Antenna selection in a SIMO architecture for HF radio links

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ABSTRACT

This work takes place in the global design of a SIMO architecture (single input multiple output) for trans horizon radio links, aiming at a significant increase in the data rate if compared with standard modems based in general on a SISO scheme (single input single output). The project is subject to available space constraints at the receive end, involving mobile stations or onboard implementation. So, we consider solutions that appear as extensions of the compact and heterogeneous antenna array that we proposed previously: collocated antennas of different types are set up with the same phase center and present diversity in their polarization sensitivities to make array processing effective.

Given the number NC of receive channels, we address the problem of selecting the most effective antennas in a set of NA possible candidates including monopoles, dipoles, loop antennas with various geometries and orientations. The criterion to be maximized is the SIMO outage capacity, a quantity based on the statistical distribution of the SIMO Shannon capacity estimated for a large number of ionospheric channel realizations, each of them being quantified by its channel impulse response including the receive antenna directional responses.

Results are presented in the context of a 1x2 SIMO structure: the identification of the 2 (NC=2) most effective antennas in a set of NA=15 sensors indicates that the optimal structures involve 2 orthogonal horizontal dipoles or 2 vertical orthogonal loop antennas. In these conditions, the outage capacity reaches up to 2.23 bps/Hz, a value that significantly exceeds the performances of standard modems.

1. INTRODUCTION

This work takes place in the global design of a SIMO architecture (single input multiple output) for trans horizon radio links, aiming at a significant increase in the data rate if compared with standard modems based in general on a SISO scheme (single input single output). The project is subject to available space constraints at the receive end, involving mobile stations or onboard implementation. So, we consider solutions that appear as extensions of the compact and heterogeneous antenna array that we proposed in [1]: collocated antennas of different types are set up with the same phase center and present diversity in their polarization sensitivities to make array processing effective.

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2. CALCULATION OF THE CHANNEL IMPULSE RESPONSE

2.1 PROPAGATION PARAMETERS

For a given point to point radio link, a channel model requires the estimation of significant parameters for the different paths: path loss, elevation angle, group delay. This estimation is provided by VOACAP which is a well known reliable tool for HF circuit analysis [2]. Restricted to mid latitudes, the simulations use the method #25. The anisotropy of the ionosphere in not rigorously taken into account; however, in a simplified approach, we consider that the propagation of an X mode is similar to the propagation of an O mode with a frequency shift equal to a half gyro frequency. Besides, Doppler shifts and temporal fadings are not considered in this description. For a given receiving site, VOACAP method #25 operates with a set of 5 input parameters: link range, azimuth of the transmitter, carrier frequency, date, hour. The transmit antenna is supposed to be isotropic. The outputs are the number NS of identified propagation modes and, for each of them, the attenuation, group delay and elevation of the incident wave. Given the receive antenna, the computation of the channel impulse response needs in addition the calculation of the antenna spatial response.

2.2 ANTENNA SPATIAL RESPONSE

In this step, the estimation of the polarization characteristics at the ionosphere exit is of major interest. The incident waves are elliptically polarized in general with a description based on 2 parameters: polarization ratio R, the modulus of which quantifies the respective lengths of the two axes of the ellipse along which the electrical field rotates, and inclination α between the ellipse main axis and the local horizontal. At the exit of the ionosphere, we express that electron density tends to zero and the collision frequency (collisions between electrons and neutral molecules) as well (Budden conditions). Denoting B_L and B_T the components of the terrestrial magnetic field at the exit of the ionosphere, respectively longitudinal and transverse components relatively to the direction of the propagation vector, the polarization ratio of the incident wave is expressed as:

$R_{\pm} = \frac{i}{2Y_L}\left\{Y_T^2 \pm \left[Y_T^4 + 4Y_L^2\right]^{1/2}\right\}$ where $Y_L = \frac{qB_L}{m\omega}$, $Y_T = \frac{qB_T}{m\omega}$, q and m are the electron charge and mass and ω is the carrier pulsation.

The sign + or – depends of the polarization type (ordinary O or extraordinary X) associated with the incoming wave : the convention is sign + for X modes and sign – for O modes.

Consequently, the polarisation characteristics depend on the receiver location and the direction of arrival (DOA) identified by a couple of angles, azimuth and elevation $\theta = (\mathrm{Az}, \mathrm{El})$. Then, the antenna spatial response is computed with the Numerical Electromagnetics Code software (NEC-2D). Based on the method of moments, it is suitable for structures described as a mesh of wires or surfaces in case of free space propagation over the ground. NEC considers incident waves with right or left circular polarizations. It has been modified to monitor elliptical polarizations with parameters R_{+-} and α estimated in the previous stage. Finally, the antenna spatial response is a complex valued gain $F(\theta, P)$ depending on the DOA θ and the polarisation type P (O or X). Its complex valued nature is linked to the elliptical structure of the polarization that can be described as a phasor vector [3] with real and imaginary components.

2.3 CHANNEL IMPULSE RESPONSE

The combination of ray tracing and antenna gain computation gives the expression of a channel response impulse h_i (t) including the receive antenna supposed to be identified with index i in a set of NA sensors :

$$h_i(t) = \sum_{k=1}^{NS} A_k \delta(t - \tau_{gk}) F_{ik}(\theta_k, P_k)$$

where NS is the number of identified paths or modes, A_k is the amplitude of mode k (depending on the corresponding attenuation), τ_{gk} is the group delay of path k and $F_{ik}(\theta_k,P_k)$ is the gain of antenna i for path k (with DOA θ_k and polarization type P_k O or X). For further exploitation, the temporal samples of h_i (t) are saved in a vector $\underline{h}_i$ which contains a number NS of non zero elements. The channel complex gain $\underline{Hc}_i(f)$, function of frequency f and defined as the Fourier transform of h_i (t), is computed through the FFT : $\underline{Hc}_i(f) = FFT(\underline{h}_i)$.

3. OBTAINING A LARGE NUMBER OF TRIALS

The selected criterion for antenna selection requests statistics of SIMO ionospheric channels. It is then necessary to prepare a collection (with a large amount of trials) of channel impulse responses or channel complex gains for each group of receive antennas (with a fixed location) under test.

To reach this goal, the parameters of the simulations to be adjusted are:

- the year, choosen in an interval with solar activity indices varying from a low to a high value. Consequently, 3 different years are considered: year 1954 with a very low solar activity, year 1969 assumed to be representative of a “mean” activity, and year 1958 for a high solar activity.

- the month in the selected year : 4 months are selected, corresponding to the 4 seasons

- the hour : one simulation is carried out every hour

- the range of the radio link, expanding from 300 km to 1500 km with a step of 300 km

- the azimuth of the link, varying from 0° to 360° with a step of 15°

- the carrier frequency varying from 3 MHz to 15 MHz with a step of 3 MHz.

The maximum number of trials is then equal to 172800. However, each configuration does not generate an operating link as it is observed if no ray propagates from the transmitter to the receiver or if rays exist, but with a prohibitive path loss. Taking these constraints into account and for given year, distance and frequency, the number of validated trials Ntr varies from several hundreds to some thousands (2000 typically).

4. DEFINITION OF THE OUTAGE CAPACITY

The antenna selection is based on the maximization of the outage capacity of SIMO channels that involves the histogram of the Shannon capacity estimated for each of the Ntr valid trials [4]. These notions are specified in the following for different schemes: non dispersive SISO channel, non dispersive SIMO channel and finally dispersive SIMO channel, case that corresponds to trans horizon radio links.

4.1 SISO, NON DISPERSIVE CHANNEL

In this first scheme, the channel impulse response for the trial with index nr is reduced to a single non zero element denoted $h_{ref}(nr)$: the channel has a flat frequency response. The Shannon capacity, (calculated in a bandwidth equal to 1 Hz) , is expressed as:

$$C_{siso}(nr) = \log_2(1 + \frac{Pe.|h_{ref}(nr)|^2}{No})$$

where Pe is the transmitted power in this frequency band and No is power spectrum density of the noise.

The outage capacity is defined as the threshold exceeded by the Shannon capacity with a probability 1-ε, ε being a given value of probability ($\varepsilon=10^{-1}$ generally).

$$C_{outsiso\ \varepsilon} = \sup_{C \geq 0}\{C : p[C_{siso} < C] \leq \varepsilon\}$$

This criterion is pertinent as it involves a large number of trials to estimate the histogram of Csiso and as it takes into account a kind of quality of service.

4.2 SIMO, NON DISPERSIVE CHANNEL

In this scheme, the NC channel impulse responses are reduced to single non zero elements; these coefficients are stored in a NCx1 column vector for each trial with index nr:

$$\underline{h}(nr) = \begin{pmatrix} h_{ref}(nr) \\ h_2(nr) \\ \ldots \\ h_{NC}(nr) \end{pmatrix}$$ where $h_i(nr), i = 1,..., NC$ is the gain (for the trial with index nr) for the channel linking the transmitter to the receive antenna with index i.

The corresponding expression of the Shannon capacity is $C_{simo}(nr) = \log_2(1 + \frac{Pe.\|\underline{h}(nr)\|^2}{No})$ and the benefit of the SIMO solution (array gain) appears through an increase in the Signal to Noise ratio (SNR) as $\|\underline{h}(nr)\|^2 > |h_{ref}(nr)|^2$.

4.3 SIMO, DISPERSIVE CHANNEL

This scheme corresponds to the ionospheric channel with NC impulse responses presenting a delay spread. Each of them is transposed in the frequency domain (channel complex gain) with Nf frequency bins identified with index nf. For the trial with index nr and the frequency bin with index nf, the NC channel gains are stored in a column vector :

$$\underline{Hc}(nf, nr) = \begin{pmatrix} Hc_{ref}(nf, nr) \\ Hc_2(nf, nr) \\ \ldots. \\ Hc_{NC}(nf, nr) \end{pmatrix}$$

The corresponding expression of the Shannon capacity is, for one frequency bin nf:

$$C_{simo}(nf, nr) = \log_2(1 + \frac{Pe.\|\underline{Hc}(nf, nr)\|^2}{No})$$

The benefit of the SIMO solution is expressed in terms of array gain (as previously) and diversity gain in addition with values of $|Hc_i(nf, nr)|$ than may be superior to $|Hc_{ref}(nf, nr)|$.

Keeping in mind that the definition of capacity refers to a 1Hz wide band, the global Shannon capacity in the case of dispersive SIMO channels is expressed as a value averaged on Nf bins :

$$C_{Simo\ LB}(nr) = \frac{1}{Nf}\sum_{nf=1}^{Nf} C_{simo}(nf, nr)$$

In this scheme, the outage capacity is defined as : $C_{outsimo\ \varepsilon} = \sup_{C \geq 0}\{C : p[C_{simo\ LB} < C] \leq \varepsilon\}$

In the project, all combinations of NC antennas among a set of NA possible sensors are then considered and, for each of them, the outage capacity is calculated. The final selection is based on the SIMO/SISO gain $G_{cout} = \frac{C_{outsimo\ \varepsilon}}{C_{outsiso\ \varepsilon}}$, which is the ratio dividing the 2 outage capacities, the SISO capacity being computed for a given receive antenna chosen as a reference. In the following, the reference antenna for SISO capacity is antenna with index 6 which is a passive vertical dipole with a 12 m length.

5. RANKING THE DIFFERENT ANTENNA CONFIGURATIONS

It appears that the outage capacity gains of different efficient antenna configurations are very close one from each other. For example, in a simulation of SIMO 1x2 solutions considering 38 antenna combinations and involving 687 valid trials of the channel with variations of month, hour and azimuth, the 10 largest values of gain are:

2.3300 2.3600 2.4100 2.4900 2.5300 2.6800 3.0600 3.0700 3.1800 3.3200

The 4 best performances appears as almost equivalent. The reason is the integration in the computation of all possible azimuths (0-360° with a step of 15°) that results in an averaging of the antenna directional responses. Consequently, the ongoing selection does not operate relatively to the only maximal gain: any antenna configuration indicating a capacity gain which exceeds a given proportion of the maximum gain (threshold of 80% in most cases) is regarded as a good candidate. Then, simulations are re-itered with variations of parameters year, distance and carrier frequency with a maximum of 3 (years) x 5 (distances) x 5 (frequencies), that is to say 75 times. Each time, the antenna configurations with a gain exceeding the threshold are identified. For a given antenna configuration, the final ranking is based on the number of occurrences the threshold is exceeded.

6. SET OF ANTENNAS UNDER TEST

In this project, a group of 15 possible receive antennas have been considered with a simple geometry due to set up constraints: mobile stations or onboard installation. Complex structures like log periodic or log spiral antennas have been ignored. Antennas with indexes #1 to #5, #12 and #13 are small size active antennas (and additionally the combinations with indexes #14 and #15). Other antennas are passive with a larger size. The list stands below:

#1 Vertical North-South oriented loop antenna (octagonal shaped ; typical size of 1 m)

#2 Vertical East-West oriented loop antenna (octagonal shaped ; typical size of 1 m)

#3 Horizontal loop antenna

#4 East-West oriented dipole antenna (typical length of 2 m in a vertical plane)

#5 North-South oriented dipole antenna (typical length of 2 m in a vertical plane)

#6 Vertical passive dipole antenna (12 m length)

#7 Vertical passive monopole antenna (12 m length)

#8 Vertical East-West oriented V shaped passive dipole (2x15m long elements)

#9 Vertical North-South oriented V shaped passive dipole (2x15m long elements)

#10 Vertical East-West oriented, two oblique elements dipole (2x15 m long, , inclination of 45 degrees)

#11 Vertical North-South oriented, two oblique elements dipole (2x15 m long, inclination of 45 degrees)

#12 Horizontal North-South oriented dipole (2x2 m long linear elements)

#13 Horizontal East-West oriented dipole (2x2 m long linear elements)

#14 Combination of 2 vertical loops NS+j*EW (matched to circular polarization)

#15 Combination of 2 vertical loops NS- j*EW (matched to circular polarization)

Antenna # 6 (vertical dipole) is considered as a reference in the SISO case. Active antennas #1 to # 5 are aerials of a device consisting of collocated sensors developed at the IETR (figure 1**Error! Reference source not found.**). This device is contained within a 1.7 m side cube and the antenna feed points are 3 m above the ground. Antennas 14 and 15 are combinations of loops #1 and #2. The passive dipoles #8 to #11 are supposed to be set up on a mast 12 m above the ground. In the computation of antenna directional responses, the ground effect is taken into account (according to the Sommerfeld method), assuming standard characteristics: a conductivity equal to 0.005 S/m and a permittivity equal to 13.

7. RESULTS

In the project, gains in performances (relatively to the SISO case) have been estimated for SIMO systems involving from 2 to 5 receive channels. In this paper, we limit the presentation to results regarding the optimisation of a SIMO 1x2 structure. In the set of 15 receive antennas, 38 couples have been considered for SIMO 1x2. An example of outage capacity gain estimation for a 900 km link, 9 MHz carrier frequency in year 1969 is given in Figure 2. It shows the sorted outage capacity gain as a function of the index of antenna couples (SIMO 1x2). In this case, selecting the only couple that reaches the maximum value of gain should be very restrictive as it may not be the best if one of the parameters distance, frequency or year is modified. Therefore, any couple with a gain exceeding 80% of the maximum value will be selected for further evaluation.

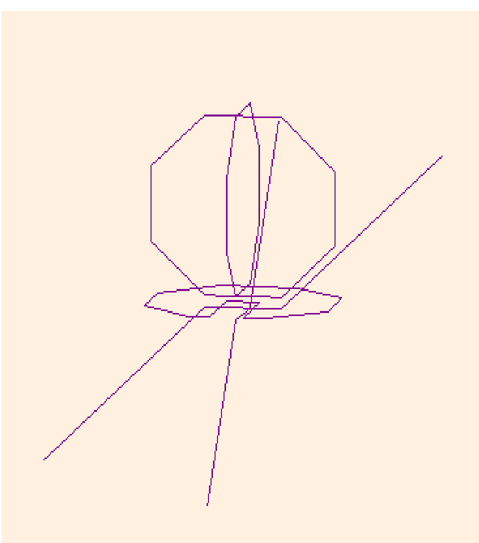

Figure 1. Array of 5 collocated antennas

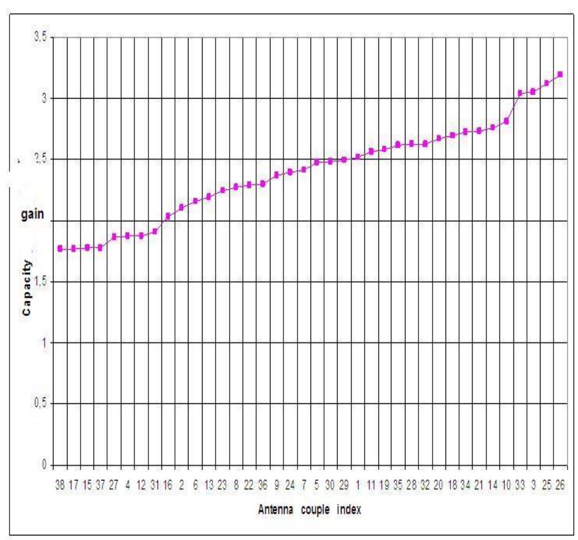

Figure 2. Example of outage capacity gain (38 couples)

Figure 3 indicates, for each couple with index varying from 1 to 38, the number of occurrences of a good ranking (capacity gain exceeding 80% of the maximum value), the total number of trials being equal to 75.

It appears that, according to the criterion of a maximal number of occurrences, the best configurations have the indexes 25 and 26 with very comparable performances: they correspond to the association of antennas #12 and #13 for the first one (2 orthogonal horizontal dipoles) and antennas #1 and #2 for the second one (2 vertical orthogonal loop antennas). The number of iterations obtained by variations of the parameters year, distance and frequency is equal to 50: the maximum number is 75, but all configurations are not valid due to poor propagation previsions or inappropriate shape of the Shannon capacity histogram. Consequently, the theoretical maximum number of occurrences is 50 and the value reached by the best antenna configuration is equal to 48 (see figure #3).

With this selection, the typical value of outage capacity gain is close to 3.1 . Given the value of the SISO outage capacity (0.72 bps/Hz), the optimal SIMO outage capacity is equal to 2.23 bps/Hz. It can be surprising that the gain value exceeds the number of receive channels (2). But, we must keep in mind that the capacity gain is estimated relatively to a SISO channel including a reference antenna (vertical dipole #6) which may be not optimal. With a reference being one antenna of couple 25, the capacity gain would be inferior or equal to 2.

On the contrary, the configuration with index 38 appears as one of the worst choices. It corresponds to the (theoretical) association of 2 identical vertical dipoles. In that situation, the benefit of a SIMO architecture is an improvement in the SNR (signal to noise ratio) but no diversity gain can be expected.

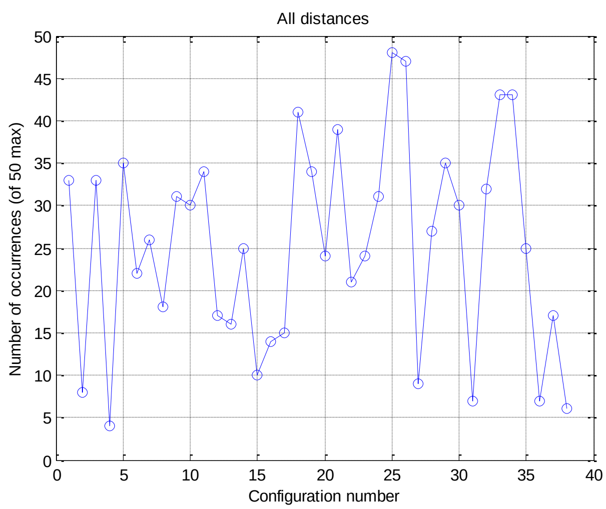

Figure 3. Number of occurrences (trials with a “good” ranking) for 38 couples of antennas

8. CONCLUSION

This paper proposes a selection criterion for receive antennas set up in a SIMO system for trans horizon radio communication. Subject to available space constraints, the antenna array must present a reduced aperture and consequently, involves non identical sensors with different directional responses set up with (theoretically) the same phase center. The proposed criterion is based on the outage capacity of SIMO channels, the computation of which resorts to the estimation of channel impulse responses including the receive antenna gains. As the outage capacity is estimated through statistics of Shannon capacity, a large number of trials of ionospheric radio circuits must be considered by variations of year, month, hour, distance, azimuth and frequency. For each trial, the propagation parameters are predicted thanks to the VOACAP software and the antenna directional responses to the incoming waves are computed with NEC 2D software.

In the case of SIMO 1x2 architecture, 2 equivalent optimal solutions are identified with the associations of 2 vertical orthogonal loop antennas or 2 horizontal orthogonal dipoles. The outage capacity gain (relatively to a SISO solution involving a vertical dipole at the receive end) is close to 3.1 and the corresponding outage capacity equal to 2.23 bps/Hz. The 2 antennas of the first couple are elements of the original device designed and built up at the IETR laboratory. Further investigations indicate that an increase in the number of antennas results in an increase in the capacity gain, but with moderate relative variations: maximum capacity gain equal to 3.82 for NC=3 and to 4.31 for NC=4.

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