Integrating ultra-wideband and free space optical communication for realizing a secure and high-throughput body area network architecture based on optical code division multiple access

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Abstract
Nodes in a body area network (BAN) are miniature wearable or implantable battery-powered wireless sensors which continuously transmit real-time vital physiological data of a patient to remote health-care center while remaining in close proximity to the human body. Therefore, BAN nodes should have the features of high data rates and low transmit powers to protect the human body, environment and bio-medical equipment from harmful exposure of electromagnetic radiations and electromagnetic interference (EMI). Ultra-wideband (UWB) signals have low allowable transmission power and high data rates. Therefore, we propose a low cost, low powered and secure optical body area network (OBAN) composed of four UWB-BAN nodes each transmitting at a data rate of 30 Mbps. At the control node, UWB signals from UWB-BAN nodes are encoded using spectral amplitude coding-optical code division multiple access (SAC-OCDMA) scheme and the combined signal is transmitted over free space optics (FSO) channel towards remote health-care center. At the health-care center, the combined signal is decoded and UWB signal of each UWB-BAN node is photo-detected for analysis of patient’s data. Log-normal channel model is considered between control node and the health-care center. The signal received from each UWB-BAN after propagation through the FSO channel is analyzed through Bit error rate (BER) results. Similarly, cost efficiency of the proposed architecture is also evaluated through a detailed cost analysis. It was observed that the proposed architecture requires the UWB-BAN nodes to have low receiver sensitivities with the added benefits of cost-efficiency and data security.

Keywords Optical body area network · Ultra-wideband · Free space optics · Optical code division multiple access

1 Introduction

Body area network (BAN) is a cutting-edge and promising wireless technology operating at the close proximity to human body which enables wireless communications between on-body sensors called BAN nodes and a control node usually mounted on human body or located at a fixed distant place near to human body [1, 2]. This control node acts as a coordinator establishing communication link with all BAN nodes as well as with other wireless or wired networks. One main application of BAN is the tele-medicine and e-health platforms, because BAN can provide continuous remote monitoring of patients having multiple diseases and thus early detection of abnormal health conditions [3]. By timely detection of abnormal health conditions, BAN can prevent diseases and thus allow reducing health-care expenditures which is a significant challenge now a days due to increasing percentage of aging population. Besides, the workload of medical staff can be decreased by integrating
BAN with medical centers thus resulting in higher efficiency of medical staff and reduction in health-care expenditures as well.

While designing a BAN, it is of prime importance that the network designer should choose such a wireless technology which promises high capacity of information transmission between BAN nodes and control node along with low power spectral density (PSD). Recent studies [4] show that EMI between RF devices and medical equipment, such as in hospitals could be critical. Moreover, prolong RF exposure to human body is undesirable. Therefore, it is imperative to use minimum transmit power BAN nodes on patient body so that the adverse effects of RF exposure to the body and EMI between RF devices and medical equipment can be mitigated. UWB is an attractive and promising wireless communication technique that provides carrier-less, high-data rate transmission [5]. Due to very low radiated power which is equal to $-41.3$ dBm/MHz, UWB can be a potential applicant in BAN technology which can resolve the issues of adverse effects of RF exposure to human body and EMI between RF devices and medical equipment.

Future BANs should have the features of high data rate, immunity to EMI, environmental friendly, license-free spectrum, low installation, and maintenance costs. Realization of these characteristics of future BANs by employing FSO technology transforms them into optical body area networks (OBANs). FSO communications can transmit high capacity wireless signals while maintaining cost-efficiency due to reduced deployment costs [6, 7]. Furthermore, a large license-free spectrum is offered by FSO that is immune to EMI, is environmental friendly, and is more secure than RF links [7]. Owing to these desirable features, FSO based OBANs are the future of BANs. However, the FSO technology is not completely free of interception. An external eavesdropper can extract information by using a wire-tapper like arrangement hidden close to the main receiver. Similarly, a receiver can be placed in the divergence region of the received optical beam whose spot size is significantly larger than the receiver size as a consequence of beam spreading through the atmosphere [8, 9]. Therefore, a secure communication system needs to be implemented for the transmission of BAN signals.

OBAN is a recent research direction; therefore, considerable research work has not been done over it so far. There are some pioneering research contributions over OBAN as proposed in [2, 10–13]. In [2], the close form expressions are derived for mobile BAN nodes in a hospital room in the presence of various blocking effects. A star topology based on diffused FSO links between mobile on-body nodes and a control node is proposed in [10]. The FSO links are secured using spreading code sequences. The performance of the model is analyzed by deriving the blocking and error probabilities. The improvement in quality of service is analyzed by employing the optical techniques in BAN by reducing the interference among BAN nodes in [11]. Close form expressions are derived for outage probability by employing diffused optical channel at different data rates and transmit powers. An OBAN consisting of four on-body nodes for efficient transmission of patient’s health data through visible light communication (VLC) technique is proposed in [12], where the data signals are secured using orthogonal codes. In [13], an indoor OBAN based on VLC technique is presented, where multiple on-body BAN nodes are communicating with the control node attached to the ceiling of the hospital room, while the data signals are secured using OCDMA. This paper proposes an OBAN architecture that is based on multiple UWB-BAN nodes, each transmitting the patient’s physiological data at 30 Mbps over an additive white Gaussian noise (AWGN) wireless channel to a fixed control node located in the patient’s room. At the control node, a continuous wave (CW) laser array is employed to generate multiple wavelengths that are used to encode the UWB signals received at the control node from the UWB-BAN nodes using SAC-OCDMA scheme. The combined signal encoded by SAC-OCDMA scheme is then transmitted towards remote health-care center over an FSO link of 0.5 km length. At the health-care center, the combined signal is decoded and each UWB signal is photo-detected followed by demodulation and performance analysis.

SAC-OCDMA technique is adapted to provide robust transmission and mitigation of the various adverse effects between the transmitter and receiver modules. Working principle of SAC-OCDMA system encompasses the translation of binary 1s or 0s into spectral domain by allowing or blocking desired bits through certain arrangement of filters in the encoder module [14, 15]. This generates multiple carriers to communicate the user information with relatively high spectral efficiency and built-in security [14]. The family of spectral amplitude codes primarily includes two types of codes, namely, (i) zero-cross correlation (ZCC), and (ii) fixed in-phase cross correlation codes [15, 16]. Both are developed to mitigate the effects of multiple access interference (MAI) along with the associated phase induced intensity noise (PIIN) for non-coherent sources and optical beat interference for coherent sources at the photo-detector through an efficient combination of code length, weight and cross-correlation [14, 15]. The prior offers efficient performance for low cardinality systems by completely removing the effects of MAI with relatively simple architecture at the encoder and decoder modules. ZCC codes, as the name suggests, offer zero cross correlation between adjacent codes, which significantly elevates performance of the system through recovery of the intended spectrum with maximum auto-correlation and zero cross-correlation between the intended and interfering subscribers, respectively.
Consequently, this work adapts ZCC code called double weight zero cross-correlation (DW-ZCC) to effectively communicate the intended signals between the control and remote health-care center and mitigate the environmental effects with added security. The proposed DW-ZCC code is constructed with reduced weight (W=2) to decrease the number of filters and elevate feasibility of the proposed setup in terms of implementation complexity and cost. Additionally, highly acknowledged direct detection technique is used to recover the intended spectrum with desired correlation properties, thereby eliminating the need for an extra arrangement in lower arm of the decoding module [15]. Another advantage of the DW-ZCC code in comparison with the conventional scheme is simplicity in code construction and support for large cardinality in relatively short reach systems [15, 17].

The novel contributions of our work in the field of OBANs are summarized below:

1. A UWB over FSO link is implemented for OBANs to take advantage of the high bandwidth offered by UWB signal and the FSO link. Due to their broad spectral width, the UWB signals are less prone to EMI which is a major issue in environments composed of multiple electrical components. Furthermore, EMI between UWB-BAN nodes and medical equipment as well as RF exposure of UWB-BAN to human body is reduced by employing low transmit power UWB wireless technology.

2. The security of the FSO link is further enhanced by implementing SAC-OCDMA with the help of multiple wavelengths generated by a single CW laser array.

3. We have demonstrated integration of RF and optical wireless channels for the implementation of OBANs. An AWGN channel is considered for the RF signal transmission, while the Log-normal channel model is considered for the optical signal transmission.

The proposed architecture is best suited for implementation of e-health and tele-medicine platforms in all kind of assisted living facilities and hospitals. The simulations in this work are performed using the commercial tool known as OptiSystem 17. OptiSystem software is a latest and powerful commercial design tool that enables the system designers to plan, test, and simulate almost every type of optical link in the physical layer of optical network. It offers optical communication system design and planning from component to system level, and visually presents analysis and scenarios. The tool is developed by Optiwave Inc., Ontario, Canada [18].

2 Application scenario of proposed OBAN

The application of our proposed OBAN architecture is best suited in old-age homes, where elder citizens having multiple chronic diseases are living. The application scenario of the proposed OBAN architecture is shown in Fig.1. It may be observed from the figure that elder citizens having multiple chronic diseases are living in their rooms located in an old-age home. We assume that each room has dimensions of 10 m x 8 m. Each patient is equipped with four on-body UWB-BAN nodes sensing pulse rate, body temperature, electrocardiogram (ECG), and electroencephalogram (EEG) activities of the patients. UWB-BAN nodes are transmitting real-time data of aforementioned vital signs of the patients in the form of low PSD UWB signals towards control nodes located at a fixed position which is 8 m high from room floor. The UWB-BAN nodes help in minimizing the EMI as well as the RF exposure to human body. Each node is transmitting simultaneously at a different radio frequency to avoid the interference among UWB signals at control nodes. The optical signals of all control nodes are combined and then transmitted over FSO link towards remote health-care center. FSO link provides a cost efficient solution to implement the


The proposed architecture as compared to RF and optical fiber based BANs. As FSO links are prone to eavesdropping, privacy and multiple access in transmission is achieved using SAC-OCDMA scheme which is implemented at control node. The combined signal is decoded at remote health-care center and after optical to electrical conversion, the patient data is processed and interpreted by the nursing staff. The application scenario promises a comprehensive and alternative e-health and tele-medicine platform for optimum nursing and look after of elder citizens living in old-age homes. The application scenario not only provides optimum nursing to elder citizens in old-age homes but also minimizes the health-care expenditures including permanent stationing of nursing staff at old-age homes, regular visits of physicians or elder citizens visits to cardiologist or neurologist etc.

3 Code construction

The proposed DW-ZCC code is developed by considering three performance parameters of DW-ZCC which includes code length \( L \), hamming weight \( W \), and cross-correlation \( C_{\text{max}} \) between the adjacent codes represented by \( X \) and \( Y \). The cross-correlation can be defined mathematically as:

\[
C_{\text{max}} = \sum_{i=1}^{L} x_i y_i = 0
\]  

(1)

In Eq.1, \( X \) and \( Y \) are two adjacent code words, where \( X = x_1, x_2, ..., x_L \) and \( Y = y_1, y_2, ..., y_L \). \( x_i \) and \( y_i \) are bit values of respective code sequences. Now the basic matrix with \( U \) code sequences of length \( L \) can be written as [14, 15]

\[
\begin{bmatrix}
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1
\end{bmatrix}_{U \times L}
\]

where \( U \) represents the number of nodes. From the basic matrix \( Z_B \), large number of nodes can be accommodated using a simple mapping technique, such as [15].

\[
Z_B = \begin{bmatrix}
Z_B & 0 \\
0 & Z_B
\end{bmatrix}_{8 \times 16}
\]

Table 1 shows the proposed code with \( U = 4 \) and \( W = 2 \), where PoS represent the position of 1 in each code sequence.

It can be observed that there are no overlapping bits between the adjacent codes and throughout the \( Z_B \) code matrix. Moreover, the association of the number of nodes and weight yields the total code length as \( L_t = U \times L \).

3.1 Code properties

To determine an efficient structure of the encoder and decoder modules, and to recover the intended spectrum with desired correlation properties, it is of primal importance to observe the correlation between code sequences of the proposed DW-ZCC code. It is evident from Table 1 that no overlapping bits exist between the codes. Therefore, correlation properties for the proposed setup can be written as

\[
C_{\text{max}} = \sum_{i=1}^{L} Z_x(i) Z_y(i) = \{ W; x = y, 0; x \neq y \}
\]  

(2)

Here, \( Z_x(i) \) and \( Z_y(i) \) denotes the \( i^{th} \) element of the \( X \) and \( Y \) code sequences, respectively. It can be observed that zero cross-correlation exists between code sequences of the proposed codes. Therefore, direct detection can be adapted to recover the intended spectrum with maximum auto and minimum cross-correlation. In addition, position of 1s in proposed code exists in pairs that significantly simplifies the implementation of encoder and decoder along with the allocation of desired spectrum.

4 Proposed architecture

The architecture of the proposed OBAN is shown in Fig.2. The working principle of the architecture has been explained in detail in coming sections.

4.1 UWB-BAN nodes

As mentioned earlier, multiple patients with limited mobility are inhabiting in rooms having dimensions of 10 m × 8 m situated in an old-age home, as shown in Fig.1. For simplicity, we consider only one patient which is equipped with four on-body UWB-BAN sensors recording the vital physiological data, such as pulse rate, body temperature, ECG and EEG activity and simultaneously communicating...
with control node. Each UWB-BAN node is transmitting the patient physiological data simultaneously over AWGN channel at 30 Mbps in the form of FCC compliant UWB mono-cycle pulses which are generated by taking the first order derivative of electrical Gaussian pulses. Each UWB-BAN node is transmitting at a different radio frequency to avoid interference at the control node. Therefore, the electrical bandpass filters (EBPFs) of UWB-BAN nodes shown in Fig. 2 are centered at $f_{C_1} = 4\text{GHz}$, $f_{C_2} = 4.5\text{GHz}$, $f_{C_3} = 5\text{GHz}$ and $f_{C_4} = 5.5\text{GHz}$. The time and frequency domain plots of UWB mono-cycle pulses generated by UWB-BAN nodes are shown in Figs. 3 and 4, respectively.

Fig. 3  Time-domain plots of UWB mono-cycle pulses. a Node-1, b Node-2, c Node-3, d Node-4
To simulate the effect of AWGN channel on transmitted UWB signals, a white noise source represented by \( n(t) \) following normal distribution is coupled with each UWB-BAN node, as shown in Fig. 2.

### 4.2 Control node

Due to channel induced impairments, the received UWB mono-cycle pulses at control node are distorted. To encode the received UWB pulses of each node using SAC-OCDMA scheme at control node, we use a CW laser array generating eight wavelengths at same power level at its output port.

These eight wavelengths are centered at \( \lambda_1 = 1552.524\text{nm} \), \( \lambda_2 = 1551.720\text{nm} \), \( \lambda_3 = 1550.918\text{nm} \), \( \lambda_4 = 1550.116\text{nm} \), \( \lambda_5 = 1549.315\text{nm} \), \( \lambda_6 = 1548.514\text{nm} \), \( \lambda_7 = 1547.715\text{nm} \) and \( \lambda_8 = 1546.916\text{nm} \). The combined spectrum of the eight wavelengths generated through a CW laser array that are being used for encoding and modulation, is shown in Fig. 5.

#### 4.2.1 SAC-OCDMA encoding

Encoding operation for the DW-ZCC code is performed using the arrangement of optical couplers shown in Fig. 2. Since the CW laser array generates eight distinct wavelengths that are 0.8 nm apart, therefore, a simple combination of optical coupler is used as an encoder to combine the specific wavelength in reference to the proposed DW-ZCC code. For example for UWB-BAN node-1, \( \lambda_1 = 1552.524\text{nm} \) and \( \lambda_2 = 1551.720\text{nm} \) are combined to translate the binary 1s in DW-ZCC code into spectral representation, as shown in Table 1. End-face of the encoder arrangement is connected to Mach-zehnder modulator (MZM) that is used to modulate the encoded signal through on-off keying (OOK) with the patient’s physiological data transmitted by UWB-BAN node-1 and received at the control node. After encoding
discussed in Sect. 5.1 of the paper. The mathematical model of the channel is based on the atmosphere. The optical signal is impaired by turbulence and attenuation from the atmosphere. The mathematical model of the channel is used to model the atmospheric turbulence between control node and remote health-care center. The Log-normal channel model is generally implemented for clear sky FSO links, where turbulence is weak [19, 20].

The full-width at half-maximum (FWHM) of the UWB mono-cycle pulses of each UWB-BAN node is around 25 ps. All four encoded optical signals after OOK modulation are combined using an optical coupler, as shown in Fig. 2. After suitable optical amplification, the combined optical signal is transmitted through a single mode fiber (SMF) having length of 3.5 m to a telescope that transmits it towards the remote health-care center over the FSO link of length 0.5 km. The total power radiated by the transmitter telescope in free space is around 30 dBm. In this work, Log-normal FSO channel model is used to model the atmospheric turbulence between control node and remote health-care center. The Log-normal channel model is generally implemented for clear sky FSO links, where turbulence is weak [19, 20]. Therefore, the values of refractive index structure parameter ($C_n^2$) and atmospheric attenuation ($\alpha_{atm}$) used in this simulation are chosen as $5 \times 10^{-16}$ and 5 dB/km, respectively.

### 4.3 Remote health-care center

At the remote health-care center, a receiver telescope receives the signal transmitted by the control node telescope, as shown in Fig. 2. The FSO transmitter and receiver telescopes employed in our simulation study have parameters similar to the commercial model# M1-10GE, manufactured by FSO Artolink [20] as shown in Table 2. The combined optical signal is impaired by turbulence and attenuation from the atmosphere. The mathematical model of the channel is discussed in Sect. 5.1 of the paper.

| Sr. No | Parameters                              | Values       |
|--------|-----------------------------------------|--------------|
| 1      | Diameter of transmitter telescope       | 5 cm         |
| 2      | Diameter of receiver telescope          | 20 cm        |
| 3      | Transmitter telescope apertures         | 1            |
| 4      | Receiver telescope apertures            | 1            |
| 5      | Material                                | GRIN lens    |
| 6      | Maximum transmission speed              | 1.5 Gbps     |
| 7      | Operating wavelength                    | 1550 nm      |
| 8      | Maximum working distance                | 2 km         |

### 4.3.1 SAC-OCDMA decoding

The encoded signal is given as input to SAC-OCDMA decoder through a SMF having length of 3.5 m. The decoding operation has been performed using the WDM-DEMUX arrangement shown in Fig. 2. Since the proposed DW-ZCC code bears zero cross-correlation between adjacent codes, therefore, the highly acknowledged direct detection scheme is adapted to recover the intended spectrum. The filter arrangement in WDM-DEMUX is utilized to receive the desired spectrum, as shown in Fig. 2. As a result, specific wavelengths corresponding to each code sequence are received and combined using an optical coupler. The proposed technique significantly simplifies the overall architecture with the added benefit of receiving the intended spectrum with maximum auto and minimum cross correlation. The output of each coupler is further given as input to a PIN photo-detector to convert the signal from optical to electrical domain. As zero cross-correlation exists between adjacent codes; therefore, no MAI and accompanying optical beat interference is generated at the photo-detector during optical to electrical conversion that significantly elevates the quality of signal. The time-domain plots of the photo-detected UWB mono-cycle pulses of each UWB-BAN node are shown in Fig. 6.

The photo-detected UWB mono-cycle pulses of each UWB-BAN node obtained at the output of PIN photo-detectors are passed through a DC blocking circuit to remove DC off-set and then amplified using electrical amplifiers. The amplified signal is self-mixed, resulting in conversion of the patient physiological data from UWB mono-cycle pulses to Gaussian pulses by removal of the negative cycle due to multiplication [5]. The resulting electrical signal is low pass filtered and forwarded to a BER estimator, as shown in Fig. 2. The summary of major simulation parameters for the setup of Fig. 2 is shown in Table 3.

### 5 Mathematical analysis of the proposed architecture

To evaluate the BER of the signal received by the intended subscriber in this optical model of DW-ZCC based SAC-OCDMA system, the mathematical analysis of the proposed architecture utilizes Log-normal channel model to determine the signal-to-noise ratios (SNRs) for back-to-back as well as for turbulence conditions. In the mathematical analysis, we are considering only those noise contributors that are being added in the system between SAC-OCDMA encoder and PIN photo-detectors, while the simulation results are being taken by considering all noise contributors between UWB-BAN nodes and PIN photo-detectors.
5.1 Log-normal channel model

A FSO link induces mainly two types of impairments known as attenuation and atmospheric turbulence. Atmospheric turbulence is the consequence of variations in the atmospheric temperature and pressure along the path of the signal. It is a major cause of signal degradation and results in random variations in signal irradiance, commonly known as intensity scintillation. Various statistical channel models have been proposed to consider the effect of attenuation and atmospheric turbulence on the optical signal [18, 19]. Some of the most commonly used channel models to estimate the effects of atmospheric turbulence on the optical signals are the negative exponential, K-distribution, Log-normal distribution, Log-normal-Rician and Gamma–Gamma channel model [20, 21]. To characterize weak turbulence conditions of a clear sky link, the Log-normal distribution is employed [21]. The probability density function of received light intensity \( I \) following a planar wave propagation in terms of variance of log-amplitude fluctuations (\( \sigma_x^2 \)) is given by [21, 22]:

\[
p_I(I) = \frac{1}{2I \sqrt{2\pi \sigma_x^2}} \exp \left( -\frac{\ln(I/I_0)^2}{8\sigma_x^2} \right),
\]

where \( \sigma_x^2 = 0.307C_n^2k^{7/6}L^{11/6} \), \( L \) is the FSO link length in kilometers, \( k = 2\pi/\lambda \) is the wave number and \( C_n^2 \) represents the refractive index structure parameter whose values vary from \( 10^{-17} \) to \( 10^{-12} \) for weak turbulence to strong turbulence, respectively [20]. Even for a specific link, the refractive index structure parameter can vary over time due to the complex dynamics of the weather.

Table 3 Major simulation parameters

| Sr. No | Parameters                          | Values          |
|--------|------------------------------------|-----------------|
| 1      | Bit rate (per UWB-BAN node)        | 30 Mbps         |
| 2      | Transmitter telescope diameter     | 5 cm            |
| 3      | Receiver telescope diameter        | 20 cm           |
| 4      | Beam divergence                    | 2 mrad          |
| 5      | Length of FSO link                 | 0.5 km          |
| 6      | Length of each SMF spool           | 3.5 m           |
| 7      | Refractive index structure parameter | \( 5 \times 10^{-16} \) |  
| 8      | Responsivity of PIN photo-detector | 0.9 A/W         |
| 9      | Optical amplifier gain             | 30 dB           |
| 10     | Optical amplifier noise figure     | 4 dB            |
| 11     | Electrical amplifier gain          | 10 dB           |

Fig. 6 Time-domain plots of photo-detected UWB monocycle pulses. a Node-1, b Node-2, c Node-3, d Node-4
5.2 BER calculations

The SNR for analysis of the proposed setup can be written as ratio of the average desired photo-current \( I_b \) received by the intended subscriber to the power of different noise sources \( i_{bn}^2 \) generated throughout the system [14]:

\[
SNR = \left[ \frac{i_b^2}{i_{bn}^2} \right]
\]

The average desired photo-current in Eq.4 can also be written as [14]:

\[
i_b = R b W_m P_{sr}, \tag{5}
\]

where \( b \in \{0, 1\} \) is value of the bit that represents the transmission of binary 1 or 0 by the intended user. \( P_{sr} \) shows the power per chip at the receiving end and is equivalent to \( \frac{P_{tx} e^{-\alpha d}}{N(\delta d)^2} \), where \( P_{tx} \) is the transmitted power, \( D \) is the aperture diameter of the receiving side telescope, \( \alpha \) is the atmospheric attenuation, \( d \) distance between transmitter and receiver side telescopes and \( \theta \) is the beam divergence. In Eq.5, \( R \) is the responsivity of the photo-detector that is used to convert the received signal from optical to electrical domain. \( W_m \) represents power units in the number of chips for each user absorbed by the photo-detector. Since our proposed setup uses direct detection that recovers the non-overlapping spectral chips only; therefore, \( W_m = W \) which indicates that maximum power units in recovered spectrum is absorbed by the photo-detector. The variance of the total noise power for the proposed DW-ZCC based SAC-OCDMA system can be written as the sum of noise sources generated throughout the system that primarily includes optical beat interference \( i_{obn} \), relative intensity noise \( i_{rn} \), shot noise \( i_{sn} \) and thermal noise \( i_{tn} \) [14]:

\[
i_{bn}^2 = i_{obn}^2 + i_{rn}^2 + i_{sn}^2 + i_{tn}^2 \tag{6}
\]

As direct detection technique recovers the intended spectrum, therefore, only the desired pulses will hit the photodetector. Moreover, cross-correlation between the adjacent codes of the proposed DW-ZCC codes is equal to 0; therefore, the value of \( i_{obn}^2 = 0 \) for the proposed setup. Relative intensity noise (RIN) is generated at the transmitter module of the desired signal. Moreover, all users in the proposed setup cause cross-talk with the desired user signal; therefore, power of the RIN with \( W_m = W \) can be written as [21]:

\[
i_{rn}^2 = RN(bWP_{sr} + xP_c)^2B_e \tag{7}
\]

Here, \( RN \) is the noise factor with typical value between -130 and \( -160 \ dBHertz^{-1} \), \( B_e \) represents the electrical bandwidth. \( P_c \) denotes the optical power in the cross-talk pulses, and \( x \) is event of the whole interfering pulses from the possible users out of U-1 that transmits bit “1”. The average value of \( x \) when the number of interfering users that are sending bit “1” at every chip is equal and can be written as [14]:

\[
x = \frac{W^2(U - 1)}{2L} \tag{8}
\]

Haphazard nature of the photons that are incident upon the PIN photo-diode generates random electrons that results in fluctuation of the photo-current. This phenomenon generates shot noise that is proportional to the incident current times \( 2EB_e \). Mathematically, the shot noise can be written as [14, 17]:

\[
i_{sn}^2 = 2RE(bWP_{sr} + xP_c)B_e \tag{9}
\]

Here \( E \) is the electron charge. Since direct detection at the intended subscriber recovers non-overlapping spectrum of the DW-ZCC code; therefore, \( P_c = 0 \) as no cross-talk is observed between the intended and interfering user at the receiving photo-diode [14, 17]. Consequently, the value of \( i_{sn}^2 \) becomes

\[
i_{sn}^2 = 2REW_mP_{sr}B_e \tag{10}
\]

The thermal noise generated at the receiving photo-diode of the intended user can be written as [14]:

\[
i_{tn}^2 = \frac{4K_TTB_e}{R_L}, \tag{11}
\]

where \( T \), \( K_B \), and \( R_L \) represents the temperature, Boltzmann constant, and load resistance, respectively. The total variance of the noise power becomes [14]:

\[
i_{bn}^2 = i_{rn}^2 + i_{sn}^2 + i_{tn}^2 \tag{12}
\]

If the decision of the received bit is carried out by comparing the total current of the received signal with a threshold current \( I_T \), then BER of the received optical signal can be calculated as [14]:

\[
BER_0(I) = Q\left(\frac{I_1 - I_0}{i_{n1} + i_{n0}}\right), \tag{13}
\]

where \( I_1 \) and \( i_{n1} \) is the total signal current and noise power for bit “1”, and \( I_0 \) and \( i_{n0} \) is the total signal current and noise power for bit “0”, respectively. The total BER of the encoded signal that is transmitted over the Log-normal turbulent channel can be written as [14, 17]:

\[
BER = \int_0^\infty \text{BER}_0(I) p_I(I) dI \tag{14}
\]

Here, \( p_I(I) \) is the probability density function of the Log-normal channel that is used under weak turbulence conditions.
to model the intensity fluctuations of the received signal at the photo-detector. The BER in Eq. 14 is used to calculate performance of the proposed system, in terms of quality of the received signal at the intended photodiode.

6 Performance analysis

6.1 BER performance

The UWB signals received at the remote health-care unit after being transmitted from the control node and propagation through the Log-normal channel are analyzed for BER performance. The eye-diagrams of the Gaussian-shaped electrical signal at the output of the electrical bandpass filters, as shown in Fig. 2, are used to statistically calculate the BER. The optical power of the signals received at the PIN photo-detector is varied with the help of an optical attenuator to observe the effect on the BER of the UWB monocyte pulses. Apart from turbulence, haze and rain induced atmospheric attenuations are major detrimental effects in the FSO links. Light haze, heavy haze, light rain and heavy rain can induce atmospheric attenuation of different values [20]. In this study, we choose the values of atmospheric attenuation in the range of 5–35 dB/km, which covers most of the weather conditions [20]. Figure 7 shows the BER versus received optical power plots obtained at different values of atmospheric attenuation, while considering weak turbulence regime which is specific to Log-normal channel model. Receiver sensitivity is defined as the minimum optical power required to achieve a BER of $10^{-9}$ [22]. Due to small difference in values of receiver sensitivity of UWB-BAN nodes, BER plots for UWB-BAN node-1 are only considered. Therefore, the minimum value of receiver sensitivity for the back-to-back (BTB) case of UWB-BAN node-1 is around $-21.8$ dBm. The sensitivity becomes $-20.3$ dBm for $\alpha_{atm} = 5$ dB/km, resulting in a power penalty of around 1.5 dB. Furthermore, the minimum receiver sensitivity of UWB-BAN node-1 is around $-17.2$ dBm for $\alpha_{atm} = 35$ dB/km, resulting in a power penalty of around 2 dB. The BER plots show that the receiver sensitivities are degraded when the value of atmospheric attenuation is increased. Small variations in receiver sensitivity are observed among the four UWB-BAN nodes. Overall, the four UWB-BAN nodes give acceptable BER values indicating the suitability of our proposed technique for employment at health-care centers. To further elaborate the effect of FSO attenuation on UWB-BAN nodes, Fig. 8 shows the eye-diagrams of the UWB-BAN nodes at different values of atmospheric attenuation. It may be observed that the opening of the eye reduces and amplitude variation increases on increasing the value of atmospheric attenuation from 5 to 35 dB/km.

Few pioneering works of OBANs have been proposed by other researchers as already discussed in Sect. 1. To elaborate the superiority of our proposed architecture, we
have compared major results obtained from this work with the results of the previous studies reported in literature [2, 10–13], as mentioned in Table 4. It may be observed from the table that the proposed architecture outperforms the previous works on the basis of various factors, such as data rate, range and security. A “dash” in a certain row of Table 4 represents that the information about this parameter is not provided in the particular study.

6.2 Cost analysis

The idea of deploying FSO links instead of the optical fiber (OF) media is based upon reduced deployment cost and lower maintenance cost along with high flexibility, mobility and lower deployment time. A major part of deployment cost for the OF media is spent on trenching between the transmitter and receiver modules, which requires relatively large number of specialized laborers to dig the trench and lay the optical fiber media [25, 26]. Furthermore, trenches are prone to fiber cuts or breaks owing to the continuous development of surrounding infrastructure. On the contrary, the employment of FSO link between the transmitter and receiver module introduces a certain level of simplicity and reduction in deployment and maintenance costs. Cost of FSO links can be as low as 1/5 times of the OF based networks. However, such figures are subject to span and the number of subscribers in the network [15, 25, 26]. To demonstrate the feasibility of FSO links as compared to OF media in terms of deployment cost and capital expenditure (CAPEX), the following expressions can be used:

\[ C_{OF} = (l \times \text{trenching}) + (l \times \text{OF}), \]

(15)

where “l” represents the total length of trenching.

\[ C_{FSO} = \frac{\text{Cost of FSO transmitter/receiver module}}{1}, \]

(16)

It may be observed from Eq. 15 that the deployment cost for OF media encompasses the total amount spent on the trenching along with cost of OF media. On the other hand, deployment cost for FSO media as given in Eq. 16 demonstrates that the overall cost is dependent on the cost of FSO transmitter and receiver modules only. With reference to Fig. 2 of the proposed OBAN architecture, the employment of OF media or FSO link between the control node and remote health-care center will affect the overall cost for a fixed number of nodes [26]. Therefore, the cost of SAC-OCDMA encoder and decoder modules is not considered in this analysis. Similarly, installation cost is also not considered owing to large variation among vendors. Table 5 shows the overall deployment cost for both scenarios by considering the costs of trenching, OF and FSO module as USD 1000, USD 25 and USD 500, respectively. Table 5 shows the comparison between the network blocks of interest including OF media and FSO link over a span of 0.5, 1, 1.5, and 2 km. It can be

| Sr. No | Network block | CAPEX($) |
|--------|---------------|----------|
|        | 0.5 km | 1 km | 1.5 km | 2 km |
| 1      | OF     | 512.5 | 1025   | 1550  | 2050  |
| 2      | FSO    | 500   | 500    | 500    | 500    |

Table 4 Comparison of major results of the proposed work with results of the past related studies

| Study  | Type of node | Data rate | FSO range | Security        | Cost analysis |
|--------|--------------|-----------|-----------|-----------------|---------------|
| [2]    | IR           | 1Mbps     | 5 m       | –               | No            |
| [10]   | IR           | 14.3 Mbps | 1.5 m     | OCDMA          | No            |
| [11]   | LED          | 4.2 Mbps  | 5 m       | –               | No            |
| [12]   | LED          | –         | –         | Walsh codes    | No            |
| [13]   | LED          | –         | 1.5 m     | –               | No            |
| [Proposed] | UWB     | 30 Mbps   | 0.5 km    | SAC-OCDMA      | Yes           |
observed that the CAPEX for the OF media increases with increase in the length of the link. On the contrary, cost of FSO link remains the same over the entire span. Thus it can be concluded that FSO link is a viable option for the deployment of a small span network with relatively high data rate requirements. Furthermore, deployment of FSO link not only minimizes the cost but also provides a certain level of simplicity in installation and maintenance costs that can be traded-off with a slight increase in CAPEX for smaller span networks.

7 Conclusion

A low transmit power, low cost and secure OBAN composed of four on-body UWB-BAN nodes, each transmitting the vital physiological data of patients at data rate of 30 Mbps to remote health-care unit over FSO link is proposed. Security and multiple access is achieved through SAC-OCDMA scheme implemented by multiple wavelengths generated using a CW laser array. The performance of the proposed UWB-BAN architecture is analyzed with the help BER calculations. A detailed cost analysis of the proposed architecture is also performed. The proposed architecture gives good BER results with added advantages of low complexity, low cost and security.

Declarations

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Conflict of interest The authors of this manuscript certify that they have no affiliations with or involvement in any organization or entity with any financial interest in the materials discussed in this manuscript

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