A LOW-COST AOA-TDOA APPROACH FOR BLIND GEOLOCATION IN MULTI-PATHS CONTEXT

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ABSTRACT

This paper proposes a low cost joint AOA-TDOA estimation strategy to locate multi-emitters in multi-paths contexts, without prior information on the transmitted signals. The proposed strategy consists in dividing the multi-emitter geolocation problem in multiple mono-emitters location ones. An AOA algorithm is firstly performed on the array of sensors of the main station and a spatial filtering with an ad hoc correlation based criterion selects the LOS paths. In a second step thanks to an auxiliary station, TDOAs are computed for each emitter which is then located with conventional AOA-TDOA techniques. The innovation consists in a simple strategy that avoid frequent ambiguities which arise when using separately estimated parameters in a multiple emitters context.

1. INTRODUCTION

The most common methods dedicated to emitter location are based on measuring specified parameter such as AOA (Angle Of Arrival), TOA (Time Of Arrival) or TDOA (Time Difference Of Arrival) (for an overview see [1] and the references herein). Most of these conventional radio location algorithms have been originally developed to operate under line-of-sight (LOS) propagation between the transmitter and the receiver [1]. But due to diffractions or reflections, the non-LOS (NLOS)-induced errors are proven to be dominant compared to noise [2]. Most of the current algorithms that deal with NLOS problem are assuming prior information on the transmitted signals especially with TOA or TDOA measurements based location [1],[3]. Recently the mitigation of the NLOS have been investigated [4], [5], [6], [7] often requiring many temporal estimations of the desired parameter and/or many base stations. The previous works assume that the location parameters are such associated with an emitter. To the best of our knowledge less efforts have been focused on the blind multi-emitters, multi-paths problems [7]. Moreover fewer attention has been paid on this critical topic from an estimation point of view starting directly from the signals a the output of the multiple arrays of sensors. As far as we know only the DPD (Direct Position determining) [8],[9] proposes a direct estimation of sources location, but leading to a rather high computational cost (a 2D optimization) and assuming no multi-path.

The purpose of our work is to propose an alternative with a low-cost signal processing algorithm in a multi-paths context and multi-emitters context. We focus on a two stations (one being eventually restricted to a single sensor) multi-stage algorithm dividing a multi-emitters multi-paths problem in many mono-emitter location ones. The outline of the paper is as follow : First a brief presentation of the principle of an AOA-TDOA location is given in section 2. In section 3 the model and the assumptions of the received signal are introduced. In section 4 the proposed algorithm is presented and some simulations in section 5 illustrates its performances.

2. MODEL OF THE RECEIVED SIGNALS

Let us consider a station S (main or auxiliary) located in (x_S, y_S) and composed of N sensors. According to Figure. 1, the emitters and reflectors are E_m $(1 \leq m \leq M)$ and R_p $(M+1 \leq p \leq M+P)$. The reflectors are scattering points reflecting in all directions. The observation vector $\mathbf{x}(t)$ at the output the array of antennas in S is

$$\begin{aligned}\mathbf{x}(t) = \quad & \sum_{m=1}^{M} \gamma_m \times \mathbf{a}(\theta_m) \times e_m(t-\tau_m) \\ & + \sum_{p=M+1}^{M+P} \gamma_p \times \mathbf{a}(\theta_p) \times r_p(t-\tau_p) + \mathbf{n}(t) \quad (1)\end{aligned}$$

where

- $\tau_m = ||E_m S||/c$ and $\tau_p = ||R_p S||/c$ denote the TOA (Time Of Arrival) of each path,
- θ_m and γ_m are the AOA and the attenuation coefficient of the mth emitter,
- θ_p and γ_p are the AOA and the attenuation coefficient of the pth reflector,
- $\mathbf{a}(\theta)$ is the steering vector (response of the array in direction θ)
- $\mathbf{n}(t)$ is the additive noise vector,
- $e_m(t)$ is the signal of the mth emitter and $e_m(t-\tau_m)$ is then associated to the direct path,
- and finally $r_p(t)$ is the following composite signal at the output of the pth reflector

$$r_p(t) = \sum_{m=1}^{M} \gamma_{mp} \times e_m(t-\tau_{mp}), \qquad (2)$$

where $\tau_{mp} = ||E_m R_p||/c$ and γ_{mp} is the complex attenuation of the mth emitter on the pth reflector. The expression (1) becomes

$$\begin{aligned}\mathbf{x}(t) = \quad & \mathbf{A}(\boldsymbol{\theta_e}) \times \boldsymbol{\Gamma_e} \times \mathbf{e}(\boldsymbol{\tau_e}, t) \\ & + \mathbf{A}(\boldsymbol{\theta_r}) \times \boldsymbol{\Gamma_r} \times \mathbf{r}(\boldsymbol{\tau_r}, t) + \mathbf{n}(t) \qquad (3)\end{aligned}$$

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where $\boldsymbol{\tau_e} = [\ \tau_1 \ \cdots \ \tau_M\ ]^T$, $\boldsymbol{\tau_r} = [\ \tau_{M+1} \ \cdots \ \tau_{M+P}\ ]^T$ are the TDOA vectors, $\boldsymbol{\theta_e} = [\ \theta_1 \ \cdots \ \theta_M\ ]^T$, $\boldsymbol{\theta_r} = [\ \theta_{M+1} \ \cdots \ \theta_{M+P}\ ]^T$ the AOA vectors, $(.)^T$ is the transpose operator and

$$\left\{ \begin{array}{l} \mathbf{e}(\boldsymbol{\tau_e}, t) = [\ e_1(t-\tau_1) \ \ \cdots \ \ e_M(t-\tau_M)\ ]^T \\ \mathbf{r}(\boldsymbol{\tau_r}, t) = [\ r_1(t-\tau_{M+1}) \ \ \cdots \ \ r_P(t-\tau_{M+P})\ ]^T \end{array} \right. \tag{4}$$

$$\left\{ \begin{array}{l} \mathbf{A}(\boldsymbol{\theta_e}) = [\ \mathbf{a}(\theta_1) \ \ \ldots \ \ \mathbf{a}(\theta_M)\ ] \\ \mathbf{A}(\boldsymbol{\theta_r}) = [\ \mathbf{a}(\theta_{M+1}) \ \ \ldots \ \ \mathbf{a}(\theta_{M+P})\ ] \end{array} \right. \tag{5}$$

$$\left\{ \begin{array}{l} \boldsymbol{\Gamma_e} = diag\ (\ \gamma_1, \ \ \ldots, \ \ \gamma_M\ ) \\ \boldsymbol{\Gamma_r} = diag\ (\ \gamma_{M+1}, \ \ \ldots, \ \ \gamma_{M+P}\ ). \end{array} \right. . \tag{6}$$

According to (3), the expression of $\mathbf{x}(t)$ becomes

$$\mathbf{x}(t) = \mathbf{A}(\boldsymbol{\theta}) \times \boldsymbol{\Gamma} \times \mathbf{s}(\boldsymbol{\tau}, t) + \mathbf{n}(t) \tag{7}$$

where

$$\boldsymbol{\tau} = \left[\begin{array}{c} \boldsymbol{\tau_e} \\ \boldsymbol{\tau_r} \end{array} \right], \quad \boldsymbol{\theta} = \left[\begin{array}{c} \boldsymbol{\theta_e} \\ \boldsymbol{\theta_r} \end{array} \right],$$

$$\mathbf{A}(\boldsymbol{\theta}) = [\ \mathbf{A}(\boldsymbol{\theta_e}) \quad \mathbf{A}(\boldsymbol{\theta_r})\ ],$$

$$\boldsymbol{\Gamma} = \left[\begin{array}{cc} \boldsymbol{\Gamma_e} & 0 \\ 0 & \boldsymbol{\Gamma_r} \end{array} \right] \text{ and } \quad \mathbf{s}(\boldsymbol{\tau}, t) = \left[\begin{array}{c} \mathbf{e}(\boldsymbol{\tau_e}, t) \\ \mathbf{r}(\boldsymbol{\tau_r}, t) \end{array} \right].$$

3. A MULTI-STAGE GEOLOCATION ALGORITHM BASED ON AOA-TDOA ESTIMATION

In this paper the radio-emitters are located thanks to the estimation of AOA/TDOA parameters. The originality of the paper is in estimating without ambiguities the AOA/TDOA parameters of multi-emitters in presence of multi-paths, leading so to separate the location problem in several low cost single-emitter location problems.

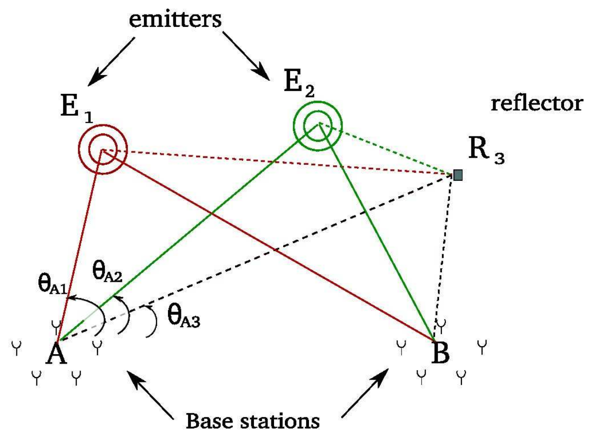

Figure 1: Propagation of two transmitters in multi-path context

Let us consider two multiple sensors stations A and B (see Figure.1). The station A is a multi-sensors array for AOA estimation, whereas B can be eventually restricted to a single sensor (used only for TDOA estimation). According to the previous assumptions in section 3 and the equation (7) the signals $\mathbf{x_A}(t)$ and $\mathbf{x_B}(t)$ collected on stations A and B respectively are

$$\mathbf{x_A}(t) = \mathbf{A}(\boldsymbol{\theta_A}) \times \boldsymbol{\Gamma_A} \times \mathbf{s}(\boldsymbol{\tau_A}, t) + \mathbf{n_A}(t) \tag{8}$$

$$\mathbf{x_B}(t) = \mathbf{A}(\boldsymbol{\theta_B}) \times \boldsymbol{\Gamma_B} \times \mathbf{s}(\boldsymbol{\tau_B}, t) + \mathbf{n_B}(t) \tag{9}$$

where the kth components of $\boldsymbol{\theta_A}, \boldsymbol{\theta_B}$, $\boldsymbol{\tau_A}$ and $\boldsymbol{\tau_B}$ are $\boldsymbol{\theta}_{\boldsymbol{A}_k}, \boldsymbol{\theta}_{\boldsymbol{B}_k}, \boldsymbol{\tau}_{\boldsymbol{A}_k}$ and $\boldsymbol{\tau}_{\boldsymbol{B}_k}$ respectively

3.1 AOA estimation with station A

Thanks to the modeling introduced in (8), the angles $\boldsymbol{\theta_A}$ are estimated with a subspace method such as the MUSIC algorithm [10] and gives $\hat{\boldsymbol{\theta}}_{\boldsymbol{A}}$. In presence of non-coherent multi-paths (mutual correlation strictly different to one) the rank of the $\mathbf{s}(\boldsymbol{\tau_A}, t)$ covariance matrix is full allowing a correct use of MUSIC.

3.2 Angular sources separation

The impinging signals $\mathbf{s}(\boldsymbol{\tau_A}, t)$ in station A is then estimated from the angles $\hat{\boldsymbol{\theta}}_{\boldsymbol{A}}$ as

$$\hat{\mathbf{s}}(t) = \mathbf{A}^{\#}\left(\hat{\boldsymbol{\theta}}_{\boldsymbol{A}}\right) \times \mathbf{x_A}(t) = \left[\begin{array}{c} \hat{s}_1(t) \\ \vdots \\ \hat{s}_k(t) \\ \vdots \\ \hat{s}_{M+P}(t) \end{array} \right] \tag{10}$$

where $\mathbf{A}^{\#}(\boldsymbol{\theta}) = (\mathbf{A}^H(\boldsymbol{\theta})\mathbf{A}(\boldsymbol{\theta}))^{-1}\mathbf{A}^H(\boldsymbol{\theta})$ is the Moore-Penrose pseudo-inverse, $(.)^H$ denotes the transpose-conjugate and $\hat{\boldsymbol{\theta}}_{\boldsymbol{A}} = [\hat{\theta}_{A_1} \ \ldots \ \hat{\theta}_{A_{M+P}}]^T$. $\hat{\mathbf{s}}(t)$ stands for the estimation of $\boldsymbol{\Gamma_A}\mathbf{s}(\boldsymbol{\tau_A}, t)$. The signal $\hat{s}_k(t)$ is now associated to the kth components $\hat{\theta}_{A_k}$ of the vector $\hat{\boldsymbol{\theta}}_{\boldsymbol{A}}$. For instance in Figure.1 there is $M + P = 3$ paths and the signal $\hat{s}_k(t)$ is either associated to one of the two emitters E_1 and E_2 or to a composite signal at the output of the reflector in R_1.

3.3 LOS Separation

The purpose is now to identify if the kth components $\hat{s}_k(t)$ of $\hat{\mathbf{s}}(t)$ is either a LOS or a NLOS signals. Indeed, there is no reason that the M first components of $\hat{\mathbf{s}}(t)$ are associated to the LOS path as the vector $\mathbf{s}(\boldsymbol{\tau_A}, t)$ in (8). In order to know if either $\hat{s}_i(t) = e_m(t - \tau_{A_m})$ or $\hat{s}_i(t) = r_p(t - \tau_{A_{M+p}})$ we propose the following delay estimation for each pair (i, j)

$$\underset{1 \le q \le Q_{ij}}{\hat{\tau}_{ij}^q} = \max_{\tau}\left(\rho_{\hat{s}_i\hat{s}_j}(\tau) > \eta\right) \tag{11}$$

$$\rho_{xy}(\tau) = \frac{|E\left[x(t)\,y^*(t-\tau)\right]|^2}{E\left[|x(t)|^2\right] E\left[|y(t)|^2\right]} \tag{12}$$

where η is a detection threshold and $E[.]$ denotes the mathematical expectation According to Schell and Gardner works [11, 12], the threshold η is fixed relatively to a targeted probability of false alarms. The LOS identification is based on the following straightforward properties where $\bar{\tau}_{A_{mp}} =$

$\tau_{A_{M+p}} + \tau_{mp}$ and Q_{ij} is the number of maxima $\hat{\tau}_{ij}^{q}$ of the criterion $\rho_{\hat{s}_i\hat{s}_j}(\tau)$

Prop 1 *$\rho_{e_m e_{m'}}(\tau) = 0, \forall \tau$ for $m \neq m'$ because the emitters are statistically independents*

Prop 2 *$\rho_{e_m r_p}(\tau)$ exhibit one extremum ($Q_{ij} = 1$ when $\rho_{\hat{s}_i\hat{s}_j}(\tau) = \rho_{e_m r_p}(\tau)$) in $\tau = \bar{\tau}_{A_{mp}} - \tau_{A_m}$ due to the presence of the mth emitter delayed signal in the pth reflected signal.*

Prop 3 *$\rho_{r_p r_{p'}}(\tau)$ exhibits M extrema ($Q_{ij} = M$ when $\rho_{\hat{s}_i\hat{s}_j}(\tau) = \rho_{r_p r_{p'}}(\tau)$) in $\tau = \bar{\tau}_{A_{mp}} - \bar{\tau}_{A_{mp'}}$ for $(1 \leq m \leq M)$ due to the presence of the M emitted signal in both reflected signals $r_p(t)$ and $r_{p'}(t)$.*

The correlation function $\rho_{ij}(\tau)$ can be either $\rho_{e_m e_{m'}}(\tau)$ or $\rho_{e_m r_p}(\tau)$ or $\rho_{r_p r_{p'}}(\tau)$ and the number M of emitters is the maximum value in (i, j) of Q_{ij}. According to the following properties, the signal $\hat{s}_i(t)$ is a LOS signal for

- $M = 1$, when $\hat{s}_i(t)$ is the first arriving on station A because the maxima of $\rho_{\hat{s}_i\hat{s}_j}(\tau) = \rho_{e_m r_p}(\tau)$ are $\bar{\tau}_{A_{mp}} - \tau_{A_m}$ and $\tau_{A_m} < \bar{\tau}_{A_{mp}}$
- $M \geq 2$, when $\hat{s}_i(t)$ is uncorrelated with each other because $\rho_{\hat{s}_i\hat{s}_j}(\tau) = \rho_{e_m e_{m'}}(\tau) = 0$ for any τ.

After the LOS identification, the Mth first components of $\hat{\mathbf{s}}(t)$ are the LOS components $\hat{s}_m(t) = \hat{e}_m(t - \tau_{A_m})(1 \leq m \leq M)$ and the sequels are the NLOS ones with $\hat{s}_{M+p}(t) = \hat{r}_p(t - \tau_{A_{M+p}})$. The LOS signal $\hat{s}_m(t) = \hat{e}_m(t - \tau_{A_m})$ is now paired to its AOA $\hat{\theta}_{A_m}$.

3.4 TDOA estimation

The TDOA of the mth emitter is then estimated from the LOS signal $\hat{s}_m(t) = \hat{e}_m(t - \tau_{A_m})$ extracted from the station A and $\mathbf{x_B}(t)$ at the output of station B as

$$\underset{1 \leq i \leq P+1}{\tau_{m,i}} = \max_{\tau}\left(f_m(\tau)\right) \tag{13}$$

where

$$f_m(\tau) = \frac{\mathbf{c}_m^H(\tau)\, \mathbf{R_{BB}}(\tau)^{-1}\, \mathbf{c}_m(\tau)}{\rho_{mm}(0)} \tag{14}$$

where $\mathbf{R_{BB}}(\tau) = E[\mathbf{x_B}(t+\tau)\mathbf{x_B}(t+\tau)^H]$ and $\mathbf{c}_m(\tau) = E[\mathbf{x}_B(t+\tau)\hat{s}_m^*(t)]$. The estimation gives $P+1$ TDOA $\tau_{m,i}$ because the LOS signals are correlated with the LOS and NLOS signals arriving in station B. As $\tau_{B_m} < \tau_{B_{m+p}}$, the TDOA $\delta\tau_m = \tau_{B_m} - \tau_{A_m}$ corresponding to the mth emitter is the following smallest value of $\tau_{m,i}$

$$\hat{\delta\tau}_m = \min_{1 \leq i \leq P+1}\left(\tau_{m,i}\right) \tag{15}$$

3.5 Location

The location $\hat{E}_m$ of the mth emitter is estimated from the AOA-TDOA parameters $(\hat{\delta\tau}_m, \hat{\theta}_{A_m})$ of this emitter. Once the AOA/TDOA parameters are known the location of a single emitter is easily performed as recalled now: As illustrated in Figure.2, let's note θ_E and $\delta\tau = \left(||EA|| - ||EB||\right)/c$ the AOA and TDOA parameters of an emitter E located in (x_E, y_E) with A and B being two receiving stations of coordinates (x_A, y_A) and (x_B, y_B) respectively. The emitter is located at the intersection of an hyperbola of equation $\delta\tau = \left(||MA|| - ||MB||\right)/c$ and a straight line of direction θ_E. Its coordinates in the $(\overrightarrow{AB}/\left\|AB\right\|, \vec{v})$ plane (where the unitary vector $\vec{v}$ is orthogonal to $\overrightarrow{AB}$) are

$$\begin{cases} x_E = & x_A + \|AE\| \cos(\theta_E) \\ y_E = & y_A + \|AE\| \sin(\theta_E) \end{cases}, \quad \|AE\| = \frac{(\delta\tau.c)^2 - \|AB\|^2}{2\left((\delta\tau.c) - \|AB\| \cos(\theta_E)\right)} \tag{16}$$

where c is the velocity of the waves.

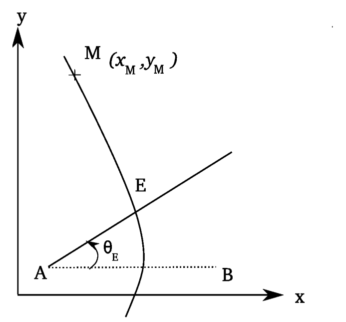

Figure 2: Principe of location based on AOA-TDOA estimation

The location $\hat{E}_m$ is then estimated according to (16) with $\delta\tau = \hat{\delta\tau}_m$ and $\hat{\theta}_{A_m} = \theta_E$. The steps of the proposed geolocation algorithm is summarized on Table.1

Step1 : Estimation of the AOAs $\hat{\boldsymbol{\theta}}_{\boldsymbol{A}}$ of the impinging paths on station A.
Step2 : Separation of the signals $\hat{s}_k(t)(1 \leq k \leq P+M)$ of impinging sources associated to the AOA θ_{A_k} with a spatial filtering (10) on station A.
Step3 : LOS detection based on an intercorrelation criterion (11) between the signals $\hat{s}_k(t)$. From $\{\hat{s}_k(t)\}$, identification of the M LOS signals $\hat{s}_m(t)(1 \leq m \leq M)$ associated to the AOA $\hat{\theta}_{A_m}$.
Step4 : Estimation of the LOS TDOA $\hat{\delta\tau}_m$, from the component $\hat{s}_m(t)$ and the signals $\mathbf{x}_B(t)$ at the output of station B, with the criterion (14).
Step5 : For $(1 \leq m \leq M)$, location of the mth emitter thanks to the AOA-TDOA couples $(\hat{\theta}_{A_m}, \hat{\delta\tau}_m)$ by using expression (16).

Table 1: A multi-stage geolocation algorithm

3.6 Simulations

The simulated emitted signals corresponds to GSM radio-cellular system where the modulation is GMSK, the bandwidth is 300kHz and the time observation is the GSM burst duration with $T = 0.577ms$. The sampling frequency is chosen to $f_e = 6MHz$. The performances criterion for an emitter located in (x, y) is the RMSE (Root Mean Square Error) defined by

$$RMSE = \sqrt{\frac{1}{K}\sum_{k=1}^{K}(x-\hat{x}_k)^2 + (y-\hat{y}_k)^2} \quad (17)$$

where K is the number of Monte-carlo runs and $(\hat{x}_k, \hat{y}_k)$ the kth estimated position. The Signal to Noise Ratio (SNR) of the mth emitter is $SNR = 20log_{10}(\gamma_m/\sigma)$, where σ is the standard deviation of the noise. The stations A and B are located in $(0, 0)$ and $(3000, 0)$ respectively and are composed of Uniform circular arrays of radius $R = 0.7\lambda$ with N_A and N_B sensors respectively. The path attenuation γ_m, γ_p and γ_{mp} are equal to 1 for all (m, p).

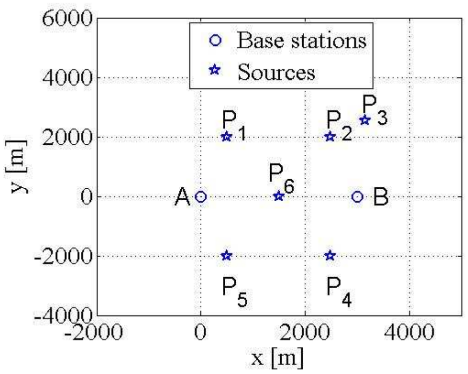

Figure 3: Illustration of the proposed scenario : the sources can be either emitters or reflectors and their locations are $P_1(500, 2000)$, $P_2(2500, 2000)$, $P_3(3160, 2530)$, $P_4(500, -2000)$, $P_5(2500, -2000)$ and $P_6(1500, 0)$. The base stations are located in $A(0, 0)$ and $B(3000, 0)$.

On Figure.3 the location A and B of the stations and location $P_i (1 \leq i \leq 6)$ of emitters or reflectors are presented. In the sequel 3 scenarios the locations P_i are either emitters or reflectors

- Two emitters are located in P_1 and P_2 and the RMSE of the emitter in P_1 is compute Figure.4. As we can see the performances improve when N_B increases.
- On Figure.5 the RMSE of the emitter in P_1 is compute in presence of a reflector located in P_2 or P_3 with $N_B = 1$ (fig 5.a) or $N_B = 2$ (fig 5.b). The proximity between P_1 and P_3 provides a time difference of arrival of the impinging paths on station B of 2 symbol duration and leads to a path correlation about 0.06 corresponding to a uncorrelated scenario. When the reflector is in P_2 the time difference of arrival of the impinging paths on station B is 0.8 symbol duration leading to a correlation about 0.6 and corresponding to a more severe scenario with correlated paths on station B. The location of P_2 and P_3 is such that they possess the same AOA on station A. We can see that even if the RMSE increases with the severity of the scenario it can be greatly improved by adding sensors on station B.

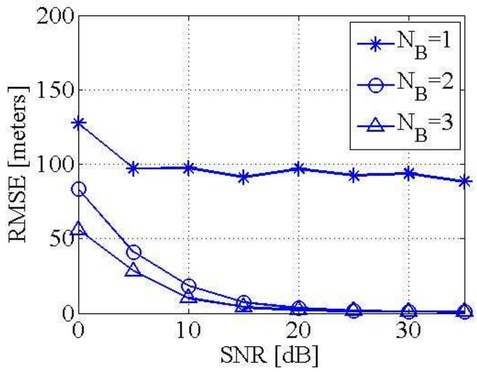

Figure 4: RMSE of an emitter in P_1 in presence of a second in P_2 with respect to the SNR. $N_A = 5$, number of Monte-carlo runs =200

- Three emitters (in P_1, P_4 and P_6) and two reflectors (in P_2 and P_5) are simulated on Figure.6 illustrating the performances of our algorithm in presence of two multi-paths and providing promising results.
- A comparison between the proposed algorithm and the DPD [8],[9] is given in presence of two emitters locate in $E_1(0, 2000m)$ and $E_2(1500m, 2000m)$ respectively. The bandwidth of the FFT channels of the DPD is $25kHz$ (250 FFT points) and the time observation is $T = 1.154ms$. Figure.7 shows that the DPD is biased whereas the AOA-TDOA algorithm is unbiased and more accurate.

4. CONCLUSION

In this paper we have proposed a simple multi-stage algorithm able to estimate the position of multi-emitters in presence of multi-paths working with only two stations and requiring only one dimensional optimizations criteria. Our first simulations are promising, further investigations needed to study performance in more depth. Further comparisons in multi-emitters context with existing algorithms is an ongoing work.

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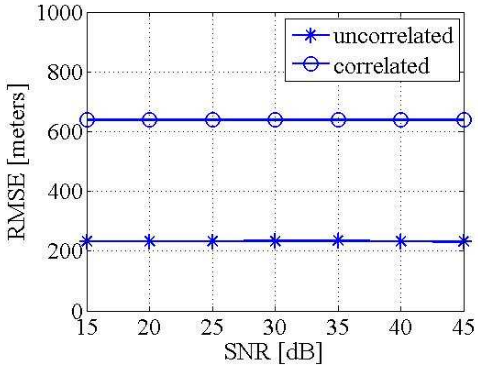
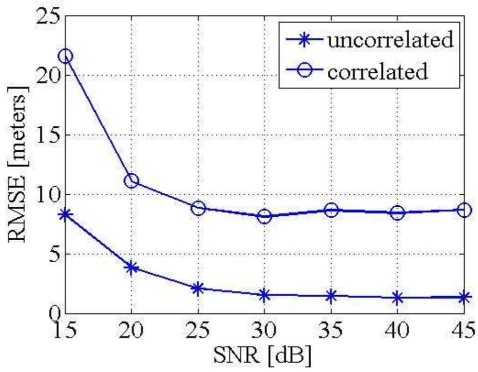


(a) $N_B = 1$



(b) $N_B = 2$

Figure 5: RMSE of an emitter in P_1 with respect to the SNR in presence of a reflector either in P_3 (uncorrelated scenario) or in P_2 (correlated scenario) with $N_B = 1$ (a) or $N_B = 2$ (b). $N_A = 5$, number of Monte-carlo runs=200

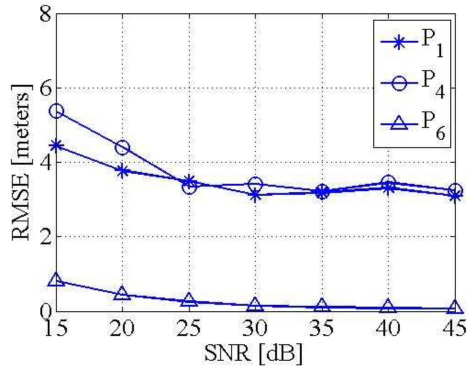


Figure 6: RMSE of the three emitters in P_1, P_4 and P_6 with respect to the SNR in presence of two reflectors (P_2 and P_5). $N_A = 11$ and $N_B = 5$, number of Monte-carlo runs=100.

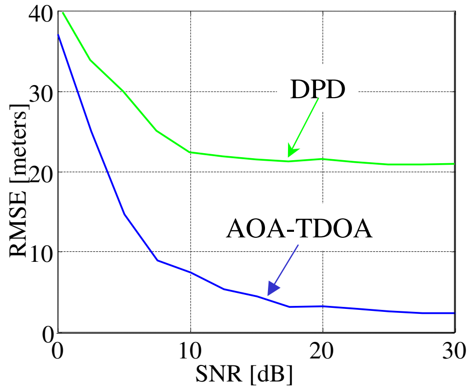


Figure 7: RMSE of an emitter in $E_1(0, 2000m)$ in presence of a second in $E_2(1500m, 2000m)$ with respect to the SNR. $N_A = N_B = 5$, number of Monte-carlo $runs = 200$.

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