Performance of Ultra-wideband Body-centric Wireless Networks

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Abstract— In this paper, we study the performance of ultra-wideband (UWB) body-centric wireless networks (BCWN). In this context, we first evaluate the capacity of UWB multiple-input-multiple-output (MIMO) on-body channels then we study the statistics of the eigenvalues of these channels. In order to study the effect of on-body antenna positions, we consider four different transmit-receive antenna location scenarios where the transmit antenna is fixed on the Waist and the receive antenna is placed in different positions. More specifically, the four considered scenarios are the Chest-Waist, Wrist-Waist, Ankle-Waist, and the Back-Waist settings. For each of these scenarios, we evaluate the channel capacities depending on the amount of channel state information (CSI) available to the transmitter. More specifically, we evaluate the equal-power capacity and the water-filling capacity for the cases where no CSI and full CSI are available to the transmitter, respectively.

1. INTRODUCTION

The main idea behind body-centric wireless communications is to connect multiple devices that are located on the human body. In this context, several research topics have covered the study of body-centric communications especially with the scope of personal area networks and body-area networks. Both narrow-band and wide-band frequencies can be used for body centric wireless communications. However, ultra-wideband (UWB) is a promising wireless communications technology that is characterized by low energy and large bandwidth and can be used for short-range, high-data-rate communications. UWBs low-power requirements makes it an ideal candidate for body-centric communication systems (BCCS) [1]. Moreover, the use of such higher frequencies reduces the propagation of waves into the human body. As the demand for higher data rate increases, new techniques that aim at achieving these data rates are evolving. Among the most popular is the combination of the UWB technology with multiple-input-multiple-output (MIMO) systems [2].

In the literature, a lot of research was dedicated to assessing the performance of UWB communications during the past decade. In this context, the characterization of on-body and UWB channels for communication systems using single-antenna-based transceivers were considered in [3–5]. By considering different antenna-types and changing the on-body antenna positions, the effect of different body positions and the in uence of various antenna types on UWB on-body channels were investigated in [6]. In a more spectrally-efficient approach, MIMO systems have been studied extensively for mobile and personal communication links in [7], and the ergodic and outage capacities of narrow-band Gaussian MIMO channels were studied in [8]. In this context, there have been several studies done to assess the benefits of multiple-antenna techniques for BCCS for narrow-band systems [9, 10] and UWB single-input-multiple-output (SIMO) systems [11–13]. In [14], the authors explore the performance of impulse radio UWB for wireless body area networks (WBAN) channels in terms of bit error rate (BER). Recently, the capacity of UWB on-body networks is investigated in [15] based on experimental measurements.

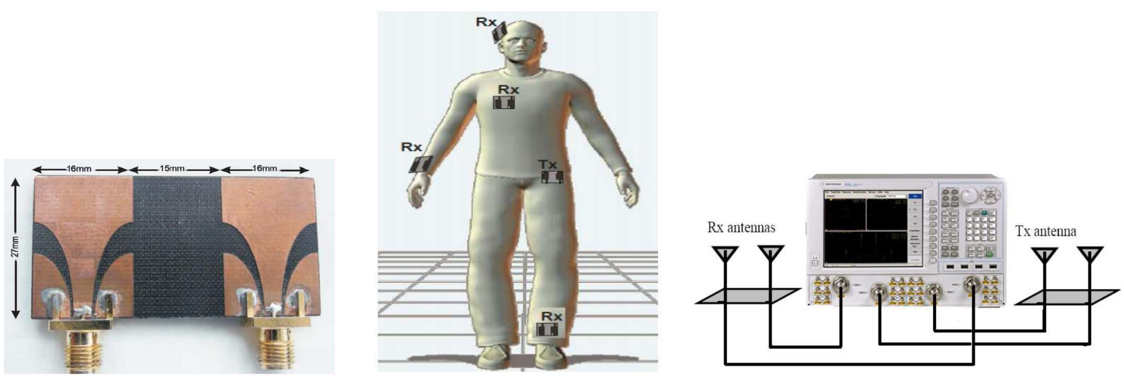
In this paper, extending the results obtained in [15], the achievable capacity gain when using UWB MIMO-aided BANs under two different power schemes (i.e., equal-power and waterfilling power allocation [16]) is evaluated and the statistics of the channels' eigenvalues are studied. The proposed model is based on a measurement campaign conducted in the 3.1–10.6 GHz frequency range using a MIMO channel measurement system. The waterfilling power scheme is adopted in an attempt to increase the channels capacity in the low signal-to-noise ratio (SNR) range. Based on the experiential results, we explore the capacity of UWB MIMO for body area networks and present its mathematical formulation.

The remainder of the paper is organized as follows. Section 2 presents the details behind the measurements setup and the used equipments. Section 3 first gives the channel model then introduces a background for the performance analysis. Section 4 illustrates and confirms this performance via selected numerical results. Finally, Section 5 concludes the paper.

2. MEASUREMENT SETUP

In the considered measurements, we consider a coplanar waveguide fed tapered slot 2×2 UWB antenna presented in [17] is used for UWB MIMO measurements over the frequency band from 3.1 to 10.6 GHz. The used antenna exhibits excellent gain and radiation properties in the 2.2–11 GHz band. The total size of the used antenna is 27 mm $\times$ 47 mm as shown in Figure 1(a) with a spacing of 0.34λ (15 mm) between the two antenna elements (where λ represents the free space wavelength). Measurements were first performed in the anechoic chamber and in an indoor environment as shown in [17] at Queen Mary, University of London in order to observe the effect of an indoor environment on MIMO radio channel for body-centric wireless networks. For on body measurements transmitting antenna (TX) was placed at waist (belt) height, whereas receiving antennas (RX) were placed on four different locations, i.e., right side of chest, right wrist, right ankle position and back as shown in Figure 1(b).

In order to analyze the considered 2×2 UWB MIMO channels, an Agilent four-port programmable network analyzer (PNA) (PNA-N5244) shown in Figure 1(c) is used. This equipment measures the scattering parameters between the transmit and receive antenna pairs at different positions on the human body. The PNA is calibrated and remotely controlled using the LabView 8.5 software. Receiving antennas were connected to ports 1 and 2 and transmitting antennas were connected to ports 3 and 4. For each measurement, random bodily activities were carried out that represent typical, everyday movements. The PNA was set to capture 3201 data samples, with a sampling time of 6.6 ms. The sampling time was carefully chosen to capture all variations made by any fast movement of the human subject by incorporating the Doppler effects.



(a) (b) (c)

Figure 1: On-body measurements set-up [10, 17]. (a) Two-element MIMO antennas. (b) MIMO antenna positions. (c) TX and RX connectivity.

3. CHANNEL MODEL

The use of MIMO offers many advantages when compared to SISO systems. Indeed, the channel capacity can be further increased in MIMO by creating multiple parallel channels and then exploiting multipath signals. The spatial multiplexing gain is proportional to $\min\{N_t, N_r\}$, where N_t and N_r represent the number of transmit and receive antennas respectively.

Considering a MIMO on-body channel with N_t transmit and N_r receive antennas, the input-output relationship between the transmitter (TX) and receiver (RX) is expressed as

$$\mathbf{Y} = \mathbf{H}\mathbf{X} + \boldsymbol{\eta}, \tag{1}$$

where the transmitted signal $\mathbf{X}$ through the channel $\mathbf{H}$ experiences an N_r-dim additive white Gaussian noise (AWGN) $\boldsymbol{\eta} = [\eta_1, \eta_2 \ldots, \eta_{N_r}]^T$.

In the general MIMO case, the channel model can be descried as

$$\mathbf{Y}(t) = \sum_{l=1}^{L} \mathbf{A}_l \mathbf{X}[t - (l-1)\Delta_\tau] + \boldsymbol{\eta}(t), \tag{2}$$

where $\mathbf{X}(t)$ and $\mathbf{Y}(t)$ are the N_t- and N_r-dimensional vectors of the transmit and receive signals, respectively. $\mathbf{A}_l$, $l = 1, \ldots, L$, are the amplitude fading matrices. Δ_τ can be set to be $1/B$, with B being the bandwidth of the transmitted signal $\mathbf{X}$.

The equal-power capacity for UWB systems can be obtained as [2]

$$C = \int_{-B/2}^{B/2} \log\det\left[\mathbf{I}_{N_r} + \frac{\rho}{N_t}\mathbf{H}(f)\mathbf{H}^H(f)\right]df, \tag{3}$$

where ρ is the SNR at the transmitter's side, $\mathbf{I}_{N_r}$ is an $N_r \times N_r$ identity matrix, $\mathbf{H}(f) = \sum_{l=1}^{L} \mathbf{A}_l$ $e^{-j2\pi f(l-1)\Delta_\tau}$, and $\mathbf{H}^H$ is the conjugate transpose of $\mathbf{H}$.

As discussed in [2], it is extremity difficult to obtain the closed form expression for (3). Thus, we use Monte Carlo simulation to evaluate the capacity for different on-body scenarios. Given the distribution $P_C(\cdot)$ of C, the outage probability of the channel capacity can be obtained for a given data transmission rate R as

$$P_{\text{out}}(R) = P_C(R) = P_{\bar{C}}(R/B), \tag{4}$$

where $\bar{C} = C/B$.

Similarly, the water-filling capacity can be obtained for the case where full channel state information (CSI) is available at the transmitter. Letting $\lambda_1(f)$, $\lambda_2(f), \ldots, \lambda_{N_t}(f)$ be the eigenvalues of $\mathbf{H}(f)\mathbf{H}^H(f)$, the channel capacity with known CSI at the transmitter is then given by

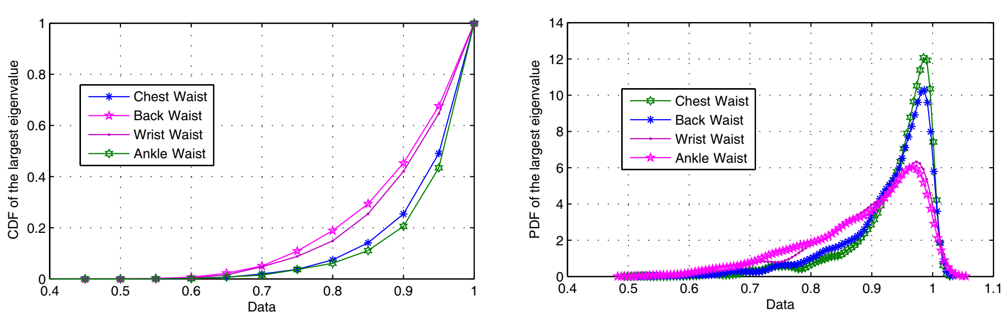
$$C = \frac{B}{\pi}\sum_{i=1}^{N_t}\int_{I_{i\theta}} \log\left[\frac{\theta}{N_0}\lambda_i(f)\right]df, \tag{5}$$

where θ is a constant independent of the frequency and $I_{i\theta}$ denote the intervals of f in which $N_0/\lambda_i(f) \leq \theta, i = 1, \ldots, N_t$.

4. NUMERICAL EXAMPLES

First, we investigate the cumulative distribution function (CDF) and the probability density function (PDF) of different channels' eigenvalues for the four considered scenarios. In this context, we depict in Figure 2 the statistics of the largest eigenvalue λ_2 for the studied 2×2 UWB MIMO system obtained from the experimental measurements. The values of CDF and PDF are obtained using the method of Gaussian Kernel estimation. Similar to [18], we alleviate the effect of the received power imbalance by different antennas by normalizing each channel realization to its corresponding Frobenius norm. Thus, we focus only on the effect of the channel on the performance of the different considered scenarios. From Figure 2, we can conclude that the Wrist-Waist and the Ankle Waist scenarios allow for using spatial multiplexing. Indeed, in these two scenarios there is no dominant eigenvalue and λ_1 and λ_2 have comparable distribution which allows for using both channels for transmission. The two other scenarios, however, offer a strong LOS component and there is always a dominant eigenvalue.

In Figure 3, we present the waterfilling and equal-power capacities for different scenarios. As expected, the capacity improves with higher values of SNR. Moreover, the waterfilling allocation offers higher values of the capacity than the equal power allocation. This better performance comes at the expense of a CSI knowledge at the transmitter which is required to find the optimal



(a) (b)

Figure 2: Statistics of the channel's eigenvalues. (a) CDF of the channel's eigenvalues. (b) PDF of the channel's eigenvalues.

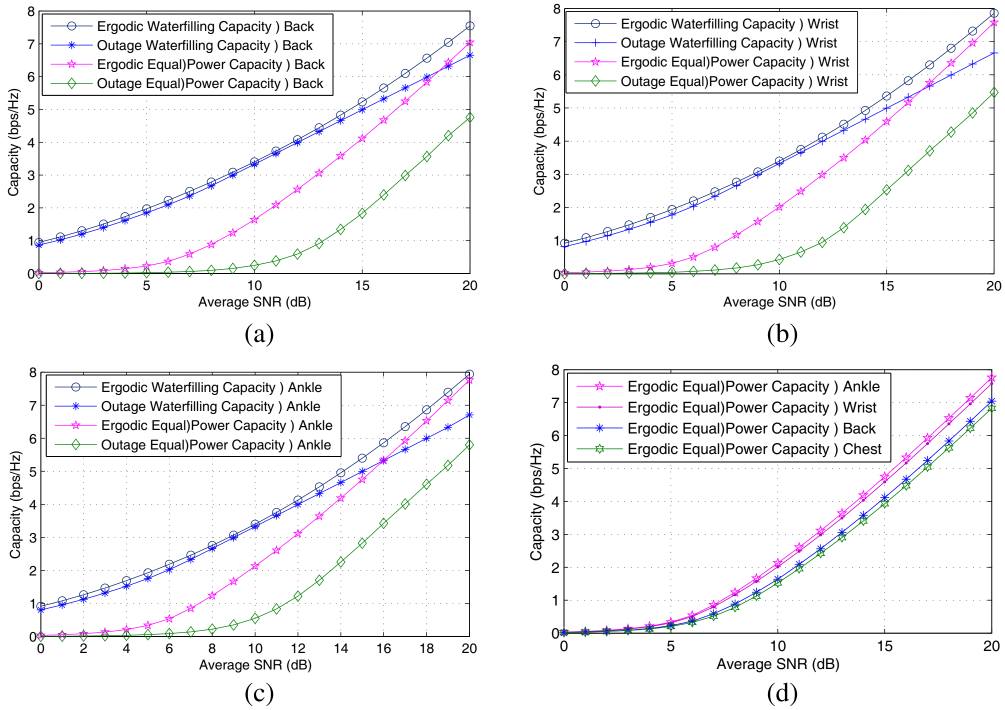


Figure 3: Capacity for different MIMO UWB scenarios. (a) Back-Waist. (b) Wrist-Waist. (c) Ankle-Waist. (d) All scenarios.

power allocation across different transmit antennas. The higher performance experienced by the waterfilling scenario is more evident in the low average SNR range. Indeed, in this range, the power among different eigen-channels is optimally assigned according to their state and power profile. At high average SNR, on the other hand, the waterfilling capacity performs similar to the equal power capacity. Indeed, in this range, the good SNR reduces the effect of the SNR knowledge at the transmitter and waterfilling does not provide major enhancement in this case.

From Figure 3(d), we can see that the Chest-Waist performance is the lowest in terms of capacity. This is mainly due to the fact the channel between the chest and the waist has many obstructions for its LOS components because of the body physique including the belly, fat, and several other factors. We can also see from this figure that the Back-Waist scenario offers also lower performance compared to the Ankle and Wrist scenarios. This is mainly du to the shadowing caused by the body of the subject to signal propagation between the Waist and the Back. This obstruction limits the received signals to the body surface propagation. On the other hand, the Ankle and Wrist scenarios offer relatively higher capacity thanks to the LOS propagation seen between the transmitter and the receiver in these cases. This better performance helps us decide on the best location to place the receive antenna for the on-body scenario in order to improve the amount of data transmitted.

5. CONCLUSION

In this paper we studied the performance of ultra-wideband body-centric wireless networks. In this context, we evaluated the capacity of UWB MIMO on-body channels considering different antenna positions and daily-activities. In order to study the effect of on-body antenna positions, we consider four different transmit-receive antenna location scenarios where the transmit antenna is fixed on the Waist and the receive antenna is placed in different positions. More specifically, the four considered scenarios are the Chest-Waist, Wrist-Waist, Ankle-Waist, and the Back-Waist settings. For each of these scenarios, we evaluate the channel capacities depending on the amount of channel state information available to the transmitter. More specifically, we evaluate the equal-power capacity and the water-filling capacity for the cases where no CSI and full CSI are available to the transmitter, respectively, and we investigate the statistics of the channels' eigenvalues.

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