Performance Analysis of Collaborative Spatio-Temporal Processing for Wireless Sensor Networks

‡*C. Fischione*, †*A. Bonivento*, †*A. Sangiovanni-Vincentelli*, §*F. Santucci*, ‡*K. H. Johansson*
‡*KTH*, †*U.C. Berkeley*, §*University of L'Aquila*
e-mail: ‡{*carlofi, kallej*}*@s3.kth.se*, †{*alvise,alberto*}*@eecs.berkeley.edu*, §*santucci@ing.univaq.it*

***Abstract*— Spatio-temporal processing (STP) is a control technique to increase the quality of the received signals in wireless networks. Outage events have a strong influence not only on the performance of the physical layer, but also on routing, MAC, and application layers. In this paper, we propose an outage-based performance analysis of collaborative STP for wireless sensor networks (WSNs). After an accurate characterization of the wireless channel, we derive the outage statistics as a function of the STP coefficients, and investigate the effects of STP on the probability, average duration and rate of the outage events. Furthermore, we show that a proper control policy for the STP coefficients can be derived according to the requirements from the application and communication layers.**

***Index Terms*: Wireless Sensor Networks (WSNs), Spatio-Temporal processing (STP), Fading, Outage, Level Crossing Analysis.**

I. INTRODUCTION

Significant performance improvements can be achieved if nodes in wireless networks cooperate. Collaborative distributed spatio-temporal processing (STP) is such a technology, which in the context of cellular radio system and ad-hoc wireless networks has been an area of intense research (see e.g. [1]). For wireless sensor networks (WSNs), however, constraints on power, memory, information processing, etc., make the extension of traditional STP techniques difficult. STP techniques for WSNs should also take into account cross-layer mechanisms, which are crucial for many sensing and control applications [2], [3].

Some recent contributions can be found in literature. In [4] the authors investigate the possibility of shaping the radiation diagram using a random distribution of nodes. Specifically, the authors show that using randomly placed nodes, it is still possible to obtain good radiation diagram. However, the analysis is based on a number of ideal assumptions, particularly a simple model of the wireless channel. In [5] and [6], an interesting framework is addressed, where nodes are grouped in clusters and collaborate to receive and transmit information using a distributed algorithm for the phase synchronization. Moreover, the authors propose the use of an STP technique based on Maximum Ratio Combining scheme, where the nodes are supposed to perform an accurate channel estimation. In [7], a maximum likelihood approach is proposed for the communication between a source and a destination with multiple relays, and the options of relay-and-forward, and decode-and-forward are investigated. A framework for performance analysis in a cellular radio system, but interesting also from a WSNs perspective, can be found in [8], where a Maximum Ratio Combining spatial diversity scheme with composite Rayleigh-Log normal channel model is studied.

Outages events can have strong influence on the performance of upper layers in the protocol stack, e.g., [9], [10], [11]. Despite their importance, outage events for WSNs have been considered in the literature only recently [12]. In fact, it is well known that outage statistics are important performance measures useful for the optimization of the MAC, time-slot duration, packet length, etc. Outage statistics are also important from the perspective of applications utilizing the WSNs. An important example is when a WSN is used to gather information for real-time control of a plant. The stability of the closed-loop control system may require outage rates lower than a certain sampling frequency of the controller and the dynamics of the plant.

The main contribution of this paper is an investigation of STP performance for WSNs in terms of the outage statistics. We provide an accurate framework for the abstraction of the properties of the physical layer with collaborative STP, taking into account all the relevant parameters that may influence the upper layer protocols and applications. After suitable modelling of the physical layer, we study the STP performance with respect to the outage events. Specifically, the outage probability, the outage rate and average outage duration are explicitly derived as a function of the STP coefficients. We aim at defining an optimal control of the STP parameters, which should be scalable with respect to application, MAC, routing and propagation conditions of the physical layer. Our approach differs from [5] and [6], because we focus on the optimization of outage performance instead of the optimal shaping of the equivalent radiation diagram for a random sensor array. For real-time applications, the outage probability is a more reasonable measure than the bit error probability analysis addressed in [7]. Moreover, none of these contributions, as well as [8], takes into account the presence of a correlation structure among wireless links, that may have strong effects on the performance.

The rest of the paper is organized as follows: after a description of the system model and the wireless channel for WSNs with collaborative STP in Section II, in Section III the outage statistics are derived; in Section IV a sketch of possible outage based STP is outlined; in Section V numerical examples are discussed, and, finally, in Section VI conclusions and future developments are given.

II. SYSTEM MODEL

Consider the scenario in Fig. 1. We have a moving sensor node, called MS, that broadcasts a signal associated to an

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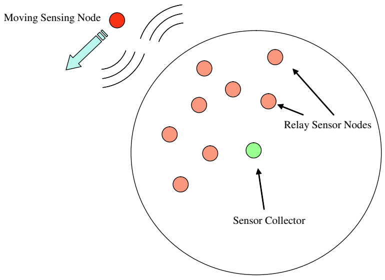

Fig. 1. System overview of the considered wireless sensor network.

application. There is a cluster of N sensor nodes that receive the broadcasted signal and retransmit it to a sensor collector (SC). For example, the MS could transmit the status information associated to an inverted pendulum as in [2], where the communication between the actuator at the MS and the controller at the SC happens through the WSN.

We assume that the relaying sensor nodes are part of a WSN where several other techniques may be implemented, e.g. source coding. Therefore, STP can be seen a complementary technique running over the relaying sensor nodes.

There is no direct link between the MS and the SC, so that the signal has to pass through the relaying nodes that cooperatively weight the received signals to improve the quality of the signal received by the SC. The sensor nodes transmit using different channels, for example they could use different frequencies, time slots or codes. We assume that the retransmission of signals happens with no appreciable delay.

The links between the MS and the relaying nodes are frequency flat, time variant and affected by path loss, shadow and fast fading. We assume that the relay sensor nodes and the SC are fixed and within range from each other. Consequently, the channel coefficients describing the links between these nodes and the SC are assumed to be known with a good approximation. This set up is basically equivalent to the one considered in [5], and is representative for the Industrial, Scientific, and Medical (ISM) transceivers, which are commonly employed in WSNs [13].

The SC receives simultaneously the retransmitted signals from the various sensor nodes, and therefore obtains the sum of the signals. Under the assumption of a BPSK modulation, the complex envelope of the received signal is expressed as follows:

$$y(t) = \sum_{i=1}^{N} w_i [h_i(t)s(t) + n_i(t)] + n(t) \ , \tag{1}$$

where w_i, $i = 1, ..., N$ are the complex values of the weighting coefficients, and for the sake of notation simplicity, we include in w_i also the known channel gains between the nodes and the SC; $h_i(t)$, $i = 1..., N$, is the channel coefficient of the wireless link between the MS and sensor i; $n_i(t)$ is the noise component at the node i, and is assumed as white Gaussian noise (AWGN), with power spectral density given by σ_i^2; finally, $n(t)$ includes the interferences and AWGN noise present at the receiver of the SC, having power spectral density σ_n^2. Note that the weighting coefficients $\mathbf{w} = [w_1, w_2, ..., w_N]$ are set by the STP algorithm.

The channel coefficient $h_i(t)$ is comprehensive of path-loss, shadowing and fast fading. We express such a coefficient using a multiplicative model as follows [14]:

$$h_i(t) = g_i(t)\sqrt{L_i(t)} \ , \tag{2}$$

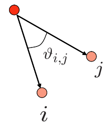

Fig. 2. The correlation structure of the channel gains is function of the angle between the link toward the node j and the node i.

where $L_i(t)$ takes into account path loss and shadowing, while $g_i(t) = |g_i(t)|e^{j\phi_i(t)}$ is the fast fading. We make the common assumption that $g_i(t)$ is a complex zero mean Gaussian random process, then $|g_i(t)|$ is Rayleigh distributed. Moreover, let us define $p_i(t) \triangleq |g_i(t)|^2$, then, $p_i(t)$ is an exponentially distributed process, with parameter σ_{p_i}. The average and correlation function of $p_i(t)$ are given as in the following [14]:

$$E\{p_i(t)\} \triangleq m_{p_i} = 2\sigma_{p_i}^2 \ , \tag{3}$$

$$E\{p_i(t)p_i(t-\tau)\} \triangleq r_{p_i}(\tau) = 8\sigma_{p_i}^4 J_0(2\pi f_m \tau) \ , \tag{4}$$

where $J_0(\cdot)$ is the zero order Bessel function of the first kind. Note that $g_i(t)$ and $g_j(t)$, with $i \neq j$, are statistically independent.

The shadowing component $L_i(t)$ has a log-normal distribution $L_i(t) = e^{B_i(t)}$, where $B_i(t)$ is a Gaussian random process having average m_{B_i} and variance $\sigma_{B_i}^2$. The shadowing component exhibits a correlation structure that is dependent on the propagation scenario. We resort here to the general model of the autocorrelation and cross-correlation functions derived in [15]:

$$C_{B_i}(\tau) = \sigma_{B_i}^2 e^{-\frac{1}{2}\left(\frac{\tau}{\tau_{B_i}}\right)^2} \ , \tag{5}$$

$$C_{B_iB_j}(\tau) = \sigma_{B_i}\sigma_{B_j} A\cos[\vartheta_{ij}(t) + B] e^{-\frac{1}{2}\left(\frac{\tau}{\tau_{B_i}}\right)^2} \ , \tag{6}$$

where τ_{B_i} is the de-correlation constant of the shadowing (measured in seconds), $\vartheta_{ij}(t)$ is the angle between the links from the MS and the node i, and the MS and the node j (see Fig. 2), and A and B are two constants such that $A + B \leq 1$. The values for A and B are dependent on the propagation environment. Consequently, the average and autocorrelation function of $L_i(t)$ can be expressed as follows:

$$E\{L_i(t)\} = e^{m_{B_i} + \frac{1}{2}\sigma_{B_i}^2} \ , \tag{7}$$

$$E\{L_i(t)L_j(t-\tau)\} = e^{m_{B_i} + m_{B_j} + \frac{1}{2}\left[\sigma_{B_i}^2 + \sigma_{B_j}^2 + 2C_{B_iB_j}(\tau)\right]} \ , \tag{8}$$

After a coherent receiver matched to the transmitted signal and keeping in mind the independence of the Rayleigh fading among different nodes, we express the Signal to Interference + Noise Ratio (SINR) corresponding to (1) as follows ([14], [8]):

$$SINR(t) = \frac{E_s \sum_{i=1}^{N} |w_i|^2 r_i(t)}{\sum_{i=1}^{N} |w_i|^2 \sigma_i + \sigma_n} \ , \tag{9}$$

where E_s is the energy of the transmitted signal, while $r_i(t) = |h_i(t)|^2$. Note that (9) depends on time since the fading is assumed to be time variant. Also, note that $|w_i|^2$ has the meaning of relaying power.

The received signal (1) is said to be in outage if the SINR (9) falls below a minimum quality threshold γ. In particular, the probability of the outage events is defined as follows:

$$P_{out} = P(SINR(t) < \gamma) \ . \tag{10}$$

III. STP Outage Statistics

Deriving the statistics of the SINR (9) is in general non-trivial. However, since the SINR is expressed as a linear combination of Rayleigh-Lognormal random processes, we can rely upon existing results [10], [16]. We resort to the well-known extension of the Wilkinson Moment matching method (see [16] and [17] for a comprehensive analysis and for the accuracy of the approach). Specifically, we consider the following approximation:

$$SINR(t) \cong e^{Z(t)} \ , \tag{11}$$

where $Z(t)$ is a Gaussian random process having average m_Z and covariance $C_Z(\tau)$, that are derived as a function of the first and second moments of the SINR:

$$m_Z = \ln\left[\frac{M_{m1}^2}{M_{m2}(0)}\right] \ , \tag{12}$$

$$C_Z(\tau) = \ln\left[\frac{M_{m2}(\tau)}{M_{m1}^2}\right] \ . \tag{13}$$

where:

$$M_{m1} \triangleq E\{SINR(t)\} \ , \tag{14}$$

$$M_{m2}(\tau) \ \triangleq \ E\{SINR(t)SINR(t-\tau)\} \ . \tag{15}$$

The SINR in dB, $SINR_{dB}$, is a Gaussian process, and is expressed as follows:

$$SINR_{dB}(t) = \beta Z(t) \tag{16}$$

with average and covariance function expressed, respectively, as $m_{SINR_{dB}} = \beta m_Z$ and $C_{SINR_{dB}}(\tau) = \beta^2 C_Z(\tau)$, with $\beta = \ln 10/10$.

The $SINR_{dB}$ Gaussian distribution allows for a straightforward derivation of outage probability $P_{out}(\mathbf{w})$, average outage rate $F_{out}(\mathbf{w})$, and outage average duration $D_{out}(\mathbf{w})$. Specifically, they can be expressed as follows (see e.g. [14] for a general reference on Level Crossing Theory):

$$P_{out}(\mathbf{w}) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{u} e^{-\frac{y^2}{2}}dy \ , \tag{17}$$

$$F_{out}(\mathbf{w}) = \frac{1}{2\pi}\sqrt{\frac{\lambda_2}{\lambda_0}}e^{-\frac{u^2}{2}}dy \ , \tag{18}$$

$$D_{out}(\mathbf{w}) = \frac{P_{out}(\mathbf{w})}{F_{out}(\mathbf{w})} \ , \tag{19}$$

where

$$u = \frac{m_{SINR_{dB}} - \gamma_{dB}}{\sqrt{C_{SINR_{dB}}(0)}} = \frac{\beta m_Z - \gamma_{dB}}{\beta\sigma_Z} \ , \tag{20}$$

$$\lambda_0 = C_{SINR_{dB}}(0) \ , \tag{21}$$

$$\lambda_2 = -\frac{d^2 C_{SINR_{dB}}(\tau)}{d\tau^2} \ , \tag{22}$$

and $\gamma_{dB} = 10\log\gamma$. In the Appendix, the expressions of (14), (15), (21) and (22) are provided.

The log-normal approximation for the SINR allows to further approximate the statistics of the outages intervals, that, when u is negative, can be described with a Rayleigh probability distribution function [10] with parameter $\varphi(\mathbf{w}) = u^2\lambda_2/4\lambda_0$, and, hence, the average outage duration is approximated with an expression simpler with respect to (19):

$$D_{out_{approx}}(\mathbf{w}) = \sqrt{\frac{\pi}{2\varphi(\mathbf{w})}} \ . \tag{23}$$

Note that in (23) there are not integral functions of $\mathbf{w}$, and this may lead to remarkable simplifications to solve optimization problems.

IV. Implementation Aspects of Outage Based STP

The outage statistics (17)-(19) and (23), together with cross-layer constraints, can be employed to formulate optimization problems, where the optimization variables are the weighting coefficients $\mathbf{w}$. The solution of the optimization problem is computed at the SC. The deterministic knowledge of the fading coefficients for the computation of the outage probability is not required, but only the estimation of the first- and second-order moments. Such estimations can be performed by each node with e.g. simple running average or recursive low-pass filters. The estimation of the fading parameters performed by the nodes are transmitted to the SC and used in the optimization. Since the channel parameters vary with a frequency corresponding to the coherence time of the wireless propagation, the weights should be updated at least with the same time scale.

An example of outage based STP is the minimization of the energy consumption of the nodes under the constraint that the outage probability is not lower than a minimum threshold. The value of the threshold could be set by the requirements of the applications, as for data or voice services in third generation wireless systems [1].

Once the weights are computed at the SC, they have to be transmitted to the nodes. This transmission might be expensive in terms of energy consumption, delay, etc. Our future work will include the investigation of distributed and suboptimal solutions.

V. Numerical Examples

In this section, numerical examples obtained with our general framework are reported and discussed. With no loss of generality, we present some specific cases that are useful to devise how the weighting coefficients may be tuned to satisfy the required constraints.

We consider a system scenario with $N = 3$ sensors, where the angles $\vartheta_{i,j}$ among the nodes are randomly chosen between $50°$ and $115°$. With no loss of generality, we set the shadowing correlation constants $A = B = 0.5$, that are associated to outdoor channels. The MS is assumed to transmit with a carrier frequency of $f_c = 2.4GHz$, and having a speed of $1.5\ m/s$. Therefore, the maximum Doppler frequency is $f_m = 10Hz$. We assume that the power spectral density of the AWGN noises on each node is $\sigma_1 = ... = \sigma_N = \sigma_n = N_0$, and the symbol energy to noise ratio Es/N_0 is set to $10dB$. The standard deviation of the Rayleigh components are assumed to be $\sigma_{p_i}^2 = 1.0$, $i = 1..3$. The SINR threshold is set to $\gamma_{dB} = 3\ dB$. See Tab. I for the shadowing setting.

The curves in Fig. 3-6 are plotted as function of $d_1 = |w_1|^2$. Each curve is referred to the value $d_2 = |w_2|^2$ specified in the legend of the figure, while $d_3 = |w_3|^2$ is set to the constant value of 0.01 for any case.

In Fig. 3, the outage probability is reported for the case 1 in Tab. I, where the parameters of the shadowing are assumed to be uniform, with the exception of the node 2 that experiences a strongest average component. By observing Fig. 3, for each d_2, a value of d_1 that ensures a minimum of the outage probability

Case	parameter	node 1	node 2	node 3
	m_{B_i}	1.0	2.0	1.0
1	σ_{B_i}	1.0	1.0	1.0
	τ_i	0.01	0.01	0.01
	m_{B_i}	1.0	1.0	1.0
2	σ_{B_i}	1.0	2.0	1.0
	τ_i	0.01	0.01	0.01
3	m_{B_i}, σ_{B_i}	1.0	1.0	1.0
	τ_i	0.001	0.01	0.01

TABLE I
PARAMETER SETTINGS FOR THE NUMERICAL EXAMPLES

can be found. Moreover, the minimum is the same for all cases of d_2, with the exception of $d_2 = 0.05$. Therefore, it could be possible to set the value of the weighting coefficients with low powers, while the outage probability is still minimized.

In Fig. 4, the outage probability is reported for the case 2 in Tab. I, where the node 2 is assumed to experience a larger standard deviation of the shadowing. The observations made for Fig. 3 are still valid. Moreover, the minimum of the outage probability is higher, and this can be explained observing that higher standard deviation of the shadowing imply that outage events last longer.

Note that the range variation of the outage probability in Fig. 3 and Fig. 4, is dependent on the STP coefficients as well as the channel parameters. Severe channel conditions lead to larger variation of the outages.

In Fig. 5 and 6, the average outage duration and outage rate are reported for the case 3 of Tab. I, where the shadowing component of the node 1 experiences a larger de-correlation delay. Looking to the results, as there is an increase of d_1, the outage rate increases, while higher values of d_2 lead to lower outage rate. By the contrary, the average outage duration decreases as both d_1 and d_2 increase, and a common minimum is reached for $d_1 > 0.25$. Therefore, a trade-off in the choice of the weighting coefficients could be devised according to the requirements mapped onto outage rates and duration.

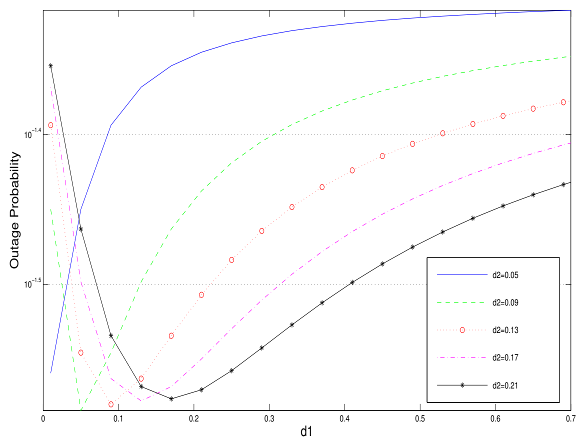

Fig. 3. Outage probability as function of the STP coefficients $d_i = |w_i|^2$ for the case 1 of Tab. I.

VI. CONCLUSIONS AND FUTURE DEVELOPMENTS

In this paper, an investigation of the outage performance of collaborative STP for WSNs was proposed. The approach is

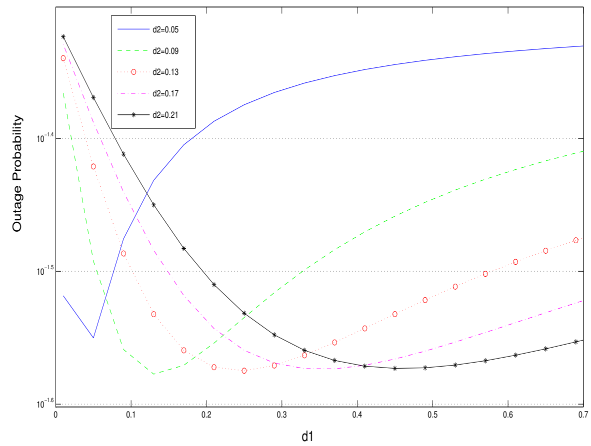

Fig. 4. Outage probability as function of the STP coefficients $d_i = |w_i|^2$ for the case 2 of Tab. I.

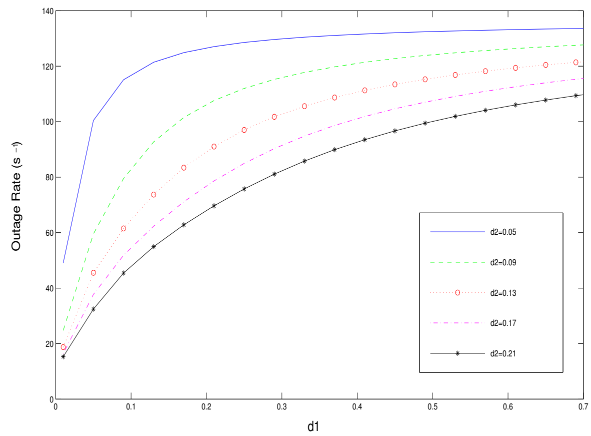

Fig. 5. Outage rate as function of the STP coefficients $d_i = |w_i|^2$ for the case 3 of Tab. I.

based on the adoption of a good abstraction of physical layer as function of the STP weighting coefficients.

Our method can be used for the derivation of an optimization policy of the STP algorithm tailored to the necessities of the upper layers of the protocol stack. For example, the weighting coefficients could be tuned in order to ensure an average outage duration and an outage rate that do not affect the control of an application monitored by the moving sensor. Another example is the use of our approach for selecting the sufficient number of nodes that ensure a desired quality of the received signal, while turning off the redundant ones and, thus, saving energy. We plan to investigate the extension of our model to include joint optimum STP-sleeping discipline algorithms for the sensor nodes. Finally, an extension of our approach to WSNs with several moving sensing nodes could be interesting.

VII. APPENDIX

The first and second order moments of (9) can be derived as follows:

$$M_{m1} = CA \sum_{i=1}^{N} d_i 2\sigma_{p_i}^2 e^{m_{B_i} + \frac{1}{2}\sigma_{B_i}^2} \quad , \tag{24}$$

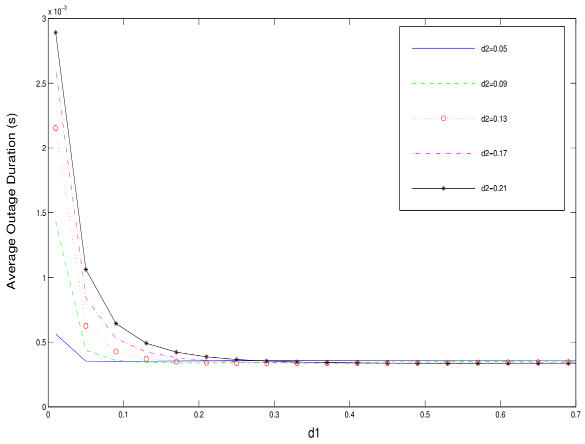

Fig. 6. Average Outage duration as function of the STP coefficients $d_i = |w_i|^2$ for the case 3 of Tab. I.

$$M_{m2}(\tau) = CA^2 \sum_{i=1,i\neq j}^{N} \sum_{j=1}^{N} d_i d_j 2\sigma_{p_i}^2 2\sigma_{p_j}^2 e^{m_{B_i} + m_{B_j} \frac{1}{2}[\sigma_{B_i}^2 + \sigma_{B_j}^2 + 2C_{B_iB_j}(\tau)]} + CA^2 \sum_{i=1}^{N} d_i^4 \sigma_{p_i}^8 J_0(2\pi f_m \tau) r_{\nu_i}(\tau) e^{2m_{B_i} + \sigma_{B_i}^2 + C_{B_i}(\tau)} , \quad (25)$$

where $CA = E_s/(\sum_{i=1}^{N} d_i\sigma_i + \sigma_n)$ and $d_i = |w_i|^2$.

λ_2 is derived as follows:

$$\lambda_2 = -\beta^2 \frac{d^2 C_Z(\tau)}{d\tau^2} \quad (26)$$

$$= \frac{\frac{d^2 M_{m2}(\tau)}{d\tau^2} M_{m2} - \left(\frac{dM_{m2}(\tau)}{d\tau}\right)^2}{M_{m2}^2} , \quad (27)$$

where, after algebraic manipulations, the following expression are obtained:

$$\frac{dM_{m2}(\tau)}{d\tau} = \sum_{i=1}^{N} \sum_{j=1,j\neq i}^{N} G_{i,j}(\tau) \frac{dC_{B_iB_j}(\tau)}{d\tau} + \sum_{i=1}^{N} H_{i,j}(\tau) + \sum_{i=1}^{N} I_i(\tau) \frac{dC_{B_i}(\tau)}{d\tau} , \quad (28)$$

where

$$G_{i,j}(\tau) = CAd_i d_j 2\sigma_{p_i}^2 2\sigma_{p_j}^2 e^{m_{B_i} + m_{B_j} \frac{1}{2}[\sigma_{B_i}^2 + \sigma_{B_j}^2 + 2C_{B_iB_j}(\tau)]} , \quad (29)$$

$$H_i(\tau) = CAd_i^4 \sigma_{p_i}^8 J_0'(2\pi f_m \tau) e^{2m_{B_i} + \sigma_{B_i}^2 + C_{B_i}(\tau)} , \quad (30)$$

$$I_i(\tau) = CAd_i^4 \sigma_{p_i}^8 J_0(2\pi f_m \tau) e^{2m_{B_i} + \sigma_{B_i}^2 + C_{B_i}(\tau)} . \quad (31)$$

and

$$\frac{d^2 M_{m2}(\tau)}{d\tau^2} = \sum_{i}^{N} \sum_{j=1,i\neq j}^{N} \frac{dG_{i,j}(\tau)}{d\tau} \frac{dC_{B_iB_j}(\tau)}{d\tau} + \sum_{i}^{N} \sum_{j=1,i\neq j}^{N} G_{i,j}(\tau) \frac{d^2 C_{B_iB_j}(\tau)}{d\tau^2} + \sum_{i}^{N} \frac{dH_i(\tau)}{d\tau} + \sum_{i}^{N} \frac{dI_i(\tau)}{d\tau} \frac{dC_{B_i}(\tau)}{d\tau} + \sum_{i}^{N} I_i \frac{d^2 C_{B_i}(\tau)}{d\tau^2} , \quad (32)$$

with

$$\frac{dG_{i,j}(\tau)}{d\tau} = G_{i,j}(\tau) \frac{dC_{B_iB_j}(\tau)}{d\tau} , \quad (33)$$

$$\frac{dH_i(\tau)}{d\tau} = CAd_i^4 \sigma_{p_i}^8 J_0''(2\pi f_m \tau) e^{2m_{B_i} + \sigma_{B_i}^2 + C_{B_i}(\tau)} + H_i(\tau) \frac{dC_{B_i}(\tau)}{d\tau} , \quad (34)$$

and

$$\frac{dI_i(\tau)}{d\tau} = H_i(\tau) + I_i(\tau) \frac{dC_{B_i}(\tau)}{d\tau} . \quad (35)$$

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