HIGH-PERFORMANCE EXTENSIBLE SOQPSK (E-SOQPSK)
MODULATION WAVEFORMS FOR AERONAUTICAL
MOBILE TELEMETRY COMMUNICATIONS

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ABSTRACT
To utilize the resilience to multipath and rapidly varying Doppler shifts offered by a multicarrier (MC) Orthogonal Frequency Division Multiplexed (OFDM) modulation waveform, and the high transmitter power efficiency offered by a single carrier (SC) Shaped Offset Quadrature Phase Shift Keying (SOQPSK) modulation waveform, we propose a novel Extensible Shaped Offset Quadrature Phase Shift Keying (E-SOQPSK) modulation waveform. E-SOQPSK is an OFDM structured single carrier modulation waveform, configurable to include OQPSK, SOQPSK, or m-QAM. Preliminary laboratory results confirmed its low Peak-to-Average Power ratio (PAPR) and high spectrum efficiency. Preliminary simulations demonstrated multipath resilience of E-SOQPSK waveform by utilizing OFDM structure based Frequency-Domain equalization at receiver.

INTRODUCTION
Three system performance criteria motivated us to search for better modulation waveforms for aeronautical telemetry communication applications:

1. To provide a robust communication link in a channel with time-varying multipath and highly dynamic Doppler shift.
2. To achieve high transmit power efficiency.
3. To achieve high bandwidth efficiency

1) Channel impairment issues and existing solutions:
   a) Multipath
Since the introduction of multicarrier (MC) Orthogonal Frequency Division Multiplexing (OFDM) in 1966 by Chang, Bell Laboratory [1] [2] the MC modulation waveform has demonstrated its robust link performance with high modulation bandwidth efficiency in wireless communication applications such as today’s Wi-Fi, Long-Term Evolution (LTE) technology.
Traditional Single Carrier (SC) modulations based wireless systems such as Quadrature Amplitude Modulation (QAM), Shaped Offset Quadrature Phase Shift Keying (SOQPSK) etc., have shown a better transmitter power efficiency when compared to OFDM based systems, while having a comparably good modulation bandwidth efficiency. It is however known that the link quality of a SC based system such as SOQPSK-TG, deteriorates noticeably in a wireless channel with multipath, especially in time-varying multipath channels [3] [4]. Over decades of research efforts, various channel equalization algorithms for QAM and other SC modulations alike, have been proposed and utilized. For example, frequency-domain adaptive equalization algorithms have been proposed and experimented with [5]. Sparse adaptive channel equalization algorithms were invented to combat wireless link degradation in terrestrial multipath environment [6], and sparse equalization of SOQPSK-TG for aeronautical telemetry applications [7]. Those equalization algorithms have mostly been in experimental stage, not being widely implemented in wireless communication applications for their limited capacity to deal with rapid time-varying wireless channels. For example it may occur in aeronautical telemetry communications link, when a Test Article (TA) is flying at low altitudes, or during take-off, landing or taxiing. These typical time-varying multipath cases still remain a major challenge for link integrity in aeronautical telemetry wireless communications.

b) Doppler shift

LTE technology has been drawing attention in aeronautical telemetry applications for its multipath immunity and flexible network connectivity. However the inability to handle high Doppler shifts is one of the major reasons to not be able to directly utilize the Commercial off-the-shelf (COTS) LTE transceivers for aeronautical telemetry applications [8]. Some methods have been studied/proposed. For example, one of the schemes proposed is to estimate/compensate Doppler shift. The core of the approach in this proposed scheme is a delay-response method to mitigate a high level Doppler shift down to a tolerable level that the subcarriers in a commercial LTE equipment can handle. The compensation of Doppler shift will require a round trip time delay between Ground station (GS) and Test Article (TA) [8]. The performance of this scheme may be limited by its long elapsed time for frequency estimation/compensation, especially, in the case of unpredictable time-varying high Doppler-shift, which would be induced, for example, by a rapid maneuver of the Test Article.

2) Transmitter power efficiency

One of the key factors affecting transmit power efficiency is the Peak-to-Average Power Ratio (PAPR) of the transmit waveform. OFDM [9] systems have a lower transmit power efficiency when compared to constant envelope modulation schemes such as SOQPSK-TG due to their high PAPR. PAPR of OFDM signal waveform can be as high as 9 to 12dB as opposed to 0dB for SOQPSK-TG [10].

3) Transmission Bandwidth efficiency:

OFDM and SC QAM modulations have similar Bandwidth efficiency
For example:
SOQPSK-TG: 1.28bit/Hz [1-e], m-QAM: m bit/Hz (m=2^k, k= 2, 3, 4...) [3]
OFDM: 1bit/Hz (BPSK, OQPSK), 2bit/Hz (QPSK), 4bit/Hz (16QAM), 6bit/Hz (64QAM) [9]
I. Proposed Extensible SOQPSK (E-SOQPSK) modulation waveforms

BACKGROUND

To utilize both the multipath resistance capability offered by an OFDM modulated waveform, and the high transmitter power efficiency of the SOQPSK-TG modulation, a scheme of adaptive coding with hybrid SOQPSK/OFDM modulations was proposed for Integrated Network Enhanced Telemetry (iNET) applications [11].

Over the past decade, Teletronics Technology Corporation (now, Teletronics a Curtiss-Wright company) has developed and delivered an OFDM modulation based IP transceiver (nXCVR-2000) [12] [13] and an SOQPSK-TG modulation based iNET IP transceiver (nXCVR-3140) to the telemetry industry for aeronautical wireless link communications. Based on firsthand field test results and performance assessment on modulation algorithms utilized in the nXCVR series transceiver products, we propose high performance E-SOQPSK, an OFDM structured flexible single carrier modulation scheme.

DESCRIPTION

The core of E-SOQPSK modulation is an OFDM structured extensible single carrier SOQPSK. This combination of OFDM and SOQPSK provides merit from both MC and SC modulation waveforms, and helps to improve the performance in a dynamic time-varying multipath and rapid Doppler shift environment, while maintaining a low PAPR and high transmitter power efficiency.

E-SOQPSK is single carrier (SC) modulation waveform, a deviation of the traditional OFDM, LTE (uplink) waveforms scheme. E-SOQPSK can be configured to BPSK, OQPSK, m-QAM or Constant Envelop (CE) SOQPSK modulation waveform.

The performance comparison of E-SOQPSK with OFDM [9], SOQPSK-TG [10], and LTE (UL) [14] is shown in Table 1 below. [8] [15]

Table 1. Modulation waveform performance matrix

<table>
<thead>
<tr>
<th>Modulation Criteria</th>
<th>Multipath immunity (time-varying channel)</th>
<th>Doppler shift impact assume C band 5GHz, TA speed Mach 3</th>
<th>PAPR (dB)</th>
<th>Bandwidth efficiency (bit/Hz)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOQPSK-TG</td>
<td>Poor</td>
<td>Good</td>
<td>0 dB</td>
<td>1.28 bit/Hz</td>
<td>IRIG-106 std. [10]</td>
</tr>
<tr>
<td>OFDM</td>
<td>Good</td>
<td>5.5% (est.)</td>
<td>9.5 dB~12.5 dB</td>
<td>1bit/Hz (BPSK) 2bit/Hz(QPSK) 4bit/Hz(16QAM) 6bit/Hz (64QAM)</td>
<td>Wi-Fi std. [9]</td>
</tr>
</tbody>
</table>

Table 1. Modulation waveform performance matrix
<table>
<thead>
<tr>
<th>LTE</th>
<th>Good</th>
<th>114% (est.)</th>
<th>4 ~ 5dB (est.)</th>
<th>Comparable to OFDM (est.)</th>
<th>LTE std. [14]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-SOQPSK</td>
<td>Comparable to OFDM (projected**)</td>
<td>5% (or less) (projected)</td>
<td>1.5 dB ~4.5 dB</td>
<td>Comparable to OFDM 1bit/Hz (BPSK, QOQPSK) 2bit/Hz (QPSK) 4bit/Hz (16QAM) 6bit/Hz (64QAM) (projected)</td>
<td>Proposed by TTC/CW</td>
</tr>
</tbody>
</table>

* Doppler shift impact to signal quality, measured by Inter Symbol Interference (ISI), defined as Doppler frequency shift to OFDM subcarrier BW ratio. OFDM parameter [9]: FFT size 64, Clock at 20MHz, subcarrier Bandwidth 312.5 kHz; ** Assuming OFDM structure parameters.

Functional Top view block diagrams E-SOQPSK system vs. OFDM system

![Functional Top view block diagrams](image)

Figure 1: Basic OFDM modulation system

Figure 2: A proposed E-SOQPSK modulation system

II. Preliminary Result

1) Characteristics of E-SOQPSK modulation signal:

In this section we show certain characteristics of the E-SOQPSK modulation waveforms in comparison with standard SOQPSK-TG waveform. The characteristics of the modulation waveforms were demonstrated in terms of (a) their I-Q component eye diagrams of the modulation waveform; (b) the signal power spectrum, (c) the signal’s PAPR, and (d) the I-Q trajectory of the signal waveform.
The results show that

- E-SOPQK has similar characteristics of its baseband waveform time-domain transition to standard SOQPSK-TG, as illustrated in eye diagram in Figure 3 (obtained by Matlab simulation), and laboratory test result in Figure 6 (obtained by laboratory test);
- E-SOQPSK has a tighter spectrum spread to compare with SOQPSK-TG waveform. The result is in Figure 4 (obtained by laboratory test);
- Near 1dB PAPR was confirmed for E-SOQPSK both in OQPSK and in SOQPSK waveform mode. The results (obtained by laboratory test) are in Figure 5, and Figure 6, respectively.

![Eye Diagram for In-Phase Signal](image1)
![Eye Diagram for Quadrature Signal](image2)

(a) (b)

Figure 3: Eye diagrams (a)(Left) E-SOQPSK (simulation result), (b)(Right) SOQPSK-TG (simulation result)

![Lab captured Spectrum](image3)

Figure 4: Lab captured Spectrum of a 1 Mbps E-SOQPSK (in yellow) vs a 1 Mbps SOQPSK-TG (In blue) waveform.
Figure 5: Lab Measured Peak-to-Average-Power Ratio (PAPR) of a 1 Mbps E-SOQPSK (experimental) waveform (a)(left): PAPR < 1.2dB, 1 Mbps OQPSK (experimental) waveform of E-SOQPSK modulator: PAPR < 1.2dB (b)(right)

Figure 6: Laboratory digital oscilloscope measurement of the OQPSK waveform generated by E-SOQPSK modulator

2) Performance of E-SOQPSK Frequency Domain Equalization – preliminary result.

The results shown in this section are from the MATLAB simulation. Figure 8 is a top view of the E-SOQPSK simulation model used to demonstrate performance of E-SOQPSK frequency-domain equalizer.

Proposed E-SOQPSK transmitter is a multi-mode modulator. It is capable of generating OFDM structured mQAM, OQPSK, or SOQPSK modulation waveform. As illustrated in Figure 7, an E-SOQPSK modulator in the OQPSK mode generates the waveform which is fed to a two-ray multipath channel, and then processed by an E-SOQPSK demodulation, including frequency-domain equalization.
In this section, through Matlab simulation, by setting various multipath parameters, we illustrate a potential capability of the OFDM structured Frequency-Domain equalization. In this test, we show simulation results of complex signal I-Q constellation of the equalizer output vs its input under a two-ray channel model with different channel model parameters, such as reflector phase rotation (theta), channel time delay (dL), and attenuation factor (rho) of the 2nd path, as well as additive noise. The results are shown in Figure 8 to Figure 10.

Figure 10 shows the equalizer input vs. its output. The channel that is set for this simulation is a severe multipath condition (90% of reflection signal in strength was delayed and rotated in phase, then added on the signal on direct path). The corresponding signal spectrum at the receiver output is shown in Figure 11 which shows the signal strength dips of up to 25.6dB.

Figure 7: Top view E-SOQPK Simulation model

Figure 8: A baseline simulation: ideal channel, w/ or w/o noise: (a) on the left, constellation of the QOQSK I-Q components as IFFT of FreqEQ output w/multipath, w/no additive noise; (b) center, constellation of the QOQSK I-Q components as IFFT of FreqEQ Input w/multipath, w/noise at SNR 15 dB (c) on the right, constellation of the QOQSK I-Q components as IFFT of FreqEQ output w/multipath, w/noise at SNR 15 dB
Figure 9: OQPSK I-Q component constellation w/ two-ray channel multipath (case 1: signal strength dips 7.4 dB, \(\rho/\theta/dL=0.4/1.7/10\)), SNR 15dB (a) on the left, IFFT of FreqEQ input; (b) on the right, IFFT of FreqEQ output

Figure 10: OQPSK I-Q component constellation w/ two-ray channel Multipath (case 2: signal strength dips 25.6 dB, \(\rho/\theta/dL=0.9/0.4/20\)), SNR 15dB (a) On the left, IFFT of FreqEQ input; (b) on the right, IFFT of FreqEQ output

Figure 11: OQPSK signal spectrum at receiver input, w/ two-ray channel Multipath (case 2: signal strength dips 25.6 dB, \(\rho/\theta/dL=0.9/0.4/20\)), SNR 15dB
CONCLUSION

In this paper we propose a novel OFDM structured Extensible-SOQPSK modulation waveform, which can be configured to: SOQPSK, OQPSK, or QAM. The embedded OFDM structure of the E-SOQPSK modulation waveform can be utilized by an E-SOQPSK receiver to improve its frequency-domain equalization performance in a time-varying multipath and high Doppler shift environment.

- Preliminary laboratory results have confirmed that E-SOQPSK modulation waveform has a near 1 dB PAPR, close to that of a traditional SOQPSK-TG modulated waveform. They also show that the E-SOQPSK modulated waveform has a similar eye diagram pattern to that of a standard SOQPSK-TG waveform.

- Preliminary simulation results illustrate that E-SOQPSK modulation waveform is capable of providing robust performance in a heavy multipath time-varying channel as expected, benefitting from the fast frequency-domain equalization techniques enabled by its OFDM structure.

FUTURE WORK

Further work in terms of full system simulations and refinement of the demodulation process, esp. channel equalization algorithms with various Doppler and multipath cases, transmitter and receiver prototype development needs to be done so as to evaluate the performance and verify the proposed advantages of the E-SOQPSK waveforms.

REFERENCES


