MODELLING UHF PROPAGATION FOR FREQUENCY ASSIGNMENT IN RADIO RELAY NETWORKS

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SUMMARY

An account is given of experiences in developing UHF-propagation models for the terrain of the North German plain which is characterised by woods and farmland. A few empirical results on the relevance of modelling the interaction between diffraction and groundwave propagation are discussed. However, the paper mainly focusses on (statistical) methods used to select appropriate models, rather than going into the (physical) details of propagation mechanisms. Since local variability of the field strength prohibits prediction of the feasibility of radio relay links with absolute reliability, (static) diversity tests are recommended to avoid antenna positioning in local multipath nulls. It is shown that such antenna position tests are only worthwhile if the propagation model forecasts local mean signal powers with sufficient reliability.

1. INTRODUCTION

The effectiveness of the planning of radio links and frequency management heavily depends on the availability of appropriate propagation models. Almost from the beginning of experimental radio communications, the properties of waves travelling above the earth's surface have been a subject of research. Especially because saturation of the radio spectrum forces towards higher frequencies, the influence of obstacles and irregularities on the diffraction and scattering of waves becomes higher and more difficult to predict.
In frequency assignment for a complex radio relay network, evaluation of many path profiles is required in order to select the optimum location and frequencies for a relay node in agreement with a tactical scenario. This does not concern operational paths only because paths over which interference signals may travel have to be considered. Further, local EMC issues have to be examined. Since relay nodes are relocated frequently, relatively simple algorithms have to be used.

Forecasting path loss from terrain data can be seen as a three-step process, as illustrated in Fig.1.

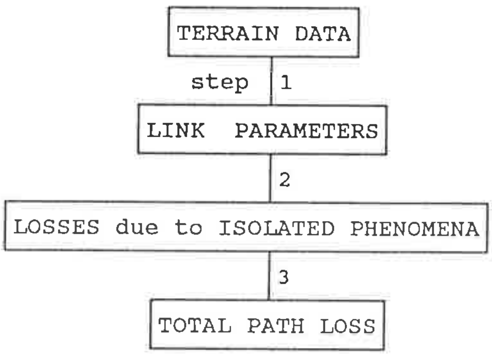

Fig.1: Three steps towards a model for propagation forecasts

The major part of the theoretical work on propagation concerns the second step only: given a set of path parameters, the loss due to isolated and idealised mechanisms can be calculated. Well-known examples are the diffraction loss A_D over an obstacle if the knife-edge geometry is known [1]-[3], or the reflection loss A_r in a two-ray model given antenna heights, and the distance of propagation over a plane, and smooth earth [4]. The reliability of the prediction of a field strength further depends on the first and third step. The first step is the interpretation of the terrain data by extracting propagation parameters. It is mainly in this step that many implementation decisions have to be made. Typical questions are "What is the effective height for diffraction of a hill covered by trees in winter?", "When does a terrain irregularity act as one single obstacle (SKE: single knife edge) and when should it be treated as two (or more) separate hills (MKE: multiple knife edge)?" and "What is the effective height of an antenna in an irregular, sloping and forested terrain?" [5],[6].

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The third step describes the transition from theory to application. Experience and expertise are required to select and combine the relevant effects. The extent to which mechanisms are present (and mutually interact) is an important consideration in the selection of a model. Although usually the total path loss is estimated by linearly adding dB's as predicted in step 2, and thus assuming superimposed isolated mechanisms, this is neither theoretically justifiable nor the best solution in terms of accuracy [7],[8]. In contrast to the sequence for forecasts (Fig.1), for research and analysis, usually a reserve sequence is followed, starting with step 3.

Analysis of narrowband propagation measurements [8] in the UHF bands (bands I and II) for the "ZODIAC" 1(Nl)lk radio relay network is reported in this paper. Operational links cover 5 to 30 km over the slightly hilly terrain (Δh is 20 to 100m) of the North German plain. The terrain is mainly agricultural, with scattered woodlands. Antennae heights range from 4 to 21 meters, which is often insufficient to exceed the tree-top level. Multipath reception and shadowing [4],[9],[10] introduce substantial local fluctuations of the field strength. Interaction of the radio wave with the earth's surface (reflection loss) and diffraction are of nearly equal importance in large-scale field strength fluctuations.

2. AVERAGE ATTENUATION

A typical example of modelling propagation is estimating the average loss A (in dB) with distance d, according to the statistical model

$$A = 10\beta \log d + \alpha, \qquad (1)$$

with α and β empirical constants. Theoretical values are β=2 in free space and β=4 in the case of propagation over a plane earth. An instructive conclusion on the relevance of propagation mechanisms can be drawn from experiments such as presented in Fig.2. In our application, it appeared that UHF propagation in forested areas ($\beta \approx 2.6$) is principally a diffraction effect in free space, while for relatively open areas ($\beta \approx 3.8$) the plane earth model is more appropriate. The effect of lower β in areas with dense forests has been investigated by Tamir [11] for VHF frequencies.

As suggested by Fig.2, adding theoretical diffraction and reflection loss (A_D + A_r), and thus β>4, can not lead to an optimum model since interaction of both mechanisms is then neglected. An appropriate and accurate VHF or UHF model is thus expected to smoothly change, e.g. as in [7], from a diffraction model for paths mainly covered by vegetation to a plane earth model for paths over farmland. Dedicated measurements near the Haarlerberg (Fig. 3) confirmed that an obstacle, though introducing diffraction loss, significantly tempers reflection loss. Field strength measurements and antenna height gain tests, gave the impression that diffraction and reflection showed their influence on different parts of the path.

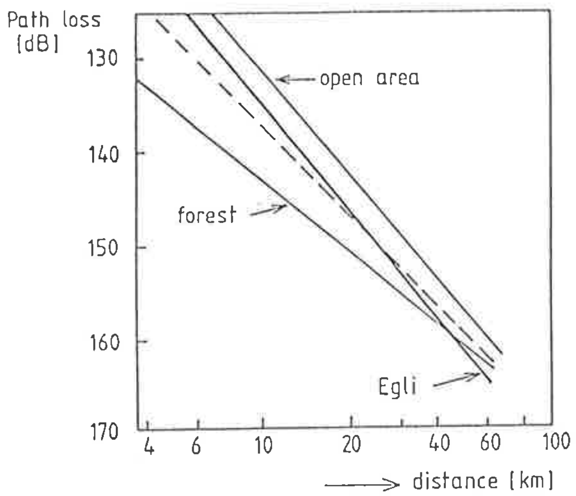
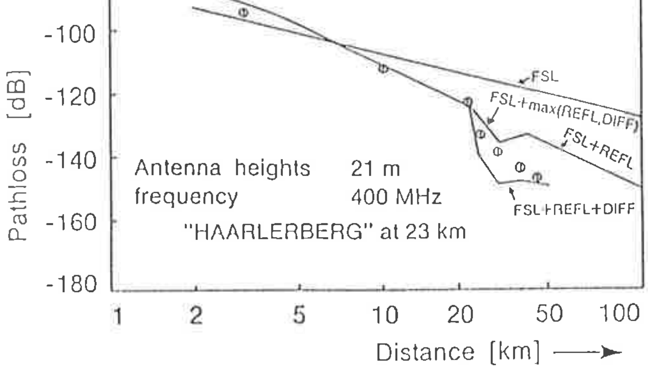


Fig.2: Average path loss in the North German plain at 300MHz



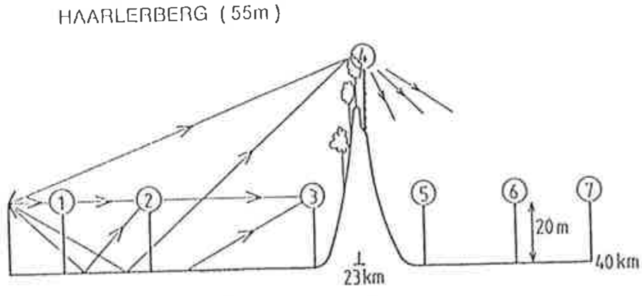


Fig.3: Propagation experiment over an isolated ridge: the Haarlerberg has a height of 55 meters above a smooth, flat ground in Holland. Propagation is best characterised by free space loss at (1), plane earth loss at (2,3), diffraction at (4) and a combination of diffraction and reflection at (6,7).

3. STANDARD DEVIATION OF PREDICTION ERROR

The logarithmic standard deviation σ_t of the error experienced when a propagation model A is verified, is defined as

$$\sigma_t^2 \triangleq E[\ (A_m - A - E[A_m - A]\ )^2\ ] \qquad (2)$$

with A_m the measured path loss (in dB) and A the forecast loss (in dB). The variance σ_t^2 is due to four statistically independent effects: model deficiencies σ_p, shadowing σ_s, multipath σ_R and measurement errors σ_m. So, if attenuation mechanisms are assumed multiplicative, σ_t is given by

$$\sigma_t^2 = \sigma_m^2 + \sigma_p^2 + \sigma_s^2 + \sigma_R^2. \qquad (3)$$

Using state-of-the-art equipment, measurement inaccuracies (though present) may be neglected ($\sigma_m \approx 1$ to 2 dB). Nevertheless, the measurements can greatly influence the results [11]. Faulty or loose connecters, damaged antennae, overloaded amplifiers etc. are not always spotted immediately and tend to introduce some outliers in the set of measurement data, rather than smoothly increasing apparent σ_t^2 by a small extra term. The selection of paths for measurements may not be limited to paths known to give satisfactory communication. Therefore, equipment has to be significantly more sensitive than operational radio relay sets, otherwise, absence of paths with heavy loss biases the population of measurements.

Shadowing and multipath reception introduce local fluctuations, usually in the range 4 to 12dB. Both effects are usually discussed in relation to mobile cellular radio-telephony [4],[9]. Assuming reasonably good antenna position, multipath reception due to local scatters gives the amplitude of the signal a Rician distribution over an area of a few tens of wavelengths. In the worst case, i.e. when no dominant wave is present as we experienced in a forest, the Rician distribution goes into a Rayleigh distribution, with $\sigma_R \approx 6$ dB (App.A). Since local phase cancelling can not be predicted, one preferably reduces multipath fluctuations σ_R before statistical processing [12],[13],[14]. Appendix A illustrates that σ_r decreases roughly with $\sqrt{m}$, where m is the number of uncorrelated samples taken at one antenna location.

Due to shadowing, the local mean power varies about the area mean with a log-normal distribution: the power in dB is normally distributed with standard deviation σ_s. In this paper, we define shadowing to occur in an area with a size equal to the resolution of the terrain data. This is in contrast to common definitions in mobile propagation, where the area is only limited in size by the requirement that shadowing remains statistically stationary. In the latter case, shadowing is typically measured over an area of a few hundreds of meters. Using the former definition, shadowing poses an insurmountable limit in achievable accuracy of forecasts ($\sigma_t > \sigma_s$). This implies that for terrain data with very high resolution, the effect of shadowing necessarily vanishes ($\sigma_s \to 0$). For average terrain, $\sigma_s \approx$ 12dB when no terrain profile (except the propagation distance d) is used [15],[16].

The remaining term σ_p represents model deficiencies. The aim of the assessment of an appropriate model is to effectively reduce σ_p to zero. In (1), even if $\sigma_p = 0$, i.e., if β is optimally established, σ_t will always be greater than $\sigma_s \approx$12dB. Errors $\Delta\beta$ only have a minor influence on σ_t. For samples homogeneously distributed for "log d" in the range 5 to 50 km, σ_p will equal

$$\sigma_p = 10\ \Delta\beta\ /\sqrt{12} \approx 2.9\ \Delta\beta \quad \text{(in dB)}, \qquad (4)$$

which is almost always much less than 12 dB. Nevertheless, the forest/open-area conclusion from Fig.2 appeared relevant in selecting a model (step 3). The gain from such experiments is only found in a later stage of the development of a model when effects from diffraction and reflection are carefully accounted for. Evaluation of representative profiles showed that the average Deygout [2] diffraction loss A_D is 20 dB with a standard deviation of 7 dB. If, on the other hand, a plane earth is assumed, the two-ray model yielded reflection losses A_r of about 12 dB, with a σ of 7 dB. It may be concluded that model errors σ_p are to be expected in the range of 7 dB if diffraction or reflection are not carefully considered.
In conclusion, well-known models such as [17],[18], can reach standard deviations of about $\sigma_t = \sqrt{\sigma_s^2 + \sigma_R^2} \approx 6$ dB if terrain data is carefully used. Only very complex models perform better, provided that antennae can be placed with sufficient clearance ($\sigma_R \approx 0$). The accuracy of most models, however, can be characterised by a standard deviation σ_t of 8 to 10 dB [8].

4. REQUIRED NUMBER OF MEASUREMENTS

Theory on combined occurrence of propagation mechanisms is scarce. As far as empirical results are reported, e.g. in [5]-[7], the validity in a different application is not guaranteed in advance and verification is required. Dedicated experiments, such as in Fig.3, can yield important insight into selecting and combining relevant mechanisms (step 3). Absence of local scattering and shadowing appears a relevant condition for the validity of single path experiments. However, usually a large set of samples is required to be able to draw statistical conclusions.

We assume a test model A to be verified by m samples at n different pairs of antenna locations. Multipath attenuation may be assumed statistically uncorrelated for all m measurements at one location because these are sampled at sufficiently different frequencies or antenna positions. Shadowing and model deficiencies are assumed equal (correlation unity) at one location but uncorrelated for different locations. The variance in the estimate for β can then be expressed as

$$\mathrm{var}[\beta] = \frac{\sigma_S^2 + \sigma_R^2/m}{n\ \mathrm{var}[10\log d]} \qquad (5)$$

We now define σ_{p0} as the model error experienced when the propagation factor under test is unjustly ignored. In this case, σ_{p0} is experienced when β=0 would be inserted in (1). Eq.(5) goes into

$$\mathrm{var}[\beta] = \frac{\beta^2}{\sigma_{p0}^2}\left[\frac{\sigma_S^2}{n} + \frac{\sigma_R^2}{n\ m}\right] \qquad (6)$$

Since σ_{p0} and the local variability are often in the same order of magnitude (about 7dB), the number of locations n to be investigated is in the order of 100 for a relative accuracy of 10%. Further, eq.(6) suggests that if a total of mn measurements can be taken, all measurements are preferably taken at different locations (m=1, large n). In practice, it is usually easier to take several samples at one location (m>>1) than to move to another site. Screening of data and evaluation of specific phenomena on individual paths can only be performed if multipath spreads are effectively reduced (m>>1).

In the analysis of step 1 (interpretation of the profile), the problem is more complicated. Few experiences are reported, while the number of degrees of freedom in defining effective heights and other compensation parameters appears unlimited. Experiments in step 1 are not as straightforward as linear parameter estimation because implementation decisions often have a discontinuous effect on path loss. A small change in terrain profile, for example changing the modelled effective diffraction height of trees, can have a step-wise influence of predicted diffraction loss if the implemented algorithm steps from single knife-edge to double knife-edge interpretation. Further, conclusions are sensitive to outliers. These effects are very difficult to optimise, and no general method can be recommended here. At least taking sufficient samples to smooth out discontinuities can be advised. It appeared from our measurements that 55 paths (n=55, and m=28) did not fully smooth out these effects. Practical experience indicated that the discontinuities sharply diminish with the accuracy of the implemented model. This is in contrast to the fact that a more detailed model generally has to take more decisions. The MKE diffraction model [2] gave a significantly better defined optimum than SKE methods.
Some of the parameter estimates concluded from a set of n=34 paths had to be revised after additional measurements became available (n=55, m=28). Linear regression or correlation of the error with terrain parameters, rather than studying the overall accuracy σ_t, can give some insight into the problems but careful interpretation is required.

5. LINEAR REGRESSION OF THE FORECAST ERROR WITH PATH PARAMETERS

A direct verification of decisions in step 3 can be made by correlating the residual error e ($e \triangleq A-A_m-E[A-A_m]$) with isolated losses as calculated in step 2. Linear regression in [8] showed that excess path loss (above free space A_{fs}) is proportional to 45% of the SKE diffraction loss as in [1]. It appeared that MKE models were required, since e was found proportional to 85% of the theoretical loss A_D over a Deygout triple knife edge [2]. Apart from deficiencies in implementing step 1, a very likely explanation of the lacking 15% is that propagation over smooth paths experiences relatively more reflection loss.
On the other hand, regression of the error e with two-ray reflection loss A_r was in the order of only 50% [2]. This is mainly due to the inverse frequency dependance of reflection loss, while diffraction and shadowing increase with frequency. We conclude that direct correlation of the error with losses from isolated and idealised phenomena thus prone to yield somewhat ambiguous results since losses have a mutual statistical correlation.

Correlation with distance is usually a more reliable indication of shortcomings in the calculation of reflection loss. Diffraction statistically also increases with distance, however, this effect was found to be limited to 10% of β. Correlation with frequency is a more complex parameter: diffraction, reflection and shadow losses all depend on frequency. Accumulated inaccuracies in various terms of the model are likely to require a final empirical correction with carrier frequency. In our case, average shadow loss has been modelled dependent on local terrain features by adding $A_{l,x}$, with

$$A_{l,x} = \begin{cases} 6 \log(f/40\text{MHz}) & \text{for a low antenna (<21m) in a forest} \\ 0 & \text{in the case of high antenna clearance (open field)} \end{cases} \quad (7)$$

or any intermediate value, depending on vegetation and buildings.

Regression of e with profile parameters is also prone to diverse interpretations. For test models without diffraction, e.g. [13], terrain roughness Δh will give a positive correlation. Once diffraction is introduced in the model, the correlation often turns to negative values, since reflection loss is higher on smooth paths. Empirical corrections for terrain roughness are not easily generalised since they depend on tactical decisions in selecting antenna sites. Nonetheless, implementation decisions in step 1 are, however, best verified by correlation of e with parameters as terrain roughness, interdecile range, density of vegetation etc. For the purpose of verification of steps 1 and 3, even defining new parameters can be useful in gaining insight. Empirical correction with these new parameters does, regrettably, not lead to reliable models.

6. RESULTS FOR PROPAGATION MODEL

In our application, diffraction has been modelled by the MKE technique by Deygout. SKE methods, for instance the main hill or [3], appeared not to be essentially better than models on the form of (1). Analysing the SKE model suggested by Bullington [3], a problem of implemention was encountered for forested terrain, because the equivalent obstacle is often only determined by trees in vicinity of the antennae. Consequently, all terrain irregualities on the propagation path are then ignored.
Our algorithm takes account of up to three obstacles. The effective height of trees is empirically set to 25 meters for coniferous forest and 15 meters for other forest. The influence of terrain irregularities on ground wave propagation appeared difficult to quantify. Several attempts have been made to empirically model the reflection coefficient as a function of angle of incidence and terrain characteristics. A small improvement can be obtained by empirically modelling reflection as a function of the density of vegetation on the path, the total diffraction loss (e.g. as in [7]) or the interdecile range Δh. No such model could be scientifically justified. The increased complexity largely increased computer time, but it did not significantly increase the accuracy of the forecasts. From this point of view, reflection loss A_r was empirically reduced by 40%, which results in the generally accepted β somewhat larger than 3.2.

Since calculation time of the algorithm had to be limited, low resolution terrain data has been applied. The data base contained information on the highest point within a 1km^2 square. However, it appeared essential to have more detailed information about the terrain height and local terrain features at the antenna site. Using the local shadow loss (7), this resulted in the model

$$A = A_{fs} + A_D + 0.6\, A_R + A_{l,tx} + A_{l,rx}. \quad (8)$$

In accordance with earlier observations, field strength forecasts are limited to about 7 or 8 dB accuracy for antennae above tree top level. For antenna heights below 20 meters in a terrain with scattered woods ($\sigma_R \approx 6$dB), σ_t could not be reduced below 9 dB.

7. NETWORK MANAGEMENT

While the propagation researcher can reduce σ_R by his measurement method (m>>1), the frequency manager has to account for a residual inaccuracy due to multipath ($\sigma_t > \sigma_R$). Local effects can not be fully predicted and accounted for but they have to be solved at the receiver and transmitter sites. If the transmission bandwidth is not too wide, a static diversity technique (e.g. testing a few alternative antenna positions) may be applied. In App.B it is shown that, although accuracy is necessarily limited, optimising σ_p (accurate model) and σ_s (high resolution) remains relevant. Conditional probabilities of successfully setting up a link suggest that only if the forecast of the local mean power has been performed sufficiently accurately and if multipath scattering is relatively severe ($\sigma_p^2+\sigma_s^2<\sigma_R^2$), local tests are worthwhile. Horizontal displacements of the receiving antenna showed that $\sigma_R \approx 2$dB for antennas with high clearance. For low antennae close to woods, the standard deviation due to multipath is significantly higher ($\sigma_R \approx 6$dB). Occasional nulls of 40 dB have been recorded.
Horizontal displacement of the antenna by a few meters may be feasible with some types of masts. With other types, however, position tests might be prohibitively time consuming.
Empirically, an average height gain of 4 to 5 dB/oct was found. However, samples at intervals of 3m did not exactly follow a smooth dB/oct trend: multipath scattering produced peaks and dips with a standard deviation of 2.5dB for 250MHz, slowly increasing to 3.5dB for 900MHz. Shadowing only influences the height gain if obstructions are very close to the antenna. An exponential height gain of 1 or 2 dB <u>per meter</u> was measured closely beyond the Haarlerberg (Fig.3, loc.4). Within small woods, an occasional 10dB is to be gained by placing the antenna between the trunks (at 7 to 10m), rather than at the height of the leaves. In general, however, vertical

(height) tests have not been found to be very effective since the height gain prohibits all too dramatic changes (reduction) of antenna height.

Measurements indicated that the local mean power is virtually constant with time, though the multipath pattern may fluctuate somewhat. Seasonal effects [23] are present but below other statistical effects. Interference powers over longer paths (d>40km) can fluctuate due to incidental transhorizon propagation under specific conditions. It is our impression that a transportable UHF link, once in operation, experiences outage mainly due to changing interference characteristics.

8. CONCLUSIONS

To assess the optimum implementation of obtaining propagation parameters from terrain data (step 1), many measurements are required. The transition from these parameters to prediction of loss if all effects would occur isolated (step 2), has been extensively covered in literature. However, experience, expertise and dedicated measurements are required to combine these phenomena in an appropriate model (step 3).

Empirical verification of UHF-propagation models, and their implementation, is deemed necessary if an accuracy better than 10 dB is required. Computer processing time rapidly increases if higher accuracy is required. Model accuracy better than about 6 dB is usually not achievable in typical UHF military radio-relay applications because of Rician scattering of waves in the direct environment of the antenna. Our measurements indicated that the agreement between mobile propagation in cellular radio and radio relay with low, camouflaged antennas in a scattering environment is surprising. In contrast to fast fading (as for instance in civil cellular telephony), the radio relay signal barely fluctuates with time; antenna masts may thus by accident be placed permanently in local multipath nulls.

The effectiveness of repositioning the antenna is evaluated (in App.B) from theoretical models on local variability. No empirical verification of the relevance of second attempts under operational circumstances is available. Nevertheless, it was learned that reliable management of the radio relay network calls for cooperation between the frequency administration and local operators, rather than conveying a computer decision to set up a link between two sites on a prescribed frequency. Shadowing and local multipath effects cannot be fully predicted and accounted for but have to be addressed locally at the receiver and transmitter sites, e.g. by (static) diversity techniques or antenna displacement tests. The frequency manager can, however, complement these efforts by providing alternative frequencies to avoid local multipath cancelling. These conclusions may ask for modifying some of the operational procedures now used in establishing radio relay links, especially if higher (band III) frequencies are used.
It is the impression of the author that, after implementing models at present available, inaccurate modelling of co-location EMC issues, rather than link attenuation, is now the main limit to the reliability of the frequency management. Co-location interference also exhibits severe fluctuations with small antenna displacements.

References

[1] K. Bullington, Radio propagation for vehicular communications, IEEE Tr. Veh. Tech., Vol VT-26, No. 4, Nov 1974, pp.295-308.
[2] J. Deygout, Multiple knife-edge diffraction of microwaves, IEEE Trans. Ant. and Prop., Vol.AP-14 (1966) pp 480-489.
[3] J. Epstein, D.W. Peterson, An experimental study of wave propagation at 850 Mc, Proceedings of the IRE, 1953, Vol.41, pp.595-611.
[4] W.C. Jakes, Microwave Mobile Communications, John Wiley and Sons, New York, 1978.
[5] M.L. Meeks, VHF propagation over hilly, forested terrain, IEEE Trans. Ant.& Prop., AP-31(May 1983), No.3, pp. 483-489.
[6] M.L. Meeks, A propagation experiment combining reflection and diffraction, IEEE Trans. Ant. and Prop., Vol. AP-30, No. 2, March 1982, pp.318-321.
[7] A. Blomquist, L. Ladell, Prediction and calculation of transmission loss in different types of terrain, AGARD Conf. Proc., No. 144, paper 32, Electromagnetic wave propagation involving irregular surfaces and inhomogeneous media.
[8] J.P.M.G. Linnartz, The modelling of diffraction, reflection and clutter loss in UHF radio wave propagation, FEL-TNO report 1988-28, FEL-TNO, the Hague, the Netherlands.
[9] F. Hansen and F. Meno, Mobile fading - Rayleigh and log-normal superimposed, IEEE Tr. on Veh. Tech., Vol VT-26, No. 4, Nov. 1977, pp.332-335.
[10] A. Blomquist, Local ground wave field strength variation in the frequency range 30 - 1000 MHz, in Electromagnetic wave propagation, M. Desirant, J. Michiels, Eds, New York: Academic, 1960.
[11] T. Tamir, Mixed-path considerations for radio wave propagation in forest environment, AGARD Conf. Proc. No. 144-33, NATO, March 1974.
[12] IEEE Trans. Veh. Tech., Special issue on mobile propagation, Feb 1988, Vol. VT-37, No.1.
[13] W.C.Y. Lee, Mobile communications design fundamentals, Howard W. Sams & Co., Indianapolis, 1986.

[14] M.M. Peritsky, Statistical estimation of mean signal strength in a Rayleigh fading environment, IEEE Trans. Commun., Vol. COM-21, No.11, November 1973, pp.1207-1213.
[15] J.J. Egli, Radio Propagation Above 40 MC/s over Irregular Terrain, Proc. IRE, Oct 1957, pp.1383-1391.
[16] J.P. Murphy, Statistical propagation model for irregular terrain paths between transportable and mobile antennas, AGARD Conference Proceedings, No. 70, 1970, paper 49.
[17] A.G. Longley and P.L. Rice, Prediction of tropospheric radio transmission over irregular terrain, a computer method, Environmental Sience Service Administration, ESSA Tech. Rep. ERL 79-ITS 67 NTIS acc. no 676874, 1968.
[18] Y. Okumura, et al., Field strength and its variability in VHF and UHF land mobile radio service, Review of the Electr. Communic. Lab, Vol. 16, 9-10, pp 825-873.
[19] Mathematical handbook of formulas and tables, Ed. by M.R. Spiegel, Schaum's Outline Series, Mc GrawHill Book Company, New York, 1968.
[20] Handbook of Mathematical Functions. Ed. by M. Abramowitz and I.A. Stegun. New York: Dover, 1965.
[21] G.W. Lank and I.S. Reed, Average time to loss of lock for an automatic frequency control Loop with Two Fading Signals and a Related Probability Density Function, IEEE Trans. Information Theory, Vol. It-12, No.1, pp.73-75, January 1966.
[22] K. Diakoku, H. Ohdate, Optimal channel reuse in cellular land mobile radio systems, IEEE Trans. Veh. Techn., Vol VT-32, No. 32, August 1983, pp. 217-224.
[23] K. Loew, UHF measurements of seasonal field-strength variations in forests, IEEE Trans. Veh. Techn., Vol. 37, No. 3, August 1988, pp.121-124.

APPENDIX A: Standard deviation of a Rayleigh fading signal

In a radio relay network, multipath reception can be described by Rician scattering. In the worst case, the direct wave does not significantly dominate the scatters and the signal strength has a Rayleigh distribution. The pdf of the received signal power p is exponentially distributed, according to

$$f_P(p) = \frac{1}{p_1} \exp\left(- \frac{p}{p_1} \right) \quad \text{(A1)}$$

with p_1 the local-mean power. The local-mean power μ_1, averaged over dB values, will be 2.5 dB below this linear average p_1. This is seen from

$$\mu_k = \int_0^{\infty} [10 \log (p/1\text{mW})]^k \exp(- p/p_1) \; dp/p_1 \quad \text{(A2)}$$

which is solved for k=1 using [19,(32.117)]

$$\mu_1 = \frac{10}{\ln 10}[-\tau + \ln(p/1\text{mW})] \approx 10 \log(p/1\text{mW}) - 2.5 \text{ dB} \quad \text{(A3)}$$

where τ the Euler's constant ($\tau \approx 0.577$). From [19, 32.119], the logarithmic standard deviation is found to be

$$\sigma_R^2 = \frac{100}{\ln^2 10}\left[\frac{\pi^2}{6} + \tau - \tau^2 \right] \approx 6 \text{ dB} \quad \text{(A4)}$$

The sum or the average of m samples has a Nakagami m-distributed envelope, or equivalently a gamma distributed power. Solutions for the higher order logarithmic moments μ_k have not been found. An approximation [13] for σ_R can be made from linear moments u and s,

$$\sigma_R^2 \approx 10 \log\left[\frac{u + s/2}{u - s/2}\right] \quad \text{(A5)}$$

For Rayleigh fading, $u=p_1$ and $s=p_1^2$, so $\sigma_R \approx 4.8$ dB. For the gamma distributed sum of m samples, one finds a linear average $u=np_1$ and a second moment equal to $u_2=(n^2+n)p_1^2$. Thus, for large m, the σ_R decreases inversely proportional to $\sqrt{m}$, since

$$\sigma_{R,m} \approx 10 \log\left(1 + \frac{1}{\sqrt{m}}\right) \approx \frac{10}{\ln 10 \sqrt{m}} \approx \frac{4.3}{\sqrt{m}} \approx \frac{\sigma_R}{\sqrt{m}} \quad \text{(A6)}$$

Appendix B: Probability of success in establishing a microwave link

In this section, benefits from applying a static diversity technique to avoid an accidentally bad position of the antenna are discussed. Two approximations are applied: the model is based on narrowband propagation, i.e., the bandwidth is assumed not to exceed a few hundreds of kHz [4]. Further, Rayleigh scattering is assumed. This represents the worst case of scattering, however, in this event, maximum diversity gain can be achieved. Results will thus tend to be optimistic for the effect of diversity.
The results presented here originally stem from (unpublished) research at D.U.T. on protocol design in mobile packet radio networks. In the original application it was concluded that the waiting time for retransmission of a lost packet can be short if shadowing fluctuates with σ_s less than 6 dB. On the other hand, if shadowing is characterised by larger σ_s, the protocol has to wait until the vehicle has moved several tens of meters to experience uncorrelated shadowing attenuation. This application comes close to common practice in Combat Net Radio (CNR), where it is known that moving the vehicle a few meters can have a dramatic influence on the success of communication.

Due to shadowing and model inaccuracies, the (experienced) local mean p_l of the received signal is log-normally spread about the predicted area mean p_a. Secondly, the actual received signal power p_s is a statistical variable with Rayleigh statistics about the local mean p_l [9]. If the power p_s is by accident below the threshold p_0, then the attempt to establish a radio link fails. Changing the antenna position gives a new (statistically uncorrelated) sample from the local process of multipath cancelling but attenuation from shadowing and inaccurate prediction remains fixed. Initially, we assume a frequency management algorithm that prescribes the use of a certain radio channel if the forecasted area-mean signal level p_a has sufficient margin α above a threshold p_0 (α*p_a/p_0, $\alpha>1$). In the second part of this appendix, the threshold is assumed to be dictated by interference signals rather than a known noise floor. In the latter case, the threshold is treated as a log-normal statistical variable. In both cases, the relevance of the second attempt is best evaluated from the conditional probability of success, according to

$$\mathrm{Prob}\{\mathrm{success}_2|\mathrm{failure}_1\} = \frac{\mathrm{Prob}\{\mathrm{success}_2.\mathrm{failure}_1\}}{\mathrm{Prob}\{\mathrm{failure}_1\}} \qquad \text{(B1)}$$

$$= \frac{I(1) - I(2)}{1 - I(1)} \qquad \text{(B2)}$$

with I(k) the probability that k successive attempts are all successful.

1. Noise limited network

Assuming a fixed threshold p_0, the probability I(k) is of the general form

$$I(k) = \int_0^\infty \exp\left(-k\frac{p_0}{p_l}\right) \frac{1}{\sqrt{2\pi}\,\sigma\, p_l} \exp\left(-\frac{(\ln p_l - \ln p_a)^2}{2\,\sigma 2}\right) dp_l \qquad \text{(B3)}$$

which is a function of the relative margin α and the model accuracy σ in natural units ($\sigma = 0.23026\sqrt{\sigma_p{}^2+\sigma_s{}^2}$). The integral is rewritten using $\exp\{\sigma t\sqrt{2}\} \triangleq \alpha p_l/p_0$ to allow application of the Hermite numerical method [20, ch 25]. Thus

$$I(k) = \sum_{i=1}^{N} \frac{w_i}{\sqrt{\pi}} \exp\left(- \frac{k}{\alpha} \exp(\sigma\, x_i\sqrt{2})\right) \qquad \text{(B4)}$$

Here w_i are weight factors at sample points x_i for an N-point integration [20]. Figs.4a and 4b illustrate the probability of success in the first attempt I(1) and second attempt (B2). The local mean forecast error $\sqrt{\sigma_p{}^2+\sigma_s{}^2}$ is 4 and 8 dB, respectively.

For a rough model ($\sigma_t \approx 12$dB, not illustrated), the probability of success in a second attempt becomes as low as 20 to 30% even for forecast margins α as high as 10 to 20 dB. A conclusion, which is intuitively agreeable, is seen from the conditional probability of success in a second attempt (broken lines): Performing a second attempt is only worthwhile if the forecasting algorithm is accurate ($\sqrt{\sigma_s{}^2+\sigma_p{}^2} < \sigma_R$ <6dB). On the other hand, if shadowing and model inaccuracies dominate local multipath variability, the most reasonable conclusion from the failure of a first attempt is that the frequency assignment algorithm produced an erroneous forecast. A second attempt then is likely to fail again. More in general, one may conclude that improving the reliability of network management requires both improved models and operational techniques, including diversity. Improving the model can not compensate inaccuracies due to multipath. Modifying operational instructions without improving the propagation model will only frustrate local operators.

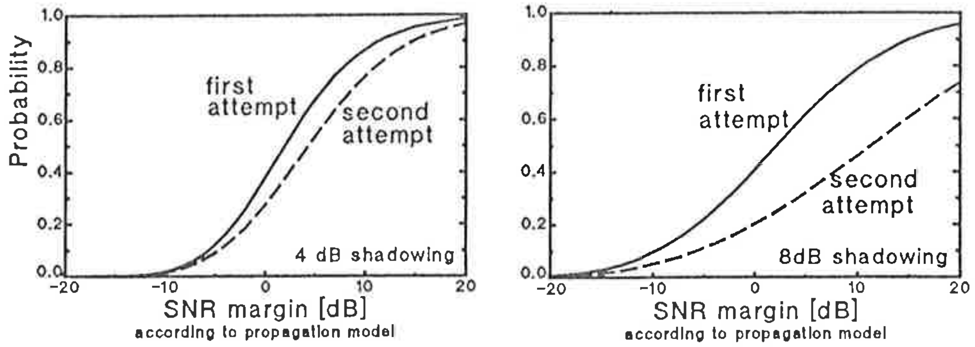


Fig.4: Probability of immediate success in establishing a radio link in a Rayleigh scattering environment, and the conditional probability that a second attempt is successful given the failure of a first attempt. Combined shadowing and model deficiencies are 4 and 8 dB, in Fig.4a and 4b, resp.

2. Interference limited network

The concept of [22] is applied for the event of one dominant interferer. The frequency assignment algorithm prescribes the use of a frequency if the signal power is expected to exceed the interference power by at least the threshold ratio z. The forecast margin above this threshold is denoted α. The desired signal and accumulated interference have correlated shadowing. For low antennae in a forest, the correlation ρ was found in the range 0.1 to 0.4, while $\rho \approx 0$ in an open field. Since the model accuracy σ_p was found relatively insensitive to the propagation distance, the effective logarithmic standard deviation σ_e is found from

$$\sigma_e^2 = (0.23026)^2 \quad (\sigma_p^2 + \sigma_s^2) \; 2 \; (1-\rho) \tag{B5}$$

The ratio w of the local-mean powers of signal and interference is log-normally distributed about the (forecast) area mean ratio αz

$$f_W(w) = \frac{1}{\sqrt{2\pi}\, \sigma_e \, w} \exp\left(- \frac{\ln^2 w/\alpha z}{2\, \sigma_e^2} \right) \tag{B6}$$

The probability I(k) of k successive successes is known from diversity techniques in cellular radio telephony [22,(8)]

$$I(k) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \left[\frac{\alpha}{\alpha + \exp(2\, \sigma_e\, t)} \right]^k \exp(-t^2)\, dt \tag{B7}$$

Using (B2), the conditional probability of success in a second attempt is calculated and portrayed in Fig.5.

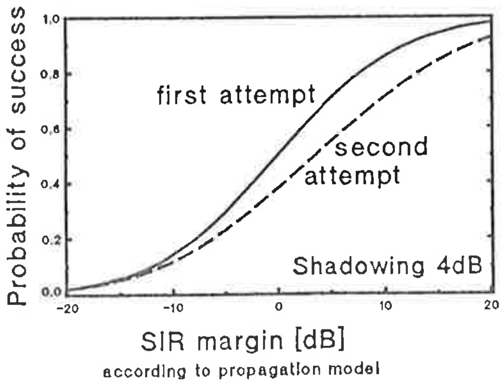


Fig.5: Probability of success in establishing a radio link in an interference limited network with Rayleigh scattering channels. Combined shadowing and model deficiencies is 4dB.

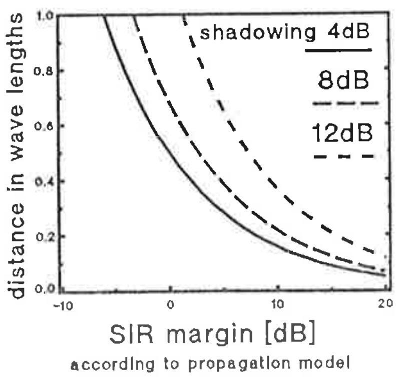


Fig.6: Expected required horizontal displacement of the antenna position as a function of the forecast margin for models of various accuracy.

Assuming exponentially distributed fade lengths, the average distance over which the C/I-ratio drops below the threshold z equals the average distance δ required to move an antenna out of a multipath null. Given the local mean C/I ratio w, δ is found from rewriting the average fade duration for two contending Rayleigh distributed signals [21].

$$\frac{\delta}{l} = \frac{\sqrt{2}\,\sqrt{z}}{\pi\,\sqrt{w}} \tag{B8}$$

Averaging over the log-normal distribution (B6), one finds

$$\frac{E[\delta]}{l} = \frac{\sqrt{2}\,\sqrt{z}}{\pi} \int_{w=0}^{\infty} \frac{1}{\sqrt{2\pi}\,\sigma_e\,\sqrt{w}} \exp\{\frac{-(\ln w - \ln \alpha z)^2}{2\,\sigma_e^2}\}\ d\ln w \tag{B9}$$

Substituting $w = \alpha z \exp\{\sqrt{2}\ \sigma_e x\}$ results in

$$\frac{E[\delta]}{l} = \int_{-\infty}^{\infty} \frac{2\sqrt{z}\ \exp\{-x^2 - \frac{1}{2}\sqrt{2}\sigma\ x\}}{\pi\sqrt{\alpha z}\ \sqrt{2\pi}\ \sigma}\ dx = \frac{2}{\pi\sqrt{\alpha}\ \sqrt{2}} \exp\{\frac{\sigma^2}{8}\} \tag{B10}$$

The expected displacement of the antenna as a function of the predicted margin α is shown in Fig.6. The curves suggest that if accidental bad positionig of the antenna is to be resolved by position tests, only minor displacements are required, since the wave length is typically less than one meter.

DISCUSSION

D. YAVUZ, TUR

Was the US-ECAC model TIREM (Terrain Integrated Rough Earth Model) which uses digitized terrain data plus multiple diffraction, reflection and other sub-models considered for your application?

AUTHOR'S REPLY

The analysis was initalized with relatively simple models because of our special application for rapid frequency assignment with relatively limited computer support. Further, we felt that converting a propagation model to a new database is not always trivial. Nevertheless, TIREM can be of interest as soon as the computer used for frequency assignment is upgraded. In present investigations on propagation in Band III (1300-1800 MHz), TIREM is one of the models considered in the analysis at FEL-TNO.

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