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Wideband outdoor MIMO channel model derived from directional channel measurements at 2 GHz

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***Abstract*— This paper describes the use of directional channel measurements to derive a MIMO channel model. The measurements were obtained using a wideband channel sounder and eight element circular array in a metropolitan area in central Bristol, U.K. The raw measurements were processed using SAGE to extract the parameters of multipath components. The analysis of these parameters revealed several interesting features, notably that their amplitude distribution was well modelled as log-normal, and that there was little evidence of clustering in the angles of arrival. Hence a MIMO channel based on the assumption of finite scattering was derived, using the distributions obtained. The model allows the channel matrix H to be derived in the narrow-band case, and a tapped delay line model is also obtained for wideband systems. While the model derived is based on only a small set of measurements, it provides a case study for MIMO modelling based on measurements.**

***Keywords*— MIMO channel modelling, directional channel measurements, clusters**

I. INTRODUCTION

It is by now well known that the independent Rayleigh model of the MIMO wireless channel is inadequate under many circumstances, and may yield unduly optimistic results for the capacity of MIMO systems in a number of scenarios. To obtain more accurate estimates requires models that can account for the correlation of fading between the antenna pairs of a MIMO channel. Two categories of such model have been developed recently: *non-physical models*, such as the Kronecker model [1] which directly model the correlation of the MIMO channel matrix **H**, and *physical models*, which account either deterministically or statistically for the individual multipath signals, such as the *geometry-based directional model* [2]. The latter can also be described as *double-directional channel models*, since they include both directions of departure at the transmitter and directions of arrival at the receiver. Such models are in principle independent of the transmit and receive antenna arrays, although given antenna array characteristics and topologies they can be used to calculate channel matrices, as we will see below.

These channel models may be based on ray-tracing, but such models are computationally complex to evaluate and require accurate databases of the environment. Alternatively they may be based upon plausible models of the statistics of the multipath. Ultimately, however, such models can only be informed and validated by measurements of the double-directional channel. This paper describes the use of a set of measurements to derive a double-directional channel model for an outdoor urban environment. It is based on only one set of measurements in only one locality, so its general applicability must be viewed with caution. However, it can be regarded as a case study in the use of measurements to derive a channel. In addition the analysis of the measurements shows some interesting features which are worth pointing out.

In the next section we describe very briefly the measurement campaign upon which the measurements are based. It should be noted that these are in fact single-directional measurements: only the direction of arrival is measured. In section 3 we analyse the statistics of the parameters of the multipath components, using plausible assumptions to extrapolate from the single-directional measurements to double-directional parameters. Finally in section 4 we use the resulting statistics to propose a set of simple channel models.

II. MEASUREMENT CAMPAIGN

The field trials were carried out in the city centre of Bristol, an area with dense urban clutter. Figure 1 shows a map of the area. The transmitting antennas were provided by a pair of UMTS panel antennas, set-up on a roof top of a five storey building (height ≈ 30m). The receiving antenna array, consisting of an 8-element uniform circular array with approximately half-wavelength inter-element spacing, was vehicular mounted. The transmitting antennas were well above the mean roof-top level of the local clutter. Hence the measurement set-up was representative of an urban small cell. The Medav RUSK BRI channel sounder [3] was used, allowing time delay of arrival to be accurately measured for each multpath component.

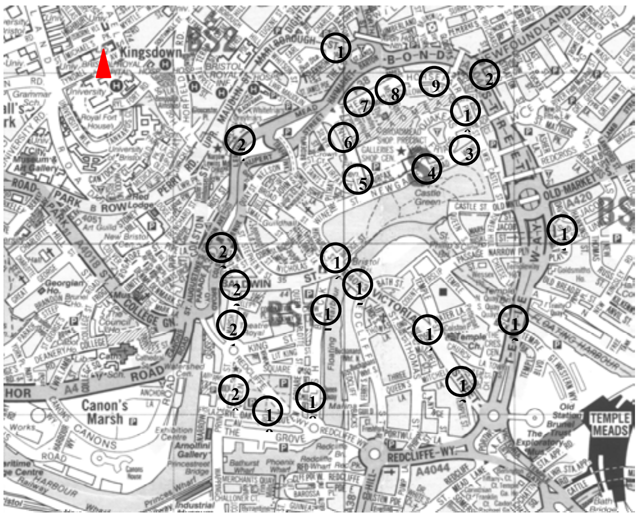


Figure 1 Map of measurement locations (circles) and transmitter location (red arrow)

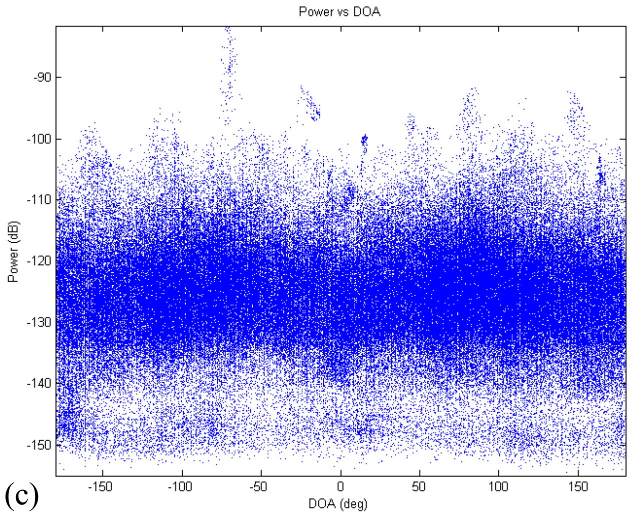
The measurements in each data block were analysed using SAGE [4] to determine directions of arrival and time delays of arrival for each identifiable multipath component (hereafter simply *multipath*). A maximum of 40 components was identified in each block.

The measurements were taken for 20s duration, while the vehicle was moving. 24 such measurement drives were carried out in and around Bristol city centre. These measurement drives include slow movements (8-16 kph) due to traffic congestion and fast drives (40-50 kph) along clearer roads. Within each measurement, 246 data blocks were collected. Each of these data blocks contains 8 back to back SIMO snapshots (instantaneous channel responses), which were accumulated well within the channel coherence time. At the start of each measurement, a GPS (Global Positioning System) reading was taken, to accurately identify the time and position of the measurements. The positions of all 24 measurements are shown in Figure 1

III. Analysis of Measurements

The raw data consisted of a list of multipaths identified by the channel sounder at each location, giving their direction of arrival (DoA), time of arrival (ToA), and amplitude. A further variable was the number of multipaths detected in a given location. The measurements were analysed to estimate the joint statistics of the three parameters of each multipath. Average statistics were obtained over all the measurement locations. Unfortunately space does not allow the full set of plots resulting from this analysis to be included in this paper.

First the correlation of the parameters was evaluated by plotting scatter diagrams of each of the three pairs of parameters (see



(c)

Figure 7, at the end of the paper). These show no significant correlation between any of the variables: there is a slight reduction in mean power with increasing time of arrival, but this is not likely to have a significant effect. This independence of the parameters allows us to determine the distributions of the parameters separately.

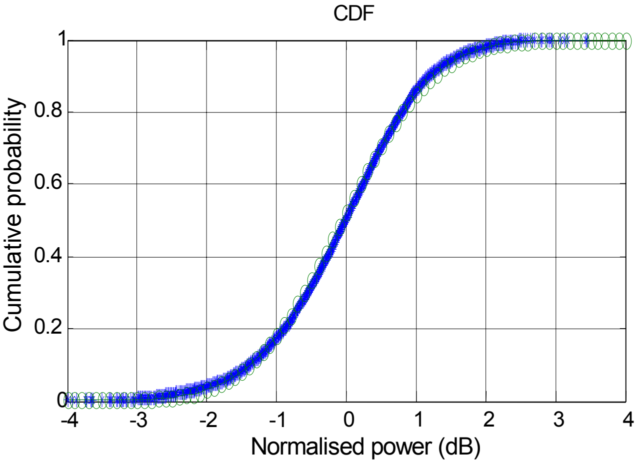


Figure 2 Cumulative distribution function of path amplitudes ('+') compared to log-normal distribution ('o') with standard deviation 1.03 dB, both in dB.

Figure 2 shows the cumulative distribution function (CDF) of the multipath amplitudes. In this analysis the effect of path loss at each location, estimated by averaging the total power in all multipaths, has been removed. The result is compared with a log-normal distribution. It shows a very good match to this distribution, with standard deviation 1 dB, contrary to the usual model of multipath amplitudes, which is Rayleigh. The difference here may be that the very good time resolution of the channel sounder is able to separate individual multipaths, whereas the commonly-used Rayleigh model assumes that a large number of multipaths will arrive in the same angular or time-delay bin, resulting in a Rayleigh amplitude distribution according to the Central Limit Theorem. The log-normal distribution can be explained by supposing that each multipath has been subject to a number of random attenuations (primarily reflection or scattering losses), which add this time in the logarithmic domain to give a Gaussian distribution of attenuation in dB.

The distribution of the time delay is shown in Figure 3, demonstrating a good match to an exponential distribution with time constant 585 ns. The distribution of direction of arrival using the arbitrary reference direction of the raw measurements is not surprisingly uniform, since the directions are averaged over a large number of locations in which the reference direction is unlikely to bear any fixed relation to the immediate environment. To attempt to find some structure a histogram (Figure 4) was plotted referenced to the direction of arrival of the strongest multipath

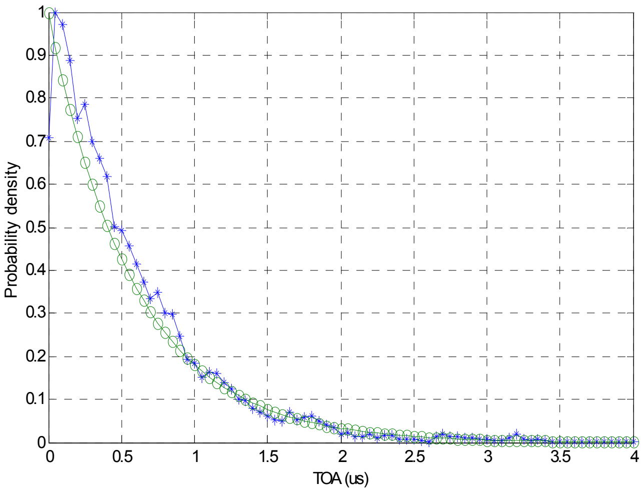


Figure 3 Histogram of time delay of components, matched to exponential decay with time constant 585 ns

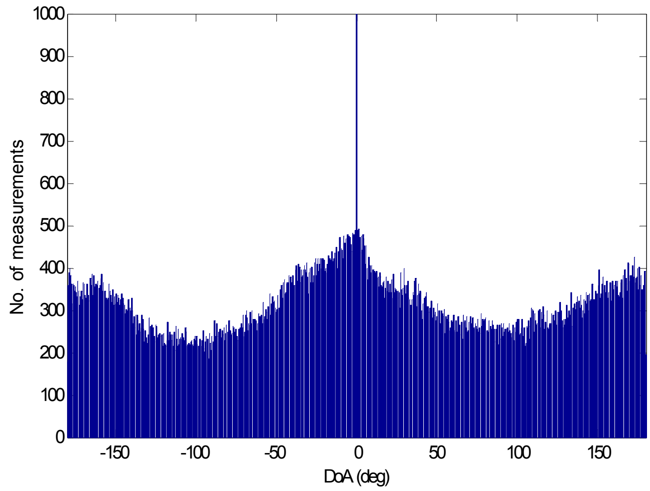


Figure 4 Histogram of DoAs, referenced to arrival of strongest multipath

This of course includes a peak at a DoA of zero, since each data block contains one multipath from this direction. Apart from that, we observe an increased density (by a factor approaching 2) of arrivals from this direction and diametrically opposite to it. This might be understood for an urban street canyon environment where most paths might travel in the direction of the street.

It has often been hypothesised that multipaths tend to arrive in clusters, corresponding to individual scattering objects. The histogram of DoAs given in Figure 4 would, however, conceal any clustering, since it shows an average taken over many locations. To investigate any clustering the distribution of inter-arrival angles has been investigated. If the arrivals were random, uncorrelated and uniformly distributed around 2π, then the arrivals in the angular domain can be treated as a Poisson process. This would imply that the distribution of the angles between adjacent components would be exponential. Figure 5 shows the CDF of the measurements, compared to two models, corresponding to clustering and no clustering respectively.

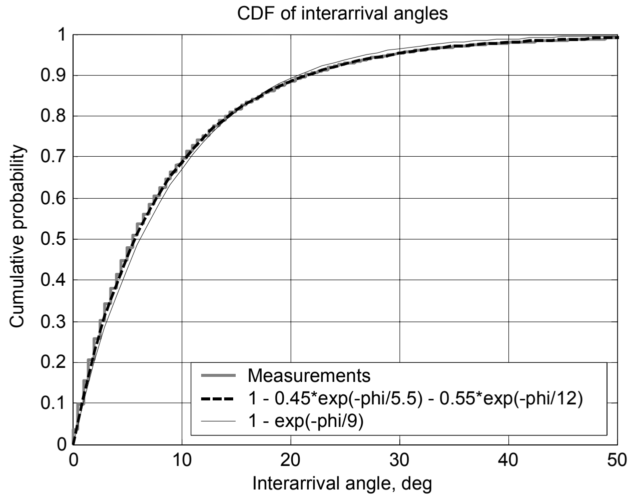


Figure 5 CDF of interarrival angles, compared clustered and non-clustered model

This analysis shows that the CDF of inter-arrival angles is in fact well matched to the sum of two exponentials, given by $P(\phi) = 1 - 0.45\exp(-\phi/0.096) - 0.55\exp(-\phi/0.21)$, where ϕ is expressed in radians: the decay constants correspond to 5.5° and 12°. However this matches reasonably well to the arrival densities expected in the denser and less dense regions of the histogram of Figure 4: there is no need to invoke any further clustering. We conclude that there is no evidence of clustering (other that that expected in any random distribution) in these measurements.

A histogram of the number of multipaths in each location has also been obtained, but it is artificially truncated at 40 components, as this is the maximum the equipment can resolve. The histogram in fact only shows that 80% of locations have at least 40 multipaths. Measurements with better resolution (for example with a larger receive array) would be required to estimate the distribution more accurately.

In the models based on these measurements we have assumed that all locations have 40 multipaths, since this is the number on which the measured statistics are based. For simplicity we have also neglected the variation in angular density of arrival shown in Figure 4. Because the measurements are single directional we have been obliged to make assumptions about the relationship between the angle of arrival and angle of departure of the same multipath. Here we assume they are uncorrelated, which seems plausible in an urban environment, in which each multipath is likely to be subject to a large number of reflections. We then use statistics on direction of arrival and on direction of departure gathered separately.

IV. CHANNEL MODELS

Using these measurements and the assumptions mentioned above we have devised channel models for the urban microcellular channel, the urban macrocell, and the suburban macrocell. The former uses the statistics described here for both ends of the link, assuming that both receiver and transmitter are low compared to the clutter.

The other two models draw on measurements made in a related campaign [5], and will not be described here in any detail. It will suffice to say that in the two macrocell models the directions of departure from the base station are assumed to follow a Laplacian distribution [6], with angular spreads of 0.22 and 0.1 radians respectively, and that in the suburban model the standard deviation of the log-normal distribution of amplitudes is 3 dB, and the number of multipaths is 8.

These modelling assumptions may be used to derive a random set of DoDs, $\phi_{T,p}$, DoAs, $\phi_{R,p}$, complex path amplitudes ξ_p, and ToAs τ_p, $p = 1..n_S$, according to the distributions described above, where n_S is the number of multipaths. We will define the receive and transmit antenna arrays in terms of a pair of vectors giving x and y coordinates for each element, in the horizontal plane. (Note that this amounts to an assumption either that the elements all lie in the same horizontal plane, or that the multipaths are all horizontal. In most outdoor environments the latter is usually a good approximation). Then the steering vector at the receiver corresponding to the p^{th} multipath (that is, the received vector for a unit amplitude signal from the corresponding DoA) is:

$$\boldsymbol{\psi}_{R,p} = \exp\left(\frac{2\pi j}{\lambda}\left(\mathbf{x}\sin\left(\phi_{R,p}\right) - \mathbf{y}\cos\left(\phi_{R,p}\right)\right)\right) \qquad (1)$$

and similarly for the steering vector at the transmitter. λ here is the wavelength. Then the channel matrix $\mathbf{H}$ can be constructed as:

$$\mathbf{H} = \boldsymbol{\Psi}_R \boldsymbol{\Xi} \boldsymbol{\Psi}_T^{\mathbf{T}} \qquad (2)$$

where $\boldsymbol{\Psi}_R$ and $\boldsymbol{\Psi}_T$ are matrices whose columns are the steering vectors $\boldsymbol{\psi}_{R,p}$ and $\boldsymbol{\psi}_{T,p}$, while $\boldsymbol{\Xi}$ is a diagonal matrix with diagonal elements ξ_p, $p = 1..n_S$. $^{\mathbf{T}}$ denotes the transpose of a matrix.

To create a wideband model, which takes account of delay, we require a tapped delay line channel model. It can be shown [7] that a channel of bandwidth W can be modelled by a tapped delay line with tap spacing $T = 1/W$, where the taps are given by:

$$\left\{H_{ikl}, i = 1\ldots n_R, k = 1\ldots n_T\right\} \qquad (3)$$
$$= \mathbf{H}_l = \sum_{p=1}^{n_S} \boldsymbol{\psi}_{R,p}\, \xi_p \frac{\sin\left(\pi\left(\tau_p - lT\right)\right)}{\pi\left(\tau_p - lT\right)} \boldsymbol{\psi}_{T,p}^{\mathbf{T}}$$
$$= \boldsymbol{\Psi}_R\left(\boldsymbol{\Xi} \bullet \mathbf{T}\right)\boldsymbol{\Psi}_T^{\mathbf{T}}, \quad l = -\infty,\ldots 0,1,2\ldots\infty$$

where $\mathbf{T}$ is a diagonal matrix whose diagonal elements are $\sin\left(\pi\left(\tau_p - lT\right)\right)/\pi\left(\tau_p - lT\right)$, and $\bullet$ denotes element-by-element multiplication of matrices. This defines a three dimensional array for $\mathbf{H}$ in which the third dimension is the tap delay, in multiples of T. Note that in principle the taps extend to infinity in both directions. In practice of course they are negligible except within a finite region around zero. However some taps with $i < 0$ will need to be retained: they form the precursors of the impulse response.

Figure 6 illustrates this process for a SISO channel, although it generalises readily to the MIMO case. (a) shows the impulse response of a channel with delay spread 300 ns, while (b) shows the taps as calculated in (3), assuming bandwidth 7.68 MHz. We note that there are a large number of non-zero terms extending to both negative and positive tap numbers. Note, however, that this assumes that the channel has a "brick wall" rectangular frequency response. To simulate a real system we muct take into account the response of the filters, which can be done by applying a digital filter to the channel taps. (In the MIMO case this can be applied to the entire three dimensional matrix $\mathbf{H}$, running along the time direction). (c) shows the result after filtering with a raised cosine filter of roll-off factor 30% and re-sampling at 3.84 Msamples/s, thus modelling a 5 MHz bandwidth UMTS system operating at 3.84 Mchip/s. We now have a reasonable number of chip-spaced channel taps, including a few precursor taps.

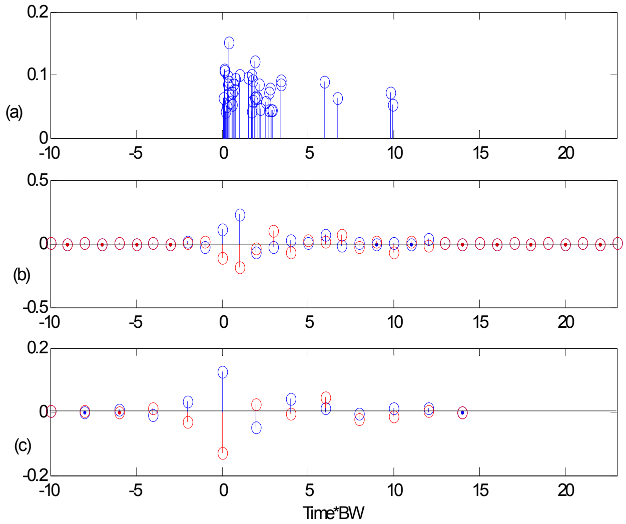


Figure 6 Use of equation (3) to derive taps for tapped delay line model for wideband channels

V. Conclusions

This paper has analysed the statistics of multipath parameters arising from a set of directional channel measurements in an urban area. It has then shown how these may be used to obtain a channel model. Some features of the statistics are of some interest in that they cast light on some questions regarding the statistics of multipaths in a directional channel. Notably we conclude that the signal amplitude, the direction of arrival and the time delay are mutually uncorrelated; that the distribution of the multipath amplitudes is log-normal (rather than Rayleigh), and that there is no evidence of clustering (although even in a dense urban environment there is evidence of a non-uniform arrival density).

Of course since the analysis is based on a set of measurements obtained in one specific locality, these conclusions should be generalised for other locations only with caution. However it would be worthwhile to repeat the measurements to check whether similar results might be obtained elsewhere. It has also been necessary to assume independence of the angles of arrival and departure, because of the lack of double-directional channel measurements, and measurements with greater resolution would also be valuable.

VI. Acknowledgements

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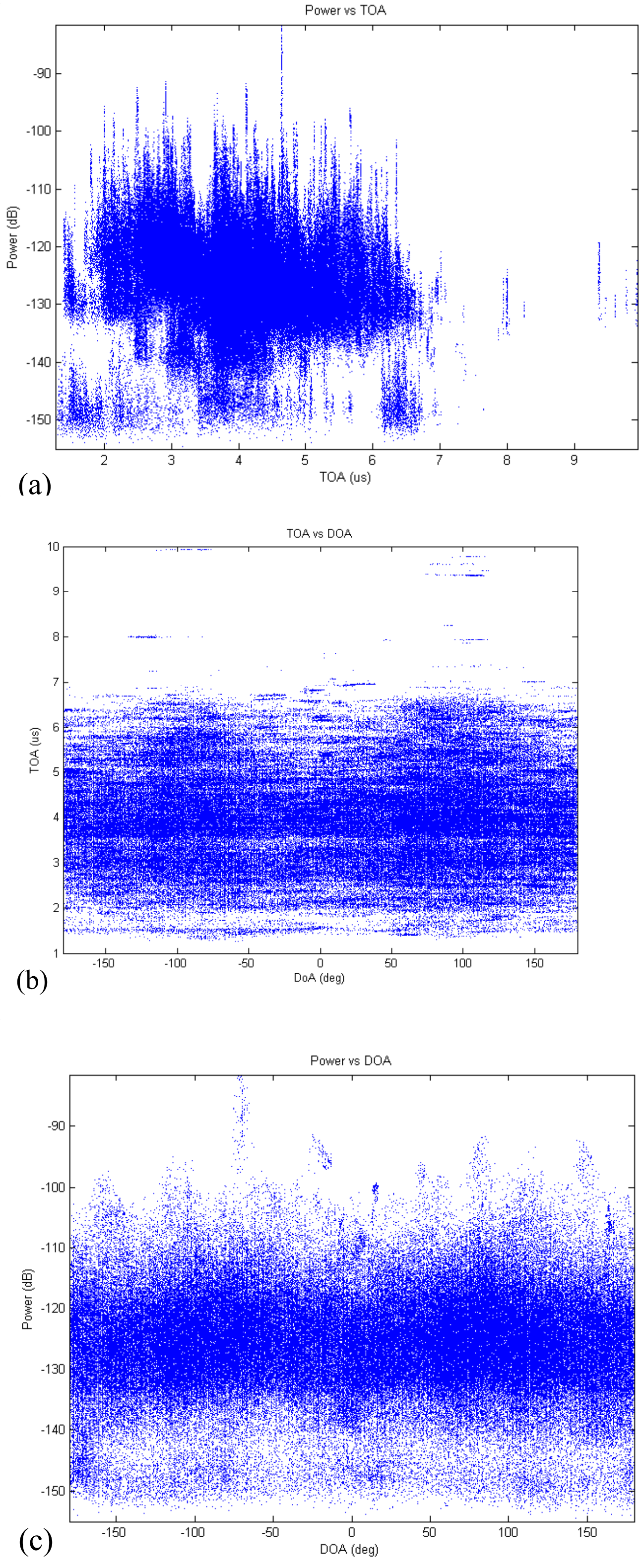

Figure 7 Scatter plots of pairs of parameters: (a) Time-delay versus amplitude; (b) Delay versus direction of arrival; (c) Direction of arrival versus amplitude

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