Distributed Detection in UWB Sensor Networks under Non-Orthogonal Nakagami-m Fading

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***Abstract*—Several attractive features of ultra wideband (UWB) communications make it a good candidate for physical-layer of wireless sensor networks (WSN). These features include low power consumption, low complexity and low cost of implementation. In this paper, we present an opportunistic power assignment strategy for distributed detection in parallel fusion WSNs, considering a Nakagami-m fading model for the communication channel and time-hopping (TH) UWB for the transmitter circuit of the sensor nodes. In a parallel fusion WSN, local decisions are made by local sensors and transmitted through wireless channels to a fusion center. The fusion center processes the information and makes the final decision. Simulation results are provided for the global probability of detection error and relative performance gain to evaluate the efficiency of the proposed power assignment strategy in different fading environments.**

***Index Terms*—UWB, Wireless Sensor Networks, Distributed Detection, Parallel Fusion Network, Nakagami-m Fading.**

I. Introduction

The emergence of new wireless technologies has enabled the development of low-cost wireless sensor networks (WSNs). A sensor netwrok is the combination of a large number of small nodes, which are equipped with one or more sensors, processing circuits, and wireless transceivers. The unique features of a WSN are, for example, random deployment in inaccessible terrains, unprecedented opportunities for a broad range of civilian and military applications such as industrial automation, military tactical surveillance, and emergency health care [1], [2].

Energy efficiency is a critical design factor in WSNs, because the sensor nodes are usually of low cost and low complexity and designed with strict restrictions on power consumption. As a result, ultra wideband (UWB) technology is a proper choice to be used in WSNs because of some of its attractive inherent features including low transmission power, low complexity and low cost of circuitry design, and resilience against multipath propagation [3], [4].

Previous research works on distributed WSNs range from general theoretic analysis, to proposing optimization solutions for the detection process [5]–[7]. However, these works mostly neglect the effects of fading in the communication channel, which is an important issue in real environments and ignoring it may cause significant degradation of performance for any designed detection process. On the other hand, the majority of these works do not consider a specific wireless technology for the sensors' transceivers. Even those that do, neither integrate the unique features of that technology in the analysis nor benefit from the UWB physical-layer technology which meets best the design requirements for sensor networks, as mentioned earlier.

In [8], a distributed detection scheme which uses two-dimensional channel coding in order to reduce the misclassification probability in WSNs is proposed. It is shown that this algorithm has a higher classification reliability and also a lower sensor complexity. In [9], an opportunistic power assignment strategy is presented in order to optimize the detection performance in terms of the global probability of error for WSNs. In [10], the saddlepoint approximation is used to compute the detection probability in distributed WSNs. The authors have shown that the saddlepoint technique is simple to compute and the results obtained by this technique are highly accurate and in good agreement with experimental measurements.

This paper addresses one of the important application classes of WSNs which is the detection of objects or events. In fact, we generalize the work in [9] and we propose a power assignment strategy for distributed detection in parallel fusion WSNs under Nakagami-m fading. Nakagami-m is a comprehensive distribution which can model fading with different intensities and covers a wide range of propagation conditions. The validity of this model for UWB communication channels has previously been reported. In [11], the best-fit distribution for the small-scale magnitude statistics in UWB channels has been shown to be the Nakagami-m one. The algorithm we propose in this paper improves the global probability of error by compensating for the effects of fading in the communication channel through updating the effective sensor weights and the assigned transmit power for the sensor nodes. In order to benefit from the special characteristics of UWB technology, We consider time-hopping (TH) UWB for the physical-layer of the sensor nodes. The UWB signal model is integrated into the analysis process and the sensor weights are periodically updated according to the TH-UWB signal specifications, i.e., pulse waveform, number of pulses per information bits, transmit power and length of the time frame, as well as the propagation characteristics. This approach gives us the flexibility to choose between a wider range of parameters for system design, while keeping the system performance at an acceptable level. Our power assignment algorithm periodically monitors the global probability of error, in order to optimally distribute a fixed budget of total transmit power to the nodes.

The remainder of this paper is organized as follows. In Section II, the distributed detection problem is formulated. Section III discusses the proposed power assignment algorithm in Nakagami-m fading. Section IV presents numerical results and comparisons illustrating the system performance based on the probability of error in the presence of different intensities for the Nakagami-m fading. Finally, concluding remarks are drawn in section V.

II. Distributed Detection

In this section, we first introduce our scenario for distributed detection in parallel fusion WSNs and then we discuss the procedure for updating the effective sensor weights.

A. Parallel Fusion Network

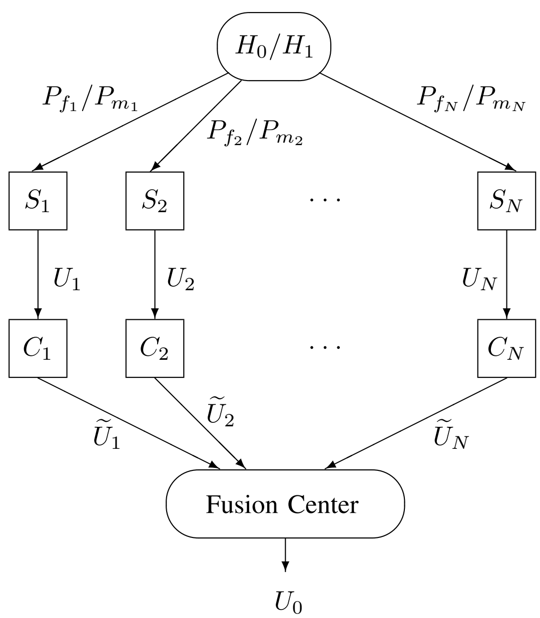

Fig. 1. Parallel fusion network with fading channels.

Fig. 1 illustrates the problem of distributed detection in parallel fusion networks. We consider a binary hypothesis testing problem with hypotheses H_0 and H_1 indicating the absence and presence of the target, respectively. The associated prior probabilities are $\pi_0 = P(H_0)$ and $\pi_1 = P(H_1)$. In order to detect the true state of nature, the network of sensors $S_1, \ldots, S_N$ collects an array of random observations $(X_1, \ldots, X_N)' \in \mathcal{X}_1 \times \cdots \times \mathcal{X}_N$. The random observations $X_1, \ldots, X_N$ are assumed to be conditionally independent across sensors given the underlying hypothesis and distributed according to $f_{X_j}(\cdot|H_0)$ and $f_{X_j}(\cdot|H_1)$, respectively. The nodes process their observations independently by forming local decisions

$$U_j = \delta_j(X_j), \quad j = 1, \ldots, N. \tag{1}$$

In case of binary quantization, the node decision rules are mappings $\delta_j \colon \mathcal{X}_j \to \{0, 1\}$. Sensor decision rules leading to optimal configurations are monotone log-likelihood ratio (LLR) quantizers provided that the observations are conditionally independent across sensors [12]. Thus, we consider decision rules δ_j that can be parameterized by real-valued quantization thresholds θ_j. In this way, each local decision, U_j of sensor S_j, is characterized by the following local false alarm and miss probabilities

$$P_{f_j} = P(U_j = 1|H_0) = P(L_j > \theta_j|H_0), \tag{2}$$

$$P_{m_j} = P(U_j = 0|H_1) = P(L_j \leq \theta_j|H_1), \tag{3}$$

where L_j is the local LLR of observation X_j. Upon local detection, the sensor nodes transmit the preliminary decisions $U_1, \ldots, U_N$ to the fusion center in order to perform decision combining. The communication channels $C_1, \ldots, C_N$ between the wireless sensors and the fusion center are usually subject to noise, interference and fading. The bit-error probability ε_j of the communication link C_j between sensor S_j and the fusion center is defined as:

$$\varepsilon_j = P(\widetilde{U}_j = 1|U_j = 0) = P(\widetilde{U}_j = 0|U_j = 1) \tag{4}$$

for $j = 1, \ldots, N$. The potentially corrupted received detection results $\widetilde{U}_1, \ldots, \widetilde{U}_N$ are combined to yield the final decision $U_0 \in \{0, 1\}$. We consider the global probability of error as performance metric

$$P_e = \pi_0 P_f + \pi_1 P_m, \tag{5}$$

which is a weighted sum of the global probability of false alarm $P_f = P(U_0 = 1|H_0)$ and the corresponding global probability of miss $P_m = P(U_0 = 0|H_1)$.

B. Optimal Channel-Aware Fusion Rule

Assuming conditionally independent local detection results $U_1, \ldots, U_N$ and independent binary symmetric channels $C_1, \ldots, C_N$, the optimal channel-aware fusion rule can be implemented by a linear threshold rule [13] according to

$$\sum_{j=1}^{N} \widetilde{\lambda}_j \widetilde{U}_j \underset{U_0 = 0}{\overset{U_0 = 1}{\gtrless}} \vartheta \tag{6}$$

with effective sensor weights

$$\widetilde{\lambda}_j = \log\left(\frac{(1 - \widetilde{P}_{f_j})(1 - \widetilde{P}_{m_j})}{\widetilde{P}_{f_j}\widetilde{P}_{m_j}}\right) \tag{7}$$

for $j = 1, \ldots, N$, and a decision threshold

$$\vartheta = \log\left(\frac{\pi_0}{\pi_1}\prod_{j=1}^{N}\frac{1 - \widetilde{P}_{f_j}}{\widetilde{P}_{m_j}}\right). \tag{8}$$

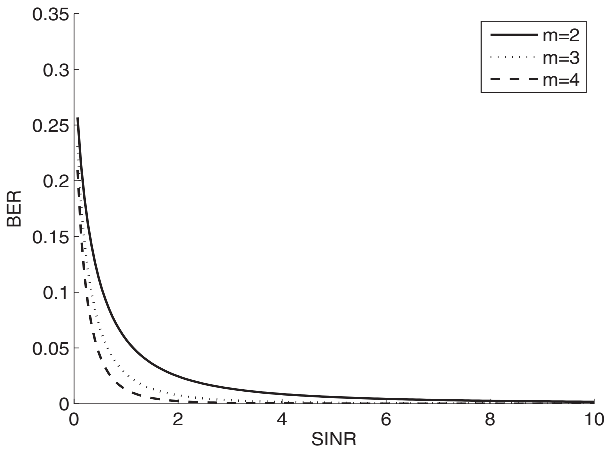

Fig. 2. BER versus SINR of the fading communication channel in the presence of different fading intensities, m.

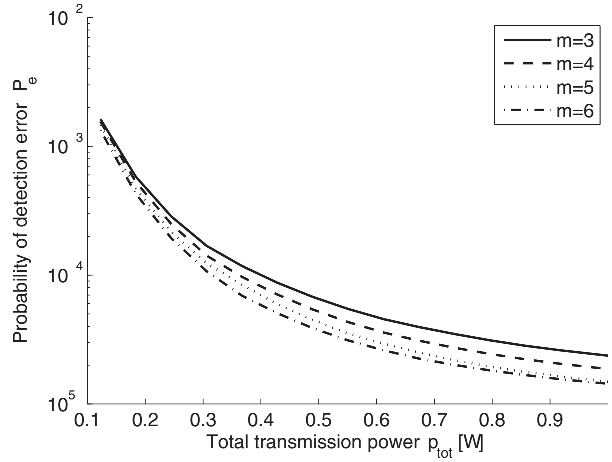

Fig. 3. Global probability of detection error P_e as a function of the total transmission power p_{tot} for different fading intensities m.

The modified error probabilities $\widetilde{P}_{f_j} = P(\widetilde{U}_j = 1|H_0)$ and $\widetilde{P}_{m_j} = P(\widetilde{U}_j = 0|H_1)$ are calculated as

$$\begin{aligned} \widetilde{P}_{f_j} &= P_{f_j} + \varepsilon_j(1 - 2P_{f_j}), \\ \widetilde{P}_{m_j} &= P_{m_j} + \varepsilon_j(1 - 2P_{m_j}). \end{aligned} \tag{9}$$

The effective sensor weight, $\widetilde{\lambda}_j$, can be interpreted as a measure for the local detection performance of a node that also includes the quality of the communication channel. Also, note that for $P_{f_j}, P_{m_j} \in [0, \frac{1}{2}]$, and arbitrary bit-error rate $\varepsilon_j \in [0, 1]$, the effective sensor weights are always less or equal to the initial sensor weight λ_j which is given by

$$\lambda_j = \log\left(\frac{(1 - P_{f_j})(1 - P_{m_j})}{P_{f_j} P_{m_j}}\right). \tag{10}$$

III. Power Assignment in Nakagami-m Fading Channels

In this section, we first introduce the TH-UWB signal model for the sensor nodes along with the fading model considered for the communication channel. Later, we will present our opportunistic power assignment algorithm.

A. Signal and Channel Models

For the transmitted signal of sensor S_j, we consider TH-UWB with pulse position modulation and pseudorandom time hopping codes as multiple access scheme according to [14]:

$$s_j(t) = A_j \sum_{i=-\infty}^{\infty} w(t - iT_f - c_i^{(j)} T_c - \xi d^{(j)}_{\lfloor i/N_j \rfloor}), \tag{11}$$

where T_f denotes the length of a time frame in which one impulse of form $w(t)$ is transmitted and ξ is the modulation index. In the frame, the impulse is delayed by an integer multiple of the chip length T_c according to the time hopping code $c_i^{(j)}$. Each data bit $d^{(j)}$ corresponding to the local decision U_j of the jth sensor node is transmitted by a number of N_j equally modulated pulses with amplitude A_j. In a multi-user scenario, the SINR, γ_j of S_j, at the fusion center is written as

$$\gamma_j = N_j \frac{g_j h_j^2 p_j}{\sigma^2 \sum_{k \neq j} g_k h_k^2 p_k + \frac{1}{T_f}\eta}, \tag{12}$$

with p_j denoting the transmission power for the sensor node S_j. The parameter σ^2 depends on the correlation properties of the employed pulse form $w(t)$. The path gain and the fading amplitude between S_j and the fusion center are denoted by g_j and h_j, respectively. The transmitted signal is subject to additive white Gaussian noise with energy η. The path gain and the fading amplitude between the interfering node, S_k, and the fusion center are denoted by g_k and h_k, respectively. The fading amplitude $h_j, j = 1, 2, ..., N$, follow Nakagami-m distribution with parameters (m_j, Ω_j). Nakagami-m distribution model is given by:

$$f_{H_j}(h_j) = \frac{2}{\Gamma(m_j)} \left(\frac{m_j}{\Omega_j}\right)^{m_j} h_j^{2m_j - 1} e^{-\frac{m_j h_j^2}{\Omega_j}}, \tag{13}$$

where $\Gamma(.)$ is the complex Gamma function, $E\left[h_j^2\right] = \Omega_j$, with $\mathbf{E}[.]$ denoting the expectation, and $m_j > \frac{1}{2}$. We assume that all the nodes experience the same fading condition and $\Omega_j = \Omega$ for $j = 1, ..., N$.

B. Power Assignment Algorithm

The assignment of transmission power to the nodes should be performed in an application-specific way, with the goal to optimally distribute a given budget of total transmission power

$$p_{\text{tot}} = \sum_{j=1}^{N} p_j \tag{14}$$

with respect to the global probability of detection error P_e. We use the same basic strategy as the power assignment algorithm described in [9]. This algorithm tries to maximize the sum of the effective sensor weights $\widetilde{\lambda}_j$ given a total transmission power p_{tot}. Our strategy consists of two steps. First, a target

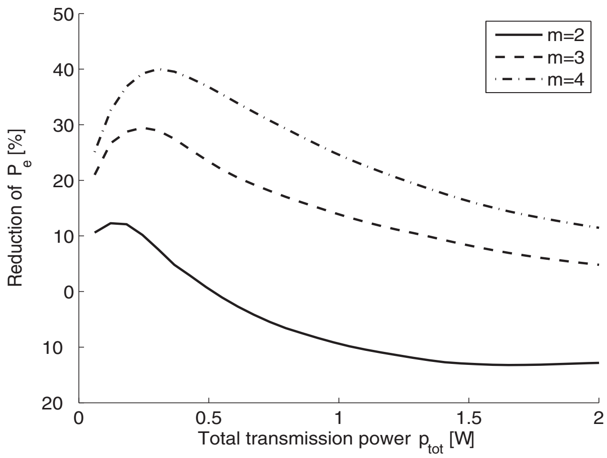

Fig. 4. Relative performance gain in terms of a decreased global probability of detection error P_e as function of the total transmission power p_{tot} for the case of power control compared to uniform power allocation for different fading intensities m.

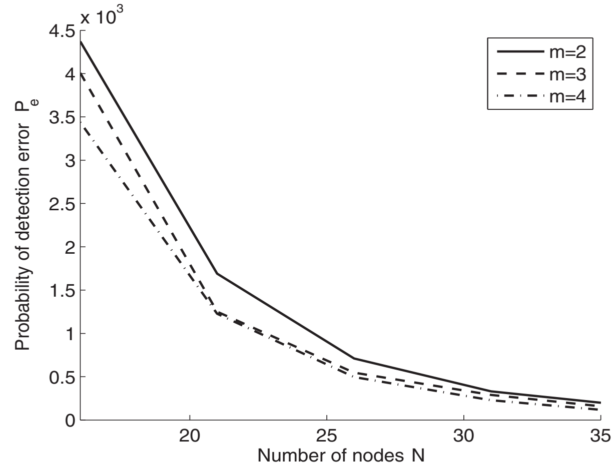

Fig. 5. Global probability of detection error P_e as a function of the number of sensor nodes for different fading intensities m and $p_{\text{tot}} = 0.5W$.

SINR, γ_j^T, of the link between S_j and the fusion center is determined with the goal of favoring the nodes near the fusion center with low path-loss, according to

$$\gamma_j^T = \left(\frac{g_j}{g_{\min}}\right) \cdot \left(\frac{\partial \widetilde{\lambda}_j}{\partial \acute{\gamma}_j}\right)^{-1} (\varrho), \tag{15}$$

where $g_{\min}$ is the minimum path gain of a node to the fusion center and the parameter ϱ is used to balance the total transmission power and the global detection quality. $\acute{\gamma}_j$ is the averaged SINR, γ_j, with respect to fading amplitudes of the interfering nodes S_k denoted by:

$$\acute{\gamma}_j = N_j \frac{g_j p_j}{\sigma^2 \Omega \sum_{k \neq j} g_k p_k + \frac{1}{T_f}\eta}. \tag{16}$$

In the second step, the target SINRs, $\gamma_1^T, \ldots, \gamma_N^T$, are jointly realized by power control. The target SINR, γ_j^T, of S_j can be realized by setting the transmission power to

$$p_j = \frac{\dfrac{\eta}{T_f \sigma^2}}{g_j \left(\dfrac{N_j}{\sigma^2 \gamma_j^T} + 1\right)\left(1 - \sum_k \dfrac{1}{\frac{N_k}{\sigma^2 \gamma_k^T} + 1}\right)}. \tag{17}$$

Assuming that channel C_j is affected by fading, its probability of error (ε_j in Eq. (4)) at the fusion center is given by

$$\varepsilon_{j|h_j} = Q(h_j \sqrt{2\acute{\gamma}_j}), \tag{18}$$

where $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-a^2/2} da$ is the Gaussian Q-function. After averaging over h_j, ε_j is given by

$$\begin{aligned}\varepsilon_j &= \mathbf{E}_{h_j}\{\varepsilon_{j|h_j}\} \\ &= \frac{2}{\Gamma(m_j)} \left(\frac{m_j}{\Omega_j}\right)^{m_j} \int_0^\infty x^{2m_j - 1} e^{-\frac{m_j x^2}{\Omega_j}} Q(x\sqrt{2\acute{\gamma}_j}) dx.\end{aligned} \tag{19}$$

To simplify the numerical analysis, we use the approximation in [15] for the Q-function according to

$$Q^n(x) \approx \frac{1}{2^n} \sum_{k=0}^{n} \binom{n}{k} \left((-1)^{n-k} e^{-A(n-k)\frac{x}{\sqrt{2}}}\right) \frac{e^{-An\frac{x}{\sqrt{2}}}}{(B\sqrt{\pi x})^n}, \tag{20}$$

where $A = 1.98$ and $B = 1.135$. By replacing equation (20) in (19), we obtain:

$$\begin{aligned}\varepsilon_j = \frac{I^{m_j} b^{-m_j}}{2\Gamma(m_j) B \sqrt{2\pi\gamma_j}} \Bigg(& b^{1/2} \Gamma(m_j - 1/2) \\ & - \sqrt{b}\Gamma(m_j - 1/2)_1 F_1 \left(m_j - 1/2; 1/2; \frac{a^2}{4b}\right) \\ & + a\Gamma(m_j)_1 F_1 \left(m_j; 3/2; \frac{a^2}{4b}\right)\Bigg),\end{aligned} \tag{21}$$

where $I = \frac{m_j}{\Omega_j}$, $a = A\sqrt{\acute{\gamma}_j}$ and $b = A\sqrt{2}\acute{\gamma}_j + I$. Fig. 2 shows the BER performance of our channel model (ε_j versus $\acute{\gamma}_j$) in the presence of different fading intensities, m. Please note, we show the target SINR in (15) with an extra superscript T as γ_j^T, to distinguish with γ_j in (16), which is the general expression for SINR at the TH-UWB sensor nodes. Please also note that, the channel fading effect is inherently taken into account in updating the sensor effective weights, $\widetilde{\lambda}_j$, through incorporating (21) into (9) and then (7). It is also taken into account in updating the assigned transmit power (Eq. (17)) for the sensor nodes through the sensors's target designated SINR, γ_j^T, by incorporating (21) into (9), (7) and then (15).

IV. Numerical Results

In this section, we analyze the performance of distributed detection in WSNs under non-orthogonal Nakagami-m fading channels using a simulations approach. The scenario is generated by randomly deploying N sensor nodes uniformly in a rectangular area A. The fusion center is located in the middle of the area. The parameters pertaining to the scenario

TABLE I
PARAMETERS USED IN THE SIMULATIONS

parameter	value
N	40
A	100 m $\times$ 100 m
σ^2	$1.9966 \cdot 10^{-3}$
N_j	10
T_c	2 ns
T_f	100 ns
η	10^{-11} J

and the UWB transceivers are summarized in Table I. We assume that the observations $X_1, \ldots, X_N$ at the local sensors are conditionally independent distributed. In the simulations, we also assume the local observed signal-to-noise ratios to be independent and identically uniformly distributed between 0 and 10 dB. For the transmission of the local decisions, we employ the power control algorithm explained in Section III-B. In this strategy, a budget of total transmission power p_{tot} is allocated to the nodes with the objective to minimize the global probability of detection error.

Fig. 3 illustrates the absolute detection performance of the system in terms of the global probability of detection error P_e as a function of the total transmission power p_{tot} for different fading intensities m. It can be observed that for low levels of p_{tot} the detection performance is almost independent of the fading intensity m. For high levels, however, the influence of the fading conditions becomes more important. It is also observed that our power control algorithm for fading channels results in a significant performance gain in terms of a reduced global probability of detection error when compared to results in [9] which employ a uniform power assignment in case of AWGN channels. Please note that for Figs. 3 and 4 the number of nodes is fixed to $N = 40$, however in Fig. 5 this amount varies to show the effect of changes in systems' performance for different numbers of nodes.

Fig. 4 shows the performance gain that can be achieved in case of Nakagami-m fading. Still a considerable performance gain can be achieved but the magnitude of the performance gain depends on the fading intensity m. With increase of m, the maximum performance gain increases too, however, the value of p_{tot} for which the maximum is attained depends on m. For high values of m, corresponding to weak fading, we achieve high performance gains, but for low values of m corresponding to strong fading the maximum is attained at the practically important case of low total transmission power, p_{tot}.

Fig. 5 shows the global probability of detection error P_e as a function of the number of sensor nodes for different fading intensities m and $p_{\text{tot}} = 0.5W$. It is observed that for higher numbers of sensor nodes, the global probability of detection error becomes less dependent to the channel fading intensities. In other words, increasing the sensor nodes not only improves the detection quality but also makes the algorithm more resilient to channel fading effect and its variation.

V. CONCLUSION

This paper addressed the power assignment problem in UWB-based wireless sensor networks (WSNs). In fact, we proposed a power assignment algorithm for distributed detection in parallel fusion WSNs under Nakagami-m fading. We considered time-hopping UWB for the physical-layer of sensor nodes, because of several attractive features of UWB which fit very well WSNs' applications. Numerical results were presented for the global probability of error in the network and the relative performance gain. Our results show that for low levels of the total transmission power, the detection performance is almost independent of the fading intensity parameter, m. It was also observed that if the number of sensor nodes increases, the global probability of detection error becomes less dependent on the channel fading intensities.

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