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Wireless Body-Area Networks in Medical Applications Using Optical Signal Transmission

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Abstract: We consider optical wireless technology-based medical wireless body-area networks (WBANs). After presenting the most recent results on channel modeling and signal transmission, a new multiple access MAC layer scheme is proposed for intra-WBAN links. © 2021 The Author(s)

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1. Introduction

Wireless body-area networks (WBANs) have recently received increasing attention thanks to the advances made in the very large-scale integration of sensors and actuators. In medical applications, WBANs can be used for real-time vital signs remote monitoring of patients in health-care centers and elderly people at home [1]. A WBAN consists of a set of sensor nodes (SN) that are connected to a coordinator node (CN) through intra-WBAN links. The CN then transmits the collected data to a mobile device or a fixed access point (AP) via an extra-WBAN link [2, 3]. WBANs have stringent requirements regarding energy consumption and latency, as well as specific characteristics such as the non-stationary nature of the networks due to the movement of the patients, and the heterogeneity of applications [4]. Concerning WBAN wireless connectivity, most research works consider the use of RF technologies in the unlicensed ISM bands, which are subject to interference and data security issues [1, 4]. This has motivated the consideration of optical wireless communications (OWC) as an interesting alternative technology for medical WBANs. OWC has the advantages of immunity to external interference, inherent security due to the indoor confinement of light, and a negligible small-scale fading effect [5].

2. OWC-based WBANs for medical monitoring

Figure 1 illustrates a typical scenario of a hospital ward with several patients equipped with medical WBANs. Intra-WBAN connectivity is realized through infra-red (IR) links, assuming that the SNs are not covered by the patient's cloths. For extra-WBANs, IR links are used for uplink (i.e., from the CN to the AP), and visible-light (VL) links are used for downlink, which can be conveniently done through the LED luminaires. Interference between intra- and extra-WBAN IR links can be avoided by using different wavelengths. Nevertheless, efficient multiple-access (MA) signaling should be used to avoid interference between the (extra-WBAN) signals of different users, as well as between the (intra-WBAN) links of the different SNs. Whereas the optical code-division multiple access (O-CDMA) has been shown to be a suitable MA scheme in the physical (PHY) layer for the case of extra-WBANs [3], managing MA interference in intra-WBAN links is more challenging.

3. Channel characterization and basic PHY design for optical WBANs

The specificities of optical WBANs include high sensitivity to body shadowing and negligible small-scale fading effect. Considering a realistic mobility model for a user inside a typical hospital room, and based on extensive Monte Carlo ray-tracing simulations, [2, 6] showed the high impact of the body position and orientation inside the room on the variations of the channel gain. The optical channels can nevertheless be considered as effectively flat for low-to-moderate data-rates. They also have slower time variations (typical coherence times of a few seconds), compared to the RF counterparts (coherence times of tens of ms). This allows using larger packet sizes for the former, thus a lower pilot overhead and a simplified power control over successive frames. To evaluate the link performance in a practical scenario, [2, 6] proposed best-fit statistical models (to ray-tracing simulated data) for the channel gain. For the cases of intra- and extra-WBAN links, the Gamma distribution and non-parametric kernel density estimation based on Gaussian kernel were proposed, respectively.

For intra-WBAN connectivity, the link performance is significantly affected by shadowing resulting from local body mobility, which also depends on the position of the CN. Another consideration is the transmit optical power, given the eye-safety limitations and the typical ambient light level, and accordingly, the choice of the photo-detector at the receiver (Rx). For the intra-WBAN case, given the constraints on the system complexity and power

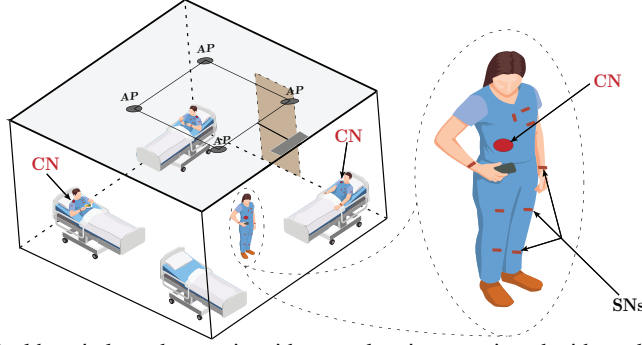


Fig. 1: Typical hospital ward scenario with several patients equipped with medical WBANs.

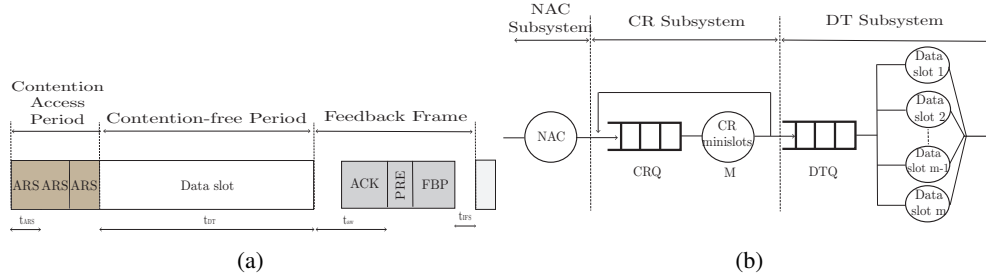


Fig. 2: (a) DQ frame structure and (b) multichannel DQ-MAC model.

consumption, a PIN-based Rx (CN) is the suitable choice. However, for extra-WBAN uplink, using an avalanche photodiode at the Rx (AP) is suggested except under strong background radiations; this allows increased robustness against shadowing when using a more sensitive PD, as well as reduced required IR power level at the Tx (CN). Lastly, the extra-WBAN link reliability can be significantly improved by using multiple APs (see Fig. 1).

4. Addressing MA for intra-WBAN links

When several patients share the same hospital ward, the used MA scheme should avoid inter-sensor interference for a given user (interference in uplink operation from SNs towards CN), as well as the interference of the sensors of a user with those of another user. Given the potentially large number of SNs that could be used for each patient, developing a robust MA scheme in the PHY layer is quite challenging. More efficient MA management can be achieved through the medium access control (MAC) layer by minimizing packet collisions and their scheduling to ensure acceptable energy consumption and access delay. MAC protocols can be divided into two major categories of contention-based and scheduled-based protocols. The former protocols such as carrier-sense MA with collision avoidance (CSMA/CA) are not energy efficient enough for our application and have a larger latency when the traffic is unpredictable, whereas scheduled-based protocols are not sufficiently spectrally efficient, given the heterogeneous traffic of the medical sensors [7]. This motivates the use of distributed queuing (DQ) based protocols, which can address the both above-mentioned issues [8]. Given the potentially large number of medical sensors and the presence of several users, even with DQ, the probability of successful access to the channel and data transmission throughput could be very low. This latter issue can be dealt with optical orthogonal frequency-division MA (O-OFDMA) or multi-band carrier-less amplitude and phase modulation (m -CAP) [9].

5. DQ MAC protocol with m -CAP signaling

Here, we propose to combine the DQ random access with multi-user (MU) m -CAP to provide both efficient random access and data transmission capability for optical intra-WBANs. As illustrated in Fig. 2a, the frame structure of DQ-MAC is composed of three parts: a contention resolution (CR) window, which is divided into M CR mini-slots for the transmission of access-request sequences (ARS); a contention-free data transmission (DT) window; and a window for downlink feedback packet (FBP) from the CN. The basic idea of DQ-MAC is to restrict the users contention to short access-requests while keeping the larger frame part for sending data. Figure 2b illustrates the system model of the proposed multichannel (i.e. m -CAP based) DQ scheme. It consists of three subsystems of new-user access control (NAC), CR, and DT. The NAC prevents newly arrived SNs to contend for CRs until the resolution of all previous collisions. Then, at the start of a new frame, SNs which have data to send and which have not yet sent an ARS, will randomly choose one of the M available CRs. Depending on the reception status at the CN side, SNs will enter either the CR queue (CRQ) in the case of collision detection, or the DT queue (DTQ) otherwise. This information is notified to the SNs in the FBP at the end of the frame [7]. For

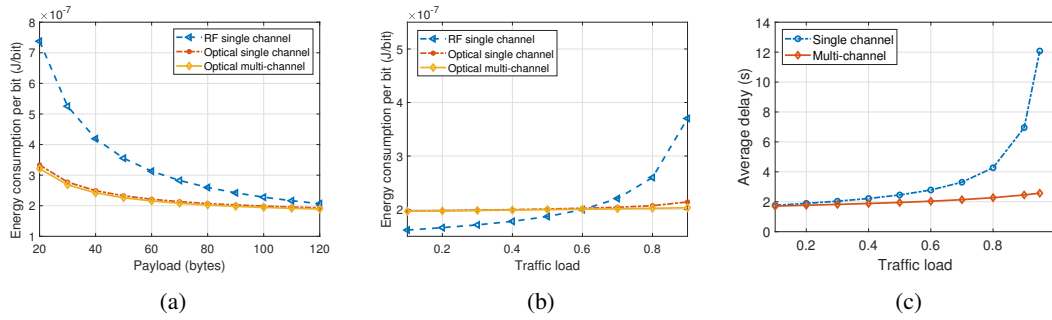


Fig. 3: (a) Energy consumption vs. payload length for $\lambda = 0.8$, (b) energy consumption vs. traffic load, (c) average delay.

SNs that enter the CRQ, a tree-splitting algorithm is used to resolve the contentions. Also, SNs that successfully enter the DTQ will be allowed to transmit their data in a first-in first-out order, where up to m SNs can transmit within a single DT window over the available m sub-bands of the MU m -CAP scheme.

6. Numerical Results

Figure 3 shows the simulation results using MAC parameters from [7, Table 1], and considering an ideal channel (i.e., with no packet loss due to transmission). For the sake of comparison, two cases of RF- and OWC-based networks are considered. Power consumption in transmit, receive, and idle modes are respectively set to 22.09, 35.23, and 0.712 mW for the RF transceiver (acc. ZigBee), and 40, 0.5, 0.3 mW for the OWC transceiver (acc. IrDA). From Fig. 3a, we notice the decrease in energy consumption of DQ schemes for the cases of RF and single channel (OOK) and multichannel (10-CAP) OWC, assuming a traffic load of $\lambda = 0.8$ packets/frame. OWC allows a reduced energy consumption for payloads shorter than 120 bytes. From Fig. 3b, interestingly, energy consumption does not increase considerably with increase in λ for OWC-based systems. Nevertheless, the RF-based system has a lower energy consumption for $\lambda \lesssim 0.6$. In fact, the energy consumption of OWC-based systems is higher in the transmit mode, but much lower in the receive and idle modes. For large λ , SNs will spend most of the time in idle/receive modes. Lastly, Fig. 3c shows the improvement in terms of average delay using m -CAP.

7. Conclusions and future research directions

This paper presented an overview of the recent research on OWC-based WBANs for medical applications. In order to manage the MA requirement, DQ in the MAC layer together with m -CAP transmission was proposed and its efficiency shown through numerical results. Future research will investigate the proposed scheme with realistic optical WBAN channel models, as well as its performance evaluation under heterogeneous traffic conditions.

8. Acknowledgment

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