Rain field modelling for fixed radio systems using fade mitigation techniques

S.A.Callaghan

Radio Communications Research Unit
STFC-Rutherford Appleton Laboratory
Chilton, DIDCOT, Oxon, OX11 0QX , UK
Phone: +44-1235-445770, Fax:+44-1235-446140, e-mail: S.A.Callaghan@rl.ac.uk

ABSTRACT

The demand for increased bandwidth for such services as satellite tv-on-demand has lead to pressure to increase spectrum efficiency and open higher frequencies to commercial exploitation. Fade mitigation techniques such as adaptive transmit power control (ATPC) have been proposed as ways of achieving this. Optimisation of radio systems using these techniques relies heavily on accurate knowledge of the spatio-temporal variation of rain fields. This knowledge is best derived from measured data, but often measurements at the required resolutions are not available. Hence we turn to accurately synthesised rain fields to determine the feasibility and efficient operation of these systems.

1. Introduction

The radio spectrum is a finite resource, and one that is coming under increased pressure as the range of applications requiring large bandwidths, such as third generation mobile phones, become more prevalent. This has lead to commercial and regulatory pressure to improve spectral efficiency and open up higher frequencies (10 GHz and above) to commercial exploitation. Previously, radio systems operated at frequencies that were not adversely affected by rain, clouds or atmospheric gases, or were able to deal with this attenuation by allocating a fixed fade margin. However, as the operational frequency of radio systems increases, using a fixed fade margin increases in cost, until it is no longer economical, spectrally efficient or practical to implement in a working system.

For this reason, new techniques to compensate for rain attenuation, called fade mitigation techniques (FMTs) have been developed. One sub-set of these techniques, known as diversity techniques, relies on the spatio-temporal inhomogeneity of rain fields for their effective operation. For example, satellite systems using site diversity have two (or more) ground stations receiving the same satellite signal, which are separated in space sufficiently so that the rain attenuation at the sites is de-correlated. In a properly configured arrangement the sites encounter intense rainfall at different times, and switching to the site experiencing the least fading improves system performance considerably. To correctly configure this and other FMTs requires a detailed knowledge of spatial and temporal rain field variation.

The fractal nature of rain has been extensively studied in past years by meteorologists and hydrologists, however the insights gained from these methods have been slow to integrate into the rain models used in radio communication systems planning. Fractal methods can be used to analyse and synthesise the spatial and temporal variation of rain fields, producing visually and statistically realistic synthetic rain fields, which may be customised for different climactic regions. These fields can then be converted to simulated attenuation time series and applied to communications engineering scenarios where measured data is not available.

This paper describes how a fractal model for creating synthetic rain fields can be applied to a number of radio systems engineering scenarios, and used as a tool to investigated the spectrum efficiency benefits to be achieved through the use of fade mitigation techniques.

2. The Fractal Nature of Rain Fields

A number of studies, targeted for communications engineers, have developed rain cell models from radar measurements, but are statistical in nature and do not enable the construction of typical two dimensional rain-rate fields [1]. Other models have disadvantages in that they only deal with the spatial variation of the rain-rate within a rain cell [2], or do not take into account the full range of rain rates that are significant for frequencies above 10 GHz [3]. These models assume regular shapes to the rain cells, such as ellipses, or Gaussian functions of position centred on the area of maximum rain rate. Other studies[4,5,6,7,8], suggest that fractal methods may be of use in characterising the shapes of rain cells.

In general, the fractal dimension D characterises any self-similar system; if the linear dimension of a fractal observable is changed by a scale factor f, then, for any value of f the values of the fractal observable will be changed by the factor

f^D. For surfaces, the value of the surface dimension, D_S, lies in the range $2 \le D_S \le 3$. A smooth surface has D_S=2. Similarly, for a contour line, the dimension of the line D_L satisfies $1 \le D_L \le 2$, and D_L=1 for smooth lines. The more twisted and "wriggly" the contour line is, the higher the value of D_L. If pathological cases are disregarded (Voss, 1985) a planar section of a fractal surface has

$$D_L = D_S - 1 \tag{1}$$

The fractal nature of rain has been studied for many years, and its characterisation as a fractal and multifractal field is well documented [9,10]. The exact fractal form of the rain field is still under debate, due to differing methods of calculating the fractal dimension and/or characteristic multifractal function. The majority of the published works use multifractal methods to deal with the intermittency and anisotropy of the rain field [9,10,11], but are also predominantly concerned with topics of importance to meteorology and hydrology, such as extreme events.

Rain field modelling for use in radio communication system design has a different emphasis that that used in climate modelling or weather forecasting. In general, radio engineers are more concerned with rain events up to and including those experienced for 0.0001% of an average year. Rarer events than these fall during the planned system outage time, and so, as far as radio engineers are concerned, can be disregarded. The following requirements for a rain model for use by radio system engineers are the ideal [12].

A physically-based rain model should:

- have a time resolution of 1 s
- have a spatial resolution of about 100 m
- be able to take inputs from a weather model
- be suitable for use in spectrum management and simulation software
- be capable of generating databases which replicate average annual statistics

The rain field models developed by meteorologists and hydrologists presented in the literature tend to have spatial resolutions on the order of kilometres, and time resolution of the order of hours/days. Hence there is a need to develop a fine-scale rain field model capable of the resolutions required by radio engineers.

The procedure used here to simulate rain fields produces simulated fields which are mono-fractal fields. This is justified by multifractal analysis of meteorological radar data recorded in the south of England [8], which shows that log rain rate fields may be accurately characterised as monofractal fields. The transformation of the variables from rain rate to log rain rate allows us to linearise the problem, showing that rain rate fields can be characterised as "meta-Gaussian". This is in agreement with other work published recently [13].

2. Example of fade mitigation techniques requiring fine-scale rain field data

Figure 1 shows an example of a fixed terrestrial radio link network which is capable of using route diversity as a FMT. Route diversity involves routing a radio signal through different links which bypass the rain-affected link to get to the same receive point. The best situation for this scenario is when the rain is de-correlated (localised rain) as neighbouring links in the network will be unaffected and can be used to route the data around the affected link.

Figure 2 shows a pair of neighbouring, unconnected fixed links and the unwanted, interfering link that occurs between them as a result of antenna sidelobes. These links use Adaptive Transmit Power Control (ATPC) as a FMT. ATPC involves dynamically increasing the transmit power on a dB by dB basis to compensate for rain fading. This also increases the transmit power on the sidelobes and unwanted paths, increasing interference into neighbouring links. In terms of the spatio-temporal variability of the rain fields, the best case for this situation is when the rain field is correlated (widespread rain) as interfering path will then be as attenuated as much as the wanted path, so increasing the power will produce no real change in the interference experienced by neighbouring links.

These two FMTs demonstrate how important it is to have accurate fine-scale information about the spatio-temporal variability of rain fields. Ideally, this data would be obtained through measurements, for example, through the use of meteorological rain radar. Unfortunately, at this time, measured databases at sufficiently fine resolutions that span several years are not available, hence the need for simulated data.

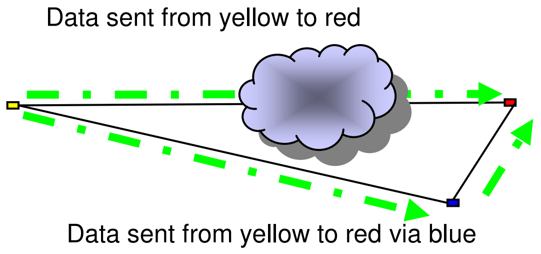

Figure 1: Schematic example of route diversity

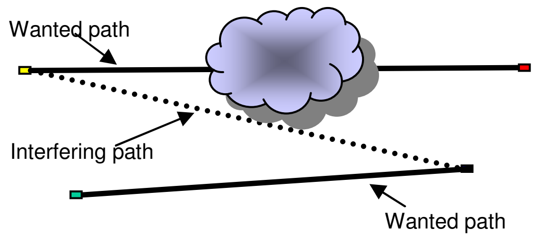

Figure 2: Schematic example of wanted and interfering paths when fixed links use ATPC

3. The Fractal Rain Field Simulator

The simulator presented here is based on the Voss successive random additions algorithm [13] for generating fractional Brownian motion in two dimensions. This is an additive discrete cascade method, which produces log, monofractal fields. The cascade process itself is iterative, and the branching number of the cascade determines whether or not the resulting field can be considered to be stratiform-like or convective-like. In order to tie the simulated fields, which are equivalent to log rain rate, to rain rate values appropriate for the climate being simulated, the simulated fields are scaled according to a rain rate parameter, $R_{0.01}$ which is the rain rate exceeded for 0.01% of an average year. This parameter can be easily obtained from rain gauge measurements, or can also be determined from the ITU Recommendation P837 [15]. Each run of the simulator produces a single realisation of a stratiform-like or a convective-like rain field. These realisations are independent of each other, hence there is no temporal component to the model (though work is ongoing). However, given enough synthetic fields it is possible to create simulated statistics for an average year. A full description of the simulator and algorithm can be found in [8].

4. The Impact of ATPC in the 38GHz Fixed Terrestrial Link Band

In the UK, the 38 GHz band is used for fixed terrestrial links, generally used to connect mobile phone base stations to each other and the wider network. In this band, there are approximately 14,000 links, unevenly distributed across the country, concentrated around major metropolitan areas. Ofcom commissioned a study to investigate the impact and potential spectrum efficiency gains that would result from rolling out ATPC in the 38GHz band for a range of ATPC/non-ATPC mixtures.

The spectrum efficiency benefits of ATPC can be achieved as follows: Given a reliable power control system, it is possible to reduce the fixed fade margin during clear sky conditions (i.e. no fading), thereby improving the rate of frequency reuse and link packing density in the geographical area of the link. This is because lower fade margins use less transmit power, which lessens the interference on adjacent links. It is relatively straight-forward (if time consuming) to re-plan the band given the reduced fade margin resulting from using ATPC. It is how the system operates when in the presence of rain that determines whether or not any spectrum efficiency gains can be made. As described above, a key factor is whether the use of ATPC will increase adverse interference on neighbouring links – a situation which is more likely during convective storms (heavy, very localised rain events).

The frequency assignments in the 38GHz band were replanned given different ATPC penetration values, and those plans were then tested using a set of measured rain fields recorded using the Chilbolton Advance Meteorological Radar (CAMRa) in the south of England, as well as a set of simulated rain fields, scaled to reproduce annual rain rate statistics as modelled by ITU Rec. P837-4 [15]. Details of this scaling procedure can be found in [17]. A full description of the planning and analysis done in this project can be found in [17].

5. Conclusions

This paper has described the application of a fractal rain field simulator to a radio engineering case study, that of the impact of implementing ATPC in the 38GHz band. Work on this and other Ofcom funded projects have identified that a (measured or simulated) 2-D rain field database is important when investigating new techniques for improving the spectral efficiency of fixed links services. In these projects work has been done to develop a method of simulating rain fields over geographic areas with a spatial resolution of 100m*100m and a time resolution of 1 minute. Comparison with rain rate measurements suggest that creating enough simulated fields will accurately reproduce annual statistics. However, the memory and processing requirements for a full annual database is impractical at this time. It is possible to create a small subset of simulated rain fields which replicate the tail of the annual statistics curve, and such a subset was used in the ATPC project. The main conclusions from the ATPC project are:

1. The implementation of ATPC in the 38 GHz band gives significant improvements in spectrum efficiency as measured by the increase in the number of links assigned to channel 1 (from ~50% to ~70%) and the decrease in the maximum bandwidth used (from ~300 MHz to ~180 MHz). The introduction of ATPC does give rise to a number of additional outages in the presence of intense rain (~10% increase in frontal rain). These additional outages can be mitigated to some extent by band-wide changes to the planning process; however, the outages cannot be wholly eliminated by the methods examined here.
2. When exposed to annualised simulated rain events, the results show that a plan constructed with the objective of achieving a 0.01% unavailability has a measured unavailability of 0.008%. This is close enough to demonstrate the general method. However, it is probable that further improvements to the simulated rain (or additional data sets) might improve the ability of that rain to provoke the expected unavailability.

Future work is planned to expand the rain field simulator to include temporal variation (evolution and advection of the rain fields), to test its applicability to other geographic and climactic regions and to apply it to other communications engineering and radio systems scenarios.

6. Acknowledgements

The support of Ofcom in providing the funding for this work is gratefully acknowledged.

7. References

1. Crane R.K. Electromagnetic Wave Propagation through Rain, Wiley Ser. Remote Sens., John Wiley, New York 1996
2. Manning, R.M., A rain attenuation model for satellite link attenuation predictions incorporating the spatial inhomogeneity of rainrate. Int. Jnl. of Satellite Communications, Vol. 2, 187-197, 1984
3. Capsoni, C., Fedi, F., Magistroni, C., Paraboni, A. and Pawlina, A., Data and theory for a new model of the horizontal structure of rain cells for propagation applications, Radio Science, 22(3), 395-404, 1987b
4. Lovejoy, S., Area-Perimeter Relation for Rain and Cloud Areas, Science, Vol 216, 185-187, April 1982
5. Rys, F.S., Waldvogel, A. Fractal Shape of Hail Clouds, Physical Review Letters, Vol. 56, Number 7, 784-787, February 1986
6. Feral, L. and Sauvageot, H, “Fractal identification of supercell storms”, Geophysical Research Letters, Vol. 29, No. 14, 2002
7. Callaghan, S.A., Vilar, E. Analysis of the Fractal Dimension of Rain Rate Contours with Reference to Wide Area Coverage of Satellite Communications. "Foreign radioelectronics. Successes of modern radioelectronics" No 6, 2003, RADIOTECHNIKA, Moscow
8. Callaghan, S.A, Vilar, E., “Fractal Generation of Rain Fields: Synthetic realisation for radio communication systems”, IET Microwaves, Antennas and Propagation, Vol. 1, Number 6, 1204-1211, December 2007
9. Lovejoy, S. and Schertzer, D., “Multifractals, universality classes and satellite and radar measurements of clouds and rain fields”, Journal of Geophysical Research, Vol. 95, 2021-2034, 1990
10. Olsson, J., and Niemczynowicz, J., “Multifractal analysis of daily spatial rainfall distributions”, Journal of Hydrology, 187, 29-43, 1996
11. Deidda, R., “Multifractal analysis and simulation of rainfall fields in space”, Physics and Chemistry of the Earth Part B – Hydrology, Oceans and Atmosphere, 24 (1-2), 73-78, 1999
12. Bacon, 2005 “Rain Modelling and the Future of Telecommunications” Rainmap Kick-off conference, Jan 2005 (http://www.rainmap.rl.ac.uk/pdfs/jan2005_workshop/Bacon.pdf)
13. Ferraris, L., Gabellani, S., Parodi, U., Rebora, N., von Hardenberg, J., Provnzale, A., “Revisiting multifractality in rainfall fields” J. Hydromet. 4, pp 544-551, 2003
14. Voss, R. F., “Random fractal forgeries”, in *Fundamental Algorithms for Computer Graphics*, editor R. A. Earnshaw, NATO ASI Series F, Computer and System Sciences, Vol 17, 1985.
15. ITU-R Recommendation P.837-4 “Characteristics of precipitation for propagation modeling”
16. Callaghan, S.A., “Generating year-equivalent databases of fractally synthesised rain rate fields”, ISART, Boulder, June 2008
17. Callaghan, S.A., Hansell, P., Inglis, I., “Impact of introducing Automatic Transmit Power Control in P-P Fixed Service Systems operating in bands above 13 GHz” Final report for Ofcom, 19th December 2005 *http://www.ofcom.org.uk/research/technology/overview/ese/atpc/atpcfinal2.pdf*