Re: Docket 16-142

I no longer have concern about the high peak-power to average power ratio (PAPR) of double-sideband OFDM wasting transmitter power, which concern I expressed in my previous comment. While high PAPR wastes transmitter power in linear radio-frequency power amplifiers of push-pull Class B type that are being used currently for ATSC 1.0 transmissions, this problem has been curtailed in designs for linear RF power amplifiers of new transmitters better suited for ATSC 3.0 transmissions.

The use of OFDM with substantially lower PAPR than that of double-sideband OFDM would, of course, avoid having to replace the high-power portions of DTV transmitters currently used for ATSC 1.0 transmissions.

Further Commentary re the Suitability of Double-sideband OFDM for DTV Broadcasting in the US

I previously commented that double-sideband OFDM might not be the best choice for DTV broadcasting in the United States. A major concern of mine at the time was the long, widely recognized problem with DSB-OFDM that the crest factor is very large, especially as the number of OFDM subcarriers becomes a few thousand or more. That is, the peak-power to average power ratio (PAPR) becomes excessive, forcing substantial hold-back of average power in the linear power amplifier of the DSB-OFDM transmitter in order to reduce the incidence of clipping signal peaks. The clipping of signal peaks tends to generate out-of-band interference, as well as introducing errors in reception of coded data.

I recently had an interesting exchange of e-mail with Prof. Jean Armstrong, who is now at Monash University in Victoria, Australia. I had run across the attached paper "Frequency Domain Equalization for OFDM systems with mapping of data onto subcarrier pairs and overlapping symbol periods" published in 2000. What sparked my interest was the finding that phase-complementary coding (PCC) could reduce crest factor (and PAPR) of OFDM by 8 dB. This implies that back-off of average power in the linear power amplifier of an OFDM transmitter could be reduced by 8 dB. This conserves appreciable power in some types of linear power amplifier, such as push-pull Class B type. Also, co-channel interference of PCC-OFDM with an ATSC 1.0 signal would be no larger than that from another ATSC 1.0 signal.

As pointed out in the attached paper by Prof. Armstrong and associates:

"Despite its many advantages, PCC-OFDM used in its simplest form has one major disadvantage — loss in spectral efficiency. The use of two subcarriers,

instead of one, to transmit each complex value, reduces the spectral efficiency by half. The elimination of the cyclic prefix, the improved spectral roll-off and the reduction in ICI will make up for some, but not all, of this loss."

In my e-mail to Prof. Armstrong I wrote that there was a probably simpler way to double the spectral efficiency of PCC-OFDM. Simply use single-sideband PCC-OFDM rather than double-sideband PCC-OFDM. The combining of similar coded data from the paired subcarriers of single-sideband PCC-OFDM would increase effective SNR as much as combining of similar coded data from the lower and upper sidebands of ordinary double-sideband OFDM.

I pointed out that while the DTV receiver would have to demodulate OFDM carriers single-sideband before the combining of similar coded data from separate OFDM carriers, this was desirable to do even when receiving ordinary double-sideband OFDM. Folding the frequency spectrum to combine OFDM carriers conveying similar coded data at symbol level halves the size of FFT, making for a cheaper receiver, and does improve effective SNR by 6 dB. However, North American Philips found some years ago in MIMO work that combining similar coded data at bit level after demapping QAM improves effective SNR by 8.5 dB. This extra 2.5 dB should increase reception range about 30%.

It also better accommodates just one of the two sets of subcarriers that convey similar coded data being corrupted. However, this is unlikely to happen in PCC-OFDM in which OFDM carriers conveying similar coded data are next to each other in the frequency spectrum. Just one of the two sets of subcarriers that convey similar coded data being corrupted, rather than both, is more likely to occur in ordinary double-sideband OFDM.

Both subcarriers that convey similar coded data being corrupted is even less likely to occur in a type of independent-sideband OFDM described in the copy of an expurgated US provisional patent application sent with my earlier comment. It is unclear whether that type of ISB OFDM would improve headroom as much as the PCC-OFDM described by Prof. Armstrong and her associates. (ATSC members chose not to explore beyond DSB-OFDM as used in the European DVB-T and DVB-T2 standards for terrestrial DTV broadcasting.)

In her response Prof. Armstrong observed that the early work on OFDM incorrectly calculated the effect of non-linearities on OFDM. She averred that the main effect of clipping is to shrink the constellation, so the in-band distortion is actually quite small, even for quite severe clipping. She reported that when she visited the R&D section of the BBC and showed them

her results their comment was: "now we know why our transmitters worked when we didn't expect them to". So, she believes her theoretical results were confirmed experimentally. Another effect that mitigates the effect of clipping noise is that it is added in the transmitter, not the receiver, she noted and so fades along with the signal. According to her thinking, this implies that clipping noise has very little effect in a frequency-selective channel.

Doherty Amplifiers Improve Efficiency of Newer Designs of OFDM Transmitters

Prof. Armstrong indicated that she recently had occasion to review newer Rhode & Schwartz transmitters, which use Doherty amplifiers to improve their efficiency. This makes the 8 dB increase in headroom less important with regard to conserving power consumption in the power amplifier of an OFDM transmitter.

In a Doherty amplifier the response of a push-pull Class B amplifier with capability to amplify average power linearly is combined by a transformer with power from another amplifier designed to augment power only on peaks. This is done to extend the dynamic range of linear power amplification.

If the Peak-to-Average-Power-Ratio OFDM Be High, the OFDM Is More Likely to Cause Co-channel Interference With 8-VSB Transmissions

While Doherty power amplification increases power efficiency in an OFDM transmitter, the avoidance of peak clipping increases co-channel interference (CCI) with any transmission from another transmitter having overlapping coverage and sharing similar broadcast channel allocation.

CCI between OFDM transmitters sharing similar broadcast channel allocation is increased during peak power excursions. However, such increase is not a particularly serious problem, because each power peak in CCI in the time domain is dissected into many separate frequency-domain components in the Fast Fourier Transform (FFT) procedures in each OFDM receiver.

CCI from a OFDM transmitter into transmissions from an 8-VSB transmitter sharing similar broadcast channel allocation is increased during peak power excursions in an OFDM signal having high PAPR. These peak power excursions are apt to increase errors in detection of coded data conveyed by the 8-VSB signal, since 8-VSB receivers do not include FFT procedures to dissect each power peak in CCI in the time domain into smaller-energy components. Since European countries went directly from analog TV

broadcasting to OFDM DTV broadcasting, they provided little if any experience concerning such possible CCI problems.

In a filing with the FCC, the Association of Federal Communications Consulting Engineers weighed in on interference concerns expressed in a filing from CTIA—The Wireless Association. AFCCE asserted that ATSC 3.0 would be no different than ATSC 1.0, the current broadcast TV transmission methodology, when it comes to interference. This assertion appears to have been based on the mistaken notion that the PAPR of COFDM is only 2.5 dB larger than that of 8VSB.

The nominal peak power of 8VSB is 7 squared or 49.

The nominal average power of 8VSB is 7 squared plus 5 squared plus 3 squared plus 1 squared, which sum is divided by 4 to equal 21.

The PAPR of 8VSB is 49/21 = 2.3333 =7.36 dB.

The PAPR of COFDM can be as high as 15 dB if there be no significant peak clipping, judging from the average power back-off in new Rhode & Schwarz transmitters for double-sideband OFDM transmissions. This is around 7.5 dB larger than that for 8VSB, so maximum peak energy in ATSC 3.0 can be expected to be 2.4 times as large as for ATSC 1.0.

However, since very large peaks in double-sideband OFDM occur infrequently, the FEC coding of the 8VSB may well be able to correct the occasional errors those peaks might cause. This is difficult to confirm theoretically, and the FCC is advised to have this matter confirmed by measurements comparing the two sorts of ICI into 8VSB, made at various levels of accompanying AWGN and receiver noise. Preferably, such measurements would be made by a party not associated with the proponents of ATSC 3.0.

CCI from an OFDM transmitter into transmissions from an 8-VSB transmitter will be of concern (if at all) during a period of transition from broadcasting DTV via OFDM signaling according to the ATSC 3.0 standard, as currently proposed, while continuing the broadcasting of some 8-VSB signaling according to the ATSC 1.0 standard. Presumably, broadcasting of some 8-VSB signaling will be continued for a few years to accommodate the many legacy DTV receivers that will still be in the field.

High Peak-to-Average-Power-Ratio of Double-Sideband OFDM Remains a Problem for OFDM Receivers

While the high PAPR of OFDM is usually thought of as transmitter problem, it presents problems in receivers, too. The problems worsen when the OFDM transmitters use Doherty amplifiers to get more headroom for peaks above average power. In order for the receiver RF amplifier not to clip more than the transmitter power amplifier and thus introduce more errors for correction in LDPC coding, gain has to be scaled back in the receiver RF amplifier. This hurts noise factor. While the scaling back of average power reduces galactic noise as much as OFDM signal, Johnson noise and any other noise from the receiver itself are not scaled back and will adversely affect the SNR of the received analog COFDM signal more.

This effect is worsened by the resolution of the analog-to-digital converter of the time-domain COFDM signal having to be increased to accommodate that high PAPR signal and keep quantization noise reasonably low.

The noise from the receiver itself will adversely affect demapping of the OFDM carriers more. This limits the highest order of QAM that can be demapped satisfactorily and reduces channel capacity to some extent. That reduction of channel capacity could be of some concern to broadcasters, even though the effects causing such reduction arise in receivers.

One should remember, however, that quadrupling the size of square QAM constellations 16QAM or larger does not increase the amount of coded digital data they convey by a factor of four. So, reduction in channel capacity may not be much of a problem. Going from 16QAM to 64QAM increases the number of bits in each constellation map label from four bits to six, an increase of 1.5 times in the amount of coded digital data. Going from 64QAM to 256QAM increases the number of bits in each constellation map label from six bits to eight, a further increase of 1.33 times in the amount of coded digital data. Going from 256QAM to 1024QAM increases the number of bits in each constellation map label from eight bits to ten, a further increase of 1.25 times in the amount of coded digital data. Going from 1024QAM to 4096QAM increases the number of bits in each constellation map label from ten bits to twelve, a further increase of 1.2 times in the amount of coded digital data. Going from 16QAM to 4096QAM triples the number of bits in each constellation map label. Going from 64QAM to 4096QAM only doubles the number of bits in each constellation map label from six bits to twelve.

It may be acceptable simply to allow the analog RF amplifier to clip the occasional peaks in the double-sideband OFDM. This would reduce the adverse effects of noise from the receiver itself. Prof. Armstrong's observation that the effects of clipping in the RF power amplifier of the OFDM transmitter were not as serious as previously thought should apply to clipping in the RF amplifier of the receiver as well.

Perhaps the FCC Should Consider Regulating OFDM Receivers, As Well as OFDM Transmissions, for DTV Broadcasting in the US

The ATSC 3.0 standard applies solely to transmitting DTV signals, not to DTV receivers. The requirement for all-channel tuners set precedent for the FCC regulating new television receivers to be sold in the United States.

Requiring that all COFDM receivers for COFDM digital television broadcasting in the United States be single-sideband (or independent-sideband) in nature, with combining of duplicate coded data from pairs of OFDM carriers being deferred until after QAM demapping, increases their reception range about 30%. This can increase the service area of a given power OFDM transmitter up to nearly 70%. Such receivers will provide better reception with indoor antennas, supposing the receiver to be a few miles from the transmitter.

This will, however, require OFDM receiver designs with twice the FFT computation capability of designs of currently conventional designs of receivers for double-sideband OFDM, which receivers fold the frequency spectrum in half during a synchrodyne to baseband prior to performing FFT procedures. This would entail some extra cost for more extensive monolithic integrated circuitry, but this extra cost would be small compared to the cost of an entire TV set.