Chapter 1

5. Wireless Body Area Communications

1.1 MAC Protocols and Upper Layers

As pointed out in previous sections, one of the most important aspect distinguishing Body Area Networks (BANs) from conventional Wireless Sensor Networks (WSNs) is the presence of the human body. *On-body* radio channels, as well as *off-body* ones, undergo to specific propagation phenomena, which differ from traditional channels (i.e., distance-dependent models) and have to be properly characterised [BSM+12], as shown in Secs. x and x. This aspect also affects the design of Medium Access Control (MAC) and upper layer communication protocols, where network reliability and energy efficiency are the most critical requirements to be fulfilled, and commonly used solutions in generic WSNs are not optimised for *body-centric communications* [CGV+11]. Moreover, considering the mobile nature of BANs along with their proposed operational frequency band (i.e. the Industrial, Scientific and Medical (ISM) band at 2.45 GHz), these networks are expected to coexist with other wireless devices working in their proximity. Therefore, interference from coexisting wireless systems (e.g. Blutooth, ZigBee, etc.) or nearby BANs could create problems on network reliability [ABSV13]. A precise characterisation of interfering sources and the evaluation of performance achievable in a interfered scenario are of outmost importance for the design of some interference management techniques, which can possibly exploit the presence of multiple users to create an *ad-hoc* network of people [Ros14].

1.1.1 MAC protocols for BANs and IEEE 802.15.6 standard

The great variety of applications suitable for BANs calls for a large set of system requirements that have to be met, and that existing air interfaces are not able to fulfill at the same time [RMM+12]. To that purpose, IEEE 802.15 Task Group (TG) 6 was established to work on a standard optimised for short-range communications in the vicinity of, or inside, the human body [IEE12], which was release in February 2012. A precise description of standard's main features is provided in [CB14, SCS13], particularly on MAC layer access techniques. Each access mode is described (*beacon mode with superframe (SF) boundaries*, *non-beacon mode with and without SF boundaries*), as well as the methods used to access the channel: *random*: nodes compete for the radio resource through Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) or Slotted aloha protocols; *improvised*: transmissions happen using post or poll packets, *scheduled*: each node transmit data during a pre-assigned time slot; *unscheduled*. Performance of *random* and *scheduled access* are evaluated and compared in [SCS13] in terms of packet drop causes, latency, Packet Delivery Ratio (PDR) and reception occurrences, for different data rates and transmit power levels. Focusing just on *beacon access mode with SF boundaries*, [CB14] proposes an analytical model to characterise the performance of IEEE 802.15.6 CSMA/CA with priority, for a star network topology. Indeed, prioritised access to the medium is one of the main novelties introduced by the standard, allowing users to compete for the radio resource with different levels of priority, according to the type of traffic generated. Network performance are evaluated in terms of packet reception success probability, when no retransmission is allowed. The validity of the model is proved by some experiments. This study can provide the designer with an idea of the behaviour of these networks, optimising the assignment of user priorities, each one undergoing to different requirements in terms of QoS [CB14].

Apart from IEEE 802.15.6, other standards are envisaged for BANs, among them the IEEE 802.15.4 [IEE06] and Bluetooth [blu10]. [RMM+12] presents the simulation results for the performance evaluation and comparison of different MAC protocols (i.e. CSMA/CA as defined by the IEEE 802.15.4 and 802.15.6 standards, and the IEEE 802.15.6 Slotted aloha), applied on top of different Physical (PHY) layer solutions. Performance of a star topology network working at 2.45 GHz are evaluated in terms of Packet

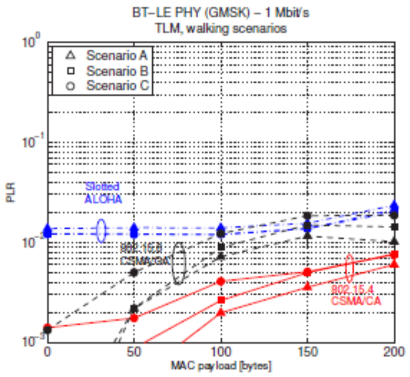

Figure 1.1: Average PLR for different MAC protocols, normally polarized antennas.

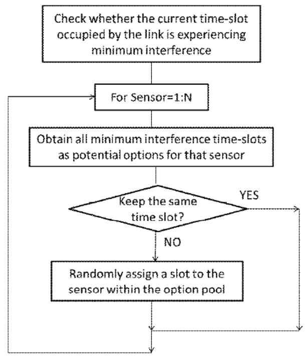

Figure 1.2: Flowchart *Minimum Interference Assignment (MIA)*

Loss Rate (PLR), average delay and energy consumption. To account for realistic propagation conditions, some real-time dynamic channel measurements performed with two sets of differently polarized antennas are used as input in the simulator [RD12]. For instance, Fig. 1.1 shows PLR results as a function of the packet payload, obtained for the three MAC protocols considering a Bluetooth-compliant PHY when normally polarized antennas are used [RMM+12]. Numerical results demonstrate that it is generally quite difficult to state which is the best performing MAC solution, as it strictly depends on the antenna type, the underlying PHY and the metric considered. For that reason, protocols should be designed as flexible as possible to adapt to the different requirement asked by the envisaged application, and the results proposed in the paper could guide this process. Some analysis on the impact on the antenna efficiency on the PLR also demonstrate the need to identify a proper trade-off between system performance and antenna dimensions [RMM+12].

Energy consumption, which is a primary issue in BANs, is the focus of [MDPRD12], which presents results on the study of dynamic relaying and cooperative routing schemes to ensure energy efficiency. Simulations were run considering a star topology network with the coordinator placed at the hip-level. The BATMAC protocol [MO11] is implemented at the MAC layer. At each simulation time, packet reception decision is based on the Packet Error Rate (PER) value, which depends on the instantaneous Signal-to-Noise Ratio (SNR). The latter is computed from real-time dynamic channel data, as explained in [DRM11]. Different communication schemes are proposed: direct transmission (*DL*); transmissions via relay (*DH*) with fixed or dynamic choice of the best relay; combination of *DL* and *DH*; *Mix* approach, selection of the best communication strategy, based on beacon PER information. Energy consumption levels are evaluated considering the characteristics of on-the-shelf Bluetooth-compliant devices. Both for an ideal case (i.e. channel conditions are stationary for the whole SF) or in more realistic conditions that account for the impact of the fast fading, the proposed *mix* strategy provides the most efficient trade-off in terms of energy consumption vs. reliability [MDPRD12]. This means that an intelligent and adaptative choice of the cooperation scheme leads to the best network performance.

1.1.2 Interference Management and Coexistence Issues in BANs

One of the envisaged working frequency band for BANs is the 2.45 GHz ISM band. Possible coexistence issues arises considering that several existing communication standards operate in the same bandwidth. To that purpose, [MV12] presents some coexistence studies carried out in order to evaluate the performance of BAN working in presence of some sources of interference, in particular: IEEE 802.11 (Wi-fi) [IEE11] and IEEE 802.15.4 [IEE06]. Simulations were run considering a star topology BAN carried around by a human subject walking in a room, where either a Wi-Fi Access Point (AP) or a Zigbee network (working based on IEEE 802.15.4 standard) are present. These sources of interference were characterised both in the frequency and in the time domain, to describe the percentage of interfering power falling into BAN receiver band and the data flows generated by them, respectively. Three possible solutions for the PHY layer were considered (see [RMM+12]), combined with two versions of the CSMA/CA MAC protocols. BAN performance are assessed in terms of PLR, average delay and average throughput as a function of the packet payload. Numerical results show that, independently from the PHY/MAC layer solution considered, the performance metric that is mainly affected by the presence of interference is the PLR, particularly when Wi-fi systems are active. Therefore, to guarantee acceptable performance, a dynamic selection of BAN operating channels is extremely important, considering the variability over time of the environment these network are supposed to operate in [MV12].

Also the presence of other adjacent BANs working in the same environment at the same frequency (e.g. 2.45 GHz) can impact the reliability and QoS of a network. A densely populated room with a variable number of BANs moving around, is the reference scenario in [ABSV13]. Based on a simple Time Division Multiple Access (TDMA)-based MAC transmission protocol, the paper proposes some smart uncoordinated scheduling algorithms to assign time slot to the nodes in each BAN to complete their transmissions, in order to mitigate and ease possible cross-interference (i.e. inter-BAN) among them. The simplest approach used is a semi-random one, where the allocation of the slots is chosen randomly in every transmission frame; if the total interference experienced by all Rx nodes is less than the current time slot, the assignment for the next frame is change according to the selected random one, otherwise it is kept unchanged as in the current frame. A more sophisticated approach called *Minimum Interference Assignment (MIA)* is also proposed, which exploits channel correlations and based on the experienced interference decide the best time slots that ateleast likely to collide with other BAN interferers (see Fig. 1.2 for the strategy flowchart). Simulation results in terms of Signal-to-Interference Ratio (SIR) and system outage probability prove that the usefulness of the proposed uncoordinated slot assignment strategies in mitigating cross-interference level, even in a quite realistic scenario where users move randomly in the environment.

A similar scenario with multiple BANs is considered also in [MBZV14]. Here, each subject is equipped with three devices that use a cooperative beamforming technique to establish a Virtual Antenna Array (VAA) to transmit their data to one of the available external sink. The latter are placed in fixed positions and are composed in their turn of multiple antennas, such that a Multiple Input Multiple Output (MIMO) transmission system is established. Simulation results demonstrated the advantages offered by cooperative beamforming in terms of SNR and Block Error Rate (BLER), over traditional Single Input Single Output (SISO) systems [MBZV14]. According to the power level received by the sinks, each BAN associates to one of them and start transmitting its data in a TDMA scheme, managed by the sinks. Assuming the sinks are able to coordinate among them, scheduling BANs transmission in order to avoid collisions, different scheduling algorithms were evaluated and compared. It is shown that if BANs should get equal amount of resources (i.e. time slots), the *proportional fair* scheme should be used. Otherwise, if the goal is to maximise the overall throughput disregarding the fairness, the *maximum throughput* algorithm is the best solution [MBZV14].

In case where sinks works independently from each other, conclusions about scheduling algorithms are the same as before, but the differences are less evident because of the possible interference among node transmissions.

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List of Acronyms

AP Access Point

BAN Body Area Network

BLER Block Error Rate

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

ISM Industrial, Scientific and Medical

MAC Medium Access Control

MIMO Multiple Input Multiple Output

PDR Packet Delivery Ratio

PER Packet Error Rate

PLR Packet Loss Rate

PHY Physical

SF superframe

SIR Signal-to-Interference Ratio

SISO Single Input Single Output

SNR Signal-to-Noise Ratio

TDMA Time Division Multiple Access

TG Task Group

VAA Virtual Antenna Array

WSN Wireless Sensor Network