On the Packet Error Rate of Correlated Shadowing Links in Body-Area Networks

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***Abstract*—Body Area Networks (BAN) offer amazing perspectives to instrument and support humans in many aspects of their lives. In this paper, we consider on-body BAN nodes transmitting information towards a common sink, in a star topology. While this setup is usual in wireless networks, the high instability of the BAN radio channel and the proximity of the body make classical communication protocols inefficient. These networks are further constrained by the low transmission power required for both battery life and health concerns. Opportunistic cooperation techniques are of great interest in such environment to ensure reliable communications. In previous works, we studied simple opportunistic relaying schemes under independent BAN links, using a packet error outage criterion. In this paper, we introduce a more realistic case where shadowing variations around the body are now assumed strongly correlated. Generally speaking, there is a lack of definitive measurements and models for the shadowing correlation in multi-hop networks, while it can play a crucial role at the higher layers. Based on the measurement and simulation results of the French BANET project, we use the BAN context as an illustrative example to exhibit how shadowing correlations have a strong impact on relaying approaches performance.**

I. Introduction

Body Area Networks are expected to rapidly grow in use in the next decades, both in the consumer area due to a large increase of connected appliances worn near one's body, and in more specialized fields like sports and medical care, where BAN are obvious facilitating tools for the professionals. Following this trend, IEEE launched a working group, 802.15.6 [1], to focus on BAN issues, from channel modeling to the MAC layer. Many contributions for channel modeling have been proposed from various entities around the world, and the working document of the 802.15.6 task group on channel model summarizes the current status of the work (see [2] or [3] and references therein). All models usually agree on the fact that the body generates a strong shadowing effect on the received signal envelope, which results in a time varying multipath fading, while the best fits are given by Rice or Nakagami models with time-varying K and m parameters respectively. In this context, the BANET project [4] aimed at gathering both academics and industrials to propose and evaluate new systems. In this context, channel models and simulators were devised. Among the results, measurements exhibited how BAN links shadowing states experienced strong correlations when the body was moving [5], [6]. A similar analysis from Cotton *et al.* tends to strengthen this result [7]. In our previous works [8], [9], we analyzed the performance of a relaying approach versus a direct transmission using a packet error criterion. This paper extends these former results to the case of correlated shadowing links. The relationship between shadowing correlation and cooperative schemes efficiency is evaluated. As a conclusion, these results enhance how the knowledge of shadowing spatial correlation can help to select appropriate relaying schemes.

II. Model and definitions

A. Context

The network model herein considered is composed of 12 peripheral nodes and a sink positioned on the body, as represented on Fig.1.

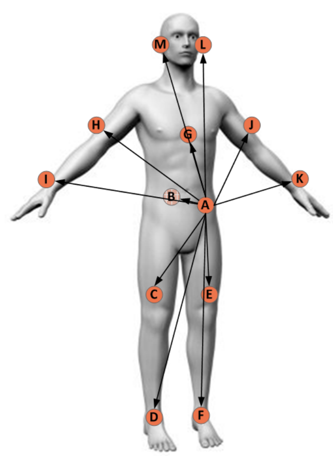


Fig. 1. Position of the BAN nodes in our model

The BAN channel characterization follows a classical superposition of shadowing and fading effects onto a mean pathloss term [10], the latter being in our case constant for a given link and independent of the distance between the BAN nodes. Previous sounding results revealed that in the BAN channel the shadowing can be modeled using a lognormal random variable, and that the fading coherence time is long enough for us to make a block-fading assumption [6]. In this case, the fading is considered to be constant over a packet duration. We define two random variables γ and $\bar{\gamma}$ respectively representing the instantaneous SNR and thus capturing fading effects on the received signal, and the short-term averaged SNR capturing the shadowing effects due to line-of-sight masking by the body. The former follows – conditionnally – a Ricean distribution with probability density function $f_{\gamma|\bar{\gamma}}(\gamma|\bar{\gamma})$ whose parameter K is a function of $\bar{\gamma}$, while as said earlier the latter follows a lognormal distribution whose mean and variance depend on the link considered.

As our main object of study here is the correlation between shadowing states, we can readily extend the previous definition of the shadowing random variable $\bar{\gamma}$ into a shadowing random vector of k components $\bar{\Gamma} = (\bar{\gamma}_1, \ldots, \bar{\gamma}_k)$, consequently following a multivariate lognormal distribution with a mean vector $M = (\mu_1, \ldots, \mu_k)$ and a $k \times k$ covariance matrix $K_{\bar{\gamma}}$ as parameters. Examples of values for these parameters are given in [6], [11], obtained respectively through measurements and subsequent body propagation simulations. We assume that the fading on each link is independent of the fading of other links, so we do not need to consider a multivariate distribution for the instantaneous SNR in our characterization, although for clarity we will identify the link considered by using the same subscript as a corresponding shadowing random variate – i.e. $\gamma_i \sim f_{\gamma_i|\bar{\gamma}_i}(\gamma_i|\bar{\gamma}_i)$.

Considering link-level correlation is obviously only interesting if information packets are transferred using multiple paths from a source to a destination. The prominent model we use in this paper is a basic relay network formed using 3 nodes as represented on Fig2.

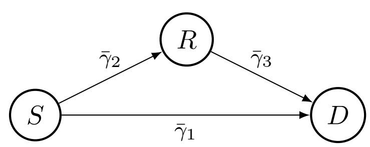


Fig. 2. Relay network with separate shadowing states.

B. Metrics

The main metric we mesure here is the packet error outage. In accordance with our previous work on uncorrelated links [8], we define it as follows. Considering a specific binary physical layer modulation, packets of length n bits, no channel coding and a block-fading hypothesis, the time averaged packet error rate can be found using the following formula [10]:

$$\mathbb{P}(\mathrm{E_P}|\bar{\gamma}) = \int_{\gamma=0}^{\infty} (1 - (1 - \mathrm{BER}(\gamma))^n) f_\gamma(\gamma|\bar{\gamma}) d\gamma \quad (1)$$

$\mathrm{BER}(\gamma)$ is the bit error rate, whose value depends on the instantaneous SNR and the considered modulation type. This expression basically gives a packet error rate conditioned on the shadowing state $\bar{\gamma}$ by taking the expected value over every possible fading states. It is of note at this point that we can define the packet success rate in a similar manner, and we shall alternatively use both in the following discussions. The packet error outage definition is derived from this expression in the following way:

$$\mathbb{P}(O) = \mathbb{P}(\mathbb{P}(\mathrm{E_P}|\bar{\gamma}) \geq \mathrm{P}^*) \quad (2)$$

The metric is evaluated on the parameter P^*, a threshold for the *acceptable* packet error rate, and can be understood as the probability that we enter a shadowing state where this condition won't be met. As showed in [8], inverting (1) leads to the packet error outage (PEO) as a function of $\bar{\gamma}^*$: $\mathbb{P}(\bar{\gamma} \leq \bar{\gamma}^*)$, which is the value of the cumulative distribution function of the shadowing random variable $F(\bar{\gamma}^*)$. To consider more complicated hypotheses, such as non-binary modulations or channel coding, we propose to redefine the packet error rate as the expected value of a function of the conditional instantaneous fading as follow:

$$\mathbb{P}(\mathrm{E_P}|\bar{\gamma}) = \mathbb{E}\left[g(\gamma, \{\phi\})|\bar{\gamma}\right] = h_e(\bar{\gamma}) \quad (3)$$

where $\mathbb{E}\left[\cdot|\cdot\right]$ is the conditional expectation operator. The function $g(\gamma, \{\phi\})$ may be viewed here as the instantaneous packet error rate, dependent on the SNR γ and a set of parameters $\{\phi\}$ that contain all relevant parameters for the underlying calculations, such as the number of bits per packet n in (1). The last part of (3) comes from the fact that the conditional expectation may be viewed as a function of $\bar{\gamma}$, and is thus a random variable in its own right. This notation simplifies greatly the transition to random vectors since the packet error outage can be restated as in (4). Let us consider the set $\Gamma^* = \{\bar{\gamma} \mid \mathbb{P}(\mathrm{E_P}|\bar{\gamma}) \geq \mathrm{P}^*\}$ as the set of values of the $\bar{\gamma}$ random variable for which the packet error threshold will be violated, or equivalently the set of preimages of the function $h_e(\bar{\gamma})$ verifying $h_e(\bar{\gamma}) \geq P^*$. We can write the packet error outage as follow:

$$\mathbb{P}(O) = \mathbb{P}(\bar{\gamma} \in \Gamma^*) = \int_{\Gamma^*} f_{\bar{\gamma}}(\bar{\gamma}) d\bar{\gamma} \quad (4)$$

This formulation is valid from a theoretical point of view as long as the set Γ^* is a subset of the sigma field $\sigma(\mathbb{R}_+)$ onto which the probability density function $f_{\bar{\gamma}}(\bar{\gamma})$ exists and is defined. By definition of the conditional expectation operator this condition is verified for (3), as it is in most practical cases of our study.

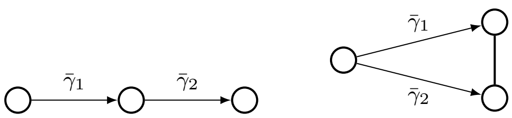
This last definition allows us to easily consider multiple links and complex relaying protocols in our analysis. We can express $\mathbb{P}(\mathrm{E_P}|\bar{\gamma}_1, \ldots, \bar{\gamma}_k)$ in the multivariate case as a function $h_e(\bar{\gamma}_1, \ldots, \bar{\gamma}_k)$, as in (3). We define the set $\mathbf{\Gamma}^* = \{(\bar{\gamma}_1, \ldots, \bar{\gamma}_k) \mid h_e(\bar{\gamma}_1, \ldots, \bar{\gamma}_k) \geq P^*\}$ of preimages of the function h_e for which our outage condition is violated, and the outage probability is thus by definition the integral of the multivariate probability density function over this set:

$$\int \cdots \int_{\mathbf{\Gamma}^*} f_{\bar{\gamma}_1, \ldots, \bar{\gamma}_k}(\bar{\gamma}_1, \ldots, \bar{\gamma}_k) d\gamma_1 \ldots d\gamma_k \quad (5)$$

We can define equivalently the packet error outage and the $\mathbf{\Gamma}^*$ set using a packet success rate function $h_s(\bar{\gamma}_1, \ldots, \bar{\gamma}_k)$ as $\mathbf{\Gamma}^* = \{(\bar{\gamma}_1, \ldots, \bar{\gamma}_k) \mid h_s(\bar{\gamma}_1, \ldots, \bar{\gamma}_k) \leq P^*\}$. Depending on the studied network both formulations may be used for simplicity, since error probabilities can be best expressed using one or the other in different contexts.

III. 2 LINKS ANALYSIS

A complete analysis of the network of Fig.2 requires 3 variable visualizations, which aren't easily readable. As an insight into the method we propose here to analyze simpler networks and decompose each step before considering more complex cases. The first network in Fig.3a is a simple 2-hops network, while on Fig.3b we have a relay network with an absolutely reliable Relay-Destination link – whose probability of error is 0. We suppose block-fading on each link, uncorrelated between the links, and for simplicity the fading will be modeled as Rayleigh. We consider a simple Decode-and-Forward (DF) half-duplex protocol as a relaying mode, with a BPSK modulation at the physical layer.



(a) 2-hops network

(b) Relay network with a reliable link

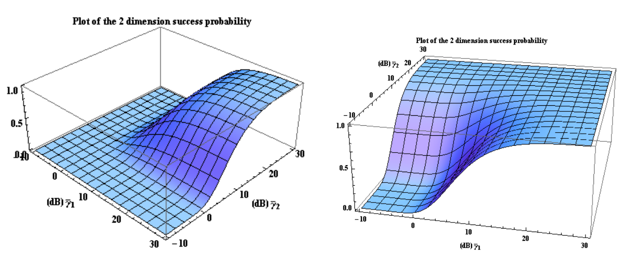
Fig. 3. Simpler networks for the 2 variables study of the model presented in this paper

We reuse the notation $h_s(\bar{\gamma}_1, \bar{\gamma}_2)$ from the preceding section for the equivalent packet success rate viewed as a function of the random vector $(\bar{\gamma}_1, \bar{\gamma}_2)$. The probability of transmission success under our hypotheses is here, for the 2-hops network and relay with a reliable link respectively:

$$h_s(\bar{\gamma}_1, \bar{\gamma}_2) = \mathbb{P}(\mathrm{S_P}|\bar{\gamma}_1)\,\mathbb{P}(\mathrm{S_P}|\bar{\gamma}_2) \tag{6}$$

$$h_s(\bar{\gamma}_1, \bar{\gamma}_2) = 1 - \mathbb{P}(\mathrm{E_P}|\bar{\gamma}_1)\,\mathbb{P}(\mathrm{E_P}|\bar{\gamma}_2) \tag{7}$$

where $\mathbb{P}(\mathrm{S_P}|\bar{\gamma}_i) = \mathbb{E}\left[(1 - Q(\sqrt{2\gamma_i}))^n \,|\, \bar{\gamma}_i)\right]$ and $\mathbb{P}(\mathrm{E_P}|\bar{\gamma}_i) = 1 - \mathbb{P}(\mathrm{S_P}|\bar{\gamma}_i)$ for a BPSK modulation [10]. Fig.4 shows the surface plot of (6) and (7).



(a) 2-hops network

(b) Relay with a reliable link

Fig. 4. Surface plot for the equivalent packet success rate

Choosing a value for P^* will basically define the integration region for the multivariate probability density function delimited in the by the contour corresponding to the chosen value. We express the pathloss on the links in decibels, thus the random vector $(\bar{\gamma}_1, \bar{\gamma}_2)$ follows a multivariate normal distribution. As an example to visualize the results on the outage probability, we consider that both components of the vector have 5 dB mean, 10 dB variance and no correlation. The resulting truncated probability density function is plotted on Fig.5 . Integrating this function will give us the desired outage probability as the volume under the curve.

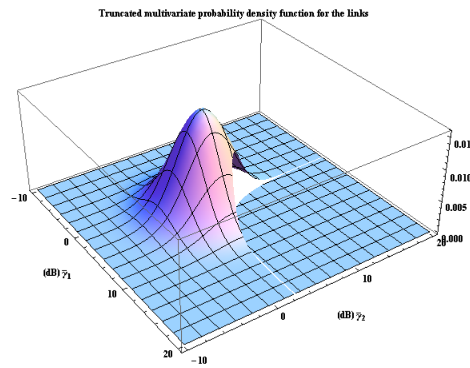
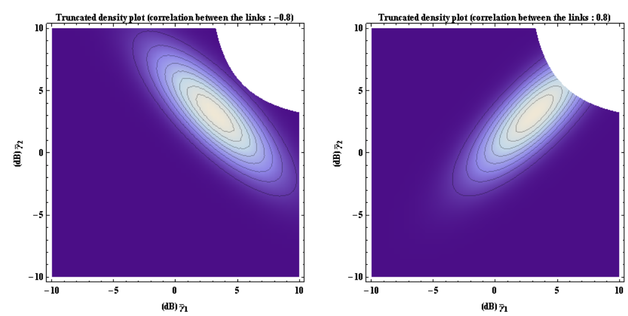


Fig. 5. Truncated probability density function for a target packet error rate of 0.1 on the 2 hops networks.

To visualize the effect of correlation, we use density plot of the probability density function delimited by the region defined by the outage threshold. As seen on Fig.6, correlation thins and extends the density function along diagonals, potentially modifying the outage value greatly in either direction.



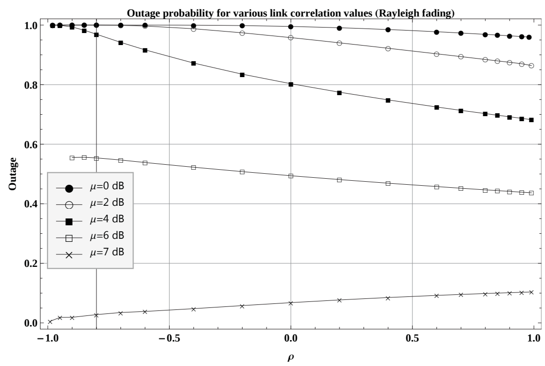
(a) Correlation value -0.8

(b) Correlation value 0.8

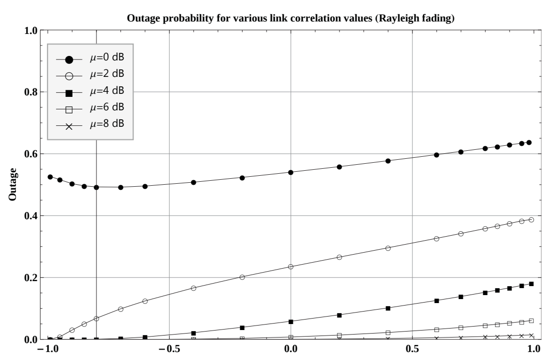
Fig. 6. Density plots at different correlation values between the components of the random vector

Depending on where the region boundary cuts the peak of the density function, correlation will have different effects. The mean of the random vector will determine the position of the peak of the density function, the variance its spread and the correlation its form. The plot in Fig.7 compares the effect on correlation with different mean values of the random vector, which effectively moves the peak of the density alongside the diagonal of its graph. Correlation is seen to have a powerful impact on the packet error outage for both network topologies. These effects are amplified at the low SNR regime, which is expected since this graphically means that the boundary will be closer to the peak of the density function. In essence, the outage region already spans most of the density function, and any deformation of the latter due to correlation will make the outage probability vary by large amounts.

We can see that for the 2-hops network (Fig.7a), positive correlation has a positive effect at low SNR and negative at high SNR. Intuitively, this is expected by looking at the density plots on Fig.6. If the outage probability is already low, positive correlation thins the density function along the diagonal, thus making the outage region span more of the probability density. Another intuition is that for the relay network with a reliable link, negative correlation on the link is very beneficial, as we should always have a *good* path to the destination, whereas positive correlation would shut both links simultaneously. Fig.7b agrees well with that observation, even at relatively low SNR.



(a) 2-hops network



(b) Relay with a reliable link

Fig. 7. Effect of the shadowing correlation on simple networks

IV. Application to Body Area Networks

We focus our interest here in the Hip-Right Hand-Right Foot relay channel here – nodes A, I and D on Fig.1. We denote through the indices $1, 2, 3$ the links A-D, A-I and I-D respectively. Values in decibels for the means, variances and correlation of the shadowing processes are taken from [5], [6]:

$$\mu = \{-62.3, -42.9, -56.7\} \quad V = \{10.77, 6.51, 3.95\}$$
$$\rho = \begin{pmatrix} 1 & -0.5 & -0.5 \\ -0.5 & 1 & 0.5 \\ -0.5 & 0.5 & 1 \end{pmatrix} \tag{8}$$

We consider through this section Rayleigh and Nakagami fading models, using for the latter parameters given as in [1], and a target packet error rate of 10%. As a first step in our analysis, we can plot the outage probability for each considered link [8] as in Fig.8.

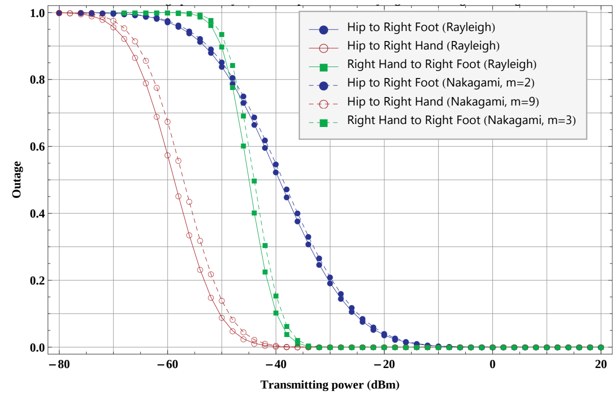


Fig. 8. Outage probability for each single link, with Rayleigh and Nakagami fading models

The most simple 2-slots half-duplex relaying protocol consists in alternated transmissions from the source and the relay. In this case, the equivalent PER is:

$$\begin{aligned}&\mathbb{P}(\mathrm{E_P}|\bar{\gamma}_1, \bar{\gamma}_2, \bar{\gamma}_3) = \\ &\mathbb{P}(\mathrm{E_P}|\bar{\gamma}_1)\left[1 - (1 - \mathbb{P}(\mathrm{E_P}|\bar{\gamma}_2)) \cdot (1 - \mathbb{P}(\mathrm{E_P}|\bar{\gamma}_3))\right]\end{aligned} \tag{9}$$

In our previous paper, we used two theorems from probability theory to express the cumulative distribution function of the equivalent packet error probability from this formula, but this approach is valid for uncorrelated shadowing links only. The new approach of this paper allows us to describe the general shadowing distribution case. In Fig.9 we plot the packet error outage for the above scheme, using a variable transmission power at the source and a fixed -55 dBm transmission power at the relay.

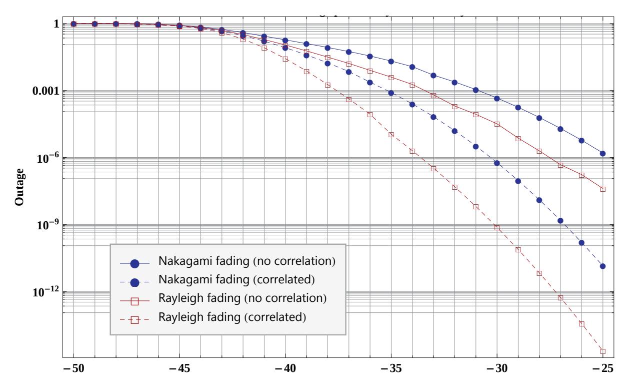


Fig. 9. Impact of the correlation on the outage probability for the relay channel

In practical cases, one would aim at lowering both the packet error outage and transmission power for energy conservation, and we argue that taking the shadowing correlation into account can allow one to further lower the transmission power. On Fig.9, we show an analysis of the outage probability with and without considering shadowing correlation. As an example, we can expect the necessary transmission power achieving an outage probability of 0.1% to be up to 5dB lower if we account for the correlation between the links. Another analysis would be to point out that not considering the correlation causes the metric to be overevaluated by a large factor at every transmission powers of interest.

Relaying schemes still require complex protocols to work. For the sake of completeness we can compare the simple relaying approach presented here with other schemes, especially retransmission schemes in correlated and uncorrelated shadowing and fading states and transmitting on the direct link at a higher power, namely direct transmission at $P + P_{\mathrm{Relay}}$. Retransmitting in the same fading state will result in taking the square of the instantaneous packet error rate before averaging over the possible fading states, which translates into the following expression for the short-term average packet error rate:

$$\mathbb{P}(\mathrm{E_P}|\bar{\gamma}) = \mathbb{E}\left[\left[(1 - Q(\sqrt{2\gamma_i}))^n\right]^2 \mid \bar{\gamma}_i)\right] \tag{10}$$

whereas retransmission in uncorrelated fading states lets one take the square of the short-term average as follow:

$$\mathbb{P}(\mathrm{E_P}|\bar{\gamma}) = \left[\mathbb{E}\left[(1 - Q(\sqrt{2\gamma_i}))^n \mid \bar{\gamma}_i)\right]\right]^2 \tag{11}$$

Retransmitting in uncorrelated shadowing states is basically equivalent to the relay channel with a reliable link presented in section III (Fig.3b), where 2 paths to the destination are available with uncorrelated shadowing processes of the same mean and variance.

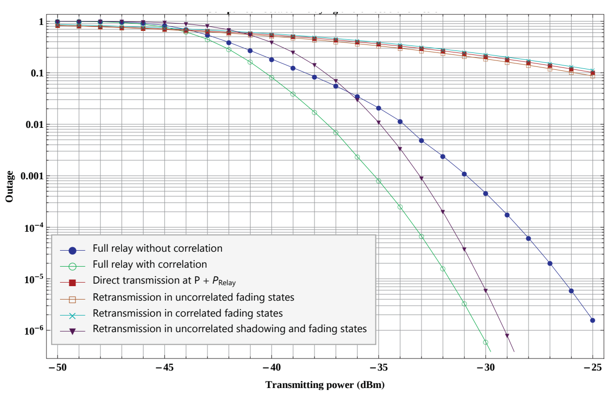


Fig. 10. Outage probability for various retransmission schemes

As seen on Fig.10 transmitting on the same link only captures diversity if two transmissions are done on uncorrelated shadowing states, and retransmission in uncorrelated fading schemes is only marginally better than transmitting only once with a higher power. Recalling from [6] that BANs have long fading and shadowing coherence times, one would have to delay the retransmission by up to 500ms for the shadowing to be uncorrelated, thus possibly violating delay constraints for the upper layers. A relaying approach can then be a valid response to mitigate the effect of shadowing holes on the packet error rate without raising a single node transmission power too high or inducing delays in the delivery.

V. Conclusion

In this paper, we studied the effect of correlated shadowing random processes acting on multiple links of a body area network. We started by introducing a simple model for the computation of a specific metric, the packet error outage, applied to relayed links in a network. This framework allowed us to compute some theoretical effects of the shadowing correlation on the packet error outage, showing with simple examples that it may have large impacts on the evaluated performance of the network. In the last part, we used BAN measurements from the BANET project [4] to provide a deeper insight on how the correlation affects the metric in a realistic case.

The formulas developed here are still hardly tractable. An obvious perspective of this work is thus to continue to try and simplify these results, relying in the least on multidimensional numerical probability density integrations, which are computationally intensive. Approximations techniques have been used in similar situations before and may well extend to this problematic. In the meantime, it would still be interesting to evaluate the performance and sensitivity to correlation of more advanced relaying schemes or combiners on the receiver side, with respect to a packet error outage metric.

References

[1] "802.15.6 Task Group Homepage," http://www.ieee802.org/15/pub/TG6.html, 2008.

[2] "Channel Model for Body Area Networks (BAN)," IEEE P802.15-08-0780-07-0006, 2008.

[3] C. Roblin and L. Ouvry, "Propagation channel models for BANs: an overview," in *COST 2100, Braunschweig*, 2009, pp. 1–29.

[4] "BANET project : Technologies for Body Area Networks, Body Sensor Networks and their applications." [Online]. Available: http://www.banet.fr/

[5] R. D'Errico and L. Ouvry, "Delay dispersion of the on-body dynamic channel," in *Antennas and Propagation (EuCAP), 2010 Proceedings of the Fourth European Conference on*, apr. 2010, pp. 1–5.

[6] ——, "Time-variant BAN channel characterization," *COST2100*, 2009.

[7] S. Cotton, G. Conway, and W. Scanlon, "A Time-Domain approach to the analysis and modeling of On-Body propagation characteristics using synchronized measurements at 2.45 GHz," *Antennas and Propagation, IEEE Transactions on*, vol. 57, no. 4, pp. 943–955, 2009.

[8] P. Ferrand, M. Maman, C. Goursaud, J.-M. Gorce, and L. Ouvry, "Performance evaluation of direct and cooperative transmissions in body area networks," *Annals of Telecommunications*, pp. 1–16, 2011, 10.1007/s12243-011-0238-y. [Online]. Available: http://dx.doi.org/10.1007/s12243-011-0238-y

[9] J.-M. Gorce, C. Goursaud, C. Savigny, G. Villemaud, R. d'Errico, F. Dehmas, M. Maman, L. Ouvry, B. Miscopein, and J. Schwoerer, "Cooperation mechanisms in bans," in *COST2100, 8th management meeting, Valencia, Spain*, May 2009, p. 24.

[10] John G. Proakis and Masoud Salehi, *Digital Communications*, 5th ed. McGraw-Hill, 2008.

[11] M. Maman, F. Dehmas, and R. D. Ouvry, "Evaluating a tdma mac for body area networks using a space-time dependent channel model," in *Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on*, 2009, pp. 1–5.