Photonic Generation of Millimeter Wave Signals for Wireless Applications

Mehdi Shadaram

Department of Electrical and Computer Engineering
University of Texas at San Antonio
San Antonio, TX

International Conference and Business Expo on Wireless Communication & Network

Baltimore, USA, September 21-23, 2015
Outline

- Introduction
- Utilization of Millimeter Waves
- Optical Modulation Scheme
- Harmonic Distortion
- Performance Analysis
- Results
- Conclusion
Millimeter Wave RoF

- Wireless transmission in the lower microwave band is congested by applications such as Wi-Fi, GSM, etc.
- Some other new wireless technologies (e.g. WiMAX) are still handled within the lower microwave regions (2–4 GHz).
- In United States, the 60 GHz band can be used for unlicensed short range (1.7 km) data links with data throughputs up to 2.5 Gb/s.
- Propagation characteristics of the 60 GHz band like oxygen absorption and rain attenuation limits the range of communication systems using this band.
- Geographical consideration is crucial for antenna base stations (BSs) installment.
- Because of large number of required BSs and the high throughput of each BS, deployment of an optical fiber backbone is beneficial.
Why 60 GHz Band?

Bandwidth-traffic (57 GHz – 64 GHz)

License-Free Spectrum

Narrow Beam Antennas (Multiple Antennas)

Highly Directional, "pencil-beam" Signal

Easy to Install and Align

Oxygen Absorption and Security (Reduced Interference)
Optical Network for RoF Transmission

Central Office (CO) → Fiber Network → BS #1 → BS #2 → BS #N

Users

UTSA
Center for Excellence in Engineering Education
Methods of Transmitting the mm-wave Wireless Signals over the Optical Fiber

- **RF over Fiber**

- **IF over Fiber**

- **Baseband over Fiber**
RF Power Degradation Versus Fiber Length for ODSB, OSSB, OCS Modulation Formats

\[ \Delta P_{rf} \approx \cos^2 \left( \pi c L D \left( \frac{f_{rf}}{f_c} \right)^2 \right) \]

Power Fluctuation
Overcoming Fiber Chromatic Dispersion

The fiber dispersion effect on optically transmitted signals is critical to be controlled specifically for long fiber link. For eliminating this impairment OCS and OSSB techniques can be used.

ODSB: MZM is biased at $\frac{V_\pi}{2}$

OSSB: MZM is biased at $\frac{V_\pi}{2}$

OCS; MZM is biased at $V_\pi$

MZM ER=1000, laser linewidth=2MHz
OSSB Modulation

\[ V_{\text{upper}} = V_{rf} \cos(\omega_{rf} t) + V_\pi / 2 \]

\[ V_{\text{lower}} = V_{rf} \cos(\omega_{rf} t + \pi / 2) + 0 \]

Dual electrode MZM structure
OSSB mm-wave generation system
Mm-Wave Generation Procedure

After first MZM

After optical filter: At the photodiode

After second MZM
Second Modulator’s Output

\[ E_{out2} = E_{in}\left\{ \frac{1}{2} J_0(a\pi) J_1(a\pi) [\cos(\omega_c + \omega_{rf_c})t + \cos(\omega_{rf_c} - \omega_c)t - \sin(\omega_c + \omega_{rf_c})t + \sin(\omega_c - \omega_{rf_c})t] - J_1^2(a\pi) [\cos(\omega_c + \omega_{rf_1} + \omega_{rf_c})t + \cos(\omega_{rf_c} - \omega_c - \omega_{rf_1})t] + \frac{1}{2} J_1(a\pi) J_2(a\pi) [\cos(\omega_c - 2\omega_{rf_1} + \omega_{rf_c})t + \cos(\omega_{rf_c} - \omega_c + 2\omega_{rf_1})t - \sin(\omega_c - 2\omega_{rf_1} - \omega_{rf_c})t + \sin(\omega_c - 2\omega_{rf_1} + \omega_{rf_c})t + \cos(\omega_c + 2\omega_{rf_1} + \omega_{rf_c})t + \cos(\omega_{rf_c} - \omega_c - 2\omega_{rf_1})t - \sin(\omega_c + 2\omega_{rf_1} - \omega_{rf_c})t - \cos(\omega_c + 2\omega_{rf_1} + \omega_{rf_c})t + J_3(a\pi) J_1(a\pi) [\cos(\omega_c - 3\omega_{rf_1} + \omega_{rf_c})t + \cos(\omega_{rf_c} - \omega_c + 3\omega_{rf_1})t] + \cdots \} \right\} \]

Photodiode’s Output

\[ PD_{out} = R \eta |E_{out2}(t)|^2 \]
Harmonics after the Photodetection

\[ PD_{out} = R \eta |E_{out2}(t)|^2 \]

\[ \omega_{rf1} - 2\omega_{rfc} \]

\[ \omega_{rf1} - 2\omega_{rfc} \]

Shifted Optical Carrier: \( 2\omega_{rfc} \)
Fundamental Frequency: \( \omega_{rf1} + 2\omega_{rfc} \)
Second Harmonic: \( 2\omega_{rf1} + 2\omega_{rfc} \)
Third Harmonic: \( 3\omega_{rf1} + 2\omega_{rfc} \)
## 2\textsuperscript{nd} and 3\textsuperscript{rd} Order Harmonic Distortions due to Nonlinearities in MZMs

<table>
<thead>
<tr>
<th>Distortion order</th>
<th>Distortion frequency</th>
<th>Noise/signal approximation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two, HD2</td>
<td>( \omega = 2 \omega_{rf_1} + 2 \omega_{rf_c} )</td>
<td>( \frac{[ -J_0(a\pi) J_2(a\pi) ]}{\sqrt{2} [ J_3(a\pi) J_2(a\pi) - J_0(a\pi) J_1(a\pi) ]} )</td>
</tr>
<tr>
<td>Three, HD3</td>
<td>( \omega = 3 \omega_{rf_1} + 2 \omega_{rf_c} )</td>
<td>( \frac{[ J_0^2(a\pi) J_3(a\pi) - J_2(a\pi) J_1(a\pi) ]}{[ J_3(a\pi) J_2(a\pi) - J_0(a\pi) J_1(a\pi) ]} )</td>
</tr>
</tbody>
</table>
Fundamental Frequency: \( \omega r f_1 + 2 \omega_{rf_c} \)

HD2: \( 2\omega r f_1 + 2 \omega_{rf_c} \)

HD3: \( 3\omega r f_1 + 2 \omega_{rf_c} \)
Second and Third order harmonic distortions due to fiber dispersion

\[ \beta_\omega \approx \beta_0 + \beta_1 (\omega - \omega_0) + 0.5 \beta_2 (\omega - \omega_0)^2 \]

\[ \beta_1 = \frac{d\beta_\omega}{d\omega} = \frac{1}{v_g} \]

\[ \beta_2 = \frac{d^2\beta_\omega}{d\omega^2} = \frac{-D \lambda^2}{2\pi c} \]

The propagation constant for each optical subcarrier is different

Second and Third order harmonic distortions due to fiber dispersion

<table>
<thead>
<tr>
<th>Distortion order</th>
<th>Distortion frequency</th>
<th>Noise/signal approximation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two, HD2</td>
<td>$\omega = 2 \omega_{rf1} + 2 \omega_{rfc}$</td>
<td>$\frac{</td>
</tr>
<tr>
<td>Three, HD3</td>
<td>$\omega = 3 \omega_{rf1} + 2 \omega_{rfc}$</td>
<td>$\frac{</td>
</tr>
</tbody>
</table>

\[
D_1 = -J_0(a\pi) J_1^3(a\pi) \cos(B_2 \left(-\frac{\omega_{rf1}^2}{2} - \omega_{rf1} \omega_{rfc}\right) L)
\]

\[
D_2 = J_0(a\pi) J_1^3(a\pi) \sin(B_2 \left(-\frac{\omega_{rf1}^2}{2} - \omega_{rf1} \omega_{rfc}\right) L)
\]

\[
D_3 = -\frac{1}{\sqrt{2}} J_0(a\pi) J_1^2(a\pi) J_2(a\pi) \cos(B_2(2 \omega_{rf1}^2 + 2 \omega_{rf1} \omega_{rfc}) L)
\]

\[
D_4 = \frac{1}{\sqrt{2}} J_0(a\pi) J_1^2(a\pi) J_2(a\pi) \sin(B_2(2 \omega_{rf1}^2 + 2 \omega_{rf1} \omega_{rfc}) L)
\]

\[
D_5 = J_1^3(a\pi) J_2(a\pi) \cos(B_2 \left(\frac{3 \omega_{rf1}^2}{2} + \omega_{rf1} \omega_{rfc}\right) L)
\]

\[
D_6 = -J_1^3(a\pi) J_2(a\pi) \sin(B_2 \left(\frac{3 \omega_{rf1}^2}{2} + \omega_{rf1} \omega_{rfc}\right) L)
\]
Second and Third Harmonic Distortion due to Fiber Chromatic Dispersion
Harmonic Distortions with and without Fiber Dispersion
SER for the 4-QAM vs. SNR

$L=80\text{km}; \, D=17 \text{ ps/(nm.km)}; \, \text{Attn: } 0.2\text{dB/km}; \, \text{RF}=62 \text{ GHz, Bit Rate}=1 \text{ Gb/s}$
Received Eye Diagrams and Signal Constellations

$a=0.04$
NSR=-12.3065 dB
SER=2.65e^{-10}

$a=0.26$
NSR= -11.0246 dB
SER= 4.55e^{-10}

$a=0.45$
NSR= -7.5331 dB
SER= 0.0011

$a=0.02$
NSR=-0.9234 dB
SER= 0.2855
Generation of Multi Single Side-Band Sub Carriers
Conclusion

- RF multiplexed OSSB mm-wave signals generated using cascaded MZMs
- Harmonic distortions caused by the MZM and chromatic dispersion are discussed
- In order to optimize the suggested system performance, it is required to adjust the RF amplitude properly.
- A compromise between high SNR and low nonlinearity effects should be considered to guarantee the system performance.
THANK YOU

Questions?