ANNEX A

The Performance of Single Carrier Multi-Tone (SCMT) Modulation

November 17, 2013
Content

ANNEX A ........................................................................................................................................................................1

The Performance of Single Carrier Multi-Tone (SCMT) Modulation ................................................................. 1

1. Introduction .................................................................................................................................................................. 3

2. Key features of the SCMT Broadcast System: ................................................................................................. 3

3. Description of the system architectures .......................................................................................................... 4

4. OFDM Waveform Generator .............................................................................................................................. 8

5. SCMT Waveform Generator .............................................................................................................................. 9

6. The main parameters of Samsung/Sony and Guarneri ATSC 3.0 Systems .................................................... 10

7. Payload bit rates of Guarneri SCMT and Samsung/Sony OFDM systems .................................................... 11

8. LDPC code performance .................................................................................................................................... 13

9. Payload Bit Rates of the Samsung/Sony and the Guarneri System............................................................... 14

10. Correct approach to compare the performance ATSC-3.0 systems with different modulations. ....... 15
1. Introduction

Guarneri proposal aims to develop an ATSC 3 physical layer that is compatible with existing ATSC A/53 systems and at the same time has abilities that significantly exceed the performance of existing systems. Guarneri proposal applies to the architecture and development of a new single carrier modulation. Implementing this proposal enables backward compatibility of ATSC 3.0 with ATSC A/53/153 and DVB-T2 based systems.

2. Key features of the SCMT Broadcast System:

1. A novel Single Carrier Multi-Tone technology
   - 6 MHz Band VSB / 12 MHz Band QAM output SCMT signal.
   - No pilot signals.
   - Reliable synchronization by PN sequences.
   - A perfect mechanism of channel estimation and equalization.

2. High power efficiency (low Peak to Average Power Ratio)
   - High efficiency RF Transmitters.
   - Better coverage.
   - Lower distortions in RF Power Amplifier.

   This system has four modes of operation:
   - ATSC A/53/153 mode.
   - ATSC A/53/153 + mobile SCMT mode (transition period).
   - DVB-T2 mode (transition period)
   - SCMT mode.

4. Increased data capacity and improved robustness
   - State-of-the-art LDPC error correcting codes.
   - Single time retransmission for mobile and handheld channels.

5. Well-defined physical layer profiles for three major user categories.
   - Fixed - 30% data increase over A/53 and DVB-T2.
   - Improved multipath performance.
   - Mobile/Handheld receiver energy conserving features.
   - Advanced - very high data rate via multiple transmitters (H/V Polarization, MIMO).


We use text and pictures from this proposal for the description of OFDM system and common blocks for OFDM and SCMT technologies.
3. Description of the system architectures

SAMSUNG/SONY

Figure 3.1: Overall OFDM system architecture diagram.

GUARNERI;

Figure 3.2: Overall SCMT system architecture diagram.

Multiple input streams received into the Input Processing block. The output of this block is one or more Physical Layer Pipes (PLPs) divided into Baseband Frames (BBFs). Each BBF is taken as an input to the Bit Interleaved and Coded Modulation (BICM) block, where BBF passes through Forward Error Correction (FEC) and constellation mapping sub-blocks. After the mapping each PLP is time interleaved. The time interleaved outputs of all PLPs feed the input of the Structure block, and they combined with signaling to produce a single stream composed of OFDM or SCMT symbols ready to be placed on a single RF channel. The Waveform Generator block takes the OFDM or SCMT symbols and generates the OFDM or SCMT signal in the time domain, producing a signal suitable for up-conversion to a higher frequency and broadcast over the air.
• **Input Processing**

The Input Processing block is shown in more detail in Figure 3.3. This block is similar in both OFDM and SCMT technologies.

![Figure 3.3 Input Processing block diagram](image)

Different types of input streams are transformed into a common format called the Baseband Packet (BBP). Each BBP consists of a data payload with a preceding Baseband Header (BBH). The BBPs are then arranged into BBFs. The size of the BBF is determined by the size and code rate of the LDPC code that is used. Finally each BBF is scrambled such that the bits input to the following BICM block are as random as possible. This is to ensure that the best performance of the FEC code is achieved.
• **BICM**

The block diagram for the Bit Interleaved and Coded Modulation (BICM) block is shown in Figure 3.4. The Baseband Frames (BBF) of different PLPs can use different BICM parameters, which means that each PLP may have different robustness and throughput from other PLPs.

![BICM block diagram](image)

**Figure 3.4 BICM block. This includes the Time Interleaver block and the optional MIMO and BB FEC.**

The BICM block is also similar in OFDM and SCMT systems. Of course there are many parameters that might be changed, but for future comparison of performance OFDM and SCMT technologies, we assume that BICM blocks in both systems are the same.

The inputs to the BICM block are randomized BBFs. These frames are then encoded with a BCH code and then an LDPC code. To ensure the best performance, a bit interleaver interleaves the encoded bits and feeds them to a Mapper. The Mapper maps the bits into constellation symbols, such as QPSK, 16-QAM, and higher QAM constellation size. The generated frames are FEC Frames. The FEC Frames are then time interleaved. A convolutional Time Interleaver is used, in order to reduce the memory requirements at the receiver. A novel stop and start method allows the broadcaster to change parameters, if necessary, with continuous reception of the broadcast signal at the receiver.

The BICM block contains two optional blocks, MIMO and BB FEC. MIMO encoding occurs between the mapper and the time interleaver. More details on MIMO can be found in section 11. To increase mobile channel errors tolerance a BB FEC might optionally applied at the input of the BICM block.
- **Structure Block**

The Structure block for frame construction is shown in Figure 3.5

**SAMSUNG / SONY**

![Figure 3.5 Structure block diagram (OFDM)](image)

**GUARNERI**

![Figure 3.6 Structure block diagram (SCMT)](image)

The Structure block takes the time interleaved PLP inputs and schedules them into a stream of data cells. After combining the PLPs, the resulting data cells are interleaved in the frequency direction, to ensure that sustained interference in one part of the spectrum will not unduly affect the performance of a particular PLP. An ATSC 3.0 frame is created from the frequency interleaved data cells. Physical layer signaling (also called L1 signaling) is carried in the preamble which is a special 8K symbol inserted at the beginning of each ATSC 3.0 frame for quick synchronization. The frequency interleaver is needed only for OFDM system, because in SCMT system each bit of unformation is transmitted over all multi-tones. MISO encoding is optionally performed between the frequency interleaver and the frame Builder.
4. OFDM Waveform Generator

The OFDM waveform generator block diagram is shown in Figure 4.1.

![OFDM Waveform Generator Block Diagram](image)

**Figure 4.1** OFDM waveform generator block diagram

Pilots, both continuous and scattered, are multiplexed with the data cells into ATSC 3.0 frames in this block. The receiver uses the pilots to estimate the channel and to correct frequency offsets. Tone reservation for optional PAPR reduction is also carried out here.

Next the inverse FFT (IFFT) operation is performed to transform the signal into the time domain. The amplitudes of Peak to Average Power Reduction (PAPR) pilots, if used, are calculated at this point. After a Guard Interval (GI) is added to each symbol to avoid inter-symbol interference, filtering is performed to ensure minimal interference with neighboring channels in the Spectrum Shaping block. Finally Digital to Analog (D/A) Conversion takes place to create a baseband analog signal suitable for up-conversion and transmission over the air.
5. SCMT Waveform Generator

The SCMT waveform generator block diagram is shown in Figure 5.1.

![SCMT Waveform Generator Block Diagram](image_url)

**Figure 5.1 SCMT waveform generator block diagram**

The SCMT Waveform Generator is different from OFDM Waveform Generator presence next blocks: QAM-to-PAM converter, Up-sample block (x2), FFT block and “Subcarriers Mapping + filter” block.

Since FFT and IFT transactions can be executed with the same FFT/IFFT core at different time intervals, the complexity of SCMT equipment is not so much differ from OFDM. The main variance is a number of FFT (IFFT) points (N).

For OFDM N is (nearly) the number of transmitting subcarriers while for SCMT, the number of subcarriers (multi-tones) is N/4 in the case of single sideband transmission (VSB, 6 MHz bandwidth) or N/2 for double sideband transmission (QAM, 12 MHz bandwidth).

The QAM-to-PAM converter is used for VSB modulation. Each complex QAM4/---QAM1024 symbol from the data cell stream is converted in 2 PAM2/---PAM32 symbols, which subsequently transforms into 2/---32/VSB signal.

The “Serial-to-Parallel block“ converts PAM (QAM) serial symbols in packets of N/2 PAM (QAM) symbols depends from (VSB/QAM) mode of operation. The “Up-sample block” converts these packets in the input of the N-points FFT.

Each FFT output is multiplied by a coefficient that corresponds to a frequency characteristic of the optimal output filter. The filtered subcarriers are divided into two groups - the first one occupies the lower part of the spectrum and the second occupies the higher part of the
spectrum. The reordering process performs relocation of these groups around the selected carrier frequency. The first group of subcarriers is placed above carrier frequency and the second group of subcarriers is placed below the carrier. This processing is offered by “Subcarriers Mapping + filter block”.

Depends on the selected mode (VSB/QAM), the digital filter forms 6 MHz/12 MHz bandwidth of output signal with selected value of PAPR.

The sequential blocks are similar to corresponding blocks of the OFDM Waveform Generator. The “Spectrum Shaping block” comprises a programmed digital filter that has several possible configurations for 6MHz/12 MHz bandwidth.

In contrast with OFDM the output of the SCMT Waveform Generator produces the VSB/QAM signal on the Intermediate Frequency (IF).

6. The main parameters of Samsung/Sony and Guarneri ATSC 3.0 Systems

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Unit</th>
<th>SAMSUNG/SONY</th>
<th>GUARNERI (VSB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td></td>
<td>OFMD</td>
<td>VSB</td>
</tr>
<tr>
<td>FFT size</td>
<td></td>
<td>8K</td>
<td>16K</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>MHz</td>
<td>6.86</td>
<td>10.76</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>MHz</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>N of data carriers</td>
<td></td>
<td>6436</td>
<td>12961</td>
</tr>
<tr>
<td>Carrier spacing</td>
<td>Hz</td>
<td>837</td>
<td>418</td>
</tr>
<tr>
<td>Symbol duration</td>
<td>us</td>
<td>1194</td>
<td>2389</td>
</tr>
<tr>
<td>GI (selected)3/64</td>
<td>us</td>
<td>56</td>
<td>112</td>
</tr>
<tr>
<td>Carrier modulation</td>
<td></td>
<td>QAM4</td>
<td>QAM16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>QAM256</td>
<td>QAM1024</td>
</tr>
</tbody>
</table>

Table 6.1. Main parameters of OFDM and SCMT System
7. Payload bit rates of Guarneri SCMT and Samsung/Sony OFDM systems

<table>
<thead>
<tr>
<th>PARAM.</th>
<th>Units</th>
<th>8VSB</th>
<th>16VSB</th>
<th>32VSB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit per symbol</td>
<td></td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Symbol rate</td>
<td>MHz</td>
<td>10.76</td>
<td>10.76</td>
<td>10.76</td>
</tr>
<tr>
<td>Without code</td>
<td>Mbps</td>
<td>29.55</td>
<td>39.37</td>
<td>49.21</td>
</tr>
<tr>
<td>Code 9/15</td>
<td>Mbps</td>
<td>17.75</td>
<td>23.62</td>
<td>29.52</td>
</tr>
<tr>
<td>Code 10/15</td>
<td>Mbps</td>
<td>19.7</td>
<td>26.34</td>
<td>32.80</td>
</tr>
<tr>
<td>Code 11/15</td>
<td>Mbps</td>
<td>21.67</td>
<td>28.87</td>
<td>36.08</td>
</tr>
<tr>
<td>Code 12/15</td>
<td>Mbps</td>
<td>23.64</td>
<td>31.49</td>
<td>39.36</td>
</tr>
<tr>
<td>Code 13/15</td>
<td>Mbps</td>
<td>25.61</td>
<td>34.12</td>
<td>42.65</td>
</tr>
</tbody>
</table>

| BIT RATE of ATSC 3.0 TRANSMITTER in A/53 mode |
| Code 9/15 | Mbps  | 19.4 | -------- | -------- |

Table 7.1. Payload bit rates of SCMT system
For \( N \) carrier = 12961 , symbol length = 2389 us, CP length = 112 us

<table>
<thead>
<tr>
<th>PARAM.</th>
<th>Units</th>
<th>64QAM</th>
<th>256QAM</th>
<th>1024QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit per symbol</td>
<td>Hz</td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Symbol rate</td>
<td>Hz</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Without code</td>
<td>Mbps</td>
<td>31.10</td>
<td>41.47</td>
<td>51.84</td>
</tr>
<tr>
<td>Code 9/15</td>
<td>Mbps</td>
<td>18.66</td>
<td>24.88</td>
<td>31.10</td>
</tr>
<tr>
<td>Code 10/15</td>
<td>Mbps</td>
<td>20.73</td>
<td>27.64</td>
<td>34.56</td>
</tr>
<tr>
<td>Code 11/15</td>
<td>Mbps</td>
<td>22.80</td>
<td>30.41</td>
<td>38.02</td>
</tr>
<tr>
<td>Code 12/15</td>
<td>Mbps</td>
<td>24.88</td>
<td>33.17</td>
<td>41.47</td>
</tr>
<tr>
<td>Code 13/15</td>
<td>Mbps</td>
<td>26.95</td>
<td>35.94</td>
<td>44.92</td>
</tr>
</tbody>
</table>

**BIT RATE of ATSC 3.0 TRANSMITTER in A/53 mode**

| Code 9/15       | Mbps  | 19.4  | -------- | -------- |

Table 7.2 Payload bit rates of OFDM system.
8. LDPC code performance

For both Guarneri SCMT and Samsung/Sony OFDM systems are using the same DVB-T2 BCH/LDPC code, which last version from Samsung/Sony has the characteristics shown on Figure 8.1.

Figure 8.1 Performance of Samsung /Sony 64KLDPC code for QPSK in AWGN channel.
9. Payload Bit Rates of the Samsung/Sony and the Guarneri System

Figure 9.1 depicts the payload bit rates in Mbps that can be achieved with a 6 MHz channel. The SNR values are taken from simulations over the AWGN channel.

![Graph showing payload bit rates for ATSC 3.0 systems](image)

- ATSC A/53 - 19.39 Mbps
- ATSC 3.0 OFDM - 18.66 Mbps
- ATSC 3.0 SCMT - 17.75 Mbps

**Figure 9.1** Payload bit rates in 6 MHz channel of the Samsung/Sony OFDM, A/53, and the Guarneri SCMT systems.

The comparison between the proposed ATSC 3.0 systems and A/53 at 14.4 dB decoding threshold for A/53, is as follows: The common to all systems 64-QAM and code rate 9/15 offers:

- ATSC A/53 - 19.39 Mbps
- Samsung/Sony OFDM - 18.66 Mbps
- Guarneri SCMT - 17.75 Mbps
corresponding to a 4% decrease for OFDM and to 9% decrease for SCMT.

So, the best solution from point of maximum bit rate is an ATSC A/53 system developed in 1996.

The difference between bit rates of SAMSUNG/SONY ATSC-3 (OFDM) and GUARNERI ATSC-3 (SCMT) for the same SNR is about 5% (in favor of OFDM). It means about 0.3 dB OFDM advantage in equivalent value of SNR.

Considering different values of PAPR of OFDM (10 - 12 dB) and PAR of A/53 and SCMT (6.5 dB) we can state that in practical cases, when the same RF Transmitter is used for all tested systems and all receivers are placed at the same point, the maximum bit rates of the ATSC 3.0 systems will be significantly different from the results shown on figure 9.1.:  

10. **Correct approach to compare the performance ATSC- 3.0 systems with different modulations.**

The results shown in Figure 9.1 do not allow determining the actual performance of ATSC 3 systems in practical cases. Indeed, these results allow us to claim that OFDM has best bit rate for selected SNR, than SCMT (Guarneri) or Single Carrier (A/53) modulation. However, this fact says nothing about systems performance.

What is a practical case, in which we want to obtain the maximum bit rate of broadcasting system? We assume that this practical case shall include:

- Standard RF Transmitter, which is connected to tested OFDM, SCMT or A/53 modem.
- The OFDM, SCMT and A/53 baseband receivers, which are placed at the same point and connected to the same RF antenna and RF Down-Converter.
- The same test equipment for all tests.
- The RF Transmitter shall work in a regime of maximal output power, in which the non-linear distortions of the transmitted signal do not exceed an allowable level.

If we accept this model, we will assume that the system, which will provide a better payload bit rate, is the system with the best performance. It's well known that the single carrier systems have significantly less Peak-to-Average Power Ratio (PAPR= 6.5-7.5 dB) than multicarrier systems (PAPR=10-12 dB). Therefore the same RF Transmitter can transmit the single carrier signal with average power about two times higher (+ 2.5-3.5 dB) than OFDM signal. It means that A/53 or SCMT receiver obtains a more power signal, than OFDM receiver, placed in the same point. Therefore, SNR in A/53 or SCMT system is approximately 3 dB better than SNR in OFDM system. Figure 10.1 depicts the payload bit rates in Mbps that can be achieved in the practical case. The SNR values are taken from simulations over the AWGN channel.
Figure 10.1 Practical payload bit rates in 6 MHz channel of the Samsung/Sony OFDM, A/53, and the Guarneri SCMT systems.

Figure 10.1 shows the real bit rates in practical case of terrestrial broadcast system, taking into account the difference of characteristics single carrier and multi-carrier modulations. Therefore, the obtained results can be used for the correct definition of the real performance of proposed ATSC-3 Systems. Instead of the generally accepted opinion, that OFDM has significantly better performance than the existing A/53 System, Figure 10.1 illustrates that real bit rate in Samsung/Sony system and bit rate in A/53 system are very close.

The comparison between the proposed ATSC 3 systems and A/53 at 14.4 dB - the decoding threshold for A/53, is as follows: The common to all systems 64-QAM offers:

- ATSC A/53: 19.39 Mbps
- Samsung/Sony OFDM: 18.66 Mbps
- Guarneri SCMT: 25.2 Mbps

corresponding to a 4% decrease for OFDM and to 30% increase for SCMT.
The Guarneri (SCMT) system bit rate increases to 35% versus Samsung/Sony (OFDM) bit rate. The advantage of SCMT versus OFDM is explained by lower PAPR level. The advantage of SCMT versus A/53 is explained by applying an advanced LDPC code.

All results discussed above refer to the operation of the ATSC systems in AWGN channel.

It is expected that the performance of the Guarneri SCMT system in multi-path channel will be about 5%-20% better than the performance of the Samsung/Sony system.