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Performance Analysis of Full and Semi Signals Integration Approaches in Digital Telecommunication Systems

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ABSTRACT

Signals integration is used in digital telecommunication systems to reduce the multipath effect. The two main approaches for signals integration in diversity telecommunication systems are full and semi signals integration. In full signals integration systems, there are multiple receivers producing very large number of bits and the entire signals integration system is closely resembled analog multiple receivers implementations. This approach achieves the optimum performance at the expense of high cost and complexity. In semi signals integration systems, only few number of bits are used after preliminary processing of signals at each individual receiver. This method could reduce system complexity and cost at the expense of overall performance degradation. This paper provides performance analysis of full and semi signals integration approaches in digital telecommunication systems in case of non-coherent differential phase shift keying receivers with Gaussian noise and Rician fading stochastic model. The performance loss due to semi signals integration is analyzed for different number of information bits.

1. Introduction

There are several ways to provide signal transmission in diversity telecommunication systems. One of the methods used for achieving diversity techniques employs a single transmitting antenna (receiver) and multiple receiving antennas [1]–[3]. Such diversity systems enhance the system performance compared to a single-antenna system. There are many models for digital signals transmission over fading digital telecommunication channels such as tropospheric scatter radio signals (UHF and SHF), shortwave ionospheric radio signals (HF) and ionospheric forward scatter (VHF). To reduce the multipath effects of fading, diversity telecommunication systems are used to provide replicas of the same information over independently channels [4]-[7].

In diversity telecommunication systems, multiple antennas are used. The output from each individual antenna is a multiple-bit information based on the received signal at the corresponding antenna. The received information from the multiple antennas are then fused in a central digital receiver to obtain the final There are two main approaches for signal processing in multiple-antennas telecommunication systems [10]-[13]. In the first method, the antennas produce very large number of bits of information [8], [9].

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information and the entire system will closely resemble analog multiple receiver's implementations. This method is called full signals integration approach. Theoretically, the full signals integration approach achieves the best performance at the expense of complexity and cost [14], [15]. In the second signal processing approach, few number of bits, instead of full signal integration approach, could reduce system complexity and cost considerably. This is called semi signals integration approach where some preliminary processing of the received signals is implemented at each individual antenna and the processed signals are then sent to a central fusion receiver that fuses the received signal information. A special case of the semi signals integration approach occurs when only one-bit information is used. The problem of one-bit information is called binary signal integration [16], [17]. This causes a high performance degradation compared to full signals integration approach.

The optimum solution of multiple-antenna signal integration systems is very complicated even for the case of only two bits per information. The optimum solutions requires complicated quantization processes and also need the actual relationships between the error probabilities and the thresholds for all receivers; therefore, the optimum solution is not feasible [18]-[20]. Some simplified signals integration approaches based on only one bit of quality information in addition to the receiver information are developed in many researches at the expense of a performance degradation [15], [16]. Other simplified signals integration approaches use suboptimum structures in case of two bits per information are also developed in many literatures and can be used [3], [20]. The purpose of this paper is to analyze the performance of full and semi signals integration in diversity telecommunication systems in case of speech signals. The performance loss due to semi signals integration is analyzed for different number of resolution bits. The results showed that the full signals integration approach achieves much better performance compared to the semi signals integration approach at the expense of required high bandwidth. The performance loss is high when semi signals integration approach with one-bit information is used and can be highly reduced by using more than three bits per information.

This paper is organized as follows. Full signals integration approach in digital telecommunication systems is introduced in Section 2. The semi signals integration approach is addressed in Section 3. The special case of one-bit information is discussed in Section 4. Section 5 compares the performance of full and semi signals integration approaches in case of non-coherent differential phase shift keying (DPSK) digital telecommunication systems with Gaussian noise and Rician fading stochastic model. Section 6 contains conclusion.

2. Full Signals Integration Approach in Digital Telecommunication Systems

In this case, there are n multiple receivers to achieve the diversity process [1], [4]. Each receiver has the structure of the standard single-antenna non-coherent DPSK receiver as shown in Fig. 1. Each receiver consists of a multiplier, a delay and an integrator (or a low pass filter (LPF)) as it is well known. The outputs of the integrators are sampled at the end of the bit period (T_b). The samples outputs are the random variables v_j which are the outputs of the jth receiver. The time-varying channels that may be occur and their fading channel characterization are treated in statistical terms. There are several fading stochastic models that can be considered as statistical characteristics of the fading channels. We consider the case of Rician fading stochastic model.

The received signal at each receiver is assumed to include additive zero-mean Gaussian noise. The noise and fading are assumed to be independent from receiver to receiver. It is worth noting that to obtain independent signals fading, certain separation is needed between any two adjacent antennas as explained in [5] - [7]. It means that the multiple antennas are sufficiently spaced such that the multipath fading components in the signals have significantly different propagation delays at the antenna inputs [5].

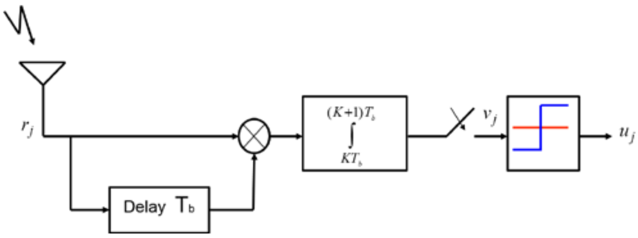

Figure 1. Block diagram of each receiver in case of non-coherent DPSK.

In case of full signals integration approach, each receiver, j, $j=1,2,.......,n$, sends its own measurements v_j, to a central fusion receiver. The central fusion receiver has access to the exact received measurements taken by all individual sensors [13-17]. We assume that the received measurements v_j 's at the n sensors are statistically independent. In this approach, all the received measurements are transmitted to the central fusion receiver in order to derive a global decision and no individual decisions are made by the individual receivers. Thus the central fusion receiver deduces a global decision u_g, based on the received receiver measurements $v_1, v_2,........, v_n$.

This is considered as a binary hypothesis testing problem with two hypotheses; H_0 decides that signal is absent and H_1 decides that signal is present.

Under each hypothesis the received measurements have known joint probability densities $P(v_1,v_2,.........v_n \mid H_0)$ and $P(v_1,v_2,.........v_n \mid H_1)$ as functions of the measurements v_j, $j=1,2,........, n$, where v_j 's are random vectors representing the receiver measurements. The goal of the central fusion receiver is to derive a global decision strategy of the form

$$u_g = \begin{cases} 0: \text{decide signal absent, i.e. } H_0 \\ 1: \text{decide signal present, i.e. } H_1 \end{cases}, \quad (1)$$

where the global decision u_g depends on the observations $u_1, u_2,........, u_n$.

According to the minimum probability of error criterion, the central fusion receiver should implement the likelihood ratio test. In this case, the optimum criterion which deduces the global decision of the central fusion receiver such that the total error probability is minimum will be [8], [12]:

(i) deterministic, so that the decision rule is a function

$$u_g(v_1,v_2,.........v_n) \rightarrow \{0,1\}, \quad (2\text{-a})$$

$$u_g = \begin{cases} 1 \quad \text{if } \ln \dfrac{\text{Prob}(v_1, v_2,....., v_n \mid H_1)}{\text{Prob}(v_1, v_2,....., v_n \mid H_0)} \geq 0 \\ 0 \quad \text{otherwise} \end{cases}, \quad (2\text{-b})$$

where $u_g = i$ is interpreted as choosing H_i.

(ii) given by a likelihood ratio test (LHR)

$$u_g(v_1,v_2,.........v_n) = \begin{cases} 0 \quad \text{if } LHR(v_1,v_2,.........v_n) < t_g \\ 1 \quad \text{if } LHR(v_1,v_2,.........v_n) \geq t_g \end{cases}, \quad (3)$$

where

$$LHR(v_1,v_2,.........v_n) = \frac{P(v_1,v_2,.........v_n \mid H_1)}{P(v_1,v_2,.........v_n \mid H_0)}. \quad (4)$$

(iii) The threshold of the fusion center, t_g, is determined according to the pre-specified total error probability.

3. Semi Signals Integration Approach in Digital Telecommunication Systems

In this case, each receiver is allowed to process its own measurements v_j to derive local decisions u_j. Therefore, each local receiver sends its own decision u_j instead of sending all its own measurements (observations) v_j. The semi signals integration approach allows the jth receiver to take on one of L values instead of sending all its own measurements.

The jth -sensor decision is based on its own samples v_j and the signal-to-noise (SNR) estimate, if it is available. Let Γ_j be a random variable which denotes the SNR estimate at sensor j and let γ_j denotes the samples of this random variable.

The optimum receiver decision structure for deriving the sensor decision u_j at a certain receiver j, is to obtain its likelihood ratio which is a function of V_j and Γ_j. It means that the values of the receiver decisions u_j are depending on its own likelihood ratio.

In this case, each receiver implements its own likelihood ratio as [3], [18]

$$\ln\frac{f_{V_j,\Gamma_j}(v_j,\gamma_j\,|\,1\text{ sent})}{f_{V_j,\Gamma_j}(v_j,\gamma_j\,|\,0\text{ sent})}=\ln\frac{f_{V_j}(v_j\,|\,1\text{ sent},\gamma_j)}{f_{V_j}(v_j\,|\,0\text{ sent},\gamma_j)}, \qquad (5)$$

where $f_{V_j,\Gamma_j}(v_j,\gamma_j\,|\,s\text{ sent})$ is the joint probability density function (pdf) of V_j and Γ_j given that s was sent ($s=0\,\text{or}\,1$). The semi signal integration approach allows the jth receiver to take on one of L values by mapping the jth likelihood ratio, which is a function of V_j and Γ_j, using N number of bits ($L=2^N$). Thus the jth receiver decides $u_j=k$ if $(v_j,\gamma_j)\in A_{j,k}$, where

$$A_{j,k}=\left\{(v_j,\gamma_j):t_{j,k-1}\le\ln\left(\frac{f_{V_j}(v_j\,|\,1\text{ sent},\gamma_j)}{f_{V_j}(v_j\,|\,0\text{ sent},\gamma_j)}\right)<t_{j,k}\right\}. \qquad (6)$$

For a given receiver threshold t_j, if $\ln\left(\frac{f_{V_j}(v_j\,|\,1\text{ sent},\gamma_j)}{f_{V_j}(v_j\,|\,0\text{ sent},\gamma_j)}\right)$ is low (or high) enough, the jth receiver decision will take the value 0 (or 1) with high probability level and vise versa.

The minimum probability of error in case of semi signals integration approach is derived in many literatures. The decision rule of the central fusion receiver is

$$u_g=\begin{cases}1;\text{if} & \left(\begin{array}{l}\sum_{j=1}^{n_0}I(u_j=0)W_{j0}+\sum_{j=1}^{n_1+n_2+\ldots+n_L}\sum_{k=1}^{L}I(u_j=u_{jk})W_{jk}\\+\sum_{j=1}^{n_+}I(u_j=1)W_{j1}\end{array}\right)>0\\ 0; & \text{otherwise},\end{cases} \qquad (7)$$

where

$$W_{jk}=\left\{\ln\left(\frac{\text{Prob}\,(\text{u}_\text{j}=c\,|\,1\text{ sent}}{\text{Prob}\,(\text{u}_\text{j}=c\,|\,0\text{ sent}}\right)\right.,k=1,2,....,L,c=0,1,u_{jk}, \qquad (8)$$

and $I(u_j=h)$ is an indicator function which is unity if $u_j=h$ and zero otherwise.

4. A Special Case of Semi Signals Integration Approach: Case of One-Bit Information

A special case of semi signals integration approach occurs when each receiver transmits one of two values; either 0 or 1. In this case, of, we are interested in discriminating between two message symbols 0 and 1, encoded as two known waveforms $s_0(t)$ and $s_1(t)$. This is called a binary hypothesis testing problem with two hypotheses; H_0 and H_1 .

We assume that there the n local receivers have statistically independent observations $v_1,v_2,.......,v_n,$ and have known probability distributions under both hypotheses $f_V(v_j\,|\,s_0)$ and $f_V(v_j\,|\,s_1),\ j=1,2,....,n.$ The j^{th} receiver output, $j=1,2,......,n,$ is a binary bit decision u_j based only on its own measurements.

For each individual local receiver, the optimum structure should calculate the likelihood ratio and compare it to a likelihood threshold. The optimal decision rule at each local receiver in case of binary can be described as [12], [17]:

$$u_j=\begin{cases}1, & \text{if } LR_j=\dfrac{f_V(v_j\,|\,s_1)}{f_V(vj\,|\,s_0)}\ge t_j\\ 0, & \text{otherwise},\end{cases} \qquad (9)$$

where LR_j is the likelihood ratio at the j^{th} receiver and the receiver's threshold, t_j , is depending on the criterion of optimality. When the receiver signal to noise ratio (SNR) estimates are available, and the receiver SNR's change so slowly such that the SNR's estimates can be sent to the central receiver with very high precision, the conditional probability distributions in Eq. (2) can be replaced by $f_V(v_j\,|\,s_0,\gamma_j)$ and $f_V(v_j\,|\,s_1,\gamma_j), j=1,2,....,n,$ where γ_j is the SNR estimate at receiver i [13].

The binary decisions from the n digital telecommunication receivers, $u_1,u_2,......,u_n,$ are then sent to the central fusion center to deduce a global decision u_g on which symbol was transmitted. According to the minimum probability of error criterion, the optimal global decision is given by [3], [4], [8], [18]:

$$u_g=\begin{cases}1 & \text{if}\ \ln\dfrac{\Pr(u_1,\text{u}_2,....., u_n\,|\text{H}_1)}{\text{Prob}\,(u_1,\text{u}_2,....., u_n\,|\text{H}_0)}\ge 0\\ 0 & \text{otherwise}\end{cases}, \qquad (10)$$

where the ratio $\frac{\Pr(u_1,u_2,..........,u_n\,|H_1)}{\Pr(u_1,u_2,..........,u_n\,|H_0)}$ is the likelihood ratio of all receiver decisions. In case of independent receiver measurements, the optimal decision rule reduces to

$$\sum_{j=1}^{n}w_j\ \underset{u_g=0}{\overset{u_g=1}{\gtrless}}\ 0, \qquad (11)$$

where the coefficients $w_j, j=1,2,.....,n,$ are given in terms of the probabilities of correct decision (P_{cj}) and the probabilities of bit error (P_{ej}) as

$$w_j=\begin{cases}\ln\left(\dfrac{P_{cj/1}}{P_{ej/0}}\right), & \text{if } u_j=1,\\ \ln\left(\dfrac{P_{ej/1}}{P_{cj/0}}\right), & \text{if } u_j=0,\ \ j=1,2,.....,n,\end{cases} \qquad (12)$$

$$\begin{aligned}P_{cj/1}&=\Pr(u_j=k|H_k),\\ P_{ej/0}&=\Pr(u_j=1-k|H_k),\ k=0,1.\end{aligned} \qquad (13)$$

5. Performance Analysis Using Simulation

The performance is evaluated in terms of probability of error of the central fusion receiver in case of non-coherent DPSK assuming Rician fading channels and additive Gaussian noise [6], [7], [10], [19], [20]. The general Rician probability density function formula is defined as

$$f(x|v,\sigma)=\frac{x}{\sigma^2}e^{-(x^2+v^2)/2\sigma^2}\; I_0(\frac{xv}{\sigma^2}), \qquad (14)$$

where I_0 is a modified Bessel function of the first kind with order zero. We assume that $\sigma=1$, and $v=0.5$.

The probability of error of the central fusion receiver is

$$P_e = \text{Prob}(0 \text{ sent})\ \text{Prob}(\text{error}\,|\,0 \text{ sent}) + \text{Prob}(1 \text{ sent})\ \text{Prob}(\text{error}\,|\,1 \text{ sent}), \qquad (15)$$

where

$$\text{Prob}(\text{error}\,|\,0 \text{ sent}) = \sum_{u_1=0,u_{11},u_{12},\ldots,1} \ldots\ldots \sum_{u_n=0,u_{n1},u_{n2},\ldots,1} \text{Prob}(u_g=1|u_1,\ldots,u_n) \times \text{Prob}(u_1\,|\,0\,\text{sent})\ldots\text{Prob}(u_n\,|\,0\,\text{sent}). \qquad (16)$$

Similar equation exists for Prob(error|1 sent). The probability density function of the signal-to-noise ratio can be found in [12] and [16].

The results of the probability of error of the central fusion receiver versus signal-to-noise ratio (*SNR*), assuming different scenarios, are shown in Fig.2 – Fig.6. Although we present only the results of 5 scenarios, the concluded remarks mentioned below are base on many scenario results.

The results of the probability of error of the central fusion receiver versus signal-to-noise ratio (*SNR*) for different number of receivers, $n=1,3,5,7,9$ are depicted in Fig.2 in case of full signals integration approach. It is clear that the error probability decreases as the number of receivers increases, as expected. The performance improvement when n changes from 1 to 3 is the best case. The performance increment decreases as the number of sensors increases. Fig.3 compares the performance of full signals integration approach for different number of receivers, $n=1,2,4,6,8,10,12,14$. Fig.3 results yield to the same previous conclusion of Fig.2.

Fig.4 compares the performance of full signals integration approach, semi signals integration approach (for two values of the number of bits per information, $N=2,6$) as well as one-bit information integration approach in case of $n=20$. The performance improvement of the full signals integration approach and the semi signals integration approach compared to the one-bit information approach is obvious. The performance improvement of the semi signal integration approach when N changes from 2 to 6 is also obvious. The full signals integration approach achieves the superior performance as expected.

Fig.5 compares the performance of full signals integration approach, semi signals integration approach (for two values of the number of bits per information, $N=3,5$) as well as one-bit information integration approach in case of $n=15$. The performance improvement of the full signals integration approach and the semi signals integration approach compared to the one-bit information approach is obvious. The performance improvement of the semi signal integration approach when N changes from 3 to 5 is also obvious. As expected, the bets performance occurs when full signals integration approach is used.

The results of the probability of error of the central fusion receiver versus signal-to-noise ratio (*SNR*) for different number of bits per information, $N=2,3,4,5$ are depicted in Fig.6 in case of semi signals integration approach assuming that $n=12$. It is clear that the error probability decreases as the number of bits per information increases, as expected. The performance improvement when N changes from 2 to 3 is the best case. The performance increment decreases as the number of bits per information increases.

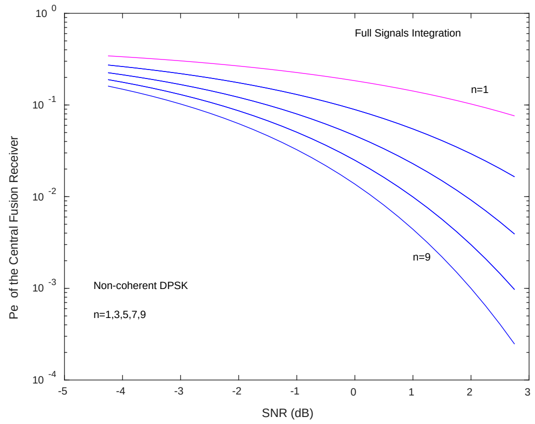

Figure 2. Performance of Full Signals Integration Approach, $n=1,3,5,7,9$.

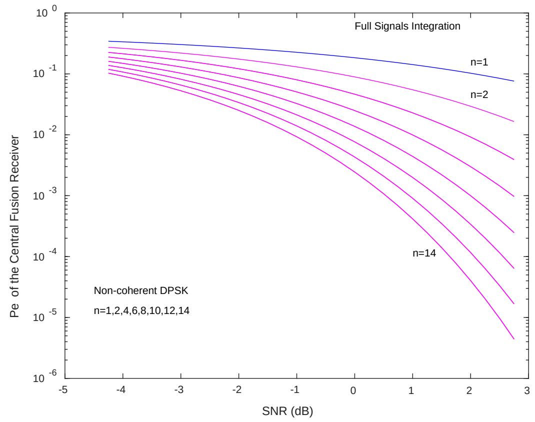

Figure 3. Performance of Full Signals Integration Approach, $n=1,2,4,6,8,10,12,14$.

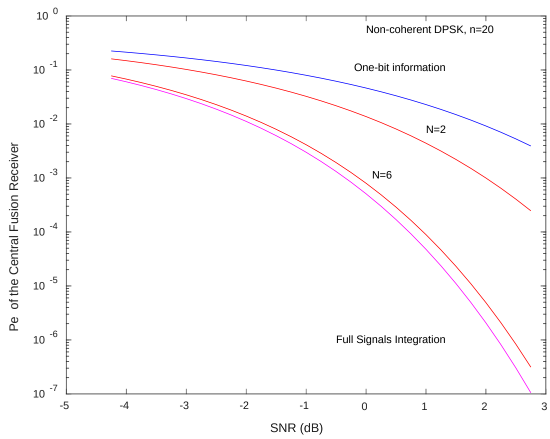

Figure 4. Comparison of Full Signals Integration Approach, Semi Signals Integration Approach ($N=2,6$) and One-Bit Information Approach in case of $n=20$.

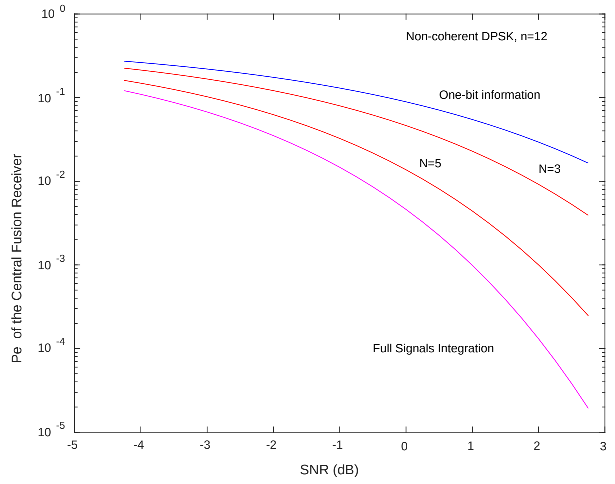

Figure 5. Comparison of Full Signals Integration Approach, Semi Signals Integration Approach ($N = 3,5$) and One-Bit Information Approach in case of $n = 12$.

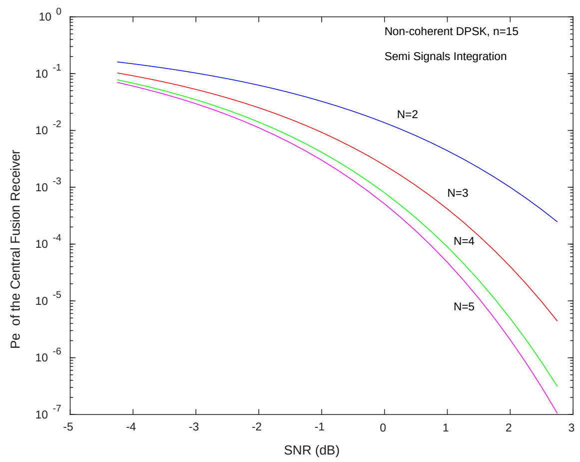

Figure 6. Performance of Semi Signals Integration Approach, $N = 2,3,4,5$, $n = 15$.

6. Conclusion

This paper presented performance evaluation and analysis of full signals integration, semi signals integration and one-bit information approaches in case of non-coherent DPSK digital telecommunication systems assuming Rician fading channel and additive Gaussian noise. The multiple receivers send their information to the central fusion receiver to be fused and global information is derived. Performance evaluation and analysis of the full signals integration, semi signals integration approach as well as one-bit information approach are presented for different values of signal-to-noise ratios (SNR) in different scenarios with different numbers of receivers (n) and numbers of bits per information (N). It has been shown that the full signals integration approach achieves the best performance at the expense of large communication bandwidth. Although the one-bit information approach achieved the lowest performance, it has the advantages of low cost, complexity and required communication bandwidth. The complexity, cost, bandwidth and performance of the semi signals integration approach are varying according to the used number of bits per information.

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