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Overlapping PPM for band-limited visible light communication and dimming

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Abstract

The synthesis of visible light communication (VLC) and lighting state control necessitates data-light modulation that can accommodate intensity control. A number of techniques that enable both optical wireless data transmission and intensity control of light-emitting diodes (LEDs) have been proposed as a response to this need. Relevant schemes leverage amplitude modulation (AM)/continuous current reduction (CCR) and/or pulse-width modulation (PWM) for dimming capability. Two-level schemes related to PWM, such as on-off keying with compensation time (OOK + CT), variable pulse position modulation (VPPM), and multiple pulse position modulation (MPPM), are most commonly investigated. In this paper, we survey and compare OOK + CT, VPPM and MPPM. Moreover, we propose a novel approach towards dimming and data transmission through the variation of codeword weights in overlapping pulse-position modulation (OPPM). The proposed approach has comparatively high spectral efficiency. Using realistic constraints of a practical VLC system, analysis reveals that OPPM can increase data rates by more than 20Mbps over expected performance of related, two-level schemes, when using LEDs suitable for lighting that have relatively low modulation bandwidths.

Keywords: Dimming; IEEE 802.15.7 standard; Light-emitting diode (LED); Lighting control; Optical wireless communication (OWC); Overlapping pulse-position modulation (OPPM); Visible light communication (VLC)

Background

Future lighting systems will be expected to be optimized to meet strict energy efficiency and light rendering quality goals. To be commercially competitive, they will increasingly have new functions providing adaptability, self-provisioning capabilities, and intelligence to react to human needs. These functions will be provided by embedded control and communications. Visible light communications (VLC) seeks to provide high-speed optical communications as an additional function, delivering additional capacity in indoor wireless networks. Although these functions leverage one another (embedded control, communications, and VLC), the common lighting task of intensity control (dimming) is in conflict with achieving optical data modulation. VLC systems, which stream data wirelessly by high frequency modulation of LED drive currents, must incorporate new modulation schemes for compatibility with lighting control [1].

These usually result in increased complexity and decreases in performance as compared to systems designed for fixed lighting conditions. Dimming schemes inherently limit the transmitted optical power and place restrictions on the modulated waveform. Additionally, reducing light intensity can result in an undesired chromaticity shift of the emitted light [2]. While a number of modulation schemes compatible with dimming requirements have been proposed to mitigate data rate and light quality losses, as described in [2–5], analysis of schemes from a comprehensive perspective is often lacking. Consequently, this paper seeks to incorporate realistic constraints, including the limited bandwidths of LEDs, in evaluating two-level baseband data modulation and dimming schemes.

We propose a novel operation through the variation of codeword weights of overlapping pulse position modulation (OPPM) to achieve dynamic dimming and data transmission at higher data rates compared to well-known common two-level modulation and dimming schemes. For noise-limited environments, other schemes may yield higher data rates than OPPM; yet, the subsequent analysis reveals that within a bandlimited regime, the higher spectral efficiency of OPPM results in significant data rate gains over comparable schemes.

In this paper, we review the VLC channel model, followed by an overview of common two-level modulation and dimming, a description of OPPM and its dimming functionality, and a presentation of the analysis revealing the advantages of OPPM. The final section concludes the findings.

Methods

VLC channel model

The basic optical wireless channel model adopted for VLC is of the form,

$$y(t) = r \cdot x(t) * h(t) + n(t), \tag{1}$$

where r is the responsivity of the photodiode receiver [A/W], $x(t)$ is instantaneous optical power, $h(t)$ is the channel impulse response, $n(t)$ is added noise, and * denotes convolution. For VLC, intensity modulation with direct detection (IM/DD) is nearly always adopted, whereby the instantaneous optical power emitted by the LED transmitter is fluctuated for data transmission. One of the ramifications of IM/DD is that $x(t)$ is always greater than or equal to zero (optical power is always a positive value). The average received power, P_r, is defined as follows for optical wireless systems,

$$P_r = H(0)P_t = \left(\int_{-\infty}^{\infty} h(t)dt \right) \left(\lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} x(t)dt \right), \tag{2}$$

where $H(0)$ is the DC channel gain calculated from the impulse response $h(t)$, T defines the integral limit for the time average of x(t), and P_t is the transmitted power [6].

VLC shares considerable characteristics and challenges with wireless infrared (IR) communications. Equations (1) and (2) are equally applicable to VLC from IR communication theory, as well as the basic signal-to-noise ratio (SNR) [6],

$$SNR = \frac{r^2 H^2(0) P_t^2}{R_b N_0} = \frac{r^2 P_r^2}{R_b N_0}, \tag{3}$$

where N_0 is the double-sided power spectral density of white Gaussian noise (assuming this noise is dominant) and R_b is the bit-rate. For the model environment considered in the analysis, it is assumed that inter-symbol interference (ISI) is negligible [7].

Dimming and two-level modulation techniques

The two most popular methods of dimming LEDs are amplitude modulation (AM)/continuous current reduction (CCR) and pulse-width modulation (PWM) (see Fig. 1). AM, also known as analog dimming, reduces the LED drive current to lessen the brightness of emitted light. PWM cycles the LED with high and low drive currents, alternating between *on* and *off* states.

AM dimming has a few significant drawbacks. AM may induce a noticeable chromaticity shift in the emitted light, *i.e.* the light color will change as the LED is dimmed, especially if dimming at low light levels. Additionally, AM dimming is nonlinear; a change in the forward current is not directly proportional to the luminance of the emitted light. Conversely, PWM generally does not induce a perceptible chromaticity shift and features a near-linear relationship between luminance and duty cycle. Dyble *et al.* demonstrated the superior color integrity properties of PWM versus AM in their evaluation of white LEDs and dimming [2].

A number of two-level baseband communication and dimming schemes are similar to PWM in that they have two states (high and low) and control brightness by varying the average time duration of the high state to the low state. This paper concentrates on these schemes as they stand to inherit the advantageous color integrity and linearity characteristics of PWM dimming. For comparative analysis, maximum-likelihood (ML) detection and high-SNR is assumed. In this case, the bit-error ratio (BER) is principally influenced by the two nearest, modulated signals in which,

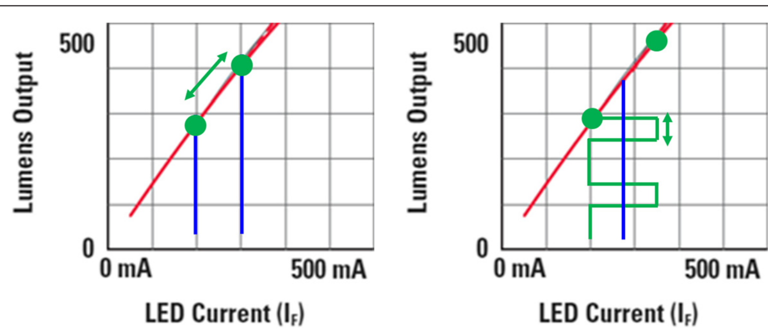

Fig. 1 AM/CCR vs. PWM. (Left) In AM/CCR, the LED current flows continuously at a set amount for a given LED brightness (Lumens output). (Right) In PWM, the current is switched between recommended minimum LED current and the rated LED current (IF). The ratio of high to low times determines the average current (blue line) and the corresponding LED brightness (Lumens output)

$$BER \approx Q\left(\frac{\sqrt{\min_{i \neq j} \int \left(x_i(t) - x_j(t)\right)^2 dt}}{2\sqrt{N_0}}\right) = Q\left(\frac{d_{\min}}{2\sqrt{N_0}}\right), \quad (4)$$

where $d_{\min}$ is the minimum Euclidean distance between signals within the valid signal set. Park, Barry, and Lee [3, 8] also adopt this approach for the additive white Gaussian noise (AWGN), IM/DD channel. An overview of two-level schemes for simultaneous communication and dimming is contained within the following subsections.

OOK with compensation time

Unipolar, non-return-to-zero on-off keying (OOK) is the simplest IM/DD communication scheme (see Fig. 2). *On* (high level) denotes a one bit and *off* (low level) denotes a zero bit. One method of guaranteeing a DC balanced signal, where the average value of the signal is equally between the low and high luminance levels, is Manchester line coding; a 0-bit is a low-high transition and a 1-bit is a high-low transition. Thus, OOK with Manchester line coding has an average power that is 50 % of the peak power and, correspondingly, the emitted light is 50 % of the maximum LED luminance. Its minimum Euclidean distance is given in (5),

$$d_{\min,OOK} = \frac{2P_{avg}}{\sqrt{R_b}} = \frac{P_{pk}}{\sqrt{R_b}}, \quad (5)$$

where the average power P_{avg} is half of the peak power P_{pk}. It is assumed that the bandwidth of OOK is approximately equal to R_b [8].

OOK with compensation time (OOK + CT) consists of a data subframe followed or preceded by a CT subframe. CT is utilized to raise or lower average power of a frame to brighten or dim. The CT subframe is fixed at a high or low level, *i.e.* the LED is

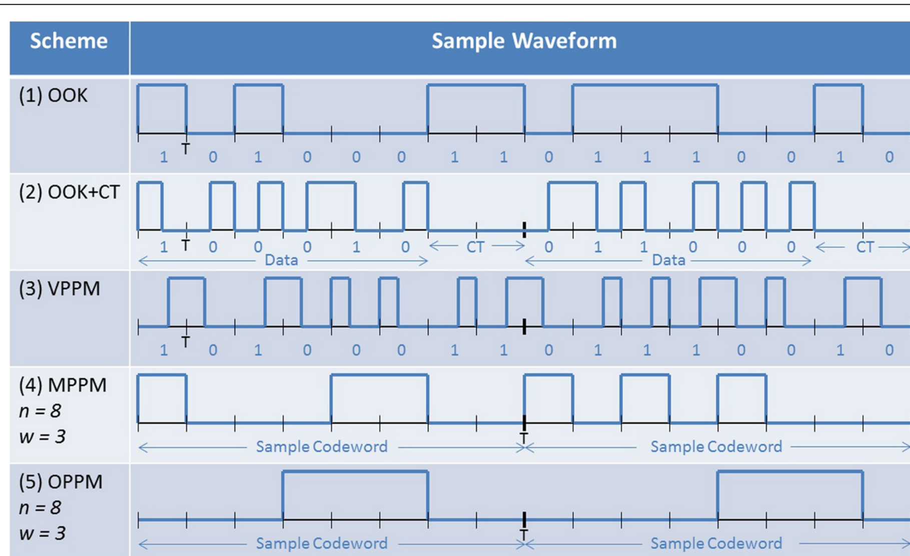

Fig. 2 Two-level modulation and dimming schemes to obtain about 60 % dimming [1]. (1) OOK: considered as reference at 50 % dimming, (2) OOK + CT using Manchester line coding, (3) VPPM: pulse width of conventional 2-PPM is reduced from 1/2 to 3/8, (4) MPPM: 56 possible codewords, and (5) OPPM: 6 possible codewords

completely driven to its *on* state or *off* state, depending on whether one wishes to brighten above 50 % or dim below 50 %. The duration of the CT determines the precise proportion of peak power, p, that is emitted ($p = P_{avg}/P_{pk}$).

Equations (4) and (5) yield the following theoretically achievable bit-rate for OOK+ CT and a given p,

$$R_b = \begin{cases} \left(\frac{P_{pk}}{Q^{-1}(BER)}\right)^2 \frac{p}{2N_0}, & 0 < p < 0.5 \\ \left(\frac{P_{pk}}{Q^{-1}(BER)}\right)^2 \frac{(1-p)}{2N_0}, & 0.5 \leq p < 1 \end{cases}. \quad (6)$$

Note that the bit-rate is scaled compared to standard OOK due to the CT for dimming and brightening. Naturally, bit-errors are only considered for the data frames. For a given bandwidth requirement B, R_b must satisfy,

$$R_b \leq \begin{cases} pB, & 0 < p < 0.5 \\ (1-p)B, & 0.5 \leq p < 1 \end{cases}. \quad (7)$$

This takes into account the fact that Manchester line-coded OOK requires twice the bandwidth of standard OOK. OOK + CT as presented is the elementary version of the first physical type of IEEE 802.15.7 Visible Light Communication Task Group standard [4].

Variable Pulse-Position Modulation (VPPM)

VPPM is a modified version of 2-PPM, in which each symbol is divided into two slots, or chips (see Fig. 2). In classic 2-PPM, a 0-bit is communicated by a pulse in the first slot and a 1-bit is communicated by a pulse in the second slot. VPPM differs in that, for a fixed symbol duration, the pulses can shrink or expand in width to achieve the desired average power corresponding to the dimming set point. Performance necessarily decreases when deviating from 2-PPM (when $p = 0.5$) due to a reduction in the Euclidean distance of the 0-bit and 1-bit symbols. VPPM has the same achievable R_b and bandwidth constraint as OOK + CT in (6) and (7). The technique is also a basic version of the second physical type of the IEEE 802.15.7 standard [4].

Multiple Pulse-Position Modulation (MPPM)

MPPM as a modulation technique for simultaneous communication and dimming was presented in [3]. MPPM is similar to classic L-PPM; however, instead of allowing for one pulse per symbol period in one of L chips, it permits multiple pulses in any of the L chips (see Fig. 2). Each unique combination of pulses within a symbol period is represented by a codeword. A possible codeword is $c_1 = [0,1,1,0]$, representing a symbol where there is no pulse in chips 1 and 4, a pulse in chip 2, and a pulse in chip 3. MPPM is characterized by two values, the number of chips per symbol, n, and the weight of accepted codewords, w. The weight, w, is equivalent to the sum of ones in a codeword. As in [3], we assume that the weight of codewords is fixed. Therefore, there are $Q = (n,w)$ possible codewords where (n,w) is the binomial coefficient. Q is the alphabet size. L-PPM is a limiting case of MPPM where $w = 1$ and $n = Q = L$.

Lee and Park utilize MPPM to brighten or dim by varying the weight of the codewords [3]. For example, (8, 2) MPPM will result in the average power of transmission being 1/4th of the peak power, $p = 0.25$. The ratio p is equivalent to w/n.

Equations (8) and (9) specify the achievable bit-rate for an AWGN channel and the bit-rate ceiling for a bandwidth limit B.

$$R_b \approx \left(\frac{P_{pk}}{Q^{-1}(BER)}\right)^2 \frac{\log_2\binom{n}{w}}{2n \cdot N_0} \tag{8}$$

$$R_b \leq \frac{B \cdot \log_2\binom{n}{w}}{n} \tag{9}$$

Overlapping Pulse-Position Modulation (OPPM)

OPPM follows directly from MPPM with the additional constraint that all pulses must be consecutive, *i.e.* all ones must be contiguous in a codeword (see Fig. 2). This extra specification necessitates a decrease in the number of permitted codewords; only $Q = n\text{-}w + 1$ codewords exist as compared to (n,w) for MPPM. The benefit of OPPM lies instead in spectral efficiency, which is greater than that of MPPM. This allows for a looser bound for R_b, given the bandwidth constraint, B. Building off the theory in [8], Equations (10) and (11) specify the achievable bit-rate and ceiling due to the bandwidth limit.

$$R_b \approx \left(\frac{P_{pk}}{Q^{-1}(BER)}\right)^2 \frac{\log_2(n-w+1)}{2n \cdot N_0} \tag{10}$$

$$R_b \leq \frac{B \cdot w \cdot \log_2(n-w+1)}{n} \tag{11}$$

As with MPPM, the value of w can be changed to switch between intensity levels to match the dimming preferences specified by the user. This is illustrated in Fig. 3. In (10), it is evident that as w approaches n, R_b decreases. The bandwidth limitation of (11) takes into account the lower bandwidths of using longer pulses with the corresponding sacrifice of alphabet size.

Bo *et al.* discussed OPPM dimming in [5]; however, their approach utilizes AM dimming, *i.e.* the P_{pk} is reduced to reduce light intensity. As explained in Section III, AM has certain

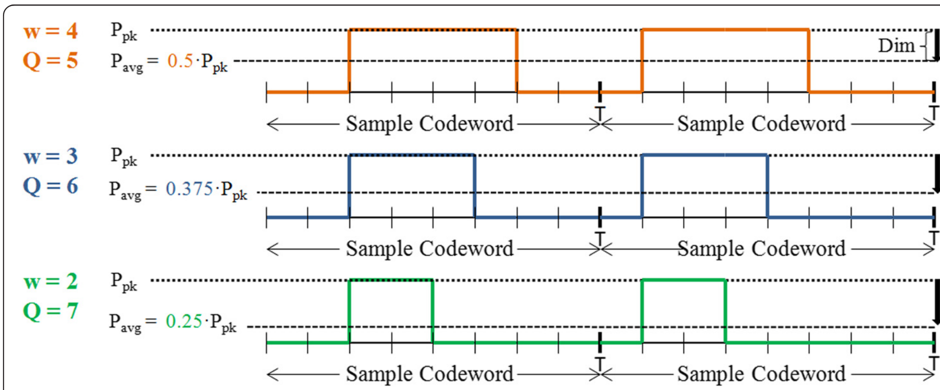

Fig. 3 OPPM dimming example. As the codeword weight, w, decreases, the P_{avg} decreases, which results in a reduction of light intensity as perceived by the human eye. The number of valid codewords, Q, for a fixed w is Q = n-w + 1, where n is the number of chips per symbol ($n = 8$ in this example)

disadvantages with regard to light quality. Nonetheless, reference [5] demonstrates that OPPM with AM dimming fares well considering a flicker severity index as compared to OOK and VPPM. Future research is necessary to conclude if a hybrid of OPPM dimming using AM and the varying of codeword weights may inherit benefits of both techniques.

Results and discussion

The analysis aims at incorporating realistic constraints of a practical VLC system. As opposed to the traditional BER versus SNR comparison, we investigate achievable bit-rate versus perceived brightness level. This approach encompasses the fixed peak power limit of artificial lighting in a given room. A BER of 10^{-6} is targeted. Perceived brightness is calculated as,

$$Perceived\,Brightness(\%) = 100\sqrt{\frac{P_{avg}}{P_{pk}}} = 100\sqrt{p}. \tag{12}$$

Equation (12) is a form of Stevens' power law also presented in [4]. It accounts for the nonlinear response of the human visual system to changes in luminance.

As evident from (6)-(11), the bit-rate can be noise-limited or band-limited at a particular perceived brightness. As one dims or brightens, changing p, it is possible to transition from a noise-limited regime to a band-limited regime (while keeping the same BER). The particular behavior is dictated by the noise and/or signal strength.

For the sake of comparison, a 5x5x3 m^3 model room is studied having the same geometry and transmitter/receiver properties as *scenario B* of Grubor *et al.*'s work in reference [7]. This configuration requires that 80 % of the illuminance at desktop level (0.85 m from floor) is above 400 lux, a typical requirement for office lighting. Four 1x1 m^2 luminaires in the model room each contain 196 LED chips capable of emitting 12.3 W of radiant flux. A photodiode with responsivity 0.28 A/W is assumed as per conformity with [7].

In order to demonstrate that the bandwidth limitation is dominant even in dimly lit regions of the model room, the minimum recorded SNR, 47 dB, and received power, 0.1 mW, were adopted from the simulation of Grubor *et al*. The LEDs are at full-brightness for the SNR calculation, but certain regions of the room receive more light than others due the lighting configuration and reflections.

N_0 can be calculated to be approximately 7.82×10^{-22} A^2/Hz using (3) and substituting R_b for a bandwidth of 20 MHz, as defined in [7]. A bandwidth of 20 MHz is approximately the maximum value for phosphor-converted, white LEDs used in conjunction with a blue-filter at the receiver. The theoretically achievable bit-rate can be seen in Fig. 4 for OOK + CT, VPPM, MPPM ($n = 32$, $n = 8$), and OPPM ($n = 32$, $n = 8$). Note that OOK + CT and VPPM are, in theory, continuous dimming schemes, whereas the others are discrete. A large number of chips can approximate continuous dimming [3]. Excluding the extremes (near 0 % and 100 %), the schemes are band-limited across all perceived brightness levels, *i.e.* the LED bandwidth is the bottleneck of communication rather than noise. OPPM proves to be superior to the other dimming and data communication schemes.

As shown in Fig. 4, OPPM ($n = 32$) achieves 40.9 Mbps at a perceived brightness of 70.7 %, which is 22.6Mbps greater than MPPM ($n = 32$) and 30.9 Mbps greater than

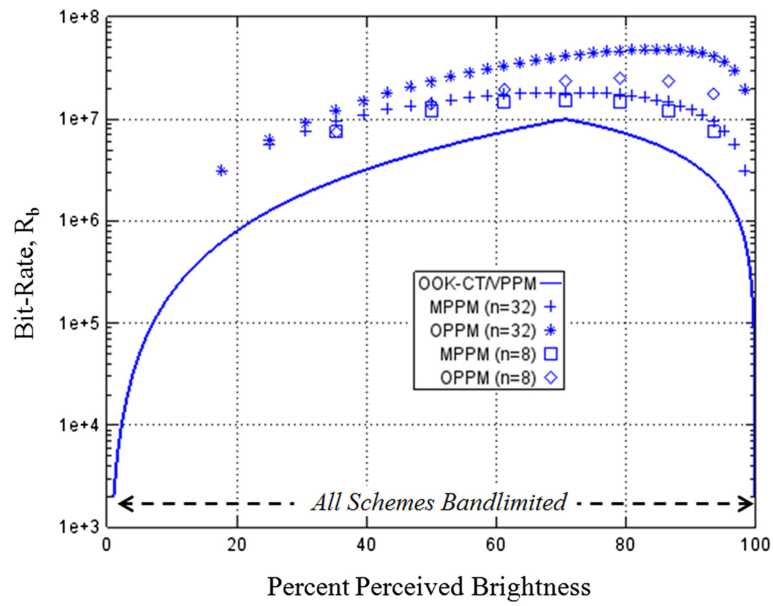

Fig. 4 Achievable bit-rate versus perceived brightness level when $N_0 = 7.82 \times 10^{-22}$ A^2/Hz (r = 0.28 A/W, P_{pk} = 0.1 mW, BER = 10^{-6}, B = 20 MHz). The superior performance of OPPM in this regime is evident. All schemes are band-limited across the entire dimming range

OOK-CT/VPPM. If brightness is increased to 98.4 % (31/32 of peak power), OPPM ($n = 32$) drops to a bit rate of 19.4 Mbps, but still maintains superiority by achieving 16.3Mbps over MPPM ($n = 32$) and 18.8Mbps over OOK-CT/VPPM. Dimming to 17.7 % (1/32 of peak power), MPPM matches OPPM at a bit-rate of 3.1 Mbps, which is 2.5Mbps greater than the bit-rate achieved by OOK + CT/VPPM. MPPM and OPPM are essentially both 32-PPM at this percentage (since $w = 1$).

Conclusions

Dimming, or intensity control, is the most prevalent and popular form of lighting control. In addition to creating the desired ambience, dimming can also provide energy savings. Unsurprisingly however, dimming presents a number of immediate challenges to VLC as modulation schemes must enable both data transmission and light intensity adjustment.

In this paper, we proposed OPPM dimming, wherein the weight of codewords is modified according to the desired dimming percentage. The technique manifests its usefulness in a comprehensive analysis of a VLC environment, which takes into account LED bandwidth limitations. Analysis reveals gains of over 20 Mbps in using OPPM rather than other two-level schemes in band-limited environments. Noise levels must increase by over two orders of magnitude than the model case considered in the analysis in order for MPPM with the same number of chips to surpass the performance of OPPM.

Competing interests
The authors declare that they have no competing interest.

Authors' contributions

TL proposed the topic, conceived and designed the study. JG carried out the study. HE analyzed the data, helped in their interpretation and collaborated with JG in the construction of manuscript. All authors read and approved the final manuscript.

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John Gancarz received his B.S. and M.S. in electrical engineering from Boston University in 2011 and 2013, respectively. His prior research work was in the field of electromagnetics and plasma science. Particularly, he studied local geomagnetic field fluctuations induced by electromagnetic heater waves injected into ionospheric plasma. In 2011, he joined the NSF Smart Lighting ERC at Boston University. His initial research concerned novel light rendering techniques in "smart" lighting systems. Additional research interests were VLC related, including adaptive data rate and coding, illumination quality effects of VLC, and the synthesis of modulation and dimming schemes. He is commencing priestly studies and formation at the Pontifical North American College and the Pontifical Gregorian University in Rome, Italy.

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Thomas D.C. Little is a professor in the Department of Electrical and Computer Engineering at Boston University. He is Associate Dean of Educational Initiatives for the College and Associate Director of the NSF Smart Lighting Engineering Research Center – a collaboration of Rensselaer Polytechnic Institute, the University of New Mexico, and Boston University. Recent efforts include research in video sensor networks and streaming in wireless settings, ubiquitous optical networking with visible light, vehicle-to-vehicle/infrastructure (V2X) communications, and the application of wireless sensors in health monitoring. Dr. Little received the BS degree in biomedical engineering from Rensselaer Polytechnic Institute in 1983, and the MS degree in electrical engineering and PhD degree in computer engineering from Syracuse University in 1989 and 1991. He is a senior member of the IEEE, a member of the IEEE Computer and Communications Societies and a member of the Association for Computing Machinery.

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