Use of weather radar data for site diversity predictions and impact of rain field advection

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Abstract—This paper presents the analysis performed on two weather radar datasets, collected at Spino d’Adda (Italy) and Bordeaux (France), for the simulation and the performance evaluation of a site diversity system. Results from the two locations are compared and the impact of different factors such as baseline and link orientation is assessed and related to the local climatologic and topographic characteristics. A link is then established between the preferable baseline orientation and the predominant direction of the rain field advection. The rain field displacement is finally shown to be well approximated by the wind speed and direction at the 700 hPa pressure level extracted from the ECMWF ERA-40 meteorological database.

Keywords—Fade Mitigation Techniques (FMT), Rain attenuation, Site diversity system.

I. INTRODUCTION

The evolution of telecommunication systems is always pushing towards the use of higher transmission frequencies. As widely known, telecommunication systems operating at Ka, Q and V bands are strongly affected by attenuation phenomena due to atmospheric impairments [1]. Still, they are expected to provide real-time multimedia services, and consequently, to be reliable and guarantee the desired system availability. In this environment, strong signal fades can no longer be overcome making use of static power margins, but require the application of Fade Mitigation Techniques (FMTs) as a viable solution [2]. To this end, telecommunication systems based on site diversity can be envisaged [3]: in fact, the use of multiple receiving (and/or transmitting) stations located at a given distance permits to take advantage of the spatial variability of rain, so that a distance of the order of tens of kilometers strongly reduce the probability that both stations are undergoing an outage. The design of a site diversity system, however, requires the evaluation of the advantages (for example in terms of outage probability) deriving from the implementation of such a countermeasure to signal fades. For that purpose, weather radar data, where available, are the most suitable source of information, as they inherently reflect the influence of the local climatologic and topography on the rain field spatial distribution, which, on turn, determines the effectiveness of a site diversity solution.

This paper presents the analysis performed on two weather radar datasets, collected at Spino d’Adda (Italy) and Bordeaux (France), for the simulation and the performance evaluation of a site diversity system. After a brief description of the two radar databanks, the site diversity gain is assessed for the two locations and, afterwards, the impact of different factors such as link and baseline orientation is investigated. Moreover, as expected, the study clearly shows the dependence of the system performance on the type of rain event (stratiform or convective) affecting the stations. Afterwards, the local climatologic and topographic features, specifically, the predominant direction of the rain field advection, are linked to the trends observed for different baselines orientation. To this end, a comparative analysis is made between the rain advection speed and direction and the wind outputs extracted from the ERA-40 ECMWF (European Center for Medium-range Weather Forecast) database. As a result, a methodology to derive the local rain predominant advection direction from the ERA-40 is proposed.

II. THE WEATHER RADAR DATASETS

The two radar datasets utilized in this study have been collected in two temperate sites, namely Spino d’Adda, Italy (45.4° N, 9.5° E) and Bordeaux (44.5° N, -0.34° E). They have the following characteristics:

- **Spino d’Adda**: approximately 15000 CAPPI radar images, extracted from rain events (in the period from 1988 to 1992) which have proven to be fully representative of the local yearly rainfall statistics. The maximum operational range of the radar considered in this study is 40 km in order to avoid the inclusion of clutter pixels due to the surrounding mountains. The spatial resolution is 0.5 × 0.5 km² and the interval between consecutive images is 77 seconds.

- **Bordeaux**: approximately 30000 CAPPI radar images, extracted from one year (1996) of continuous operation (also non-rainy images have been recorded). The maximum operational range of the radar is 100 km, the spatial resolution is 1 × 1 km² and the interval between consecutive images is 5 minutes.

Despite some differences between the two radar datasets (period of data acquisition, number of images at disposal, spatial and temporal resolution), the work presented in this paper suggests that they permit to derive fully comparable results, obviously as long as the same image dimension is considered. To this aim, a circular area with a 40-km radius has been selected in the South-Western portion of each original Bordeaux radar scan, as it is a flat zone, over which reliable data, seldom affected by clutter and by anomalous propagation effects, are obtained.
III. SIMULATION OF SITE DIVERSITY SYSTEMS USING RADAR IMAGES

The radar derived rainfall images have been used for the simulation of an Earth-satellite site diversity system with tunable characteristics. Both in Spino d’Adda and Bordeaux, the rainfall snapshots have been converted into maps of attenuation experienced by a radio link pointing to a geostationary satellite, under a fixed yearly mean rain height \( H_r \), derived from the ITU-R Rec. P.839-3 [4]. The path attenuation \( A \) has been calculated through the numerically integration of:

\[
A = \int k R(l)^\alpha dl \quad [\text{dB}]
\]

where \( L = H_r / \sin(\theta) \) is the path length affected by rain, \( \theta \) is the link elevation, \( k \) and \( \alpha \) provided by the ITU-R Rec. P.838-3 [5], are rain-to-attenuation conversion coefficients that depend on the link elevation and on the radiowave frequency and polarization (always vertical in this work). Obviously, \( R(l) \), indicating the rain intensity value at position \( l \) impairing the transmission link, is strongly dependent on the local precipitation characteristics and therefore is expected to be tightly bound to the system performance. In this work, all attenuation maps have been calculated at the reference frequency of 30 GHz, though results could be easily extended to different frequencies and link geometries with a little effort.

The gain \( G \) offered by a two-site diversity system, with separation \( D \) between the stations, has been calculated as:

\[
G(D, A_i) = A_i(P) - A_i(D, P) \quad [\text{dB}]
\]

where \( A_i \) and \( A_s \) are the attenuation values of the cumulative distribution functions (CDFs) (both for the same probability level \( P \)), respectively relative to a single station and to a two-site diversity system (depending on \( D \)), for which the minimum attenuation value is always selected (see Figure 1). The calculation of \( G \) has been performed according to the following options:

- reference attenuation level \( A_i \): from 4 to 32 dB with a 4-dB step, so that the minimum percentage level of the single-site CDF is approximately \( 10^{-1} \% \);
- distance \( D \) between the receiving stations: from 4 to 56 km in 4-km step;
- link orientation \( \phi \), defined as in Figure 2: -20° (towards the East), 0° (coinciding with the South) and 20° (towards the West).

Each value of \( \phi \) corresponds to a rain-to-attenuation conversion procedure, as different rain rates \( R(l) \) affect the link. For a geostationary satellite, the link elevation \( \theta \) is univocally defined by \( \phi \):

- baseline orientations, defined as in Figure 3: horizontal (H), vertical (V) and 45° (HV) with respect to the horizontal direction;
- type of rain event: stratiform or convective.

Considering all maps, the single-site CDF has been calculated starting from the attenuation value relative to the reference pixel (blue link in Figure 3), whereas the two-site joint attenuation CDF (for given \( D, \theta, \phi \)) has been obtained from the minimum attenuation value between the one experienced by the reference pixel and the one relative to the associated site diversity link. In order to improve the statistic robustness of the analysis and to prevent results from being dependent only on the climatologic and/or topographic peculiarities of specific areas, attenuation CDFs consist of all the values obtained by moving the stations pattern depicted in Figure 3 across the whole map.

A. Gain dependence on the link orientation

In this section, the dependence of the system performance on the link orientation is analyzed. Table I lists the link characteristics as a function of \( \phi \), for both sites. Figure 4 shows the site diversity gain comparison in Spino d’Adda, for the three selected values of \( \phi \): -20°, 0°, 20°. In this case, the baseline orientation is horizontal, but very similar results (omitted here for brevity) have been obtained also for baselines V and HV (the same applies to Bordeaux): in all cases, the dependence of the system gain on the
link orientation is clearly negligible. Such conclusion is a positive one, if a real system is concerned: in fact, the link orientation usually is not a design parameter, as it obviously depends on the relative position between the satellite and the receiving stations (e.g., broadcasting systems). Thus, a system designer could disregard the impact of \( \phi \) in estimating the system performance through prediction methods.

<table>
<thead>
<tr>
<th>( \phi ) [°]</th>
<th>( \theta ) [°]</th>
<th>( H ) [km]</th>
<th>( L ) [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spino</td>
<td>Bordeaux</td>
<td>Spino</td>
<td>Bordeaux</td>
</tr>
<tr>
<td>-20</td>
<td>34.6</td>
<td>33.5</td>
<td>2.86</td>
</tr>
<tr>
<td>0</td>
<td>38.7</td>
<td>37.7</td>
<td>2.86</td>
</tr>
<tr>
<td>20</td>
<td>34.6</td>
<td>33.5</td>
<td>2.86</td>
</tr>
</tbody>
</table>

Table I. Elevation angles and rain heights relative to the considered links in Spino d’Adda and Bordeaux.

Figure 4. Spino d’Adda, site diversity gain comparison for different link orientations: -20° (solid lines), 0° (dashed lines with circles), 20° (dashed lines with crosses). The baseline orientation is horizontal.

\( B. \) Gain dependence on the baseline orientation

If the dependence of \( G \) on \( \phi \) is negligible (therefore, hereinafter, \( \phi \) will always be set to \( 0° \)), the opposite is true if the baseline orientation is considered.

Figure 5 and Figure 6 depict the comparison of the system gain, respectively for Spino d’Adda and Bordeaux, both for \( H \) (solid lines) and \( V \) (dashed lines with circles) baseline orientations. The gain results relative to the HV baseline orientation have been omitted as they are less interesting: in both cases, they are comprised between the ones relative to the horizontal and the vertical baselines. Figure 5 and Figure 6 clearly point out how the choice of the system baseline may affect the achievable system gain. Specifically results show that for Bordeaux, a horizontal baseline between the stations would improve \( G \), whereas the opposite is true for Spino d’Adda, where a vertical baseline would assure a better performance. It is worth noting that for \( D = 4 \) km, in both cases, a horizontal baseline provides a higher gain: in fact, making reference to the geometry in Figure 3, when the links point towards the South, the correlation between the associated attenuation values is higher (and therefore, the gain is obviously lower) when a vertical baseline geometry is applied. For higher values of \( D \), this explanation no longer holds as attenuation values get uncorrelated after some tens of kilometers. The local preferable baseline orientation can be roughly linked to the prevalent elongation direction of the rain field. In fact, a visual inspection of radar data suggests that, most of the time, rain structures tend to stretch orthogonally to the rain field advection direction. More details about this effect will be given in section IV, which also suggests how to derive the preferential direction of the rain field advection from the ERA-40 database.

C. Gain dependence on the rain event type

With the aim of assessing the impact of the rain event type on the system performance, in both sites, rain events have been classified as stratiform or convective if belonging respectively to “colder” (from November to April) or to “warmer” (from May to October) months. Although this is quite a rough selection criterion, nevertheless, in temperate zones, it can provide at least a first approximated discrimination between weak and widespread rain phenomena and intense and spatially limited precipitations. If stratiform single-site rain attenuation CDFs are considered, obviously strong fades tend to be less probable. For this reason, in order to deal with reliable statistics, in this section, the reference attenuation \( A_i \) ranges from 4 to 14 dB using a 2-dB step.

Results are reported in Figure 7 (Spino d’Adda) and Figure 8 (Bordeaux), where solid and dashed lines depict \( G \) relative to stratiform and convective events, respectively. As expected, the system performance increases when convective rain events affect the stations: in fact, convective phenomena are characterized by intense rain rate values but cover limited areas. Obviously, both these characteristics concur to reduce the spatial correlation of rain...
(and of the associated attenuation). As a consequence, the site diversity gain obtained during convective events shows a steep increase especially within the first 15 km, while the one relative to stratiform events definitely increases more gradually with distance. Bordeaux, probably linked to the proximity of the Atlantic ocean and to its influence on the rain structures. The higher convectivity seems to be confirmed also by Figure 9, where the radar-derived rainfall rate CDF relative to Bordeaux denotes a higher convective contribution (i.e. more probable intense rain rate values) if compared to the Spino d’Adda CDF.

D. Comparison between the two sites

In this section, the system performance calculated for Spino d’Adda and Bordeaux is compared. However, since $G$ depends on the chosen baseline, as pointed out in section B, results relative to the H, V and HV orientations have been average and are compared in Figure 10. The higher gain values in Bordeaux seem to confirm the strongest convectivity of that site, as already mentioned in the previous section. However, it is worth noting that, despite the reduced temporal (5 min) and spatial (1×1 km$^2$) resolution of the Bordeaux dataset, such radar scans are clearly suitable for site diversity simulations, as they provide results that are fully comparable with those obtained from a dataset with a finer temporal (77 sec) and spatial (0.5×0.5 km$^2$) resolution.

IV. COMPARISON OF RAIN FIELD ADECTION AND ERA-40 WIND OUTPUTS

As underlined in section B, the diversity gain in a given location exhibits significant changes for different baseline orientations and results in both sites suggest that a link can be established between the rain front orientation and the predominant rain advection direction. Indeed, most of the rain structures appear to elongate orthogonally to their motion direction. Consequently, the knowledge of the prevailing advection direction could help the choice of the system optimum baseline orientation. To this aim, in this section, the rain advection speed and direction derived from radar data are compared with the ERA-40 wind data. Specifically, the rain advection is shown to be tightly correlated to the wind relative to the ERA-40 700 hPa isobar. This study can furthermore provide inputs for the parameterization of the rain advection in space-time channel model such as those proposed in [6] and [7].

A. The ERA-40 reanalysis datasets

The ERA-40 data considered in this study are the wind values, relative to different isobars, provided on a latitude-longitude regular
grid of $2.5^\circ \times 2.5^\circ$. The period of radar data acquisition is concurrent with the one of the ERA-40 reanalysis database, so that a comparison of the rain advection estimated from both sources is possible.

Figure 11. Position of the observation area and of the cells of the reanalysis model

Data of vertical (North to South) and horizontal (West to East) winds for the following pressure levels have been considered in this study: 850, 775, 700, 600, 500 hPa, corresponding roughly to heights between 1.5 and 5.5 km. These heights correspond to reasonable mid-height values of rain cells typical of temperate climates.

As illustrated in Figure 12, the wind direction in Bordeaux, that lies in the proximity of the ocean and whose area is not characterized by a significant orography, is mainly eastward. On the contrary, in Spino d’Adda, air fluxes from the North are blocked by the Alps and consequently most of the time, air streams flow from West or South.

Figure 12. Distribution of the wind direction at 775hPa computed from one year of ERA-40 data for Spino d’Adda and Bordeaux

B. Determination of rain advection from radar data

The rain advection direction and speed has been determined from successive radar scans at time steps $t$ and $t+\Delta t$. It was implicitly assumed that the rain advection has a single direction and magnitude on the whole radar coverage. Let $R(x,y,t)$ be the rain field at a given time step $t$ on the radar coverage. The advection is considered to be the vector $(x_a, y_a)/\Delta t$ such that $R(x-x_a, y-y_a, t+\Delta t)$ and $R(x, y, t)$ show the maximum cross correlation $\rho$. According to this procedure, the structural evolution of the rain fields is obviously disregarded and only its advection is taken into account. Specifically, $\rho$ is computed for all the $x_a$ and $y_a$ couples that correspond to plausible displacements of the rain fields, i.e. by assuming a maximum motion velocity of 150 km/h.

An example of the cross correlation between two consecutive rain maps of Bordeaux is shown in Figure 13. The peak of $\rho$ plotted in Figure 13 was found for $y_a = 5$ km (North to South) and for $x_a = 4$ km (West to East). This displacement is thus considered to be the advection for that 5 min interval. The algorithm performs accurately if the correlation peak is higher than 0.7. This condition implies that the time interval between the two radar observations is short because the evolution of the rain field degrades the peak value of $\rho$. Empirically, with a spatial resolution of 1 km, a time interval of 10 min between consecutive images was found to be the upper bound guaranteeing a reliable estimation of the advection. Moreover, in order to get a sufficiently robust estimation of $\rho$, the fraction of the observation area affected by rain has to be significant. For this reason, radar observations for which the rainy area is smaller than 2% of the whole radar coverage have been discarded. The time step between two successive images used to compute the advection was of 5 min for Bordeaux and of 3.5 min for Spino d’Adda (one every three maps).

Figure 13. Cross correlation for different displacement between two consecutive rain maps of Bordeaux. The maximum correlation corresponds to the most plausible advection between the two images.

C. Comparison of radar derived wind speed and direction and ERA-40 wind outputs

In order to compare the rain advection speed and direction retrieved from radar data with the ERA-40 winds outputs, the following methodology has been applied. Concerning ERA-40 data, the wind speed and direction for both locations have been derived by bilinear interpolation of the values relative to the four closest ERA-40 pixels, as indicated in Figure 11. Afterwards, the radar derived rain advection speeds and directions have been averaged for each 6-hour period, corresponding to the time resolution of ERA-40 data. Considering the averaging operation and the constraints proposed in the previous section for the calculation of the rain field advection, 160 and 64 samples are respectively obtained for Bordeaux and Spino d’Adda.
correlation between the rain advection derived from radar datasets and from ERA-40 wind data at several pressure levels is listed in Table II both for Bordeaux and Spino.

**Table II. Correlation between the Rain Advection Derived from Radar Data and from ERA-40 Wind Outputs for Bordeaux and Spino d’Adda**

<table>
<thead>
<tr>
<th>Pressure level (hPa)</th>
<th>Direction</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bordeaux</td>
<td>Spino d’Adda</td>
</tr>
<tr>
<td>850</td>
<td>0.66</td>
<td>0.71</td>
</tr>
<tr>
<td>775</td>
<td>0.82</td>
<td>0.83</td>
</tr>
<tr>
<td>700</td>
<td>0.90</td>
<td>0.83</td>
</tr>
<tr>
<td>600</td>
<td>0.84</td>
<td>0.77</td>
</tr>
<tr>
<td>500</td>
<td>0.82</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Among all the levels in Table II, the 700 hPa isobar presents the highest overall correlation. Lower levels (850 hPa, 775 hPa) underestimate the rain advection speed, as well as higher layers tend to overestimate it. Moreover, the direction estimation is perturbed at lowest levels by the proximity to the ground.

As an example, the sample by sample comparison between the rain advection speed and ERA-40 wind speed at 700 hPa is shown in Figure 14 both for Bordeaux (blue asterisks) and Spino d’Adda (red circles). The agreement between radar derived advection and ERA-40 wind outputs is slightly poorer for Spino d’Adda (the same happens for the wind direction). This trend may be explained by the large impact of the mountainous area surrounding Spino (see Figure 11) that probably leads to a less reliable estimation of wind flows provided by the reanalysis model. In fact, the mean height associated to the four ERA-40 cells surrounding Spino d’Adda is over 1000 m a.m.s.l. whereas the site lies only at 81 m a.m.s.l.

As a result, this study shows that the rain field advection can be approximated by the ERA-40 wind outputs relative to the 700 hPa isobar with a relatively high confidence. On turn, the knowledge of the local predominant rain field advection direction, retrievable from this worldwide available database, can provide a useful indication for the choice of the optimum baseline orientation in the design of site diversity systems.

**V. Conclusions**

In this work, weather radar data collected at two sites have been used to evaluate the performance of Earth-satellite site diversity systems with different link and baseline orientations. Results have shown a negligible dependence of the system performance on the link orientation, whereas, on the contrary, the system gain has proven to be tightly linked to the choice of the baseline direction. This is due to the overall anisotropy of rain structures which generally tend to elongate perpendicularly to the prevalent direction of the wind in the site. Therefore, a baseline orientation parallel to the prevailing wind direction (i.e. from North to South for Spino d’Adda and from West to East for Bordeaux) has shown to maximize the system gain. ERA-40 wind data relative to the 700 hPa isobar have proven to be the most correlated with the rain advection direction and can therefore provide a useful indication for the choice of the optimum baseline orientation in the design of site diversity systems. As a further result of this study, a rough classification of rain events into stratiform and convective according to “colder” and “warmer” months has allowed to point out a strong dependence of the system performance on the type of precipitation, due to the different spatial correlation characteristics associated to stratiform and convective phenomena.

As a general conclusion, the analysis has shown that, despite the reduced temporal (5 minutes) and spatial (1×1 km²) resolution of the Bordeaux dataset, those radar scans have proven to be adequate for site diversity simulations, as they provide results that are fully comparable with those obtained from a dataset with a finer temporal (77 seconds) and spatial (0.5×0.5 km²) resolution. Specifically, this study underlines the usefulness of radar data for the simulation and the performance evaluation of a site diversity system, as they reflect the local climatologic and topographic characteristics, which, on turn, may reveal some properties on the diversity gain that are hardly caught by analytical estimation models.

**Acknowledgment**

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**References**


