Exploring and Improving the Performance of Radio-Relay System Under Frequency-Selective Fading Channel

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Abstract – **In this paper we describe one simple method for exploring the performance of digital radio-relay system under frequency-selective fading propagation channel, and for improving it with linear adaptive equalizer. System M-curve signature measurement with fading simulator is explained in details, the calculation of system's BER performance and availability are reviewed, the structure of designed equalizer is described and results of its application within the radio-relay system are presented.**

Keywords – **Frequency-selective fading, M-curve signature measurement, Radio-relay system performance, Equalization.**

I. Introduction

Frequency-selective fading is the dominant propagation factor for digital radio-relay (RR) systems operating at frequencies below about 10GHz, and is increasing rapidly with path length [1]. Multipath propagation caused by tropospheric layers is strongly frequency dispersive and may cause serious degradation of transmitted signal's quality, or even complete outage of communication system. Impact of frequency-selective fading on digital microwave radio is briefly explored in many works [2], and is treated in recommendations regarding design and operation of RR systems ([1], [3], [4]). The robustness of digital microwave radio to frequency-selective propagation conditions is commonly defined in form of M-curve signature measurements, performed with propagation simulators during laboratory tests of RR devices.

The operation of propagation simulator having the role of frequency-selective channel is usually based on Rummler's simplified three-ray model (two-ray model) [5], described with modelling function given by:

$$H(j\omega) = a\left[1 - be^{-j(\omega-\omega_0)\tau}\right] \qquad (1)$$

where a stands for non-frequency selective fading (scaling factor), b describes amplitude of the ray delayed by τ from unity amplitude direct ray, and ω_0 stands for angular frequency of minimum in the response – *notch frequency*. The fade level is measured in decibels as $A = -20\log a$, and the relative notch depth as $B = -20\log(1-b)$. Thus, $A + B$ gives the total fade depth at the response minimum – *notch depth*. The amplitude response for this function is shown in Fig. 1 [2]. The value of delay between the main and secondary path ray (τ) is usually fixed at 6.3ns without any loss of generality, and it has no associated physical interpretation, although other delay values can be used for signature measurements.

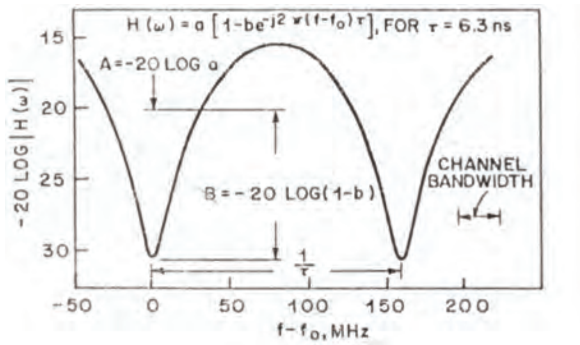

Fig. 1. Amplitude response of the modelling function.

The two possible solutions for response consist of one with $b < 1$ - minimum phase function, and one with $b > 1$ - nonminimum phase function. The case where the main path leads the secondary path is referred to the minimum phase case, while the case where the main path lags the secondary path is referred to the nonminimum phase case.

II. M-curve signature Measurement

M-curve signature describes system's ability to combat multpath fading as a function of frequency. The procedure used to construct M-curve signature (shown in Fig. 2) requires that a notch be created at a given frequency offset from the carrier frequency; the notch depth is increased until a specified bit error rate (BER) is attained. Typically two BER limits are explored: 10^{-3} and 10^{-6}. The depth of the notch is then plotted at this frequency offset; the shape of the resulting plot of notch depths versus frequency offset is responsible for its name [5]. M-curve signatures for both minimum phase and nonminimum phase transfer function case must be measured to obtain a true picture of digital radio's robustness to multipath fading, since some communication systems perform differently under these conditions. Thus, propagation simulator used for signature measurement should be able to operate in both of these modes.

When the signature curve measurement is done, the values of signature width and depth should be calculated. The signature width for particular system is defined as distance between frequencies (left and right from the centre frequency) where notch having depth value of 40dB causes no

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degradation on system performance. Signature depth stands for mean value of measured M-curve signature bounds within the signature width bandwidth, and may be calculated as fraction of area under M-curve signature and value of signature width.

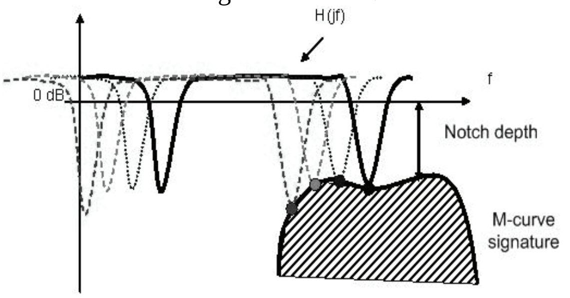

Fig 2. Radio system M-curve signature measurement.

Simulation of frequency-selective fading channel is performed at receiver intermediate frequency (IF), having the most common values of 70MHz or 140MHz. Signal at receiver IF is routed through simulator, and than back to receiver in IF closed loop structure. For evaluation of BER an autonomous device - BER tester, independent of fading simulator may be used. This device is used as a source of digital test signal (realized in form of appropriate pseudo-random sequence) that's been routed through radio RF closed loop, and then formed IF loop, back to receiving point of the unit in order to be compared with original sequence for the purpose of BER calculation. This measurement scheme is presented in Fig. 3.

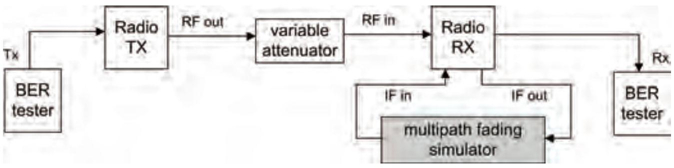

Fig. 3. Measurement with multipath fading simulator and autonomous BER tester device.

Multipath fading simulator should be able to operate in bandwidth area of interest around central (IF carrier) frequency. The bandwidth of interest value depends on radio bitrate and channel spacing, i.e. spectrum efficiency class of RR device; signature width and depth limits for medium capacity systems valid for both minimum and nonminimum phase cases are defined in [4].

During previous work we have explored performance of RRU13A/34 and RRU23A/34 - medium capacity RR systemsoperating at 13GHz and 23GHz frequency bands and having 34.368Mbit/s (17x2) bitrate with commercial propagation simulator device [6]. The results we have achieved show that for a given capacity and modulation according to OQPSK scheme, system signature width for different RR devices closely match and have the values around 26.7MHz for minimum phase and around 24.7MHz for nonminimum phase case (according to [4], less than 30MHz is required for a Class 1 system at BER=10^{-3} limit). Also, minimum notch depth values in M-curve signature are always positioned around 135MHz and 145MHz points, for both operating modes. Thus, fast evaluation of system signature depth may be achieved by measuring system signature in range between these two points; for this purpose we have used parallel resonant RLC structures that perform as notch filters in the frequency area of interest. The position of the notch in such a structure may be controlled by adjusting the value of capacitance in resonance (for a fixed value of involved inductance), while the notch depth may be controlled via value of involved resistance. Usage of JFET as voltage-controlled resistance and varicap diode as voltage-controlled capacitance showed to be applicable for this purpose. An external circuitry for appropriate polarization of these elements may be used in order to achieve full controlling of notch filter transfer function by simply adjusting the polarization voltage values.

For the purpose of M-curve signature measurement we have used easy-to-construct resonant structure described above to simulate minimum and nonminimum phase frequency-selective fading channels at receiver IF; polarization voltages for JFET and varicap diode are generated by external DACs driven from the microcontroller (Fig. 4). Digital signal values corresponding to predefined set of attributes (notch position and depth) are stored in memory of microcontroller and may be addressed by the user via PC serial interface. Also, either minimum or nonminimum phase operating mode may be selected.

The simulator we have designed has the following characteristics: notch frequencies may be settled within the range from 133MHz to 147MHz with 1MHz step and 0.1MHz precision, while notch depth may be chosen from 0 to 30dB with 0.5dB step and 0.2dB precision. System may work in both minimum and nonminimum phase mode, and is fully controlled by the user PC – for this purpose we have developed hyperterminal software for communication between PC and on-board microcontroller.

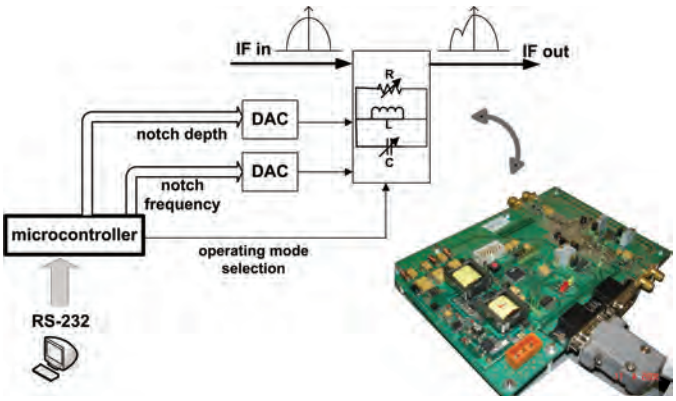

Fig. 4. Structure of frequency-selective fading simulator with controllable notch frequency and depth.

III. System Performance Calculation

When M-curve signature measurement is done, and values of signature width and depth are found, the probability of outage caused by multipath fading and thermal noise can be computed using the formula:

$$P = (P_S^{\alpha/2} + P_F^{\alpha/2})^{2/\alpha} \quad (2)$$

where P_F stands for probability that system flat fade margin is exceeded and can be calculated according to [3], while P_S stands for probability of outage due to selective fading. There are several methods that use concept of signatures to compute P_S [1], the method recommended in [3] assumes $\alpha = 2$ and P_S is given by:

$$P_S = 2.15\eta(W_M \times 10^{-B_M/20} \frac{\tau_m^2}{|\tau_{r,M}|} + W_{NM} \times 10^{-B_{NM}/20} \frac{\tau_m^2}{|\tau_{r,NM}|}) \quad (3)$$

where W_x stands for signature width (GHz), B_x for signature depth (dB), $\tau_{r,x}$ for the reference delay (ns) used to obtain signature, with x denoting either minimum phase (M) or nonminimum phase (NM) fades. τ_m stands for the mean time delay (ns) that can be calculated using the path length d (km):

$$\tau_m = 0.7(\frac{d}{50})^{1.3} \quad (4)$$

The propagation parameter η is related to the deep fade occurrence factor P_0:

$$\eta = 1 - \exp(-0.2 \cdot P_0^{3/4}) \quad (5)$$

Multipath occurrence factor P_0 is corresponding to the percentage of the time (%) of exceeding fade depth boundaries in the average worst month. Its value depends on carrier frequency, path length, antenna heights and area terrain profile and can be calculated according to [3].

Using above expressions probability of outage due to frequency-selective fading (given in the percentage of time) can be computed, and its value can be compared with system availability limits calculated according to [7] (0.006% of time for long haul, 0.04% of time for short haul and 0.05% of time for access networks – path lengths up to 50km) and system quality limits corresponding to severely error second ratio (SESR) calculated according to [8] (0.0012% of time for 0.01 long haul, 0.0022% of time for 0.02 long haul, 0.015% of time for short haul and access networks – path lengths up to 50km). We have calculated probability of outage due to multipath fading for system signature depth values of 14dB, 20dB and 25dB and present them as a function of frequency and path length in Table I.

The values presented in Table 1 (calculated for hypothetical system with assumed OQPSK modulation scheme, 100m antenna heights, 39dBi total antenna gains, 25dBm system output power, 28 MHz channel spacing, 6.3 ns nominal echo delay, 30 MHz signature widths at 1+0 link configuration) clearly show that impact of multipath fading on system performance increases rapidly with path length and operating frequency. When outage due to multipath fading exceeds the recommended limits, involving some kind of protection against frequency-selective fading is necessary.

TABLE I
OUTAGE DUE TO MULTIPATH FADING (HYPOTHETICAL SYSTEM)

d[km]	f[GHz] / depth	2	4	7	15
20	14db	0.000383	0.000452	0.000615	0.001753
	20db	0.000195	0.000242	0.000365	0.001363
	25db	0.000112	0.000149	0.000256	0.001191
30	14db	0.002704	0.003198	0.004394	0.012961
	20db	0.001380	0.001719	0.002649	0.010260
	25db	0.000798	0.001069	0.001881	0.009073
40	14db	0.010681	0.012664	0.017557	0.053378
	20db	0.005460	0.006848	0.010724	0.042986
	25db	0.003165	0.004290	0.007719	0.038417
50	14db	0.030610	0.036367	0.050843	0.159303
	20db	0.015677	0.019790	0.031493	0.130536
	25db	0.009110	0.012500	0.022985	0.117886

IV. IMPROVING THE SYSTEM PERFORMANCE

While the nature of some communication systems, like spread-spectrum and OFDM-based systems, decreases the impact of frequency-selective fading itself, many systems require additional countermeasures to propagation effects. There are two countermeasures to propagation distortion commonly used: diversity techniques and adaptive channel equalizers. Since the usage of diversity within RR systems seriously increases realization and maintenance costs, adaptive equalizers are considered to be very attractive solution to combat multipath fading effects.

In most communication systems that employ equalizers channel characteristics are unknown a priori, and, in many cases, channel response is time-variant. In such a case, the equalizers are designed to be adjustable to the channel response and, for time-variant channels, to be adaptive to the time variations in the channel response [9]. Time domain equalization is the most natural approach, since it attacks intersymbol interference directly: during the acquisition process previously distorted signal can be processed with the goal to re-establish its original quality, commonly observed in context of signal eye-pattern. Digital equalizers have the form of transversal filters whose internal structure depends on assumed algorithm for adaptation of filter tap coefficients and specific application. Various adaptation algorithms have been developed that differ on complexity, precision and convergence rate; the simplest structures of adaptive equalizers are linear adaptive equalizers based on Least Mean Square (LMS) or Zero Forcing (ZF) algorithm.

We made experiments in order to explore the optimal structure of adaptive equalizer in context of minimum complexity that satisfies demand for improving the performance of a system degraded by multipath fading. LMS adaptation algorithm was assumed (Fig. 5).

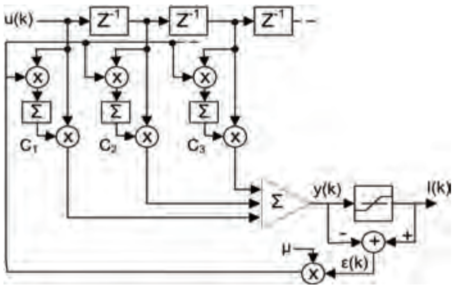

Fig. 5. Linear adaptive equalizer based on LMS algorithm

The functionality of LMS algorithm may be expressed by the following equations:

$$y(k) = \sum_{j=1}^{N} C_j u(k - j + 1) \qquad (6)$$

$$C_i(k+1) = C_i(k) + \mu \cdot \varepsilon(k) \cdot u(k-i) \qquad (7)$$

$$\varepsilon(k) = I(k) - y(k) \qquad (8)$$

Where $u(k)$ stands for (unequalized) input signal, $y(k)$ for signal after equalization, $I(k)$ for results of comparation $y(k)$ with threshold value, $\varepsilon(k)$ for error signal and μ for multiplication constant for weighting the adaptation of values of tap coefficients C_i. In [10] we have described in details the accepted structure having only three taps, that has been implemented on Spartan-3 FPGA and included in RR devices IMTEL Komunikacije Series A with E3+E1 capacity (Fig. 6). The ability of RR system RRU 8A (8GHz, E3+E1 capacity) to combat frequency-selective fading was tested in order to explore achieved improvement in performance with equalizer involved. Frequency-selective channel was simulated with propagation simulator previously described (the signal spectra at input and output port of simulator is shown in Fig. 7: notch freq. 133MHz, notch depth 15dB) and corresponding M-curve signatures for simulator operating in NM phase mode are given in Fig. 8.

Fig. 6. IMTEL Komunikacije adaptive equalizer unit

Demands for at least 3dB of improvement in signature depth for both M and NM phase modes with 3-tap LMS equalizer are completely satisfied. Amount of achieved improvement would increase significantly if equalizer is designed with more complexity, the design limitations that should be considered correspond to available digital resources and maximum operating frequency of digital logic. Having this in mind, FPGAs may be a good choice for low-cost realization platforms of adaptive equalizer structures.

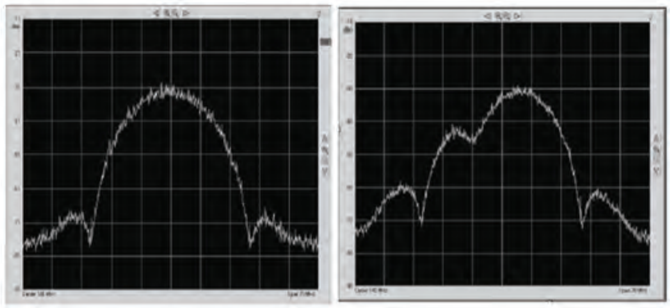

Fig. 7. Signal spectra at input (left) and output (right) of fading simulator: IF 140MHz, notch freq. 133MHz, notch depth 15dB

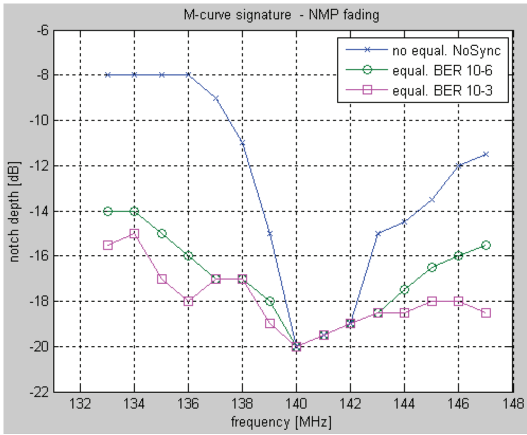

Fig. 8. M-curve signature for RR system with and without equalizer – NM phase fading case, E3+E1 bitrate, OQPSK modulation

V. Conclusion

In this paper the importance of measurement of multipath fading impact on RR system performance has been presented. Proposed easy-to-implement solution for propagation simulator can be used for the purpose of laboratory measurements, according to mentioned recommendations system performance can be computed and proposed equalizer structure can be used for its improvement.

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