Channel Dynamics in Body Area Networks: Recent Results and Challenges

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***Abstract*—Recent results about body area radio channel dynamics are analyzed, considering on-body and body-to-body transmissions. Investigations are based on experimental data around 4 GHz. Regarding the on-body case, the dynamics of cross-channel correlation are measured and analyzed for stationary periodic and non-stationary motions, with a clear impact of the walking mode being observed. For body-to-body scenarios, measurements conducted in room-to-room environments show again some strong non-stationary behaviors. In both cases, Markov chain-based models are developed to represent transitions between fading states.**

I. Introduction

Wireless Body Area Networks (WBANs) typically consist of transceiver nodes placed on or in the vicinity of the human body and encompass a large number of applications, such as e-health, remote monitoring, sports and entertainment [1]. Understanding the radio channel behavior is critical to develop efficient body-area communications systems, especially when relay and cooperative techniques are considered to overcome the severity of on-body pathloss and/or body shadowing [2]. In particular, the prediction and modeling of channel dynamics may strongly differ from classical wireless transmissions. Recently, first- and second-order fading statistics were investigated in dynamic multi-node scenarios [3]–[9]. In parallel, body-to-body transmissions were analyzed in [10], [11] at various frequencies around 2.4 GHz.

In this communication, we will summarize recent results focusing on the characterization and modeling of channel dynamics, including non-stationary behaviors. In a first part, we will deal with on-body channels, considering on the one hand, the Doppler spectrum for harmonic and regular walks, and on the other hand, the analysis of cross-channel correlations for realistic walks. In a second part, we will investigate body-to-body propagation mechanisms, especially when subjects are located in different rooms and move freely, so that channels are again highly non-stationary.

II. On-Body Channel Dynamics

1) Stationary Motion: In this first section, we characterize the Doppler spectra for on-body channels with transmit and receive sensors located on the torso, the transmission being impacted by the regular harmonic motion of the arms [12]. Two experimental scenarios are considered: one anechoic scenario at 2.45 GHz and one typical indoor scenario at 4.2 GHz. In both cases, the Doppler spectrum is centered around 0 Hz, as none of the nodes are moving with respect to each other, but exhibits strong harmonics resulting from the swinging of the arms, as depicted in Figures 1 for the anechoic case.

In the anechoic case, the Doppler spectrum $\mathcal{S}(\nu)$ can be empirically modeled by

$$\mathcal{S}(\nu) = \frac{1}{1+s\nu^2} + \sum_{m\neq 0}^{\infty} \frac{1}{ma + s(\nu - m\nu_0)^2} \frac{1}{\beta b^{(|m|-1)}}, \quad (1)$$

where ν_0 is the fundamental Doppler frequency, m is the order of the harmonics, β and b describe the global and local decaying of the Doppler spectrum at the frequency harmonics, and a describes the local Doppler spread of the harmonics.

Regarding the indoor regular walking scenario [5], similar Doppler spectra are observed, with significant frequency harmonics corresponding to the walking cycle (around 1.5 seconds).

2) Non-Stationary Motion: When the walking mode is non-regular, the channel becomes highly non-stationary. This implies first that the Doppler spectrum can only be defined over very short periods of time, but most importantly, that cross-channel correlation properties also change rapidly between successive stationary states. To illustrate this observation, let us compare two experimental results, taken from [13], [14]. In both cases, one is interested in the correlation between two links, from the chest to the right hand (CRH) to the left hand (CLH) respectively. However, in the first measurement setup, the subject walked uniformly along a straight line with periodic arm swing, whereas in the second setup, the trajectory followed by the subject and the arm swings were completely random, likely representing a more realistic type of walk.

In the first scenario, Figure 1 highlights that both links exhibit strongly anti-correlated fading behaviors. This is the direct consequence of the regular (soldier-like) swinging of the arms. This pattern is expected to result in high anti-correlation values (typically smaller than -0.4), that could be exploited in multi-hop approaches.

By contrast, Figure 2 shows that the correlation values strongly vary over time in the second set of measurements. Moreover, the proximity with some objects in the environment could yield to very slow variations of the long-term fading that are included in the shadowing contributions.

Although both measurement campaigns have been performed in walking scenarios, the space-time correlation char-

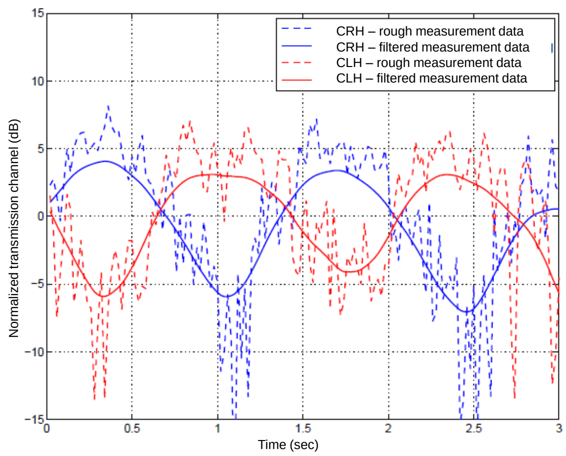

Fig. 1. Transmission channels for both considered links (fast and slow-fading behaviors) for a regular walk

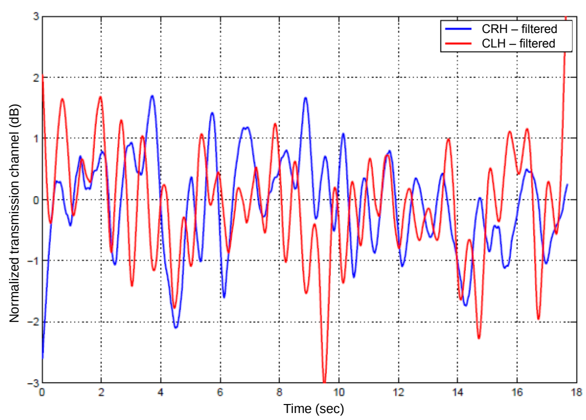

Fig. 2. Transmission channels for both considered links (slow-fading behavior) for a non-regular walk

acteristics are different. More generally, this correlation analysis shows a non-stationary behavior of the channel, whose correlation characteristics do not only depend on the observation duration T_{obs} but also on the observation instant. This analysis confirms the observation of non-stationary on-body channel characteristics outlined in [15].

III. Body-to-Body Non-Stationary Channel Dynamics

Body-to-body communications are emerging as a key component of emergiging 5G networks. They consist in transmissions between different bodies, or more generally, persons, who can be located in the same room or in neighboring rooms. Several authors have recently investigated such channels, which can be characterized by a highly non-stationary behvior. In [4], [11], the $\kappa - \mu$ distribution was used to fit the distribution of small-scale fading for transmissions between firefighters, in comparison to other fading models such as Nakagami-m, lognormal, Rice and Weibull. Low cross-channel correlations were also observed. Similar conclusions were also presented in [16]. By contrast, in [10], the small-scale fading component was modeled by a Ricean distribution, whereas shadowing is statistically described by a mixture distribution composed of two normal distributions.

Most studies usually assume that the channel is stationary: while this is justified in many case by the careful choice of experimental scenarios, it is likely that typical body motion and shadowing will induce non-stationary conditions. In [17], a body-to-body measurement campaign was carried out in two environments: subjects were either grouped in a large room or isolated in different rooms (th elatter being represented in Figure 3, upper graph). In both cases, they moved freely on their own, avoiding regular motions. The experimental set-up relied on the use of UCL Elektrobit Propsound MIMO channel sounder, used in a distributed fashion [18] at the frequency of 3.8 GHz. The distributed body nodes were connected to the sounder by multiple 32-meter low-loss RF cables.

Based on this experimental campaign, small-scale fading was found to strongly differ from one stationarity period to the next one, and its distribution ranged from double-Rayleigh to highly Ricean. In our previous works [17], [19], we showed that this type of fading could be described by a single distribution, consisting of a weighted combination of line-of-sight (LOS), Rayleigh and Double-Rayleigh contributions. Hence, any realization of the channel can be directly written as

$$h(t) = \omega_0 e^{j\theta} + \omega_1 h_1(t) + \omega_2 h_2(t) h_3(t) \tag{2}$$

where h_1, h_2, h_3 are i.i.d. complex normal random variables with zero mean and unit variance, and θ is a constant phase shift angle in [0, 2π]. Weights ω_0, ω_1 and ω_2 describe the relative impacts of the LOS, Rayleigh and Double Rayleigh components, respectively. The probability density function of $g = |h|$ is given, as shown in [19], [20], by the so called SOSF distribution:

$$\rho_{SOSF}(g) = \int_0^\infty \omega e^{-\omega_1^2 \omega^2/4} \frac{4 J_0(g\omega) J_0(\omega_0 \omega)}{4 + \omega_2^2 \omega^2} \, d\omega \tag{3}$$

where J_0 is the Bessel function of the first kind and zeroth order.

Since $\mathbb{E}\{g^2\} = 1$, we have that $\omega_0^2 + \omega_1^2 + \omega_2^2 = 1$ and we can parameterize the distribution by two factors [20]

$$\alpha = \frac{\omega_2^2}{\omega_0^2 + \omega_1^2 + \omega_2^2} \tag{4}$$

$$\beta = \frac{\omega_0^2}{\omega_0^2 + \omega_1^2 + \omega_2^2} \tag{5}$$

where (α, β) are constrained to the triangle $\alpha \geq 0$, $\beta \geq 0$, and $\alpha + \beta \leq 1$.

The lower graph of Figure 3 illustrates the variation of the characteristic fading parameters (α and β) as time evolves. The horizontal axis represents time index at the rate of 1.25 Hz. Interestingly, α varies significantly from Rayleigh ($\alpha \approx 0$)

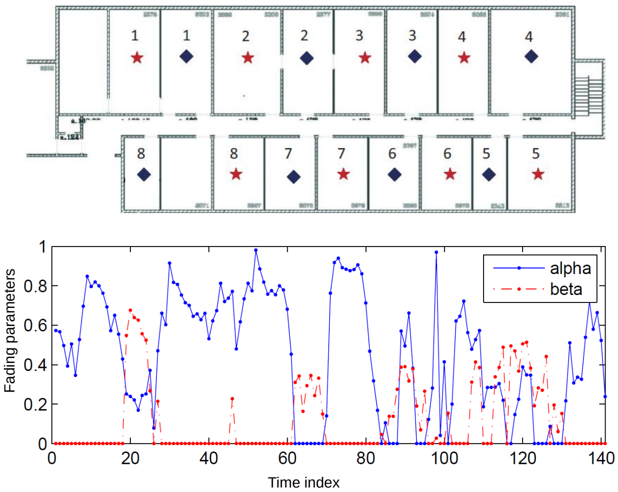

Fig. 3. Upper: Body-to-body configuration (stars are receive nodes, diamonds are transmit nodes); lower: Variation of fading parameters along time (total duration is 113 s)

to double-Rayleigh ($\alpha \rightarrow 1$), wheras the channel sometimes contains a fixed component ($\beta > 0$). To model the transitions between fading states (i.e. from one set (α, β) to the next one), a hidden-Markov model [17] is used.

It is interesting to notice that in the case of double-Rayleigh fading, a keyhole scenario was actually observed: transmit and receive correlation were found to be quite small, but the rank of the equivalent MIMO channel matrix was found to be similarly low. This can be explained by the wave-guiding effect of the corridor, which tunnels the energy from one room to another room. This mechanism was however not measured when rooms were separated by plasterboard partitions.

IV. Conclusions

In this paper, we have illustrated through various measurement-based models that body-centric communications are often far from stationary. This non-stationarity has a significant impact on the channel models and signal processing techniques to be developed, as real-world propagation may strongly deviate from the behavior obtained in canonical scenarios.

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