Performance Analysis of Multiple Access m-CAP for Optical-Based Intra-WBAN Links

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Abstract—Optical-based wireless body area networks (WBANs) are a promising solution for remote monitoring of vital signs in radio-frequency sensitive environments such as healthcare facilities. When dealing with a large number of sensors coexisting within the same vicinity, multiple access (MA) solutions are necessary to manage the simultaneous access to the medium. In this paper, we investigate the use of MA multi-band carrierless amplitude and phase (m-CAP) for intra-WBAN links. Using the outage probability criterion, we evaluate the performance of such a solution while accounting for realistic statistical channel models. Furthermore, we study the impact of system parameters such as bandwidth, number of sub-bands, and roll-off factor on the link performance.

Index Terms—Wireless body-area networks; Optical wireless communications; Multiple Access m-CAP; Link performance; Outage probability.

I. INTRODUCTION

E-health applications such as remote vital sign monitoring and remote therapeutic stimulation are gaining increasing popularity in healthcare systems thanks to the advances made in sensor miniaturization, and the development of low power wireless communication technologies. Wireless body-area networks (WBANs) are considered as the main building block of such applications by enabling the acquisition and transmission of the medical data from medical sensors. In WBANs, a set of sensor nodes (SNs), typically placed on the patient’s body, send the collected data to an on-body coordinator node (CN), which forwards it to an access point (AP) prior to being transmitted to medical staff for further analysis [1].

WBANs have specific characteristics requiring particular connectivity solutions ensuring a lower latency, high mobility tolerance, and heterogeneity of the transmitted data (i.e., a mixture of continuous-time signals like electroencephalogram (EEG) and event-based signals like temperature, for instance) [2]. While most of the current WBAN solutions use the unlicensed frequency bands in the radio-frequency (RF) domain, optical wireless communication (OWC) is regarded as a promising complementary technology due to concerns on RF-induced electromagnetic interference, data security, and the possible impact of RF waves on human tissues [3].

Managing the multiple access (MA) in this context is a big challenge, as one should deal with transmission from multiple users, each with a number of SNs and sharing the same communication channel. Therefore, suitable MA techniques should be employed by sharing the available resources among the users, e.g., using time, frequency, or code division schemes [4]–[7]. Here, we classify MA schemes into scheduled- and contention-based techniques.

Scheduled-based techniques include: (i) time division MA (TDMA), where different time-slots are assigned to different users; (ii) frequency division MA (FDMA), where users are allocated different frequency sub-bands; and (iii) code division MA (CDMA), where users are distinguished by different codes. Contention-based or packet radio techniques, on the other hand, such as ALOHA and carrier-sense MA with collision avoidance (CSMA/CA), can be viewed as a particular form of TDMA, where time-slots are allocated to the users in an adaptive manner [8], [9].

A few recent works have studied some of these MA schemes within the context of OWCs. For instance, the authors in [10] employed a dynamic TDMA scheme to maximize the spectral efficiency of a visible light communication (VLC) downlink transmission system. Also, non-orthogonal MA (NOMA) and orthogonal FDMA (OFDMA) have been extensively studied for VLC applications [11]–[13]. In [13], the asymmetrically-clipped O-OFDMA signaling was considered for optical extra-WBAN links while accounting for synchronization errors. In [14], a MA multi-band carrierless-amplitude-and-phase modulation (m-CAP) was considered for multi-user VLC links. The practical implementation of MA non-orthogonal m-CAP in the context of multi-user VLC links was also considered in [15]. In the context of WBANs, [16] and [6], [7] studied the use of optical CDMA for intra- and extra-WBAN connectivity, respectively. Lastly, a contention-based MA distributed queuing scheme with a slot reservation mechanism was proposed in [17].

For intra-WBAN links, optical CDMA is not a suitable
scheme due to its high complexity and low bandwidth efficiency for relatively large numbers of users, resulting from the requirement of long orthogonal complementary codes [13]. Also, TDMA is not well suited for managing the heterogeneous traffic of WBAN links given its highly accurate synchronization requirements. NOMA-based schemes require a relatively high signal-to-noise ratio (SNR) to perform optimally, which is not often the case for optical intra-WBANs. OFDMA is not a suitable scheme due to synchronization requirements and high signal peak-to-average power ratio, which make it sensitive to the system non-linearity. On the other hand, contention-based MA schemes benefit from a rather simple implementation, at the cost of relatively low energy efficiency and induced large random delays due to the high probability of collisions, especially for a relatively large number of users.

This paper aims to study the use of MA \( m \)-CAP for intra-WBAN links. In fact, MA \( m \)-CAP is a MA technique that can be considered as a variation of FDMA. Here, the signal bandwidth is divided into multiple independent sub-bands, which can be then dynamically allocated to each user to satisfy their needs in terms of the data-rate and signal quality. Using the outage probability criterion, we evaluate the performance of \( m \)-CAP within the intra-WBAN context while considering realistic statistical channel models, previously developed in [18]. In addition, we investigate the impact of the system parameters such as bandwidth, number of sub-bands, and pulse shaping roll-off factor on the system performance.

The remainder of the paper is organized as follows. Section II, introduces the concept of MA \( m \)-CAP. Next, the main assumptions and the considered scenario are presented in Section III. Numerical results including the outage probability for different SN positions and different system parameters are presented in Section IV. Lastly, Section V concludes the paper.

II. MULTIPLE ACCESS \( m \)-CAP

When using \( m \)-CAP, the signal bandwidth is divided into \( m \) independent sub-bands using digital filters, where the modulation order and the transmit power can be set independently for each sub-band. In MA \( m \)-CAP, one or several sub-bands are allocated to each user. That is, users that need higher data-rates or experience a low quality of the received signal can be dynamically allocated by more sub-bands to improve their performance.

The block diagram of MA \( m \)-CAP is shown in Fig. 1. At the transmitter (Tx), data streams of each user are divided among the allocated sub-bands. The \( m \)-symbol streams are mapped on their corresponding quadrature amplitude modulation (QAM) mapper, each with a specific modulation order. The mapped symbols are then up-sampled and decomposed to their in-phase (I) and quadrature (Q) components, which are then filtered with orthogonal square-root-raised-cosine (SRRC) pass-band filters centered at different frequencies depending on the sub-band index, as shown in Fig. 1(a). Each component of the sum represents a sub-band that can be assigned to a user. The impulse response of the SRRC filter \( g_{\text{SRRC}}(t) \) along with the I/Q filters corresponding to sub-band \( n \) are given as [19]:

\[
g_{\text{SRRC}}(t) = \frac{\sin \left( \pi (1 - \beta) \frac{t}{T_s} \right) + 4\beta \frac{t}{T_s} \cos \left( \pi (1 - \beta) \frac{t}{T_s} \right)}{\pi \frac{t}{T_s} \left( 1 - \left( 4\beta \frac{t}{T_s} \right)^2 \right)},
\]

where

\[
g_{I}^{n} [t] = g_{\text{SRRC}}(t) \cos \left( \frac{\pi}{T_s} (2n - 1) (1 + \beta) \right),
\]

\[
g_{Q}^{n} [t] = g_{\text{SRRC}}(t) \sin \left( \frac{\pi}{T_s} (2n - 1) (1 + \beta) \right).
\]

Here, \( 0 < \beta < 1 \) is the SRRC roll-off factor, \( T_s \) denotes the symbol duration, and \( n \) is the index of the sub-carrier. Note that \( \beta \) is kept small in order to increase the spectral efficiency. Up-sampling is done by means of zero-padding, where the number of padded zeros per symbol is given by [20]:

\[
n_s = 2 \left[ 2m(1 + \beta) \right],
\]

where \([.]\) is the ceiling function. The overall transmitted \( m \)-CAP signal \( S_{\text{tot}}(t) \) is then expressed as:

\[
S_{\text{tot}}(t) = \sum_{n=1}^{m} s_n^{n}(t) = \sum_{n=1}^{m} \left[ s_I^n(t) @ g_I^n(t) - s_Q^n(t) @ g_Q^n(t) \right],
\]

where \( s_n^{n}(t) \) stands for the \( n^{th} \) user signal with \( s_I^n(t) \) and \( s_Q^n(t) \) I and Q components, respectively, and \( @ \) denotes the time convolution function.

At the receiver (Rx) side, for the user \( n \), the down-sampled I/Q components for each of the user’s assigned sub-bands are recovered from the received signal \( R_{\text{tot}} \) using matched filters \( g_I^n(-t) \) and \( g_Q^n(-t) \), respectively, as illustrated in Fig. 1(b). The recovered data stream is obtained after recombining the de-mapped symbol streams.

III. GENERAL ASSUMPTIONS

We consider an intra-WBAN network for a patient walking inside a hospital room. A star network topology is considered with a number of SNs \( N_{\text{SN}} = 10 \), which are connected to a CN, placed on the patient shoulder, see Fig. 2 [18]. We consider an accurate representation of the body parts by taking a 3D mesh representation of the patient’s body, as shown in Fig. 2. Also, we consider a hospital room of dimensions \((5 \times 5 \times 3)\) m \(^3\) with plaster walls and a pinewood floor with the reflectivity values given in Table I [21], together with the other main simulation parameters. The room is considered without any furniture for simplicity.

The link performance is evaluated using Monte Carlo simulations, where channel realizations are generated using statistical models that account for both patient’s local and global mobility and body shadowing. The global mobility is modeled using a modified random waypoint model, see [18] for more detail. The above-mentioned statistical models are derived based on ray-tracing simulations with Zemax Opticstudio software, which is used to obtain the channel impulse response and the channel DC gain \( H_0 = \int h(t) \, dt \). These models are fitted to the simulated cumulative distribution function of \( H_0 \) based on the non-parametric kernel density estimation (KDE) method for a
Gaussian kernel [22], [23]. Figure 3 shows the simulated and fitted cumulative distribution functions (CDFs) for each link between SNs and the CN.

We placed at each SN an infrared LED with a frequency response, modeled as a first-order low-pass filter (LPF) with the cut-off frequency $f_{\text{LED}} = 20 \text{ MHz}$, with central wavelength $\lambda_0 = 850 \text{ nm}$ and full-width at half-maximum spectral width $\Delta \lambda = 30 \text{ nm}$, assumed to have a Lambertian radiation pattern with order 1. At the CN, a PIN photo-detector (PD) is used with active area $1 \text{ cm}^2$ and a Rx field-of-view (FOV) of $60^\circ$.

The received signal at the PD output can be written as:

$$r_n = R \sum_{k=1}^{m} s^k H_0^k + n_{\text{tot}}^k,$$

(6)

where $R$, $s^k$, and $H_0^k$ stand for the PD responsivity, the $k$th transmitted m-CAP signal intensity and the DC gain of the $k$th channel, respectively. Also, $n_{\text{tot}}^k$ is the $k$th user total photocurrent noise, accounting for thermal, background, dark, and shot noises, and modeled as Gaussian with variance $\sigma_{\text{tot,k}}^2$:

$$\sigma_{\text{tot,k}}^2 = \sigma_0^2 + \sigma_{s,k}^2,$$

(7)

where $\sigma_0^2 = \sigma_{\text{th}}^2 + \sigma_{b}^2$ with $\sigma_{\text{th}}^2$ and $\sigma_{b}^2$ being the variances of thermal and background noises, respectively, which depend on

---

Fig. 1. The concept of MA m-CAP with functional blocks of: (a) the Tx, and (b) the Rx.

Fig. 2. Considered placements of the CN and SNs [24].
TABLE I
SIMULATION PARAMETERS.

<p>| | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Tx (SN)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\lambda_0)</td>
<td>850 nm</td>
<td></td>
</tr>
<tr>
<td>(\Delta \lambda)</td>
<td>30 nm</td>
<td></td>
</tr>
<tr>
<td>(f_{RF})</td>
<td>20 MHz</td>
<td></td>
</tr>
<tr>
<td><strong>Rx (CN) [25]</strong></td>
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<td></td>
</tr>
<tr>
<td>FOV</td>
<td>60°</td>
<td></td>
</tr>
<tr>
<td>Active area</td>
<td>1 cm(^2)</td>
<td></td>
</tr>
<tr>
<td>(\kappa)</td>
<td>0.85 A/W</td>
<td></td>
</tr>
<tr>
<td>TIA load resistor</td>
<td>50 Ω</td>
<td></td>
</tr>
<tr>
<td>(J_0)</td>
<td>200 μA</td>
<td></td>
</tr>
<tr>
<td><strong>Room [21]</strong></td>
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<td></td>
</tr>
<tr>
<td>Dimensions</td>
<td>(5 (\times) 5 (\times) 3) m(^3)</td>
<td></td>
</tr>
<tr>
<td>Walls reflectivity</td>
<td>0.5T (Plaster)</td>
<td></td>
</tr>
<tr>
<td>Ceiling reflectivity</td>
<td>0.85 (Plaster)</td>
<td></td>
</tr>
<tr>
<td><strong>Body</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimensions</td>
<td>(1.7 (\times) 0.3 (\times) 0.2) m(^3)</td>
<td></td>
</tr>
<tr>
<td>Reflectivity</td>
<td>0 (absorbing)</td>
<td></td>
</tr>
<tr>
<td><strong>MA m-CAP</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(m)</td>
<td>10, 20, 30</td>
<td></td>
</tr>
<tr>
<td>Filter length</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>(\beta)</td>
<td>0.1, 0.5, 0.9</td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td>BPSK</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Simulated CDF for the DC optical channel gain \(H_0\) for 518 realizations and the corresponding estimated CDF by KDE with Gaussian kernel.

For the considered system, we present here numerical results on the performance of the intra-WBAN links in terms of the outage probability \(P_{out}\), which is calculated considering a target bit-error-rate (BER) of \(10^{-3}\). For this, we generated \(10^3\) realizations of \(H_0\) for each SN-CN link, and we transmitted through each of these channel realizations a data stream of length \(10^4\) bits. Signal demodulation at the Rx is done at the output of matched filters. The considered scenario by default is that of a patient having 10 SNs (communicating with a CN), as shown in Fig. 2, and walking inside a hospital room. Lastly, the TIA load resistance \(R_L = 50 \Omega\), a relatively high background noise level with \(J_0 = 100 \mu A\), and a length of 12 for the m-CAP filter are considered.

IV. NUMERICAL RESULTS

A. Performance of MA m-CAP for an ideal channels

Let us consider first the case of a fixed channel DC gain of \(H_0 = 2 \times 10^{-6}\) for all SN-CN links. We allocate to each user a unique sub-band, i.e., we take \(m = 10\), and consider three different values of the SRRC roll-off factor \(\beta = 0.1, 0.5\), and 0.9. It is assumed that each SN transmits at a data-rate of 500 kbps with binary-phase shift keying (BPSK) modulation and occupying each a sub-band of 1.1, 1.5, and 1.9 MHz (given the considered values of \(\beta\)); the resulting total system bandwidth are then 11, 15, and 19 MHz, respectively. Figure 4 shows BER plots versus the average transmit power per user, \(P_t\), where we notice an improved performance by increasing \(\beta\). In fact, a higher \(\beta\) results in reduced inter-channel interference, and hence, in a lower required \(P_t\) to achieve a given BER. Nevertheless, this also results in increased overall system bandwidth. So, for relatively high data rates, the low pass characteristics of the LED will cause a power penalty at higher frequencies, which can be addressed in part by bit and/or power loading.

B. Performance of MA m-CAP for WBAN channels

Consider now the case of practical WBAN channels accounting for the user local and global mobility. The data rate per SN links is set to 500 kbps with BPSK, considering SRRC with \(\beta = 0.1\), corresponding to a total electrical signal bandwidth on the order of 10 MHz. Figure 5 shows the outage probability \(P_{out}\) plots versus \(P_t\) for a range of SNs and \(\beta = 0.1\). For instance, we notice from \(P_{out}\) plots for SN9-CN and SN2-CN (placed on the ear and right leg, respectively, see Fig. 2) that the former link has a lower performance, which means that it is more subject to mobility, compared to the latter. We observe the same trend between SN5-CN and SN10-CN links. Interestingly, despite being slightly affected by the user mobility, SN8-CN has a relatively worse performance, compared to SN7-CN (SN8 and SN7 are placed on the waist and on the shoulder of the patient, respectively). This can be explained by the periodic shadowing resulting from the swing of the right arm during the walk (please refer to [18] for more details). Also, SN3-CN has a better performance compared to SN2-CN (SN3 and SN2 being placed on the chest and on the ear, respectively). This is

Fig. 4. BER versus average transmit power per user \(P_t\) for MA 10-CAP system. BPSK modulation for all sub-bands.

The BER curves are defined as the probability of error per bit, i.e., the fraction of bits received in error. The considered BER target is 10\(^{-3}\) for all the SN-CN links.
due to the fact that the former experiences first-order reflections, whereas the latter involves more second-order reflections. Lastly, the maximum $P_t$ to achieve a target $P_{out} = 10^{-2}$ is approximately 50 mW (SN4), which is far less than the eye safety threshold of 300 mW/Sr, corresponding to a transmit power of 1150 mW [6], [27].

C. Impact of $m$-CAP parameters on the link performance

Figure 6 depicts the $P_{out}$ versus the sum rate (i.e., the whole WBAN data rate, assuming equal rate for all SN-CN links) for a range of SNs, $P_t = 50$ mW, and $\beta$ of 0.1, 0.5, and 0.9. Note that, for SN10-CN link, $P_{out}$ is lower than $10^{-3}$ for $\beta = 0.9$. We notice, an improved performance with increase in $\beta$. For instance, the maximum throughput values to achieve a target $P_{out}$ of $10^{-2}$ for the SN5-CN link are about 5.5, 8.5, and 12.5 Mbps for $\beta$ of 0.1, 0.5, and 0.9, respectively. This can be explained by the reduced ICI for higher $\beta$.

To investigate the impact of the number of sub-bands per link $N_{sb} = m/N_{SNs}$, plots of $P_{out}$ versus the sum rate are shown in Fig. 7 for several SN-CN links, $P_t = 15$ mW, $\beta = 0.1$, and $m = 10, 20, and 30$. As expected, the system performance improves with the increased $N_{sb}$, elucidating hence the benefit of using narrower sub-bands. This is because the channel frequency response (including that of the LED) within a sub-band is closer to a flat response when using a larger $m$.

V. CONCLUSIONS

We studied the performance of MA $m$-CAP for optical intra-WBAN links in a typical medical application while considering realistic statistical models for the channel and accounting for the frequency response of the LED. The impacts of different signaling parameters, including the SRRC pulse shaping roll-off factor, number of sub-bands per link $N_{sb}$, transmit power, and overall sum rate, were investigated based on the outage probability criterion. The presented results suggest using $m$-CAP as a promising scheme with acceptable implementation complexity in the considered application scenarios.

ACKNOWLEDGMENT

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REFERENCES

The text appears to be a page from a research paper or a document, containing references to various studies and publications. Here are some key points:

2. Wireless Communications - Principles and Practice (A. Goldsmith).
4. Key findings and applications in medical settings, such as optical signal transmission (O. Haddad, M. A. Khalighi, and A. Zubow).

This page likely contains a list of references, possibly including journal articles, conference papers, and books relevant to the field of wireless communications and their applications in medical contexts.