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# DOPPLER ESTIMATORS USING PILOT TONES FOR OFDM COMMUNICATION SIGNAL IN SHALLOW WATER ENVIRONMENT

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**Abstract:** *Underwater acoustic communications constitute a very difficult issue since the transmission channel is severely doubly dispersive. Indeed, radio waves suffer from strong attenuation so that the only solution is to use acoustical modems. Thus, achievable bandpass is very reduced (typically less than 20kHz) and narrowband signal approximation cannot be assumed since sound velocity is around 1500 m/s and frequency carrier is around 10kHz. A natural choice to fight against time dispersivity is the use of OFDM (Orthogonal Frequency Division Multiplex). Unfortunately, this choice increases the sensitivity to the Doppler effect. That is why the subject of this paper, the estimation of this Doppler effect, is so crucial. For this purpose, we use ZP-OFDM (OFDM with Zero Padding) modulation in order to consider independent time blocks with duration chosen such that the Doppler effect can be considered as approximately constant. Our study is restricted to the case of a single path. Firstly, Doppler is estimated thanks to a correlation between the received signal and a pilot signal. Then, another estimator is also studied, using the minimization of a cost function based on the exponential base of the OFDM signal.*

**Keywords:** *Underwater communication, shallow water, OFDM, Doppler estimation, Pilot tones.*

## 1. GENERAL CONTEXT

Underwater acoustic communication channel being severely doubly dispersive, the use of ZP-OFDM in order to mitigate time dispersivity also imposes to develop a strategy in order to evaluate and compensate Doppler effect. Several methods based on pilot tones have already been published, but with some limitations. Thus the method developed in [1] applies to Doppler shift inferior to the intercarrier spacing. In [2] the Doppler shift in frequency is considered to be the same over all subcarriers and this approximation involves errors during Doppler compensation and demodulation.

The principle of ZP-OFDM is to use several carriers in parallel,  $f_m$  ( $f_m = f_0 + mF_0$ ),  $-M/2 \leq m \leq M/2 - 1$ , with  $M$  the number of carriers, with a symbol duration slightly higher than necessary. Indeed, since the frequency spacing  $F_0$  is identical between each carrier frequency, then the minimum symbol duration is equal to  $T_0 = 1/F_0$ . And yet, in ZP-OFDM, a symbol duration is in fact equal to  $T = T_0 + T_g > T_0$  where  $T_g$  is called a guard time. If this guard interval is long enough, there will be no interference between OFDM symbols at reception [3]. Among the  $M$  carriers, we choose pilot tones for whom we know the transmitted symbols  $c[m]$ . We note  $V$  the set of natural numbers between  $-M/2$  and  $M/2 - 1$ .  $V_p$  represents the set of natural numbers for the pilot carriers and  $V_i$  the set for information carriers:  $V_p \cup V_i = V$  and  $V_p \cap V_i = \emptyset$ . Then, for  $-T_g - T_0/2 \leq t \leq T_0/2$  (one symbol duration), the ZP-OFDM baseband signal writes:

$$s(t) = \sum_{m \in V} c[m] e^{j2\pi m F_0 t} g(t) = \underbrace{\sum_{m \in V_p} c[m] e^{j2\pi m F_0 t} g(t)}_{s_p(t)} + \underbrace{\sum_{m \in V_i} c[m] e^{j2\pi m F_0 t} g(t)}_{s_i(t)} \quad (1)$$

with  $g(t) = 1/\sqrt{T_0}$  for  $t \in [-T_0/2, T_0/2[$ , and  $g(t) = 0$  otherwise. Thus,  $s(t) = 0$  for  $-T_g - T_0/2 \leq t < -T_0/2$ , which results in a Zero Padding operation after sampling of the signal. Moreover  $s(t) = s_p(t) + s_i(t)$  writes as the sum of two independent signals, the first one containing pilot symbols, known at reception,  $s_p(t)$ , and the second one containing information symbols,  $s_i(t)$ .

## 2. UNDERWATER ACOUSTIC CHANNEL MODEL

In our model, the emitter-receiver distance is supposed to be close to one kilometer and the deep is about 100 meters. Considering the geometry of the problem, we use the ray theory for sound propagation [4]. First of all, we suppose that the acoustic channel can be described thanks to a time-varying multipath model. We moreover assume that the time-varying nature of the channel during one OFDM block is mainly caused by the relative motion between the receiver and the transmitter [5]. Then, assuming a constant relative speed  $v$  between the emitter and the receiver, the received low pass signal  $r(t)$  writes:

$$r(t) = \sum_{l=1}^L A_l s(d_l t - \tau_l) e^{j2\pi f_0 (d-l)t} e^{-j2\pi f_0 \tau_l} + n(t) \quad (2)$$

with  $L$  the number of propagation paths,  $A_l$  the amplitude of the  $l$ -th path,  $\tau_l$  and  $d_l$  the corresponding initial path delay and Doppler parameter, respectively,  $n(t)$  an additive white Gaussian noise in the band of interest,  $f_0$  the central carrier frequency. Note that if we denote  $\theta_l$  the arrival angle of the  $l$ -th path and  $c$  the sound velocity, then  $d_l = 1 - v \cos(\theta_l) / c$ . The received signal is sampled at the period  $T_s = 1 / 2MF_0$  in order to respect the sampling theorem even if the Doppler effect enlarge the bandwidth of the signal. We consider the beginning time of sampling  $t_0 = -T_g - T_0/2 - \Delta$ , with  $\Delta = T_0/2(d_{min} - 1)$  with  $d_{min}$  the minimum Doppler parameter  $d$  we can encounter. So finally, after sampling at  $t_k = kT_s + t_0$ , we get  $K$  samples of the received signal :  $r[k] = r(kT_s)$ .

### 3. DOPPLER ESTIMATION

From this part, we restrict to the simplified one path case :  $r[k] = s_i(dt_k) + s_p(dt_k) + n[k]$ . We consider that the received signal has been temporally synchronized with the beginning of the OFDM symbol. Without loss of generality, given that each block begins with a guard time constituted of a signal equal to zero, we can assume that  $0 \leq k \leq M + M_g - 1 = K - 1$ , with  $T_g = M_g T_s$ . The number of pilot and information carriers are denoted  $M_p$  and  $M_i$ , respectively.

#### 3.1. CORRELATION MAXIMISATION

In this section, pilot subcarriers are based on P-QAM symbols known by the receiver. We denote  $\mathbf{r} = [r[0], \dots, r[K-1]]^T$ ,  $\mathbf{n} = [n[0], \dots, n[K-1]]^T$ ,  $\mathbf{s}_i(d) = [s_i[0](d), \dots, s_i[K-1](d)]^T$  and  $\mathbf{s}_p(d) = [s_p[0](d), \dots, s_p[K-1](d)]^T$ , with  $s_p[k](d) = s_p(dt_k)$ ,  $s_i[k](d) = s_i(dt_k)$  and  $^T$  the transpose operator. At reception, we suppose the signal  $\mathbf{s}_p(d)$  to be known. The signal  $\mathbf{r}$  is affected by an additive white Gaussian noise in the band of interest. The first idea to get an estimate of  $d$  is to compute the likelihood and to maximize it:  $\Lambda(d) = p(\mathbf{r} | \mathbf{s}_p(d))$ . By maximizing the likelihood, we look for the value of  $d$  which is the most likely to appear, knowing one realization of  $\mathbf{r}$ . If we note  $\mathbf{S}_i(d)$  the set of all the possible values taken by  $\mathbf{s}_i(d)$ , then the likelihood becomes :

$$p(\mathbf{r} | \mathbf{s}_p(d)) = \sum_{\mathbf{s} \in \mathbf{S}_i(d)} p(\mathbf{s}) p(\mathbf{r} | \mathbf{s}_p(d) | \mathbf{s}) \quad (3)$$

The likelihood depends on all the values that can be taken by  $\mathbf{s}_i(d)$ . All information messages have the same probability of appearance. Using P-QAM modulation we have  $\text{Card}(\mathbf{S}_i(d)) = P^{M_i}$  and  $p(\mathbf{s}_i(d)) = 1/P^{M_i}$ . Given that the components of  $\mathbf{n}$  are complex Gaussian, independent, zero-mean and with variance  $\sigma^2$ , we have :

$$\Lambda(d) = \frac{1}{P^{M_i} (\pi\sigma^2)^K} \sum_{\mathbf{s} \in \mathbf{S}_i(d)} \exp \left( - \frac{\|\mathbf{r} - (\mathbf{s}_p(d) + \mathbf{s})\|^2}{\sigma^2} \right) \quad (4)$$

Thus, we have to compute a sum containing  $P^{M_i}$  terms which may be prohibitive. It can be simplified considering that  $\left\| \mathbf{r} - \mathbf{s}_p(d) \right\|^2 - \left\| \mathbf{s} \right\|^2 \leq \left\| \mathbf{r} - (\mathbf{s}_p(d) + \mathbf{s}) \right\|^2 \leq \left\| \mathbf{r} - \mathbf{s}_p(d) \right\|^2 + \left\| \mathbf{s} \right\|^2$ . Indeed,

for  $\mathbf{s} \in \mathbf{S}_i(d)$ ,  $\left\| \mathbf{s} \right\|^2 \leq \sum_{m \in V_i} \sum_{k=0}^{K-1} |c_m|^2 \leq AM_i K$  (with  $|c_m|^2 \leq A$ ) so that we get, after a few

$$\text{calculus} \frac{e^{\left( \frac{-AM_i K}{\sigma^2} \right)}}{(\pi \sigma^2)^K} \exp \left( - \frac{\left\| \mathbf{r} - \mathbf{s}_p(d) \right\|^2}{\sigma^2} \right) \leq \Lambda(d) \leq \frac{e^{\left( \frac{AM_i K}{\sigma^2} \right)}}{(\pi \sigma^2)^K} \exp \left( - \frac{\left\| \mathbf{r} - \mathbf{s}_p(d) \right\|^2}{\sigma^2} \right).$$

Therefore, we can compute a suboptimal approximation of  $d$  with the formula:

$$\hat{d} = \underset{d}{\operatorname{argmax}} \left( \exp \left( - \frac{\left\| \mathbf{r} - \mathbf{s}_p(d) \right\|^2}{\sigma^2} \right) \right) \quad (5)$$

Furthermore,  $\left\| \mathbf{r} \right\|^2$  and  $\left\| \mathbf{s}_p(d) \right\|^2$  are almost independent from  $d$ , so that, after a few calculus, we get  $\hat{d} = \underset{d}{\operatorname{argmax}} \Re \{ \langle \mathbf{r} | \mathbf{s}_p(d) \rangle \}$ . In the special case where all the emitted symbol  $c[m]$  of the OFDM signal are known by the receiver, equation (5) meets the expression of the Maximum Likelihood (ML) estimator of the Doppler parameter  $d$ . This estimator has been developed in a previous publication [4] with the calculation of the Cramer Rao bound in this case.

### 3.2.COST MINIMIZATION USING EXPONENTIAL BASE

In this part, the pilot subcarriers contain no energy:  $\forall m \in V_p \quad c[m] = 0$ . We consider the vector  $f_{n\delta}$  with elements  $f_{n\delta}[k] = e^{j2\pi F_0 k T_s \delta} g(\delta t_k)$  and we compute the following scalar product:

$$\langle r | f_{n\delta} \rangle = \sum_{k=0}^{K-1} \sum_{m=-M/2}^{M/2-1} c[m] e^{2j\pi F_0 k T_s (dm - \delta n)} \quad (6)$$

Let us now denote  $r_f$  the vector composed of the  $M$  components  $\langle r | f_{n\delta} \rangle$ . We also consider the  $M$  by  $M$  matrix  $G(d, \delta)$  with  $[G(d, \delta)]_{m,n} = \sum_{k=0}^{K-1} e^{2j\pi F_0 k T_s (dm - \delta n)}$  so that  $r_f = cG(d, \delta)$ , with  $c$  the vector composed of the emitted QAM symbols. For the special case where  $d = \delta$  it is possible to write  $r_f G(\delta, \delta)^{-1} = c$ . Thus,  $d$  may be approximated by:

$$\hat{d} = \underset{\delta}{\operatorname{argmin}} \sum_{m \in V_p} \left| r_f G(\delta, \delta)^{-1} \right|^2 \quad (7)$$

The estimator consists in minimizing the energy on null subcarriers. The time computation of this estimator is strongly affected by the inversion of matrix  $G(\delta, \delta)$ , which might be non invertible or badly conditioned ( $\det(G(\delta, \delta)) \approx 0$ ), depending on the value of  $\delta$ . When the Doppler effect provokes a time compression of the signal, we may have aliasing. We have aliasing if:  $\delta(M-1)F_0 > 1/T_s$ . Then a way to avoid bad conditioned matrix is to oversample the signal by a factor 2. Then  $F_0 T_s = 1/2M$  and aliasing appears only if:  $\delta > 2M/(M-1)$ . Considering that the velocity of the mobile will always be really inferior to the speed of sound in water (1500 m/s), this condition will always be fulfilled.

#### 4. SIMULATION RESULTS

The emission of a ZP-OFDM symbol through the channel presented before is simulated. The UWA channel is doubly dispersive. As presented in [6] the coherence time is close to the second for communication distance over one kilometer, while the typical delay observed in shallow water environment is around 40 ms. We choose a carrier frequency  $f_0 = 20$  kHz,  $T = 200$  ms and the guard interval has a duration  $T_g = 53.5$  ms. Communications are simulated over  $M = 1500$  subcarriers. Subcarrier spacing is 6.8 Hz. QPSK modulation is used. The pilot tones or null subcarriers are equally spaced among the  $M$  subcarriers.

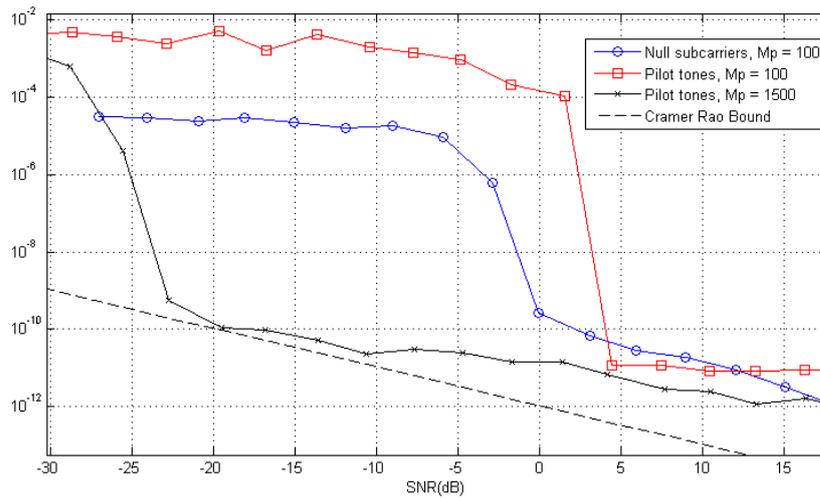


Fig. 1: CRB and variance of the estimators for 100 pilot or null subcarriers.

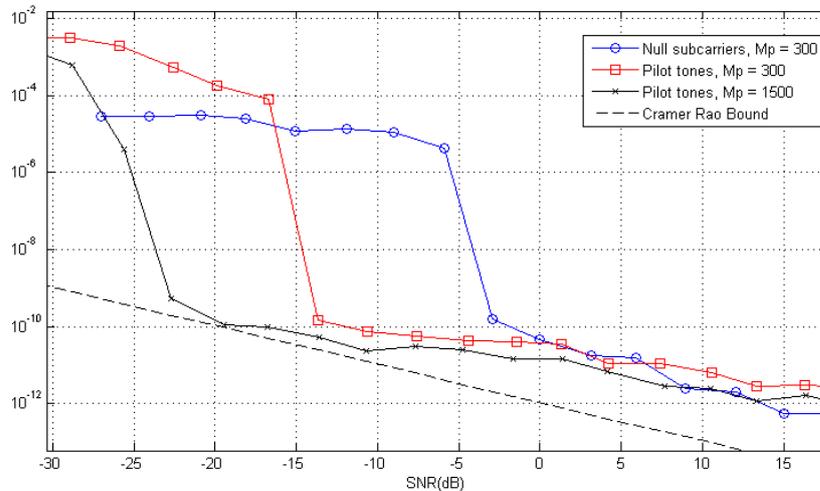


Fig. 2: CRB and variance of the estimators for 300 pilot or null subcarriers.

Typical transmission will concern underwater vehicles moving around 6 to 12 knots, corresponding to a Doppler parameter of  $d = 1 \pm 0.002$  and  $d = 1 \pm 0.004$ , depending on the

movement direction. The Doppler shift will be between 40 and 80 Hz. As presented in [6], considering the number of subcarriers and the value of  $f_0$ , we need an estimate of  $d$  very accurate. The desired estimator should have a standard deviation inferior to  $2.10^{-5}$  in order to guarantee the decoding of the information after demodulation with a limited error rate. A one path channel is simulated with a Doppler parameter  $d = 0.9974$ . Both estimators are compared with 100 (Fig. 1) and 300 (Fig. 2) pilot or null subcarriers. Each figure also recalls the Cramer-Rao Bound of the first estimator when all subcarriers are known that is to say for  $M_p = M = 1500$  (dashed black line), as well as the variance of this estimator in this latter case (black, solid line). The optimization of (5) and (7) is realized using Nelder-Mead algorithm in Matlab. Our purpose is to have a variance inferior to  $4.10^{-10}$ . For  $M_p = 300$ , this target is achieved even with strong noise, SNR up to  $-13.70$  dB. But for  $M_p = 100$ , the variance is inferior to the target only for SNR up to  $4.5$  dB. For the second estimator, using the inversion of matrix  $G(\delta, \delta)$ , all the null subcarriers are equally spaced among the spectrum.

## 5. CONCLUSION

In this paper, we have investigated the application of two estimators of the Doppler effect using perfect knowledge of pilot tones of a ZP-OFDM signal in UWA channel. The receiver is based on block-by-block processing. In the first method, pilot subcarriers yield QPSK symbols. In the second method, null subcarriers are used. These methods allow us to estimate the channel parameters and communicate information in the same time. We have to assume that the Doppler parameter will not change during one OFDM block. The proposed method is tested in simulations for a channel with different intercarrier spaces for the pilot tones. Simulations show the variance of the estimator compared to theoretical Cramer Rao Bound. Further improvements will focus on perfect Doppler compensation and application to multipath channel.

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