



# Channel Allocation for Medical Extra-WBAN Communications in Hybrid LiFi-WiFi Networks

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**Abstract.** Electronic health (e-health) systems based on optical wireless communication (OWC) provide a means of meeting the low latency requirements of medical applications, while ensuring little or no interference to sensitive devices. Notwithstanding, an optical wireless link is susceptible to temporal obstructions and a reliable radio frequency (RF) link may still be required. Against this backdrop, hybrid radio-optical extra-body area networks are considered viable solutions towards the attainment of pervasive healthcare in the Internet of Things (IoT) era. In practice, these networks will more often than not be used for both medical and non-medical applications, which will increase the competition for limited channel resources. Thus, in this paper, we propose a channel allocation framework for hybrid LiFi and WiFi networks, with the objective of safeguarding the quality of service (QoS) of medical applications. The scheme allocates channels for medical applications first, and then shares the remaining channels in a proportionally fair manner. Simulation results validate the effectiveness of the proposed solution in minimizing the waiting time of the delay-constrained medical packets.

**Keywords:** Channel allocation · Optical wireless communications · Remote health monitoring · Wireless body area networks · Wireless sensor networks

## 1 Introduction

To overcome the shortcomings of legacy healthcare systems, information and communication technologies (ICTs) are being introduced to enable new healthcare services such as remote health monitoring. Upcoming electronic health (e-health) systems will achieve pervasive healthcare, by providing quality and cost-effective services to patients irrespective of their location using ICTs,

enabling the efficient monitoring of patients with chronic conditions and provision of proactive treatment [1]. Key to the realization of ubiquitous e-health systems is the application of wireless body area networks (WBANs).

A WBAN that is deployed on a patient typically consists of a gateway and heterogeneous medical sensors for monitoring physiological signals such as body temperature, respiratory rate, and blood pressure [2]. Real-time communication among medical sensors, the gateways or coordinator nodes (CNs), and the access points (APs) is critical to ensure that the sensed medical data is sent to the appropriate medical center on time for processing and analysis. This will allow for timely treatment decisions to be taken by the health professionals [3]. The unique requirements of medical WBANs poses a number of technical challenges to be overcome including ensuring reliable, low latency, and energy-efficient communications [4]. Yet, medical sensor nodes in a WBAN may have different data rate and latency requirements. Another daunting task in WBAN networking is maintaining uninterrupted communications, in view of physical obstructions and signal interference from nearby wireless networks. Owing to the non-stationary nature of their surrounding networks, adaptive strategies will have to be devised to meet the quality of service (QoS) targets of WBAN transmissions over extra-body links.

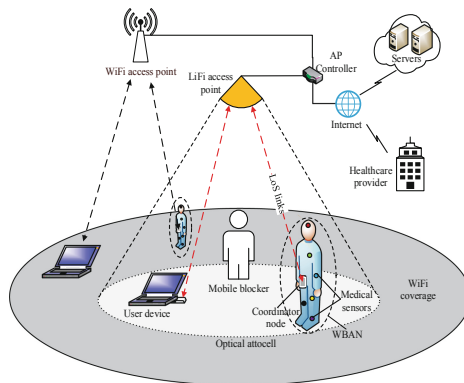
Due to the interference caused by radio frequency (RF) technologies to sensitive devices, the non-interfering optical wireless technologies are becoming attractive for application in healthcare systems [5]. Besides avoiding interference, optical wireless communication (OWC) offers tremendous data rates on the back of license-free high bandwidth channels. However, link reliability is of more concern, due to the possibility of misalignment between transceivers, and the vulnerability of optical wireless links to blockages. In [6], the authors focused on channel characterization for the uplink (UL) communication between the CN on a patient's body and an optical wireless AP in a typical hospital room, taking into account the impact of local body movements, user's mobility, and body shadowing. An all-optical wireless network was designed in [7] for off-body sensor communications using infrared (IR) in the UL and visible light for the downlink (DL). As an alternative to RF-based body area networks, an optical body area network (OBAN) was proposed in [7] to capture vital signals from several patients by means of visible light communication (VLC) and orthogonal codes. In terms of remote health monitoring, OWC and RF access networks can be integrated to achieve reliable high rate extra-body communications with minimal or infrequent interference to devices. For instance, the authors in [8] developed a dual hop communication system, in which an optical wireless transceiver acts as relay node, by converting optical signals to RF signals and transmitting them to a distant laboratory via RF links. Envisioning the hospital of the future, the authors in [9] presented a hybrid wireless network that can be reconfigured for both optical and radio-based extra-body wireless communications.

WBANs located at the home or the workplace may have to integrate with the existing wireless networks such as WiFi or LiFi, and coexist with their associated user devices (UDs). This suggest the need for channel reservation for medical

applications, to ensure that the activities of UDs do not jeopardize their QoS. However, to the best of our knowledge, none of the preceding works on OWC networks for e-health tackled the issue of channel allocation for the extra-body tier. Hence, in this paper, we address the channel allocation problem in hybrid LiFi and WiFi networks for extra-body communications, in consideration of traditional UDs normally associated with local area networks. The rest of the paper is summarized as follows. Section 2 describes the system model of the hybrid LiFi and WiFi extra-body area network. In Sect. 3, we present the channel allocation strategy for the network. The performance of the proposed scheme is evaluated in Sect. 4 and the conclusions are drawn in Sect. 5.

## 2 System Model

The hybrid network consists of a LiFi AP coexisting with a WiFi AP in an indoor setting, to provide enhanced wireless coverage and capacity for the wireless devices. Both LiFi and WiFi offer bi-directional communication for UDs equipped with a multimode transceiver. UDs receive visible light or radio signals in the DL and transmit infrared or radio signals in the UL. Additionally, there are coexisting WBANs consisting of medical sensors and a CN as shown in Fig. 1. Data from the medical sensors are collected by the CN and transmitted via a LiFi or WiFi AP. In this sense, an extra-WBAN link refers to a wireless link that connects an WBAN and a wireless AP via the CN. The AP controller routes data between the Internet and indoor network, and selects an AP for DL transmission to a UD within coverage area of that AP. In addition, the controller manages the channel resource allocation and packet scheduling for UDs and extra-WBAN communications simultaneously.



**Fig. 1.** System model of hybrid LiFi and WiFi access network.

In our system model, each WBAN contains heterogeneous sensors for collecting different medical data including electrocardiogram (ECG), electroencephalogram (EEG), electromyogram (EMG), blood glucose level, blood pressure, and

respiratory rate. Based on the type of data, medical packets have different delay constraints. For instance, the ECG, the EEG, and the EMG packets require a maximum delay of 250 ms, whereas medical packets with information on blood glucose, blood pressure, and respiratory rate have delay requirements of 20 ms, 750 ms, and 600 ms respectively [10]. Fulfilling the delay requirements of medical packets is critical for the early detection of complications and the timely intervention by healthcare practitioners. Besides, if the waiting time of a medical packet in the queue exceeds its delay requirement it will be dropped by the CN. We classify the data packets into two main categories, based on the nature of information carried. Packets sent from the WBANs are referred to as medical packets, whereas the packets that emanate from traditional UDs, such as smart-phones and laptops, are known here as general packets. The medical packets are further grouped according to their delay requirements, where  $C$  is the number of classes. In this work, we consider four classes of medical packets ( $C = 4$ ). A class refers to a group of medical packets with the same delay requirements, such as blood glucose ( $c = 1$ ), ECG/EEG/EMG ( $c = 2$ ), respiratory rate ( $c = 3$ ), and blood pressure ( $c = 4$ ).

We denote the general and medical packets by  $g$  and  $m$  respectively. Packet arrivals follow a Poisson distribution, in which  $\lambda_g$  represents the aggregate arrival rate of general packets and  $\lambda_m$  denotes the aggregate arrival rate of medical packets. Moreover,  $\tau_c$  denote the delay requirement of class  $c$  medical packets. Supposing there are  $|W|$  WBANs and  $|U|$  UDs in the hybrid network and each device has its own queue for packet transmissions, the number of UL queues for medical data and general data transmissions are  $W$  and  $U$  respectively. There are  $L$  channels for UL transmissions in the LiFi network, and the WiFi network has  $R$  UL channels. Part of the UL channels resources in each network is allocated to the UDs and part for extra-WBAN transmissions. Packets from a WBAN or UD could be served by the LiFi or WiFi UL resources, depending on the condition of optical wireless channel and the transmission mode. To this end, a portion of the UL channels in the WiFi network is allocated for extra-WBAN medical data transmissions and part for the general packets transmissions. The wireless infrared connections are prone to link interruptions, during which a change of transmission mode to RF may be required to maintain data transmission.

### 3 A Proposed Channel Allocation Strategy

In this section, the strategy for allocating the UL channels resources is presented, taking into account the occurrence of optical wireless link blockages and the need for link switching.

Let  $E[D_w]$  be the expected transmission delay of medical packets of the  $w^{th}$  CN and  $\hat{D}_m$  be the delay threshold for meeting the QoS requirements of any medical packet. Then, we should always aim at fulfilling the following requirement:

$$E[D_w] \leq \hat{D}_m \quad (1)$$

Given an  $M/M/1$  queuing system with a first-in, first-out (FIFO) policy [11], average waiting delay  $D$  can be computed as

$$D = \frac{1}{\mu - \lambda}, \tag{2}$$

where  $\mu$  is the service rate of the queue and  $\lambda$  is the arrival rate of packets to the queue. Thus, to satisfy Eq. 2, the service rate must meet the following constraint for a LiFi UL:

$$\hat{\mu}_w^{IR} \geq \frac{1}{\hat{D}_m + \lambda_w}, \tag{3}$$

where  $\hat{\mu}_w^{IR}$  is the minimum LiFi service rate offered to the UL queue of the  $w^{th}$  CN and is obtained by

$$\hat{\mu}_w^{IR} = \frac{X_{IR} \hat{N}_w^{IR}}{\hat{\kappa}_m}, \tag{4}$$

where  $\kappa_m$  and  $X_{IR}$  are the expected size of medical packets and the LiFi per-channel transmission rate respectively.  $\hat{N}_w^{IR}$  is the minimum UL channel resources allocated to the  $w^{th}$  CN for medical packet transmissions. Combining Eqs. 3 and 4,  $\hat{N}_w^{IR}$  can be expressed as

$$\hat{N}_w^{IR} = \frac{\kappa_m}{X_{IR}} \left[ \frac{1}{\hat{D}_m} + \lambda_w \right], \tag{5}$$

Due to the criticality of extra-WBAN transmissions, we derive the amount of LiFi UL channel resources allocated for the  $w^{th}$  CN, when transmitting over LiFi network, as

$$N_w^{IR} \simeq \hat{N}_w^{IR} + (L - A)(\lambda_w / \lambda'_m), \quad A \leq L \tag{6}$$

where  $\lambda_w$  is the arrival rate of UL medical packets at the  $w^{th}$  CN and  $\lambda'_m$  is the aggregate arrival rate of UL medical packets of the CNs in LiFi network.  $A = \sum_{w=1}^W \hat{N}_w^{IR} + \sum_{u=1}^U N_u^{IR}$ , where  $N_u^{IR}$  is the number of LiFi UL channel resources allocated to the  $u^{th}$  UD in LiFi network and is given by

$$N_u^{IR} \simeq \left[ L - \sum_{w=1}^W \hat{N}_w^{IR} \right] \frac{\kappa_g \lambda_u}{\kappa_g \lambda_g + \kappa_m \lambda_m} \tag{7}$$

By integrating the LiFi network into an existing wireless local area network (WLAN) such as WiFi network, packets from CNs that cannot be served by the LiFi network, due to blockage or coverage limitations, can be served by the WiFi after a switching delay. To this end, the number of UL channel resources reserved for medical packet transmissions of the  $w^{th}$  CN over WiFi network, is given by

$$N_w^{RF} \simeq \hat{N}_w^{RF} + (R - H) \left( \frac{T'_w}{\sum_{w=1}^W T'_w} \right), \quad H \leq R \tag{8}$$

where  $T_w'$  is the cumulative connection time of the  $w^{th}$  CN to the WiFi network and  $\hat{N}_w^{RF}$  is the minimum amount of UL channel resources reserved for the medical packet transmissions of the  $w^{th}$  CN over WiFi network.  $H = \sum_{w=1}^W \hat{N}_w^{RF} + \sum_{u=1}^U N_u^{RF}$ , where  $N_u^{RF}$  is the number of WiFi UL channel resources allocated to the  $u^{th}$  UD and is obtained as

$$N_u^{IR} \simeq \left[ R - \sum_{w=1}^W \hat{N}_w^{RF} \right] \frac{\kappa_g \lambda_u T_u'}{\kappa_g \lambda_g \sum_{u=1}^U T_u' + \kappa_m \lambda_m \sum_{w=1}^W T_w'}, \quad (9)$$

where  $T_u'$  is the total connection time of the  $u^{th}$  UD to the WiFi network.  $\hat{N}_u^{RF}$  is the minimum WiFi UL channel resources allocated to the device and is given by

$$\hat{N}_w^{RF} = \frac{\kappa_m}{X_{RF}} \left[ \frac{1}{\hat{D}_m} + \lambda_w \right], \quad (10)$$

where  $X_{RF}$  is the per-channel transmission rate of WiFi network.

## 4 Simulation and Results Discussion

In the simulation scenario, there are two WBANs within the network area. One of the WBANs is stationary in the LiFi attocell and is described as WBAN-S. The other WBAN, which is denoted as WBAN-M, is mobile between the LiFi and the WiFi only coverage areas. In addition, a number of UDs that can connect to either LiFi or WiFi are integrated into the simulation process. The UL queue of the CNs of each WBAN is modeled and simulated using the  $M/M/1$  queuing model, in which the packet arrival process is Poisson distributed and the service time is exponentially distributed. We also factor the blockage of the optical wireless link via the Bernoulli distribution, using the link blockage probability as parameter. The switching delay encountered during a change of UL transmission mode from LiFi to WiFi is considered to be a normal random variable with a mean value of 100 ms and a variance of 20 ms. Besides, four (4) classes of medical packets with equal probabilities of arrival, and delay requirements as in Sect. 2, are used for the simulation. For the general packet transmissions, we assume the interactive non-real-time service class, which includes Web browsing and voice messaging.

We compare our proposed channel allocation scheme with a heuristic method which is a modified version of a general allocation scheme given in [12]. In the heuristic method, channel allocation for the  $w^{th}$  WBAN in LiFi is obtained by

$$N_w^{IR} \simeq L \left[ \frac{\kappa_m \lambda_w}{\kappa_g \lambda_g (1 - \rho) + \kappa_m \lambda_m \rho} \right], \quad (11)$$

where  $\rho = E[\hat{D}_m]/(E[\hat{D}_m] + \hat{D}_g)$  is a normalizing factor, accounting for the relatively stringent delay requirements of medical packets.  $E[\hat{D}_m]$  is the expected delay requirements of an arriving medical packet and  $\hat{D}_g$  is the delay threshold

**Table 1.** Simulation parameters

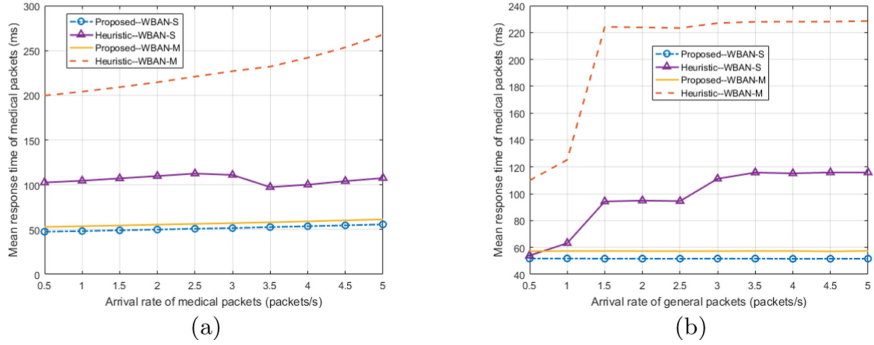
Parameter	Value
Number of user devices (UDs)	3
UL packet arrival rate for UD	1 packet/s
UL packet arrival rate for CN	0.5–5 packets/s
Number of LiFi UL channels $L$	50
Number of WiFi UL channels $R$	20
LiFi per-channel transmission rate $X_{IR}$	2 Mbps
WiFi per-channel transmission rate $X_{RF}$	0.5 Mbps
Probability of UD in LiFi coverage area	0.3
Probability of mobile WBAN in LiFi coverage area	0.2
Probability of optical wireless link blockage	0.2
Mean value of switching delay	100 ms
Variance of the switching delay	20 ms
Expected size of medical packets $\kappa_m$	50 Kbits
Expected size of general packets $\kappa_g$	500 Kbits
Expected delay constraint of medical packets $E[\hat{D}_m]$	405 ms
Delay threshold of general packets $\hat{D}_g$	1 s
Number of medical packets for M/M/1 simulation	500
Number of iterations	1000

for meeting the QoS requirements of any general packet. Based on the heuristic method, channel allocation in WiFi for the  $w^{th}$  WBAN is also given as

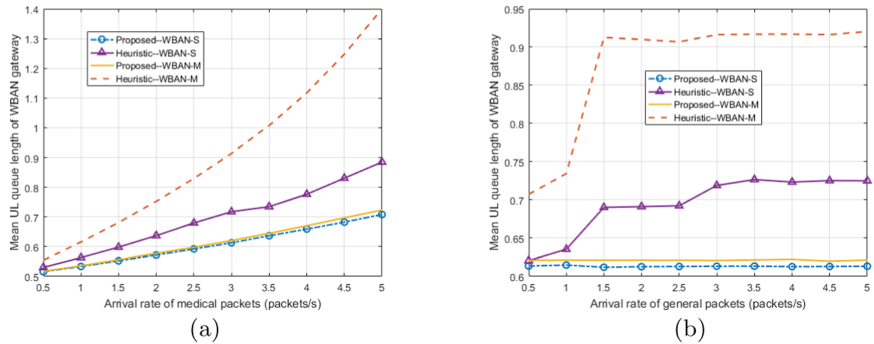
$$N_w^{RF} \simeq R \left[ \frac{\kappa_m \lambda_w}{\kappa_g \lambda_g (1 - \rho) + \kappa_m \lambda_m \rho} \right], \quad (12)$$

The average UL queue length and the average response time of the system are used as performance metrics in the analysis. These metrics are measured against the arrival rates of medical and general packets, considering the outcomes for both the stationary WBAN and the mobile WBAN (Table 1).

Figure 2 investigates the impact of arrival rates of the two type of packets (medical and general) on the response times of medical packets in the queueing system. Our proposed channel allocation strategy is shown to be more effective than the heuristic method, in terms of minimizing the response time of medical packets. When the medical packet arrival rate increases, the heuristic method allocates more channels to WBAN UL with the goal of enhancing channel utilization. Meanwhile, our proposed method aims specifically at meeting the delay requirements of medical packets by allocating more UL channels for medical data transmissions. This correctly offsets any additional waiting time and its impact on response time. Hence, it is striking to note in Fig. 2a that the response time performance of our scheme remains relatively stable, irrespective of the arrival



**Fig. 2.** Mean response of medical packets against the (a) arrival rate of medical packets at the gateway (b) per-UD general packets arrival rate



**Fig. 3.** Mean UL queue length of WBAN gateway against the (a) arrival rate of medical packets at the gateway (b) per-UD general packets arrival rate

rate of medical packets or the movement of WBAN. However, the stationary WBAN attains a lower response time than that of the mobile WBAN for both allocation methods, since it is connected to the higher service rate LiFi network for a longer period of time. Medical packets are given priority in our proposed allocation scheme. Therefore, any increase in the general packet arrival rate has minimal impact on the allocations for medical packet transmissions, as indicated in Fig. 2b. The heuristic method does not prioritize medical packets and, thus, decreases the allocations for medical data transmissions in favor of general packets, with a view of better channel utilization.

We proceed to examine the effects of arrival rates of the two type of packets (medical and general) on the mean queue length of the CN uplink in Fig. 3. By relying on our proposed allocation strategy, an increase in medical packet arrival rate has little impact on the UL queue length. The proposed method allocates more channels for WBAN UL transmissions in response to higher arrival rates of medical packets. This results in faster service rates and the reduction of significant waiting periods, resulting in smaller queue lengths than expected.

Due to a minimal change in service rate, the heuristic method fails to address the additional waiting periods, leading to a significant increase in the queue length. From Fig. 3a, our proposed method outperforms the heuristic one irrespective of the mobility of WBANs. A shorter UL queue length arises in the case of the stationary WBAN, because it is hooked onto the bigger bandwidth LiFi network for a longer period and only falls on the WiFi network as a backup when the LiFi link is obstructed. Thus, it attains significantly higher service rates on average than the mobile WBAN. Since allocations for CNs precede that of UDs in our proposed scheme, any changes in general packet arrival rates has no significant impact on the UL queue length, as is the case in Fig. 3b. Meanwhile, the heuristic method causes longer queue lengths, owing to its strategy of reducing allocations for medical data transmissions when the arrival rate of general packets increases, resulting in lower service rates and longer response times.

## 5 Conclusion

In this paper, we presented a dynamic channel allocation strategy for the hybrid LiFi and WiFi access networks serving WBANs and traditional UDs. Our goal is to ensure that the activities of UDs do not unduly affect the performance of medical WBANs. To this end, the proposed allocation scheme initially allocates channels to the WBANs only, and shares the remaining among UDs and WBANs in a proportionally fair manner. A heuristic channel allocation method was devised for performance comparison. Simulation results show that our allocation framework yields better results, in terms of the response time and queuing length at WBAN gateway. Based on its response times, ranging between 38–61 ms, the proposed scheme has clearly proven its ability to meet the stringent QoS targets of medical packets. Nevertheless, the packet dropping probability will be investigated in our future work.

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