Effects of coupling and overspeeding on performance of predictor antenna systems in wireless moving relays

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Nima Jamaly[1] ✉, *Tommy Svensson*[2], *Anders Derneryd*[3]
[1]*Innovations Department, Swisscom AG, Postfach 3050, Switzerland*
[2]*Department of Electrical Engineering, Chalmers University of Technology, Gothenburg 41296, Sweden*
[3]*A-konsult Eriksberg, Gothenburg 41764, Sweden*
✉ *E-mail: jamaly@gmx.ch*

Abstract: Using predictor antenna systems for modern wireless moving relays and base stations on top of vehicles such as buses, trains etc. proves to be a reliable approach for collecting channel state information to such fast moving nodes. Recently, it has been shown that coupling between different ports of a multiport antenna system used as a part of a predictor system can reduce the prediction performance. In this study, by integrating position and velocity vectors in the channel covariance matrix as seen at the antenna ports in a rich multipath environment, the authors quantify the impact of antenna coupling on prediction performance. Moreover, practically these predictor systems are designed for a certain target velocity. They further quantify the adverse effect of velocities, different from the target velocity, on prediction performance. In case open-circuit decoupling is necessary, the sensitivity of the predictor antenna system performance with respect to the accuracy of the input network parameters is disclosed.

1 Introduction

No doubt, in modern mobile communications systems, channel state information (CSI) at the transmitter side plays a remarkable role in enabling many salient features. Among these features, beam-forming, multi-user scheduling, spatial multiplexing, and space division multiple access stand out. As the wireless communication systems evolve and progressively become more sophisticated, delays in the feedback control loops become more critical. This naturally results in outdating of the CSI at the transmitter in particular when transmitting to a moving vehicle. The issue becomes more severe for larger control loop delays, higher velocities, and higher carrier frequencies whose occurrence is highly likely in practise.

To alleviate the issue, for speeds up to pedestrian velocities, prediction based on the past received channel estimates by Wiener or Kalman methods can be used. Nevertheless, these prediction methods become insufficient for vehicular velocities beyond 50 km/h at typical mobile carrier frequencies [1–5].

To resolve the foregoing problem, Sternad *et al.* in [1] propose the use of a predictor antenna system on the vehicle, wherein at least two in-line antennas are used. The first one, referred to as predictor antenna, is there to constantly measure the CSI and feed it back to the transmitter. The second antenna – in the direction of travel – is the receive antenna. To communicate with this receiving antenna, the transmitter can use the measured CSI by the predictor antenna.

This concept has been already demonstrated by field measurements in [1]. It was clarified that the presence of the coupling between the nearby predictor and receive antennas can reduce the prediction reliability and deteriorate the system performance. The latter is a discipline of its own which was first treated in [6] and later studied further in the frame of the predictor antenna system in [2].

In [2], different decoupling methods available in the literature were briefly reviewed [7–10]. It was concluded that among different decoupling methods, the *open-circuit method* is computationally the most effective one. In the aforementioned reference, the limitation in the accuracy of this decoupling method was also clarified [2]. Consequently, it was stressed that the foregoing method works best for the multiport antenna systems which approximate *minimum scattering antennas* [11, 12]. The fidelity of the open-circuit decoupling method has also been verified through an extensive measurement campaign in downtown Dresden, Germany [2].

In this paper, we first find a method to model a moving multiport/multi-element antenna system. We later provide a generic formula rendering the covariance matrix of received signals at the ports of a moving multiport antennas system. This formula yields the covariance in a rich Rayleigh fading environment. By virtue of this formula, we can precisely quantify the prediction performance reduction caused by coupling.

In addition, as described in [1, 2], unless the predictor system benefits from a mechanically sophisticated antenna system, wherein the separation between the predictor and the receive antennas varies in real-time proportional to the velocity of the vehicle, in practise a predictor system can be optimised only for a specified velocity. In the latter case, even in an ideal scenario, i.e. no coupling between the elements etc., any deviation from the intended velocity results in a reduced prediction performance. In this paper, we further quantify the prediction deterioration caused by varying velocity.

In addition, in case decoupling is necessary, it is important to reveal the impact of defective decoupling on prediction performance. For instance, the accuracy of the proposed open-circuit decoupling method depends on the accuracy of the input network parameters. In this paper, we disclose the effect of the accuracy of the input network parameters used for decoupling on predictor antenna system performance.

The overall structure of this paper is as follows. We present a notion of the phase centre matrix for multiport antennas in order to model its movement. Using this matrix, we introduce a formula for calculation of the covariance matrix in a Rayleigh multipath environment in Section 2. Section 3 is dedicated to quantify the effects of coupling in the predictor antenna system performance. Accordingly, Section 4 investigates the accuracy of the predictor antenna system against the variation in velocity of the vehicle. Investigation on the accuracy of the open-circuit decoupling method on prediction versus relative errors in input network parameters is presented in Section 5. This paper ends with a conclusion in Section 6.

To set the notations, matrices are denoted by bold letters. The column vectors are shown by an overbar sign. The superscript $\cdot^T$ indicates transpose and the dagger sign is the Hermitian transpose.

2 Multiport antenna movement modelling

The main concern in this paper is to quantify the performance deterioration caused by coupling in the predictor antenna system as well as the inaccuracy caused by the variation in the velocity of the vehicle. To address it, before anything, we need to formulate the antenna movement and insert it in the covariance matrix. The resultant formula can be used not only to address the foregoing issues but also to study the dependency of the open-circuit decoupling method on the accuracy of the input network parameters. To this end, first, we define an essential parameter which models the antenna movement. This parameter serves to derive an analytical formula to obtain the random received signals in an arbitrary general multipath scenario at the ports of a moving multiport antenna system.

To compactly formulate the problem, we assume both predictor and receive antennas to be part of a multiport antenna system which can, in general, have an arbitrarily large number of radiation elements or ports. Here, $\boldsymbol{G}_{2\times n}(\Omega)$ represents the matrix of open-circuit embedded far-field patterns of this, say, n-element antenna system whose rows are its corresponding vertical θ and horizontal ψ polarisation components. The symbol Ω signifies the solid angle and $\boldsymbol{Z}_{n\times n}$ is the input impedance matrix of this multiple antenna system whose terminated embedded far-field pattern matrix is denoted by $\boldsymbol{G}_r(\Omega)$.

2.1 Phase centre matrix

To analyse the performance of a moving multiport antenna system, we first need to mathematically model the movement of a multiport antenna. It is known that for short distances the displacement of a single-port antenna can be modelled by an appropriate change in its phase centre. For a multi-element antenna system, defining a suitable *phase centre matrix* containing information about its array configuration proves to be useful. For this purpose, let us decompose the open-circuit embedded far-field pattern matrix as

$$\boldsymbol{G} = \boldsymbol{G}^P \cdot \boldsymbol{P} \tag{1}$$

where the diagonal phase centre matrix, $\boldsymbol{P}$, is defined as

$$\boldsymbol{P} = \mathrm{diag}\big(\exp(-\mathrm{j}k\boldsymbol{r}_1 \cdot \hat{\boldsymbol{r}}),\ \ldots,\ \exp(-\mathrm{j}k\boldsymbol{r}_n \cdot \hat{\boldsymbol{r}})\big) \tag{2}$$

The vectors $\boldsymbol{r}_1, \ldots, \boldsymbol{r}_n$ indicate the position vectors of the radiation elements' phase centres. The vector $\hat{\boldsymbol{r}}$ is the unit vector in the spherical coordinate system and k is the wave number. Moreover, $\boldsymbol{G}^P$ is a $2 \times n$ matrix whose columns contain information about the open-circuit embedded far-field pattern of each element when located at the global phase reference point. If a multiport antenna system has similar radiation elements that approximate *minimum scattering antennas*, the columns of $\boldsymbol{G}^P$ are all the same. Now, if we assume that this multi-element system moves with the speed of $\boldsymbol{v}$, after a certain time, τ, the foregoing position vectors become

$$\boldsymbol{r}_{\tau_i} = \boldsymbol{r}_i + \boldsymbol{v} \cdot \tau \quad i = 1, 2, \ldots, n. \tag{3}$$

If τ is not too long to violate first-order approximation on the embedded far-field pattern calculations, the above position vectors can replace $\boldsymbol{r}_i$ ($i = 1, 2, \ldots, n$) in (2) yielding a new phase centre matrix, denoted by $\boldsymbol{P}_\tau$. Then, the open-circuit embedded far-field pattern matrix of this antenna system in the new position, $\boldsymbol{G}_t$, can be simply achieved by

$$\boldsymbol{G}_t = \boldsymbol{G}^P \cdot \boldsymbol{P}_\tau. \tag{4}$$

2.2 Covariance matrix for moving multiport antennas

Having defined the phase centre matrix, it is sufficient to pursue a similar path to those formerly published in [13, pages 32–34] (see also [14, eqs. 3–8]) in order to derive the desired formula. Doing so and after some algebra, we derive the temporal covariance matrix of the received signals, $\boldsymbol{C}_{r_\tau}$, at different ports of a multiport moving antenna system at a certain time delay, τ. The result is given in (5).

In (5), λ and η denote the wavelength and the free space intrinsic wave impedance, respectively; $\boldsymbol{G}_r$ is the embedded (or terminated) far-field pattern matrix in volts per metre; and $\boldsymbol{Z}_r$ in ohm is a diagonal matrix of terminating impedances at different ports; $\boldsymbol{\Gamma}$ shows the *polarisation matrix* containing information about incoming waves of co- and cross-polarisation from Ω and Ω' directions; and finally, $\mathrm{P}(\Omega, \Omega')$ stands for the *joint probability density function* of the incoming waves from foregoing directions, known as angle of arrival (AoA). This equation plays a key role in the remainder of this paper and is credible in a general correlated non-uniform zero-mean complex Gaussian multipath environment. Note that for the sake of conciseness, we used the embedded (or terminated) far-field pattern matrix instead of the open-circuit one in the equation below:

$$\boldsymbol{C}_{r_\tau} = \frac{4\lambda^2}{\eta^2}\boldsymbol{Z}_r^\dagger \int\int_{4\pi} \boldsymbol{P}_\tau^\dagger(\Omega') \cdot \boldsymbol{G}_r^{\mathrm{P}^\dagger}(\Omega') \cdot \boldsymbol{\Gamma}(\Omega', \Omega) \cdot \boldsymbol{G}_r^{\mathrm{P}}(\Omega) \cdot \boldsymbol{P}(\Omega)\mathrm{P}(\Omega', \Omega)\mathrm{d}\Omega'\mathrm{d}\Omega\boldsymbol{Z}_r \tag{5}$$

3 Coupling effects on prediction performance

The presence of antenna elements in the vicinity of each other causes mutual coupling, which in turn deforms the shapes of their far-field radiation patterns. In predictor antenna systems, this difference can degrade the performance. In this section, we wish to reveal the influence of pattern perturbation due to coupling in deterioration of temporal correlation ρ as the main performance metric for predictor antenna systems [1, 2].

Note that the eventual prediction performance may rely on several factors including the velocity of the vehicle, sampling rate, antenna properties etc. Nevertheless, to concentrate on the effect of coupling alone, we first assume that the equidistant radiation elements are aligned with the velocity vector with separation $d = \boldsymbol{v} \cdot \tau_d$. This leads to $\boldsymbol{r}_{\tau_i} = \boldsymbol{r}_{i-1}$ $i = 2, \ldots, n$. In addition, throughout this paper, we presume that the coherence length of the channel is far longer than the radiation element separation (i.e. $\gg d$). In other words, we assume that the spatial coherence time of the channel is substantially longer than the time it takes for the receive antenna to reach the spatial measurement location of the predictor antenna.

Furthermore, we arbitrarily choose two classical types of two-element lossless thin wire antennas with separation d above an infinite perfect electric conductor (PEC) plane: (i) quarter-wavelength monopoles and (ii) horizontal half-wavelength dipoles at a height $h = 0.10\lambda_\circ$ above the PEC plane whose orientation is perpendicular to the direction of the vehicle. Remember that throughout this paper, $\lambda_\circ$ indicates the wavelength at the resonance frequency of the corresponding antennas in the open-circuit state. These antennas approximate minimum scattering antennas, and therefore represent proper choices for our study [2]. It is worth stating that we choose the second antenna type only as an example of a low-profile antenna just for double verification of the presented formulation. In particular, their configuration makes the effect of coupling between them slightly exaggerated, highlighting the impact of decoupling even more than the case of quarter monopoles. The embedded element far-field patterns plus the input network parameters for these structures are simulated based on the method of moments [15, Section 8.4]. For better illustration, Fig. 1 shows this setup for the case of quarter-wavelength monopoles.

First of all, formula (5) has been used to realise the temporal correlation between the two-port signals at $\tau = \tau_d$ time delay in a rich uniform multipath environment. This multipath environment is a reference environment likely due to the fact that it can be

emulated in a reverberation chamber [16]. The corresponding results are shown in Fig. 2.

Undoubtedly, a rich uniform multipath environment represents only an ideal scenario. In reality, the AoA – at least in the elevation plane – is non-uniform. This gives rise to a question as for how the coupling, in general, can impact the predictor performance in non-uniform multipath environments. To address this curiosity, we need to choose a certain distribution for the AoA. Since the predictor antenna system can have any arbitrary direction in the azimuth plane, we presumably consider uniform AoA in this plane. In contrast, for the elevation (or zenith) plane, we resort to the double-exponential distribution as one of the most common ones in the literature [17]. The double-exponential distribution is specified by the *mean elevation angle* θ_m and the *spread angles* $\sigma^{\pm}$. The parameter σ^{+} refers to the spread angle for the $\theta < \theta_m$ (toward the sky) and σ^{-} belongs to the $\theta > \theta_m$ range (toward the ground).

The results of the correlations for the two antennas under study are all presented in Fig. 2. In these figures, the selected values for θ_m and $\sigma^{\pm}$ are given within the figures. Recall that ideally, the correlation for the predictor antenna system at τ_d delay is one, rendering zero normalised mean square prediction error (NMSE) $= 1 - |\rho|^2$ [1, 5]. We observe that coupling for different spread angles $\sigma^{\pm}$ and mean elevation angles θ_m affect differently and alter the prediction performance. However, all in all, the NMSE does not exceed 0.2 for the monopole case and 0.6 for the horizontal dipole case. These results are in harmony with the measurement results in [2], and clearly confirm the effectiveness of the predictor antenna system. Last but not least, using the open-circuit decoupling method, as shown in [2], one can compensate for the coupling and remove its impact. At the right velocity, the foregoing decoupling results in perfect correlation regardless of the separation between the two antennas. This has been demonstrated through an independent simulation tool and the corresponding results are presented by circles in Fig. 2.

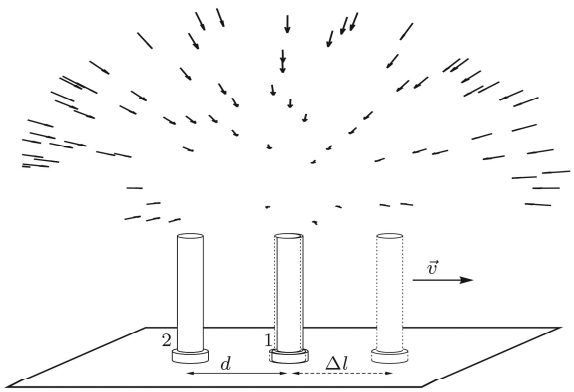

Fig. 1 *Sample scenario in which two monopoles above a PEC plane move with speed of* $\mathbf{v}$ *in an isotropic environment* ($\Delta l = d = 0.2\lambda_\circ$)

4 Effects of velocity variation in predictor antenna system performance

Remember that the element separation between the predictor antenna and the receive antenna in this system is directly proportional to the velocity of the vehicle [1]. If the element separation is fixed, dependent on the sampling rate and the number of radiation elements, the prediction is probably only optimum for one or a certain number of specified speeds, which is in practise hard to hold onto. Thus, the predictor system is subject to sampling quantisation error in time and consequently space since they are linked through the velocity vector. This could be due to coarse sampling or inaccurate speed estimation.

A predictor antenna system should be designed in a way that the front (i.e. predictor) antenna has placed a distance d metres ahead of the nearest rearward antenna, where

$$d = v_m \cdot \tau_m \tag{6}$$

with v_m being the maximum design velocity and τ_m being the maximum predictor horizon in time that the communication system is expected to require [1].

4.1 Effect of underspeeding in prediction performance

If the velocity of the vehicle is less than the design velocity $v \le v_m$, then the condition (6) ensures that $\tau \le \tau_d$. Thus, the rearward antenna at time delay τ is guaranteed to be located at a position behind the position at which the predictor antenna produced the latest channel estimate. Therefore, in case of underspeeding, we can obtain the appropriate channel prediction estimate for the rearward antenna (i.e. receiver antenna) at the corresponding delay by interpolating among the present and past channel estimates from the predictor antenna. One such interpolation scheme was suggested and used in [3]. Note that in this way, the error in prediction can be avoided in the digital domain which requires only computational resources. As long as the sampling is sufficiently dense, the adverse impact of quantisation error on the predicted CSI is negligible. Clearly, too high sampling rate on the predictor antenna signal adds unnecessary computation burden on the system, and therefore should be avoided.

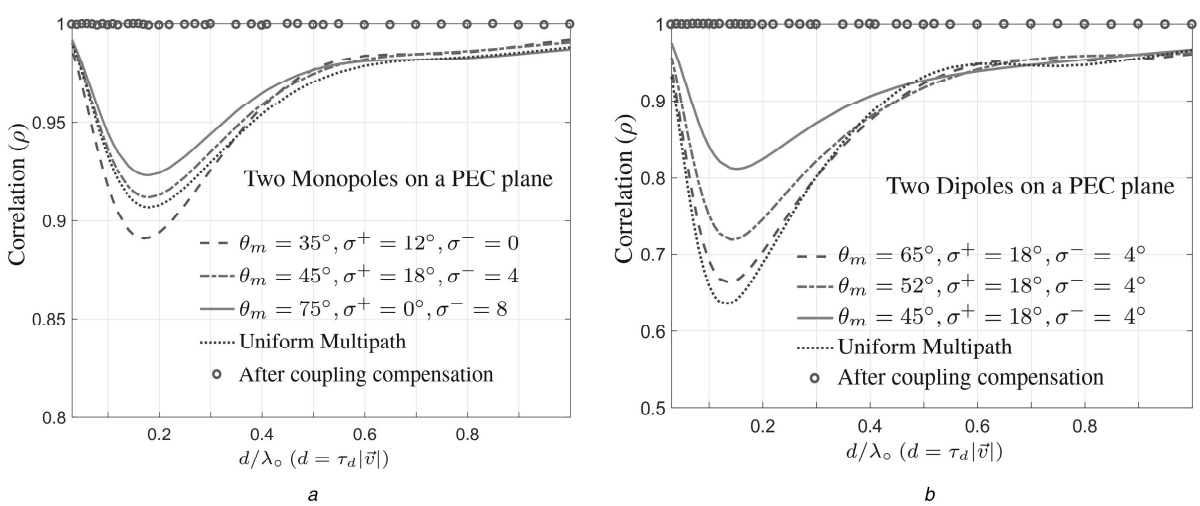

Fig. 2 *Normalised temporal correlation versus the element separation in double-exponential non-uniform multipath environments. The AoA distribution in the azimuth plane is uniform. Parameters* θ_m *and* $\sigma^{\pm}$ *stand for mean elevation angle and the associated spread angles around it. The minimum antenna separation is* $0.03\lambda_\circ$

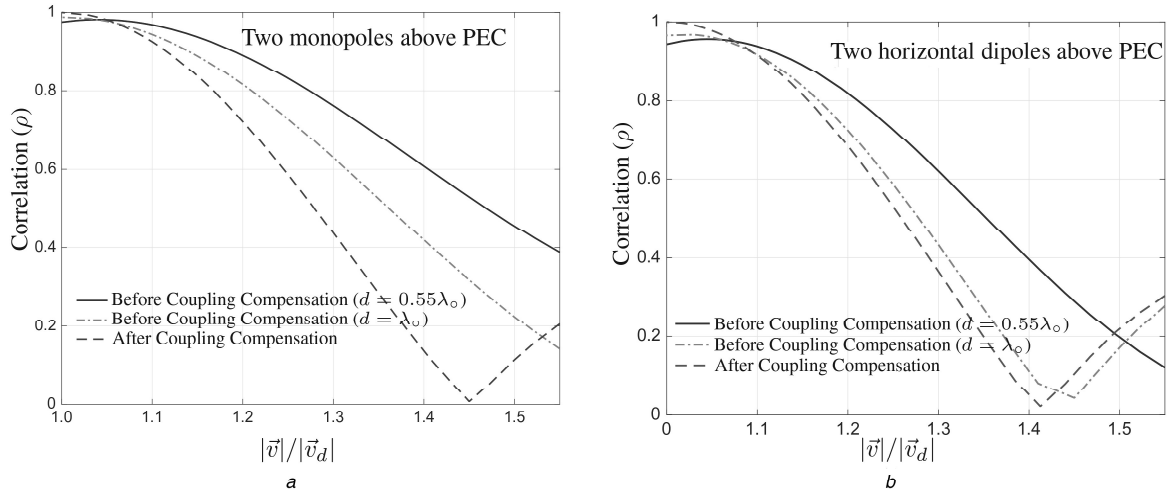

Fig. 3 *Temporal correlation for the overspeeding scenario. $\mathbf{v}_d$ denotes the intended speed*
(a) Case of two monopoles above the PEC, ***(b)*** Case of two horizontal dipoles above the PEC

4.2 Effect of overspeeding in prediction performance

In contrast, in a scenario in which the vehicle's speed exceeds the design speed, the condition (6) is not fulfilled. Thus, we can no longer obtain the channel prediction estimate for the receive antenna by interpolation, rather extrapolation to the positions in front of predictor antenna must be used. This will have rapidly increasing errors when the extrapolation horizon increases, which must be quantified. Thus, the main goal in this section is to reveal how sensitive the prediction performance is with respect to overspeeding. In this framework, we also answer the question about whether removing coupling will be still beneficial in cases, where there is a discrepancy between the speed of the vehicle and the design speed.

To resolve this issue we only need to use the expression in (5), with a proper phase centre matrix, $\boldsymbol{P}_\tau$, in the presence and the absence of coupling. For the sake of simplicity, let us again assume that the antenna elements are in-line with the vehicle's velocity vector. Clearly, the role of the embedded far-field patterns of the antennas is crucial in this paper. To see how, let us again choose the cases of two quarter-wavelength monopoles, and also two horizontal dipoles at $h = 0.10\lambda_\circ$ above an infinite PEC plane with $d = 0.55\lambda_\circ$ and $\lambda_\circ$. Fig. 3 shows the temporal cross-correlation versus the relative speed of the vehicle in the presence of coupling and after its removal using the open-circuit decoupling method [10].

It is clear from this simulation that for overspeeding exceeding 10–20% of the target speed, coupling compensation does not seem to be advantageous for the two selected antennas with the specified separations. We stress that these results are quite dependent on the element separation and the types of antennas used. Therefore, for an arbitrary antenna setup, one needs to use (5) and plug in a proper phase centre matrix corresponding to the desired speed to determine whether the coupling compensation is still useful or not.

5 Dependency of open-circuit decoupling method on *Z*-matrix

The open-circuit decoupling method (or short-circuit decoupling method) depends on the input impedance matrix (or input admittance matrix) for a voltage driven (or current driven) antennas, as well as the termination impedances (admittance) [7, 8, 10, 12, 18]. Therefore, the accuracy of the decoupling method is also a function of the accuracy of the corresponding input network matrices. To the best of our knowledge, this dependency has not been studied yet likely because a reliable metric for its study has been missing. Nevertheless, the temporal cross-correlation at a certain time delay which has been defined in the frame of the predictor antenna system on moving vehicles can play the role of a reliable criterion for the aforementioned accuracy study. In this section, we study the temporal cross-correlation at the different separation between the elements to find out how the open-circuit decoupling method depends on the errors which exist in the input impedance matrix.

For the sake of conciseness, we resort to one of the two former selected antennas, say monopoles. First of all, let us assume that the diagonal terminating impedance matrix, $\boldsymbol{Z}_r$, is presumably error free. The impedance matrices of these antennas, $\boldsymbol{Z}$, have four entries. Owing to symmetry within the structure and reciprocity, the impedance matrices are symmetric. Thus, the number of variables that exist in each matrix is two, say, z_{11} and z_{21} which both have independent real and imaginary components.

Our study reveals that the impact of variations in resistance and reactance of z_{11} and z_{22} are negligible. Thus, we only concentrate on the presence of an error in z_{12} or z_{21} on the temporal cross-correlation. For this specific example, to study the impact of errors in the mutual impedance, we use a normalised error for its non-zero resistive and reactive parts. In this respect, the relative resistive and reactive errors are, respectively, defined as

$$\delta_{r_{12}} = \frac{\delta}{\Re[z_{12}]} \quad \& \quad \delta_{x_{12}} = \frac{\delta'}{\Im[z_{12}]} \tag{7}$$

wherein δ and δ' are arbitrary added independent errors. Bear in mind that the temporal cross-correlation of unity indicates no error. The less the temporal cross-correlation with respect to unity, the more the impact of the error on the open-circuit decoupling method. The results of our study are shown in Fig. 4. In this figure, the contours of maximum temporal cross-correlation with respect to the relative error in resistive and reactive components of the mutual impedances are plotted. Note that this study is made for two different multipath environments: first, in a rich uniform multipath environment which is a common reference multipath environment in the literature [16], and second, in a double-exponential non-uniform multipath environment which is more compliant with measurement campaigns [17].

We observe that for the same element separations, the sensitivity of the open-circuit decoupling method with respect to the mutual impedance error is larger in uniform multipath environments compared with non-uniform environments. Although not shown, we also noted that half-wavelength horizontal dipoles above an infinite PEC are more sensitive to the mutual impedance error compared with quarter-wavelength monopoles above the PEC.

In general, the sensitivity of the maximum temporal cross-correlation in a predictor antenna system with respect to the relative mutual impedance error is not significant. This is in harmony with former studies on the measurement data as illustrated in Figs. 3 and 4 in [2]. Recall that this sensitivity is subject to our criterion or judgement metric. One could use an alternative parameter to describe this sensitivity. Nevertheless,

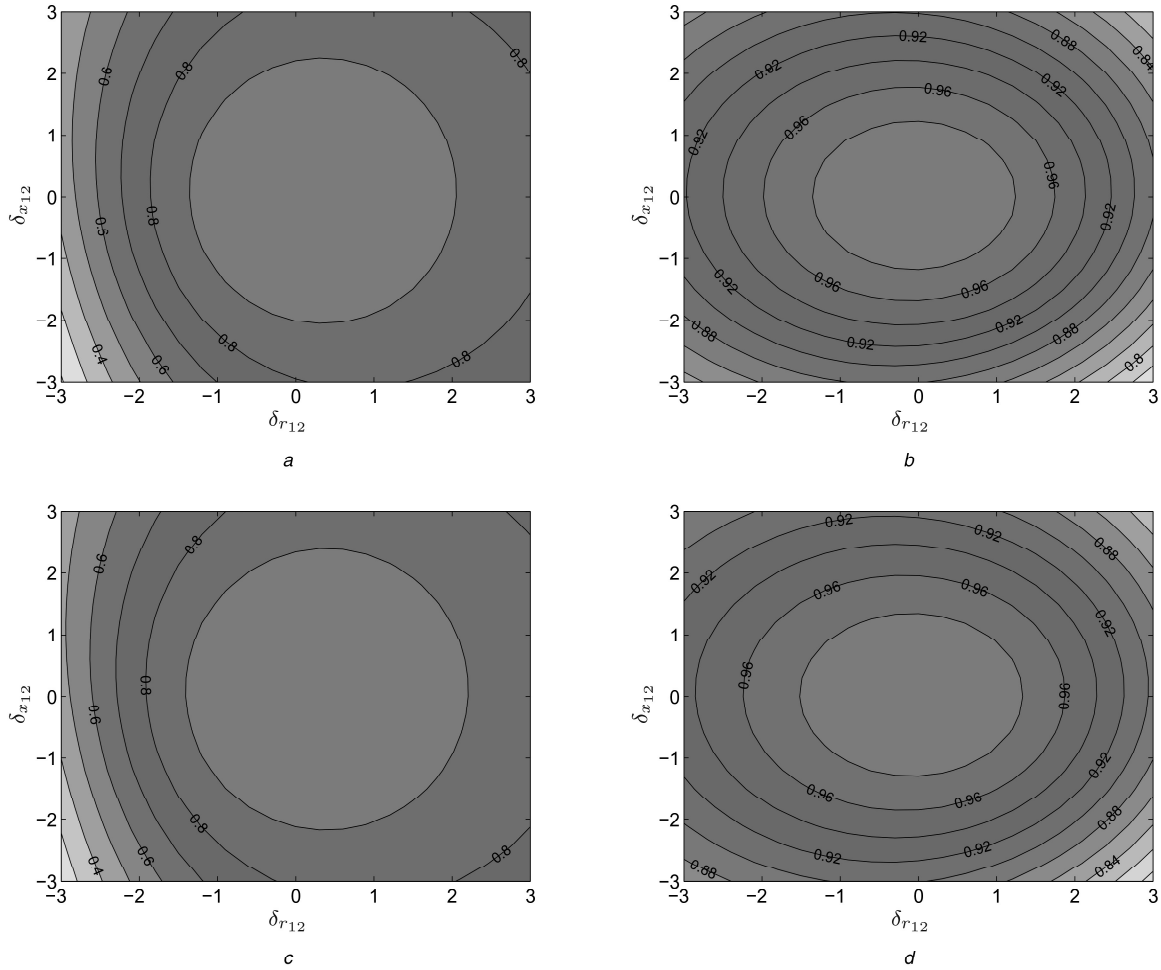

Fig. 4 *Contours of maximum temporal cross-correlation versus relative errors in resistive and reactive components of mutual impedances for two monopoles above an infinite PEC plane. For the non-uniform multipath case, we selected uniform distribution for the AoA in the azimuth plane and double-exponential distribution in the elevation plane with $\theta_m = 45°$, $\sigma^+ = 18°$ and $\sigma^- = 6°$*

when it comes to multipath environments, temporal cross-correlation (at the corresponding time delay) makes sense.

As a final point, the impact of overspeeding and underspeeding (i.e. misalignment of positions of the two antennas at the intended time delay) seems to be more critical than the application of the open-circuit decoupling method for the two investigated antenna cases. Note that all the foregoing points are solely credible for a rich multipath environment and may not be generalised to other applications in which the open-circuit decoupling method is used.

6 Conclusion

The main concern of this paper was the predictor antenna system in moving relays. We clarified that the pattern deformation in the presence of coupling reduces these systems' performances. We introduced a general formula whereby one can quantify the impact of different factors such as coupling, velocity, position misalignment etc. on prediction performance. For cases of quarter-wavelength monopoles on an infinite PEC plane and half-wavelength horizontal dipoles at 0.10 of the resonant wavelength above this ground plane, we quantified the reduction of performance due to coupling in terms of element separation. We showed that due to the adverse effect of coupling, the NMSE does not exceed 0.2 for the case of monopoles and 0.6 for the horizontal dipole case.

To avoid mechanical complexity in the implementation of the predictor antenna system, typically this system is designed for a certain target velocity [1]. However, a vehicle can barely hold onto a constant speed. Any variation in speed can potentially deteriorate the prediction performance. The effect of underspeeding can be alleviated by continuous sampling of the signal at the port of the predictor antenna and some extra processing in the digital domain. Nevertheless, this method does not help for cases of overspeeding. In the latter scenario, we further quantified the prediction performance reduction versus velocity. This paper also showed that decoupling is not generally useful for prediction reliability.

Finally, our simulations revealed that, when it comes to predictor antenna system, the impact of the accuracy of the self-impedances on the open-circuit decoupling method is negligible. Thus, we investigated the effect of relative error in resistive and reactive components of the mutual impedance on the accuracy of the open-circuit decoupling method. We observed that the impact of error in mutual impedance was relatively higher in uniform multipath environments. Moreover, though not shown, we also clarified that the open-circuit decoupling method for monopole antennas showed less sensitivity with respect to the relative mutual impedance error compared with horizontal dipoles at $h = 0.1\lambda_\infty$ above a PEC ground plane. In this paper, our metric for performance evaluation of a predictor antenna system and accuracy study of the open-circuit decoupling method was the temporal cross-correlation at the desired time delay. Be it of interest, this parameter can simply be mapped to the NMSE of time-varying complex orthogonal frequency-division multiplexing channel coefficients by virtue of [1, eq. 8]. Last but not least, despite the fact that the presented study was restricted to a two-port predictor antenna system, the formula introduced here holds for any array of an arbitrary number of radiation elements.

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