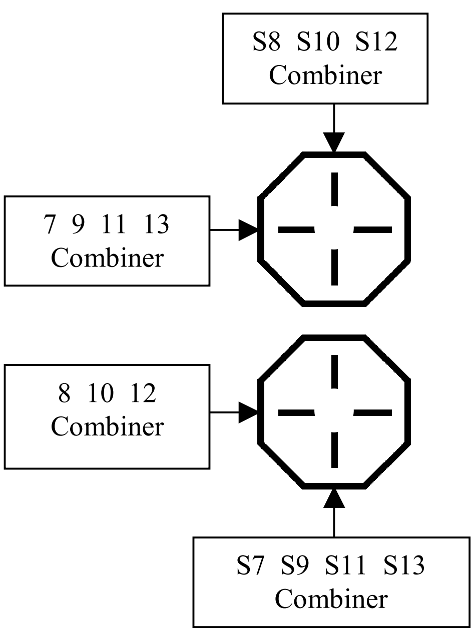

Figure 6: Combining High-power Adjacent Channels and Sub-channels.

Additional benefits that will accrue to contiguous channel operation are the ability to construct a low-cost single frequency network (SFN), possibly using spread spectrum modulation, and to dynamically share excess bandwidth among channels. These will be discussed in more detail in the following sections.

V. TRANSMISSION IMPLEMENTATION

Efficient high-power amplification is limited to a single TV channel. That is so because of the limited gain-bandwidth product of high efficiency and tube-type power amplifiers. Therefore, high-power channel combining must be inserted between the output of transmitters and the shared antenna.

Combining high-power adjacent channels is particularly difficult due to the phase/amplitude response of the band-pass and band-reject filters that constitute the combiner. Ideally, the filter amplitude response would be flat shape across the channel and brick-wall shape at the channels' edges with a flat group delay. Because the ideal filter cannot be realized, combining adjacent channels results in degradation to the SNR margin. To date, no more than two high-power adjacent channels have been combined with an "acceptable" reduction of the SNR in both channels.

Implementing filters for combining multiple non-adjacent channels separated by at least one channel is practical. Therefore, the ultimate solution to combining multiple adjacent channels at high-power lies in using a dual-polarization or circular polarization transmission. In the case of circular polarization, the even and odd channels would be transmitted, using left and right-hand rotations respectively. The isolation between the odd and even channels is a function of the antenna's design and manufacture and it could exceed 30 dB.

For the system of adjacent channels and sub-channels described in this paper, the combining solution requires two identical stacked antennas as shown in Figure 6. Each antenna would be capable of independently transmitting horizontal and vertical polarization. As shown, the sub-channels, designated Sn, would be transmitted using vertical polarization and the main channels would be transmitted using horizontal polarization. Note that the even sub-channels are transmitted from the antenna that serves the odd main channels and vice versa.

The concept of contiguous DTTV channels is especially attractive for medium and low power transmission due to the availability of solid-state, broadband transmitters. Therefore, channel combining at a low level, similar to that used by cable systems, would be practical. Unlike the reactive high-power combiner which are very large and very low-loss, typically <.5 dB, the low-level combiner is resistive and very small but results in a higher loss. For two channels, the pass-through combiner loss would be 3.5 dB. For eight channels, the loss could reach 10.5 dB. In order to maintain flat amplitude response at the output of the transmitter the loss can be compensated for by selective insertion of linear amplifiers in some branches of the combiner, and attenuation in other branches.

Using a common UHF omnidirectional antenna with power gain of 25 (14 dBd) with a common 10 kW transmitter, a maximum ERP of 200 kW for each of the combined channels could be reached. If sub-channels are added, they would be combined and amplified separately from the main channels and then transmitted using a dual polarization antenna such as shown in Figure 6.

Technically and financially, low-level combining with a common transmitter is the most attractive configuration for distributed on-channel transmitters. Any other approach may be subject to higher cost, adjacent channel interference and community objections.

Initially, distributed on-channel transmission, especially in the case of 8-VSB modulation, could be applied to areas where coverage by the main transmitters is terrain-limited. For example, TV reception in many communities inside New York City's DMA is impossible due to the mountainous terrain between Manhattan and these communities. In those communities, cochannel interference with the main channels and with the network of distributed transmitters could be minimized to an acceptable level.

Eventually, distributed on-channel transmission will play a critical role in the transition to software-defined DTTV. As the pressure for efficient reuse of the vacated TV spectrum mounts and S^2Rx receivers become available, the modulation of distributed transmitters could be switched from 8-VSB to COFDM. The main transmitter, using 8-VSB modulation, will continue to serve all legacy receivers. Meanwhile, switching to COFDM modulation will significantly increase the quality of service in areas not covered by the main 8-VSB transmitter and will create an entirely new service for mobile DTTV users.

Cochannel self-interference among 8-VSB distributed transmitters is troublesome[16]. Time Domain Equalization (TDE), especially where the channel impulse response is long, severely limits the practicality of distributed on-channel repeaters using 8-VSB modulation. Even if TDE could be implemented with negligible cochannel self-interference area, the required large number of equalizer taps would make quick carrier recovery and synchronization impractical under long and dynamic impulse response. Also, TDE of a long channel impulse response may raise the noise power to an undesirable level.

Replacing TDE with Frequency Domain Equalization (FDE) has been suggested as a possible solution to the implementation of on-channel, distributed repeaters, in single-carrier systems[17,18]. Some of the original assumptions and conclusions were later challenged[19]. It is true that TDE and FDE are mathematically equivalent. However, the practical implementation of the two operations is quite different. The implementation of FDE prior to the demodulation of the 8-VSB signal would necessitate additional time-frequency domain transformations. With S^2Rx utilizing high-speed signal processing, FDE followed by TDE, could be combined on one chip and the division between FDE and TDE equalization optimized for any modulation at each receiver.

VI. CONCLUSIONS

Consumers could more efficiently use the vacated VHF and UHF spectrum if television stations were assigned a block of channels in each market. The pressure for efficient use of the spectrum cannot but grow as its value to other broadband applications grows and the available alternatives diminish. As outlined in this paper, television broadcasting would derive significant benefits from the transition to software-defined DTTV and from the assignment of contiguous blocks of channels in each market. Not the least of the benefits is avoidance of interference from other unlicensed and licensed transmitters.

It would be better to plan ahead for this transition. It is likely that the viewers of OTA TV in the US will continue to migrate to cable and other TV program distributors unless the broadcasting community shifts from reliance on "dumb" TV sets tethered to rooftop antennas and inefficient bandwidth usage. Broadcasters could grow the number of OTA viewers by embracing new technical and business models. This paper addresses aspects of a new technical model that would allow for new business opportunities.

Distributed on-channel transmission could play a critical role in the transition to software-defined DTTV. As S^2Rx receivers become available, the modulation of distributed on-channel transmitters would be switched from 8-VSB to COFDM. The main transmitter, using 8-VSB modulation, will continue to serve all legacy receivers. Meanwhile, switching to COFDM modulation will significantly increase the quality of service in areas not covered by the main 8-VSB transmitter and create entirely new service for mobile DTTV users.

APPENDIX

Earlier in this paper it was shown that the available spectrum could be more efficiently utilized by inserting new sub-channels between adjacent channels by taking advantage of polarization diversity at the transmitter and at the receiver to achieve acceptable SNR in the main and sub channels.

Additional throughput efficiency is possible by dynamic sharing of managed payload capacity. Most TV programs are pre-recorded, which makes their data rate usage profile known a priori. The data rate usage profile of live programs can be estimated from previous similar telecasts. Figure 7 depicts a hypothetical bandwidth usage over time. The data rate of the priority program can be lowered at certain hours on an “as needed” basis in order to accommodate demand for excess bandwidth by other services depicted as blocks of data which are time-division-multiplexed (TDM) between the priority program’s managed payload and the available peak rate.

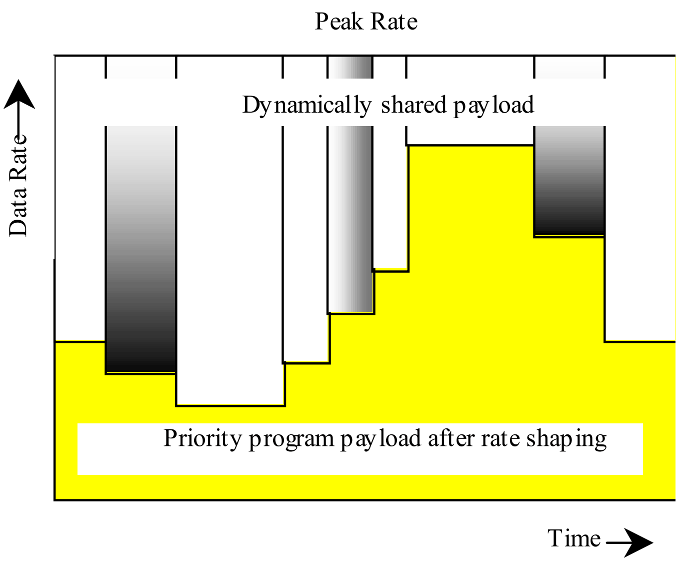

Figure 7: Available Payload with Prioritized Time Slots

A conceptual management for dynamic sharing of the 8VSB standard is shown in Figure 8. The lower priority data, such as software and movies, that can be stored for later use is advance-coded and buffered. The programmable Payload Manager assigns priorities to the payload requests by the competing programs (heavy arrows). The packets of the priority and ancillary data are time-division-multiplexed in segments (52 segments to a field, 2 fields per frame) such as to produce deterministic frames in which the position of every packet is prescribed [A-VSB].

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