Ultra-low Phase Noise Oscillators and Synthesizers for Managing and Relieving Spectral Congestion: A Tutorial Introduction

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***Abstract*—Precise timing in shared-user, wireless data communications systems directly affects the growing concern in establishing and managing 'spectrum harmony'. For shared spectrum, an efficient and widely accepted modulation type is orthogonal frequency division multiplexing (OFDM). The main advantage of OFDM to other modulation protocols is its efficient use of spectrum and substantial resistance to multipath effects and fading. This report discusses how ultra-low -phase noise (ULPN) oscillators from stabilized optical frequency dividers (OFD's) might be used to improve the efficiency in shared-user, wireless data communications systems. In particular, spectral congestion might be alleviated by simply increasing the number of sub-carriers. This can only be done by lowering phase noise, especially near the carrier, in the local oscillators (LOs) used throughout a particular network of users. We find that the number of users in wireless communications systems can be increased by using new low-phase noise oscillators that are being developed for other applications. The improved long-term (>1s) phase stability can significantly narrow the bandwidth (BW) to 1 Hz in the clock (tracking) used in the receiver. This BW further increases resistance to other shared users and jammers, multipath fading, and eavesdropping, thus increasing range. How much advantage depends on a multitude of factors and is beyond the scope of this overview. Our intent is to show how ULPN-OFD technology can and should be a part of the roadmap toward improved spectrum management.**

Introduction

This writing accompanies the tutorial introduction presented on December 5, 2013, at the Precise Time and Time Interval (PTTI) planning meeting, Bellevue, WA. Manuscript is not subject to NIST editorial review. The summary is top-level only. A detailed journal article will appear in *IEEE Comm. Letters*. This and other related publications will be available at tf.nist.gov.

Summary of 2013 Presentation

Orthogonal Frequency Division Multiplexing (OFDM) is today's primary data protocol that maximizes information capacity while minimizing vulnerabilities in bandwidth-limited radio-frequency shared-spectrum wireless networks. OFDM uses a large number of overlapping, yet orthogonal, sub-carriers that are generated by an inverse fast Fourier transform (IFFT), that is clocked and upconverted from a single reference oscillator. In OFDM the spectra of individual subcarriers overlap, but because of the IFFT's orthogonality property, as long as the channel is linear, the subcarriers can be demodulated without interference and without the need for analog filtering to separate the received subcarriers. The spectrum of each subcarrier has a form of $|\sin(x)/x|^2$, and so has significant spectral side lobes. The side-lobe peak frequencies exactly align with side-lobe nulls of all other subcarriers as shown in Figure 1. This alignment naturally occurs in OFDM and is the limiting cause of one of its major disadvantages, a high sensitivity to phase noise [1][2][3]. The sensitivity to the difference in the phase noise of the transmitter reference, or local oscillator (LO), and the receiver LO precisely occurs at multiples of the first null-offset frequency, or $M \cdot f_{null}$. Unmodulated pilot sub-carriers are used primarily to remove transmit-receive phase difference and secondarily to remove frequency offset and drift in the receiver LO [4].

Demodulation and demultiplexing are performed by a forward-FFT and time division, respectively. Quadrature Amplitude Modulation (QAM) is a method of signaling

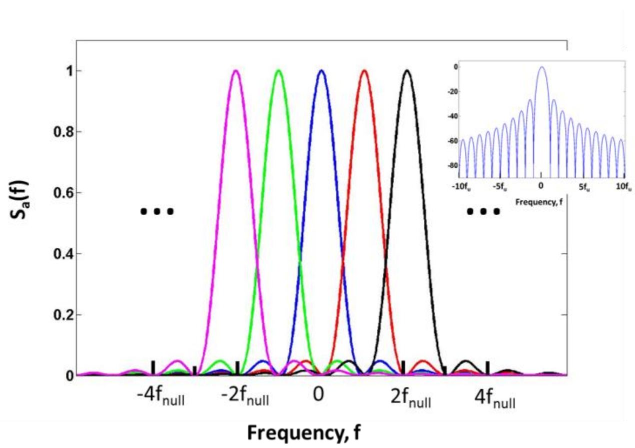

Figure 1. With OFDM, adjacent sub-carrier's side-lobes overlap as shown in the log plot of of the power spectrum in the inset. In the larger linear plot, one sees easily how multiple sub-carriers overlap so that many sub-carriers are spaced precisely by f_{null}. Sub-carriers are synthesized by an inverse fast Fourier transform (IFFT) that could be clocked by new ultra-low phase noise (ULPN) microwave oscillators that frequency-divide stabilized optical oscillators. Such optical frequency dividers (OFD's) can be used as local oscillators (LO's). With such spectrally-pure LO's, sub-carriers can be further modulated by many more levels of quadrature amplitude modulation (QAM) such that one data link can have a much higher overall data-rate than with LO's of typical quartz or MEMS LO's.

where information is contained both in the phase and the amplitude of the sub-carriers. For example, it is possible to send one of sixteen different four-bit patterns using this technique with the right choice of low-phase noise LO's. The limit to the number of bits and speed of transmission in a sub-carrier is ultimately determined by the telecommunications channel noise and the spectral purity of the transmitter and receiver LO's.

In fiber optic links, it is well-known that coherent optical (CO), OFDM, and QAM are all susceptible to phase noise [5][6][7]. A simulation with a transmission model in the presence of phase noise shows the symbol error rate (SER) floors from finite laser linewidth for CO-OFDM systems with high-order QAM constellations [8]. Compared to the best commercially available microwave oscillators, a factor of 1000 spectral-purity improvement at a few Hz offset-*f* near the carrier is achieved using ultra-low phase noise (ULPN) microwaves from stabilized optical frequency dividers (OFD's) [9].

The advent of ULPN microwave oscillators has created speculation that a sizeable improvement might be possible in broadband *microwave* links that *share spectrum* among many users such as with Wi-Fi, cell phones, etc. One example is that ULPN LO's circumvent bandwidth occupied by pilot signals. To alleviate the so-called "spectrum crunch," other desirable improvements would be: (1) increased data throughput, (2) increased usable bandwidth, i.e., by narrower sub-carrier linewidth and by reduction of number of pilot and guard-channel signals, (3) increased number of shared users, i.e., jam resistance to other users, (4) increased coverage, (5) reduced processing lag time, and (6) privacy.

The presentation focuses primarily on how ULPN OFD's provide advantage to shared-spectrum, microwave communications. Mathematical treatment and experiments will be described in subsequent journal publications. The authors are involved in development of small ULPN-OFD reference oscillators. For publications, please access "Publications" at tf.nist.gov.

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