Submission Title: High-speed VLC for Wireless backhaul communication

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Abstract: In response to «Call for Proposals for OWC Channel Models» issued by 802.15.7r1, this contribution presents the PHY technologies proposal of outdoor free space VLC long distance transmission for high rate PD communication in wireless backhaul (mobile back haul).

Purpose: Call for Proposal Response

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High-speed VLC for Wireless backhaul communication
Outlines

- Background and Introduction
- Scenario Targets
- Description of Proposed Solutions
- Some Experiment Results
- Occlusions
4.5.1 Applications/Use cases

The following High Speed Photodiode Receiver applications/use cases were presented in response to TG7r1 Call for Applications.

……

4. **Wireless Backhaul (Small Cell Backhaul, Surveillance Backhaul, LAN Bridging)**

4.5.3 ……The standard must define a range of data rates with minimum supported connectivity of at least 1 Mbps at the PHY SAP. The standard must support at least one PHY mode that supports peak data rates of 10 Gbps at the PHY SAP.

B4: Wireless Backhaul
Application Scenarios: Mobile backhauling

Backhaul

Backhaul is a top priority for small cell deployments
• 80% of small cells will have wireless backhaul
• Cost of fiber is ~4x greater than wireless (cumulative CAPEX/OPEX)
• Small Cell mesh inter-connectivity over ~250m
• Large indoor and outdoor public spaces

* According to InterDigital Whitepaper 2013

- VLC outdoor free-space high speed PD communication for mobile backhaul

- It shares the same CAPEX/OPEX advantages with mmW
- More competitive with lower device cost

Characters:

- Large indoor/outdoor public spaces
- Distance: ~50 m~1 km
- Speed: ~Gbps
- Link: mainly Point-to-point

*A typical mmW backhaul link
Wireless Backhaul

- Requirements

<table>
<thead>
<tr>
<th></th>
<th>Single Hop Wireless Backhauling</th>
<th>Multiple Hop Wireless Backhauling</th>
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<tbody>
<tr>
<td># of hops</td>
<td>1</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Distance per link</td>
<td>&lt;1km</td>
<td>&lt;150m</td>
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<tr>
<td>Data Rate</td>
<td>~2-20Gbps</td>
<td>~2-20Gbps</td>
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<tr>
<td>Latency</td>
<td>&lt;35ms</td>
<td>&lt;35ms (total)</td>
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<tr>
<td>QoS/QoE</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Availability</td>
<td>99.99%</td>
<td>99.99%</td>
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</tbody>
</table>

Requirements are open for discussion

Source: from 802.11 TGay Use Cases Submission
Targets

- High-speed VLC Out-door long-distance communication for mobile backhaul
- Data Rates Speed: \( \sim \text{Gbps} \)
- Distance: 50m~1km, typical \( \sim 50-500 \text{ m} \)
- Environment: Large indoor/outdoor public spaces
- Link: mainly Point-to-point

To provide a Out-door VLC free-space link for high-speed user applications.
Proposal Research Route

### VLC Free Space Transmission Channel Model
- LED/PD Modulation Property
- Optics System design
- Free-space channel

### Key Technique for High Speed Outdoor VLC Transmission System
- Modulation formats
- Multiplexing Technology
- Pre Equalization and post-equalization
- Diversity reception technology

### Simulation for Outdoor Long Distance VLC Transmission System
- System Structure and Simulation Parameters
- Simulation Results and Analysis

### Outdoor Transmission Experiments
- System Structure
- Results and Analysis
Physical Layer of VLC system

**TX**:
- electronics: LED driving circuit, signal processing (coding, modulation, equalization)
- optics: transmitter antenna

**RX**:
- optics: receiver antenna, PD
- electronics: signal processing (decoding, demodulation, equalization)
To achieve the high speed VLC

- The pre-equalization and post-equalization technology for the high-speed VLC systems

- Modulation formats:
  - Single-carrier based CAP-QAM
  - Multi-carrier based OFDM or **DMT with bit-loading**

- Multiplexing Technology
  - Multiplexing Technology using different color LED
  - MIMO for multiplexing gain
  - Receiver-diversity reception technology
1. LED bandwidth limitations

- Phosphor LED 10dB bandwidth < 15MHz
- RGB LED 10dB bandwidth < 25MHz

2. VLC system Nonlinear

- LED Nonlinearity
- Inter-symbol interference
- LED nonlinearity

Higher order modulation and pre-equalization

- Software/hardware pre-equalization
- OFDM/DMT
- Single Carrier, CAP and so on

Advanced post-equalization techniques

- ZF, DFE, RLS, DD-LMS
- CMMA, M-CMMA
- Volterra
VLC Channel Pre-equalization

Pre-equalization schemes:

- **Hardware Equalization**: hardware circuit design
- **Software Equalization**: digital signal processing
Software Pre-equalization

- Pre-equalization
  - Obtain the channel knowledge ($H$) at the RF domain
  - Make pre-equalization $Tx^*1/H$ at the baseband

**Hardware bridged-T amplitude equalizer**

- $Z_{11}$: RLC network1 ($R_1$, $C_1$ and $L_1$)
- $Z_{22}$: RLC network2 ($R_4$, $C_2$ and $L_2$)
- $R_2 = R_3 = R_0$

$Z_{11} \times Z_{22} = R_0^2$

\[ S_{21} = \frac{1}{1 + \frac{R_L}{R_4 + \frac{j\omega L_1}{1 - \omega^2 C_1 L_1}}} \]

X. Huang, et al, OFC 2015, Tu2G.1
Hardware bridged-T amplitude equalizer Performances

✓ Spectrum of a 250-MHz CAP signal after pre-EQ
Carrier-less Amplitude Phase (CAP) modulation format

\[ s(t) = I(t) \otimes f_I(t) - Q(t) \otimes f_Q(t) \]

- Carrierless Amplitude and Phase (CAP) is a multi-level modulation scheme proposed by Bell Lad in 1970
- At transmitter a pair of orthogonal filters is used as Hilbert pair for modulation
- At receiver a pair of matched filter is used for demodulation
DMT with Bit-loading Background

The diagram illustrates the process of DMT with bit-loading background. It shows the stages from serial to parallel conversion, computation of complex coefficients, IFFT, parallel to serial conversion, and finally, D/A conversion. Each stage involves operations on data bits and complex numbers to transmit information efficiently. The diagram is a visual representation of the DMT technique, which is crucial for understanding the underlying principles of data transmission in wireless communication systems.
Bit-loading based OFDM-DMT modulation for Gbps VLC

Bit-loading based OFDM-DMT modulation for Gbps VLC

(a) SNR estimation (dB)

(b) Bit allocation

(c) Power allocation

Volterra nonlinear equalizer

- LED nonlinearity seriously degrades the system performance;
- The LED forward current exhibits strong nonlinearity with the bias voltage;
- Two factors dominate the nonlinear effects: DC bias voltage and the input signal peak-to-peak value (Vpp);
The Volterra series based equalizer is considered as a promising solution to mitigate the LED nonlinearity;

The Volterra series expansion contains a linear term and nonlinear series.

M-CMMA is utilized to update the weights of the nonlinear equalizer without using training symbols.
Color-division Multiplexing

- Same idea of Wavelength-division multiplexing (WDM) used in fiber-optics
- To triple the capacity or speed of VLC system
- RGB bandwidth is larger than the p-LED
RGB LED (LED Engine) Multiplexing for high-speed VLC (WDM)
Out-door Long distance testing results

**BER vs distance**

- At the distance of 50m, the total data rate of 1.8Gb/s can be achieved with the BER less than the 7% FEC limit of 3.8x10^{-3}.
- The illuminations for each color chip are 15lx, 19lx and 10lx at 50m.
- It should be noted that the experiment is conducted at about 9:00 PM. The ambient light noise mainly comes from the artificial light sources such as the street lights.
<table>
<thead>
<tr>
<th>LED</th>
<th>Equ.</th>
<th>Modulation</th>
<th>Data rate</th>
<th>receiver</th>
<th>distance</th>
<th>institution</th>
<th>Data source</th>
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<tr>
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Conclusion

In this contribution, we propose several general technique considerations for high rate PD VLC out-door communications.

- The out-door high-speed VLC modeling including three parts
  - LED/PD Modulation Property
  - Optical system design
  - Free-space channel

- The pre-equalization and post-equalization technology for the high-speed VLC systems

- Modulation formats:
  - Single-carrier based CAP-QAM
  - Multi-carrier based OFDM or DMT with bit-loading

- Multiplexing Technology
  - Multiplexing Technology using different color LED
  - MIMO for multiplexing gain
  - Receiver-diversity reception technology
Appendix
Post-equalization solutions:

- **ISI Equalization**: Classical DFE $\rightarrow$ Modified Eqs
- **Nonlinear Compensations**: Volterra series
Receiver diversity technology

In receiver diversity, the outputs of multiple receivers are combined which is a weighted sum of the different branches

\[ \sum_{i=1}^{M} \alpha_i r_i \]

The output SNR:
\[ \gamma_{\Sigma} = \frac{r^2}{N_{tot}} = \left[ \frac{\sum_{i=1}^{M} \alpha_i r_i}{\sum_{i=1}^{M} \alpha_i^2 N_i} \right]^2 \]

The goal of MRC is to find the weight to maximize the output SNR

According to the Schwarz inequality, it is found that:
the maximum SNR of the combiner output is the sum of SNRs in each branch:
\[ \gamma_{\Sigma} = \sum_{i=1}^{M} \frac{r_i^2}{N_i} = \sum_{i=1}^{M} \gamma_i \]