Rain Outage Modeling for Tactical Applications

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Introduction

Advances in rain-outage modeling to meet tactical communications systems planning needs have been made as a result of research and development (R&D) by a propagation-reliability working group convened by the Space and Terrestrial Communications Directorate (S&TCD) in the Research, Development and Engineering Center (RDEC) of the U.S. Army Communications-Electronics Command (CECOM). The attenuation of radio signals by rain increases with radio frequency and is perhaps the most significant factor affecting the propagation performance of microwave links above approximately 8 GHz.

New methods are being developed to address the propagation reliability of tactical communications networks that are deployed only for days or perhaps just hours. Traditional propagation-reliability methods consider average communications outage based on long-term (historical) meteorological statistics. Propagation-reliability forecasting methodology based on short-term (predictive) meteorology improves communications and avoids the waste of resources associated with overdesign in tactical communications networks. The focus of this paper is on a new model that forecasts rain outage for selectable time periods at any location worldwide.

A precedent for forecasting is the use of the expected properties of the ionosphere to plan the use of radio frequencies for HF radio transmission. For dynamic terrestrial networks, including earth-space links, meteorological phenomena such as temperature, rain, fog, wind, and clear-air layering can be forecast, but advances must be made in translating these meteorological forecasts into propagation forecasts suitable for estimating the propagation reliability of radio systems. The feasibility of propagation forecasting has been demonstrated by the ability to forecast microwave clear-air fading up to a day in advance [1].

This paper introduces approaches to network planning and management that incorporate forecasting ideas. A conceptual 24-Hour Network Performance Management System (24NPMS) using propagation forecasts derived from meteorological forecasts is discussed. For network planning, the emphasis is on 24-hour forecasting because many meteorological phenomena have a diurnal cycle.

The rain-outage forecasting method is based on the International Radio Consultative Committee (CCIR) rain-attenuation model extended by an outage-probability scaling factor determined by rain characteristics for the selected time interval and geographical region. This method accounts for the variations in rain quantity and intensity that affect propagation performance and are critical in determining the reliability of rain-impacted tactical communications systems.

The paper also describes a calendar-month rain-outage model developed for application to Mobile Subscriber Equipment (MSE) network planning. This new methodology supports the planning of MSE SHF down-the-hill links (14.5-15.35 GHz) which are impacted by rain attenuation because of their operating

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This work has been sponsored by the Improved Spectrum Efficiency Modeling and Simulation (ISEMS) project of the Space and Terrestrial Communications Directorate (S&TCD) of the Research, Development and Engineering Center (RDEC), U.S. Army Communications-Electronics Command (CECOM).

frequency. The methodology has been implemented and integrated into the MSE Network Planning Terminal (NPT). This integration includes the development of a method for combining the effects of rain attenuation and multipath fading on SHF links in a manner that supports tactical link-planning requirements.

Network Planning with Forecasting

New approaches to network planning and management become possible with forecasting. 24NPMS is a conceptual system proposed by a network management automation and integration working group convened by S&TCD [2]. 24NPMS will automatically plan, engineer, and direct the installation and operation of a tactical military communications network anywhere in the world, with a higher probability of successful operation than that of a communications network engineered and maintained manually. This automated network management concept is characterized by planning that integrates the effects of propagation forecasts, traffic forecasts, and real-time network status; a dynamic statistical network model; and automatic improvement of the algorithms underlying the dynamic model as a result of physical-network feedback. Implementation of this concept will integrate state-of-the-art models, algorithms, and computer simulations with available tactical system and network management technology such as the MSE NPT, a new battlefield automated system, fielded in 2QFY94, designed to efficiently integrate network planning, communications engineering, frequency management, and electronic-threat analysis.

The planning phase of 24NPMS uses propagation forecasts derived from meteorological forecasts to accommodate the dynamics of tactical communications networks (Figure 1). For network planning, the emphasis is on 24-hour forecasting because many meteorological phenomena have a diurnal (24-hour) cycle. Historical databases of meteorological information will be included in 24NPMS to allow propagation prediction in the absence of meteorological forecasts. The historical information will be superseded by local forecasts. Algorithms will be included for evaluating the applicability of forecasts and for extrapolation to areas for which meteorological information is not available.

The flow of propagation-related information in the planning phase of 24NPMS is shown in Figure 1. The "Propagation Forecast Algorithms" block converts meteorological forecasts into propagation forecasts. The "Link Reliability Models" block relates propagation information to link performance. The "Network Planning Algorithms" block relates force laydown, reliability requirements, and link performance information. The "Network Model" block generates a network model and produces a plan.

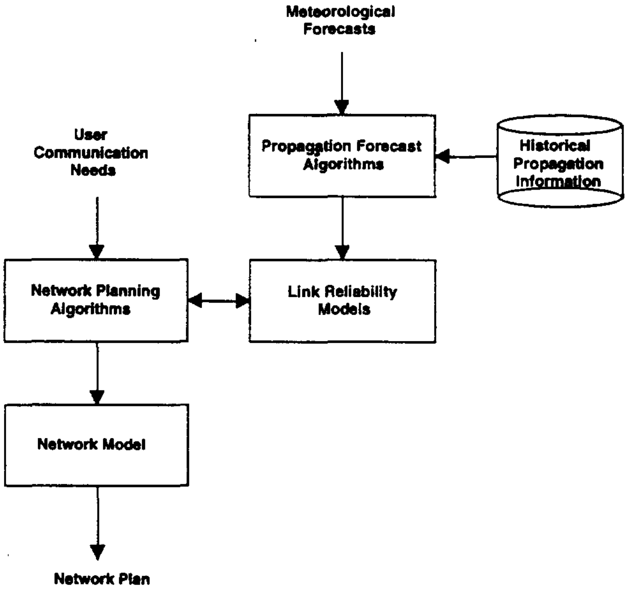

Figure 1. Use of Meteorological Forecasts

Rain-Outage Forecasting Method

The rain-outage forecasting method described in this paper requires knowledge of the expected accumulation of rain in the forecast period and invokes scaling to relate outage (t) in a forecast period to annual rain outage (T)

$$t = \beta \times T \qquad (1)$$

where β is a scaling coefficient. Scaling allows access to existing information about rain that includes world description of the occurrence of rain and the calculation of rain-attenuation probability.

The value of β for a forecast period depends on the expected amount of rain. The expression for β used in the rain outage forecasting method is

$$\beta = s / S \qquad (2)$$

where s is the expected accumulation of rain in the forecast period, and S is the annual accumulation of rain for the forecast location, both expressed in millimeters.

The expression for ß in Equation 2 should be viewed as a first approximation that allows development and initial application of the method. The ratio s/S is certainly a significant indicator of the expected rain outage in the forecast period, but influences related to the type of rain or season of the year may also need to be considered.

The steps in the application of the rain-outage forecasting method follow from Equations 1 and 2:

a. Obtain allowed rain outage (t) for the forecast period from network-planning information.
b. Obtain expected rain accumulation (s) from meteorological forecast.
c. Calculate scaling coefficient (ß) from s and the annual rain accumulation (S) for the forecast location.
d. Calculate annual outage (T) from the allowed outage (t) using the scaling coefficient (ß).
e. Perform link engineering using rain attenuation calculated by a method that uses annual outage (T) as input.

These steps and the rain-attenuation calculations are illustrated and discussed below.

Allowed Outage

As an illustration, suppose that the allowed rain outage in a 24-hour forecast period is, from planning information,

$$t = 1 \text{ minute} \tag{3}$$

An outage objective of one minute may actually be lenient if the link is to be used for data transmission and the outage occurs as a single one-minute event during the peak of a rain storm while critical data are being transmitted.

The outage time can be related to MSE propagation-reliability requirements by converting the outage time (t) to a percent outage (p) for the forecast period

$$p = 100 \times t / (24 \times 60) = 0.07 \text{ percent} \tag{4}$$

The corresponding propagation reliability is 99.93 percent, obtained as the complement (100 – p) of the percent outage. The MSE propagation-reliability requirement is 99.9 percent for critical users on single-thread links, and it can be as high as 99.99 percent in an environment with a high probability of fading [3].

Further suppose that a rain accumulation of 24 millimeters for the 24-hour period is obtained from a meteorological forecast

$$s = 24 \text{ millimeters} \tag{5}$$

for a location where the annual rain accumulation is

$$S = 1200 \text{ millimeters} \tag{6}$$

obtained from a historical reference database. The scaling ratio (ß) for this case is, from Equation 2,

$$ß = 24 / 1200 = 0.02 \tag{7}$$

Using this scaling, the one-minute outage for the forecast period translates to an equivalent annual outage, from Equation 1,

$$T = 1 / 0.02 = 50 \text{ minutes} \tag{8}$$

This scaled annual outage is needed as an input to the calculation of rain attenuation.

Rain Attenuation

The allowed outage and the amount of rain determine the rain attenuation (A_{rain}) that a link must withstand to operate satisfactorily in the forecast period. The approach of the CCIR is used to calculate the rain attenuation [4]

$$A_{rain} = 0.12 \times \tilde{A} \times D_{eff} \times P^{-[0.546 + 0.043 \log(P)]} \tag{9}$$

where $\tilde{A}$ is the specific rain attenuation, D_{eff} is the effective path length, and P is the annual percent outage calculated from T. The extension of the CCIR method is in the calculation of P from T.

The CCIR baselines its rain outage calculations on rain rates that are exceeded 0.01 percent of the time. World contours of these rain rates are available. These rain rates are used to obtain $\tilde{A}$, expressed in dB per kilometer, exceeded 0.01 percent of the time

$$\tilde{A} = a \times R^b \tag{10}$$

where R is the rain rate, expressed in millimeters per hour, that is exceeded 0.01 percent of the time. The coefficients a and b depend on radio frequency, polarization, and rain temperature. Tabulated values of these coefficients are available [4].

An effective path length, shorter than the length of a link, is used to calculate the rain attenuation for a link that is exceeded 0.01 percent of the time. This accounts for the non-uniform distribution of rain along the path caused by the cellular structure of rain. The equation for this effective path length (D_{eff}), expressed in kilometers, is

$$D_{eff} = D / (1 + 0.045\ D) \qquad (11)$$

where D is the length of the link in kilometers. This effective path length is valid only as a multiplier for $\tilde{A}$ in Equation 9.

To provide an example of numerical values of A_{rain}, consider rain attenuation for a 5-kilometer 15-GHz link. The annual probability corresponding to the previously calculated annual outage of 50 minutes is

$$P = 100 \times 50 / (365 \times 24 \times 60) = 0.01 \text{ percent} \qquad (12)$$

The coefficients a and b in Equation 10 for the specific attenuation due to rain are

$$a_h = 0.0367 \qquad (13)$$

$$a_v = 0.0335 \qquad (14)$$

$$b_h = 1.154 \qquad (15)$$

$$b_v = 1.128 \qquad (16)$$

where the subscripts h and v indicate horizontal and vertical polarization respectively. The effective path length is

$$D_{eff} = 5 / (1 + 0.045 \times 5) = 4.08 \qquad (17)$$

The calculated rain attenuation that is exceeded for 0.01 percent of the time on the 5-km 15-GHz path is shown as a function of the rain rate in Figure 2. The rain attenuation is

$$A_{rain} = 24.7 \text{ dB} \qquad (18)$$

assuming that CCIR world charts characterize the example location by an R value of 100 mm/hour for vertical polarization. The link must be planned to withstand this attenuation during the 24-hour forecast period.

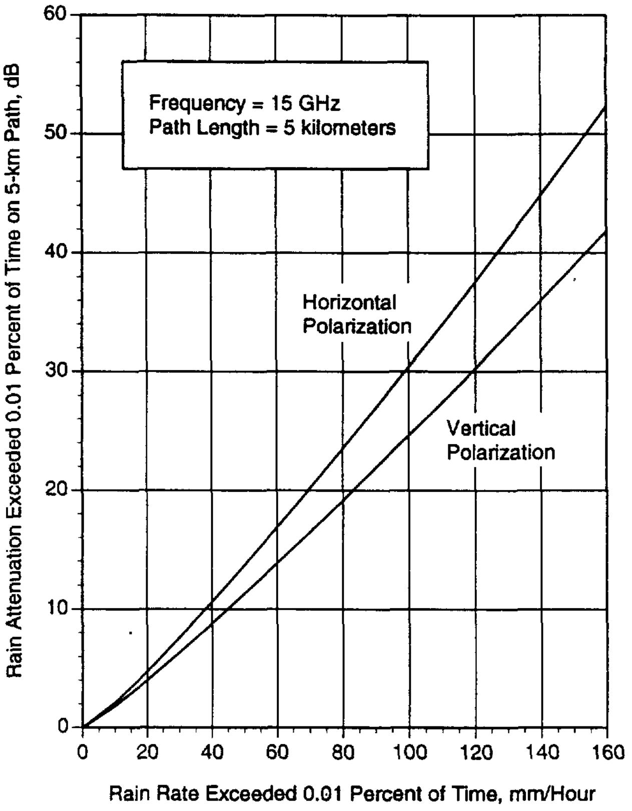

Figure 2. Rain Attenuation Example

The example illustrates an application of the rain propagation-reliability forecasting method. The substantial rain attenuation at 15 GHz affects network design and link performance. The attenuation depends on location, as illustrated for four regions of the world in Table 1. Radio equipment may not operate satisfac-

Table 1.
Path Rain Attenuation Exceeded 0.01 Percent of Time
Frequency = 15 GHz, Path Length = 5 km

Region	Rain Rate R mm/hour	A_{rain} Horizontal Pol. dB	A_{rain} Vertical Pol. dB
Yugoslavia	40	10.6	8.8
Korea	60	16.9	13.9
Northern Florida	100	30.4	24.7
Central America	160	52.4	41.9

torily in the presence of the larger of the rain attenuation values in Table 1. If the attenuation is too large, the link must be made shorter or a smaller propagation reliability must be accepted. Vertical polarization is better than horizontal polarization because it has smaller rain attenuation. The difference in attenuation due to polarization in a high-rain region such as Central America can be large (about 10 dB in the example in Table 1).

Rain Performance Model for MSE

Principal elements of an MSE network are the circuit/packet switches and the UHF line-of-sight (LOS) radios used to interconnect them. The radio and switch shelters are interconnected by either cable or SHF LOS radio, depending on the distance between the two shelters. The SHF radios are impacted by rain attenuation since they operate in the 14.5-GHz-to-15.35-GHz band. The rain attenuation models described previously have been integrated into the link engineering modules of NPT to provide the capability for planning and engineering tactical SHF communication links. This integration includes an innovation in that rain outage is calculated on a calendar-month basis. Previously available methods provide annual or worst-month calculations [4]. Calendar-month calculations are made possible by using the monthly accumulation of rain in Equation 2.

An asset-placement module of NPT provides a network laydown that interconnects the communications assets required to effectively support the battlefield force structure [5]. A follow-on module evaluates the network laydown by determining the predicted path reliability of each radio-communications link, using rain attenuation, multipath fading, and radio-equipment-characteristics models. The predicted reliability result for each link is compared to a user-specified reliability objective. If the predicted path reliability equals or exceeds the objective, the link is acceptable. Otherwise, the link is reengineered until it meets its reliability objectives.

Performance Models

Effective MSE tactical link engineering requires planning for specific months of the year. The reliability objective and the particular month of interest for each link are specified by the user. The default value for average monthly path reliability is 90 percent; however, it is recommended that this value be increased to at least 99 percent or even 99.9 percent for single-thread and critical-service UHF and SHF links.

The dominant propagation impairment affecting UHF links is multipath fading [6]. The propagation impairments affecting SHF links are multipath fading and rain attenuation. An example of the impact of multipath fading at 15 GHz is depicted in Figure 3 for a fixed fade depth of 8 dB as a function of climate factor. A climate factor, $C = 1$, is used for areas of average propagation (most of the continental United States [CONUS]). For difficult CONUS climates and terrains (e.g., the U.S. Gulf coast), $C = 10$ is used. The value of $C = 10$ is also appropriate for similar international climates and terrains. For worst-case conditions, $C = 100$ is used. This would be appropriate for cases of extreme heat and humidity, such as the Red Sea or Persian Gulf coastal plain or equatorial conditions. Monthly climate factors are part of NPT [7].

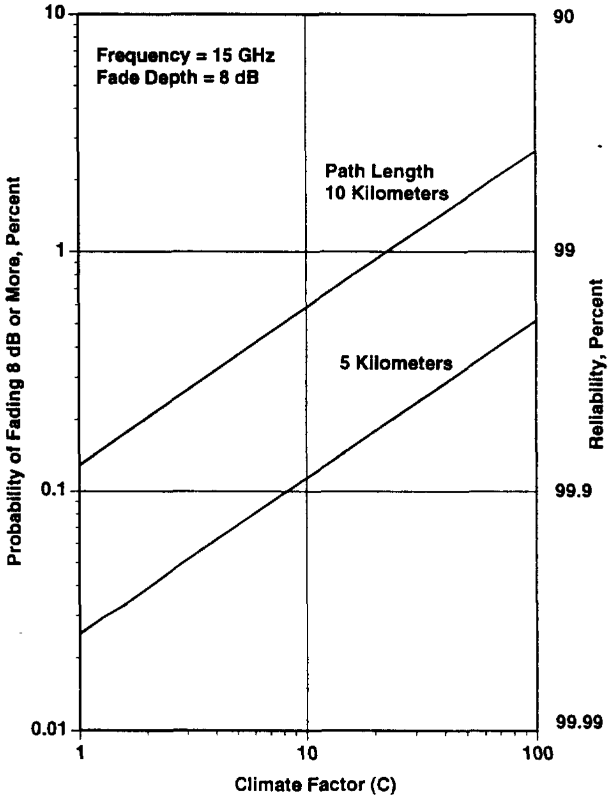

Figure 3. SHF Radio Multipath Fading

The general path-reliability engineering process is depicted in Figure 4 in terms of fade margins. Fade margin is the dB difference between the normal received signal strength and the radio's operating bit-error rate threshold. A required fade margin is derived from the reliability objective by application of the rain attenuation and multipath fading models. The minimum value is 8 dB, which accounts for variations in radio and antenna equipment and possible link installation difficulties. The predicted fade margin is calculated from path length, path location, path clearance, and equipment parameters. If the predicted fade margin equals or exceeds that required, the link is incorporated into the network plan. If not, the link is reengineered.

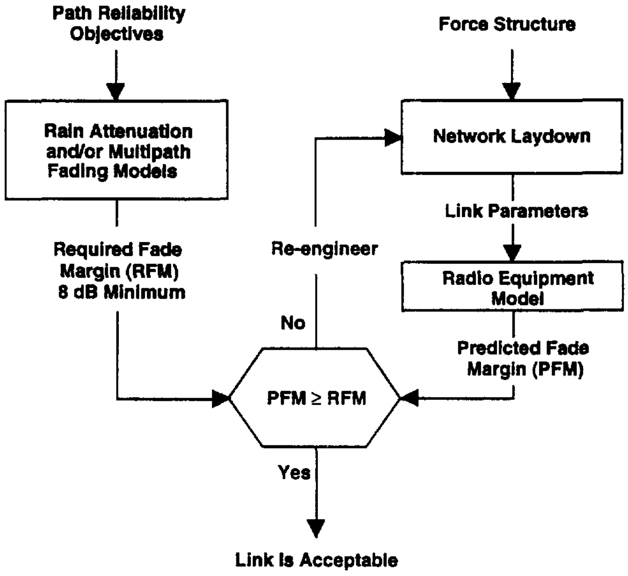

Figure 4. Path Reliability Engineering Process

The derivation of the required rain fade margin is depicted in Figure 5. The inputs to the NPT rain attenuation module are link length, location, polarization, and frequency, the reliability objective, and the month during which the link would be installed. Internal databases provide annual rainfall, monthly rainfall, and rain-rate data. The center coordinates of the link are used to find the reference triangle in the database that contains these coordinates. The monthly rain data are in the database for each of the triangle's vertices. The monthly rain data for the center of the link are obtained by three-dimensional linear interpolation using a plane defined by the three points. The required rain fade margin, 8 dB minimum, is calculated from the outage objective, the effective path length, and the specific attenuation values. The required multipath fade margin is derived in a similar manner using a climate factor database [7].

SHF radio performance can by impacted by rain attenuation, multipath fading, or both, depending on path length and application climate. The method for combining the effects of rain attenuation and multipath fading on SHF links used in NPT is depicted in Figure 6. Required fade margins, rounded up to the next higher integer value with an 8 dB minimum, are calculated separately for rain attenuation and multipath fading, with each starting from the total reliability objective. The larger of the two fade margins is then used to separately calculate the predicted rain and multipath reliability. If the sum of the two equals or is greater than the reliability objective, the link is incorporated into the network plan. If not, the larger

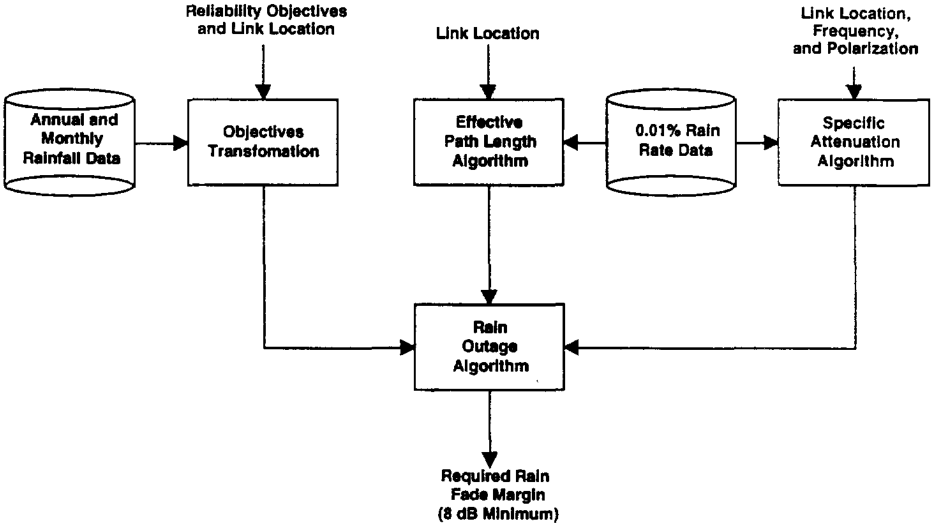

Figure 5. Rain Attenuation Model

calculated fade margin is repeatedly increased by one dB until the predicted reliability equals or is greater than the reliability objective. The resulting required fade margin is then used as described in Figure 4 to determine if the link is acceptable.

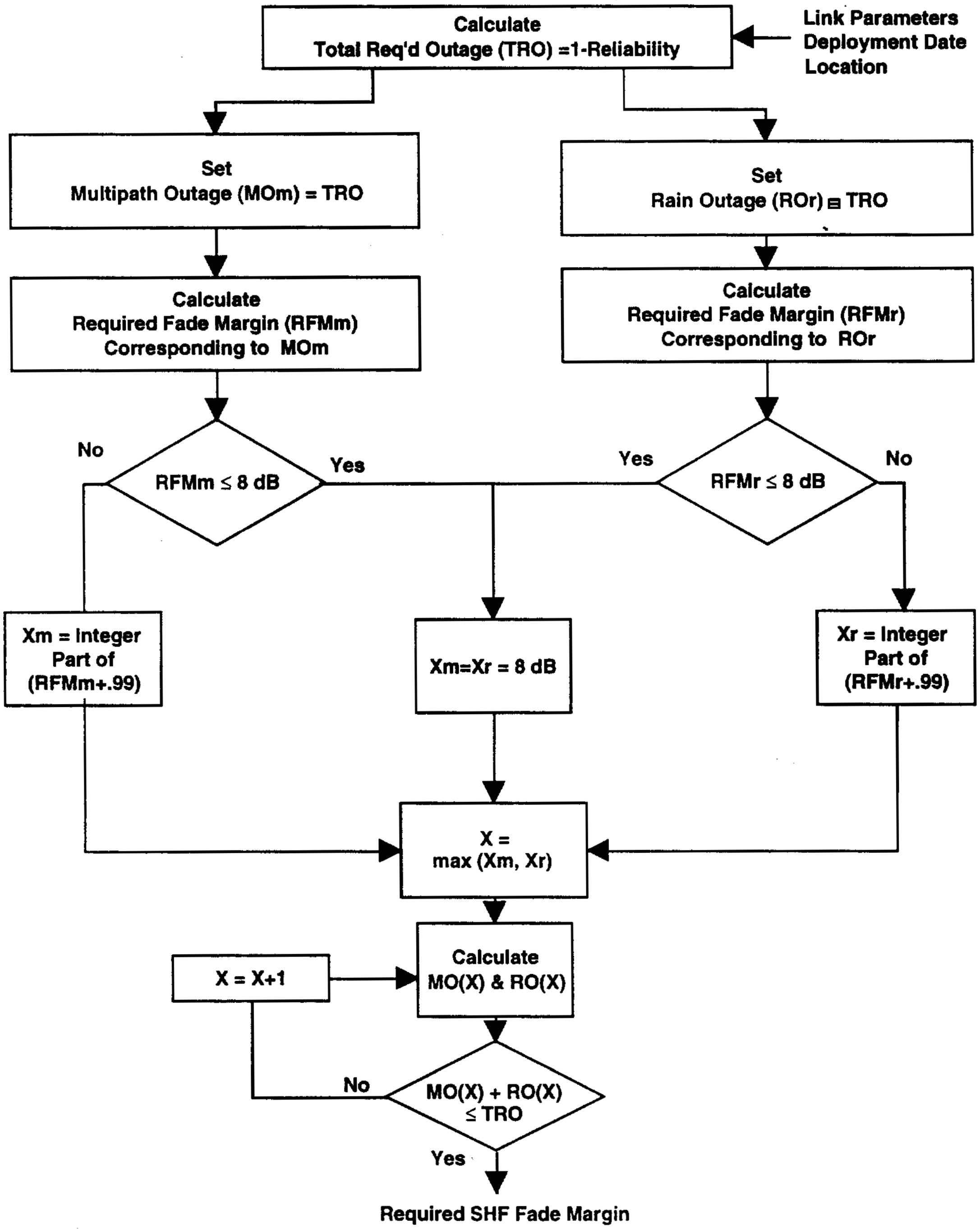

Figure 6. SHF Combined Rain and Multipath Required Fade Margin

The calculation of reliability from the fade margin requires inversion of Equation 9. This inversion, derived for application in NPT, is

$$P = 10^{2.355968\,(-2.694789 + y)} \tag{19}$$

$$y = [3.403848 - 4.189796 \log(A_{rain}/(\tilde{A}\, D_{eff}))]^{1/2} \tag{20}$$

This inversion has six-digit accuracy for the physically meaningful range of values used in NPT.

Conclusions

The rain propagation-reliability forecasting method provided in this paper improves the planning of tactical communications networks by including expected rainfall in the planning process. Forecasting has stimulated new approaches to network planning and management. Calendar-month performance engineering of SHF links in NPT has been made possible by the rain propagation-reliability forecasting method.

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