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Effect of Noise in Optically-Fed Phased Array Antennas for CDMA Wireless Networks

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ABSTRACT

The characteristics of an optically fed phased array antenna are affected by the amplitude and phase noise introduced by optical amplifiers (EDFA) used in the system. A theoretical derivation and a numerical computation of the effect of phase noise on antenna performance are given in this paper. The phase fluctuations make the main beam to jitter around a mean value directly related to the mean and the variance of the amplified spontaneous emission induced random phase change.

INTRODUCTION

Wireless code division multiple access (CDMA) systems require a careful radio frequency (RF) planning for proper functionality. System optimization requires continuous antenna adjustments namely main lobe down tilting and beam azimuth changing which could be easily performed using phased array antennas. Also, the antenna arrays give the opportunity to better serve heavy traffic regions (Hot Spots) by dynamically switching beams of the base stations oriented towards lower traffic to those areas of higher traffic. A second phased array antenna can be used for global positioning system (GPS) timing acquisition. The overall synchronization of the CDMA network is provided through timing acquired via GPS satellites. The currently used method is vulnerable to physical obstruction and jamming signals. The usage of antenna arrays would give the ability to perform easy beam steering which would dynamically steer the antenna main lobe to the strongest GPS satellite signals available.

However, for phased array antennas, the usage of time delay network is required to provide the necessary phase shift for each antenna element, and phase shifting at microwave frequencies is cumbersome and seriously affect the compactness of the system. Optical feed offers a better alternative. Also, since optical fibers have very low loss over wide bandwidth, optical fiber is a good candidate for antenna remoting [1]. In the technique described here, all phase shifting and amplification are done in the optical domain. The conversions from optical frequencies to microwave frequencies and vice versa are accomplished by a transmit/receive module (TX/RX) consisting of internally modulated laser diodes and avalanche photo-detector as shown in Fig.1. The far-field radiation pattern of an antenna array consisting of N elements,

each having an element factor F_e , separated by a distance d , all fed with same excitations C_0 and having a linear phase shift of α , is given by [2]- [4]:

$$F_a(\theta, \phi) = \sum_{n=0}^{N-1} F_e C_0 e^{jn(k_0 d \cos \psi + \alpha d)} \quad (1)$$

This polynomial is a geometric progression and can be written in a closed form

$$F_a(u) = F_e C_0 \frac{\sin\{(N)(u + u_0)/2\}}{\sin\{(u + u_0)/2\}} \quad (2)$$

where

$$u = k_0 d \cos \psi \quad (3)$$

and

$$u_0 = \alpha d. \quad (4)$$

Here, $k_0 = 2\pi/\lambda_0$ is the microwave signal wave number in free space and $\cos \psi = \sin \theta \cos \phi$, where θ and ϕ are the angular coordinates of the spherical coordinate system.

Several techniques to control the phase of signals in a phased array antenna have been successfully tested [5], among which the most widely used are: the unilateral injection locking method [3], the electro-optic switching method [6] and the piezoelectric method [3]. In the first methods, the optical signal undergoes desired phase shift using classical electro-optical phase shifter such as Mach-Zehnder interferometer. In the piezoelectric (PZT) method, the linear phase shift between the array elements is realized using a simple PZT crystal over which optical fibers are wound. The desirable linear phase shift is achieved by applying a DC bias voltage to the crystal causing it to expand and thereby causing the fibers to stretch. Depending on the number of windings of fiber for each element, a different phase shift is experienced by each signal feeding different antenna elements. This phase shift is linear if the number of winding varies linearly. The phase shift in radians is given by [3]:

$$\Delta\Phi = 2 \times 10^{-2} N_w \pi^2 DV / \lambda_g \quad (5)$$

where N_w is the number of windings for the fiber feeding a particular antenna element, D is the diameter of the PZT ring, V is the DC bias voltage in volts and λ_g is the guide wavelength of the microwave signal modulating the optical carrier. Losses induced during splitting and processing of the optical signal could be considerable especially when the

number of antenna elements is large. The best possible way to compensate for these power losses is to incorporate an Erbium-doped fiber amplifier (EDFA) in the system. Since no isolator is needed between the optical digital signal processing module (Optical DSP) and the Transmit/Receive module, one EDFA could serve in both receiving and transmitting modes.

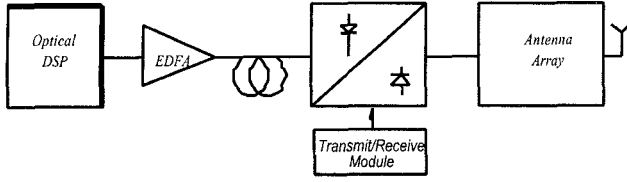


Fig.1. Antenna remoting over fiber using one EDFA in TX/RX modes

This paper discusses the effect of amplitude and phase noise on the beam jitter and consequent performance on the antenna array. Section 2 discusses the effect of EDFA amplitude noise on the antenna array characteristics whereas section 3 discusses the effect of EDFA phase noise on the antenna array characteristics. The conclusions are given in section 4.

EDFA AMPLITUDE NOISE

In a classical description, an EDFA could be modeled as a coherent device that amplifies the electrical field amplitude of the input signal E_{in} by a factor $\sqrt{G}$ where G is the power gain of the EDFA [3]. In the case of an ideal amplifier, with no amplified spontaneous emission (ASE), the output signal field strength is given by $E_{out} = \sqrt{G}E_{in}e^{-jnk_0L}$ where L is the amplifier length, n is the refractive index and k_0 is the wave number of the optical signal in free space. But in the case of a real amplifier with amplified spontaneous emission, quantum description [7] predicts an increase in the photon number variance resulting in an amplitude noise. In fact this amplitude noise can be seen either as the result of amplified signal and ASE fields mixing in the detector, or as an intrinsic effect of photon number fluctuations in the amplified light [8]. Due to the nonlinearity of the detection process, several beat terms appear in the expression of the output power, besides the shot noise term and the thermal noise term that are inherently present in the any optical detector. However, in the case of a system with just one amplifier, the beat terms have negligible contribution to the amplitude noise compared to the shot and thermal noises [7]. The variances σ_{shot} and $\sigma_{thermal}$ of these terms are given by [7], [8]:

$$\sigma_{shot}^2 = 2eF_a B_e \{I_d + R_{APD}(P_{signal} + P_{ASE})\} \quad (6)$$

$$\sigma_{thermal}^2 = \frac{4kTB_e}{R_L} \quad (7)$$

Here $e = 1.6 \times 10^{-19} C$ is the electron charge, F_a is the excess noise factor, B_e is the electronic bandwidth, I_d is the

dark current, $R_{APD} = M.R$ where M is the multiplication factor of the Avalanche photo-diode (APD) and R is the responsivity of the APD, P_{signal} is the desired signal power and P_{ASE} is the ASE signal power. Also, $P_{ASE} = \frac{1}{2} F_n G h \nu B_0$ where F_n is the EDFA noise figure, h is Plank's constant, ν is the optical signal frequency, G is the EDFA gain and B_0 is the optical bandwidth. Typical fluctuations of the desired signal amplitude due to these noise terms are $\leq 5\%$. Since all elements are identically fed, the fluctuations will affect only the term C_0 of Eq.1, that describes the array factor F_a . This will result in increasing the variance of the term $F_a(u)$ and therefore changing the maximum directivity by an amount proportional to the fluctuation of the detected signal as shown in Fig.2. The effect of the amplitude noise would be more noticeable on the side lobe levels and the beam width if the elements are fed differently.

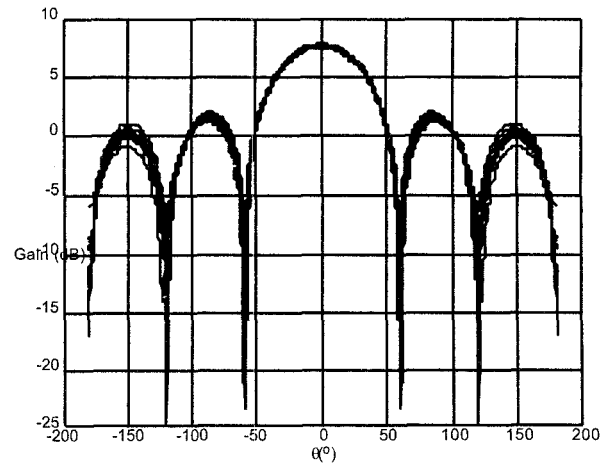


Fig.2. Effect of EDFA amplitude noise on antenna array radiation pattern (N=6).

EDFA PHASE NOISE

The signal phase noise could be seen as the superposition of a deterministic amplified signal and a random phase ASE field [8], [9]. In this case, the standard phase deviation is given by [8]:

$$\Delta\phi = \sqrt{\frac{n_{sp} h \nu B_0 (G - 1)}{2GP_{in}}} \quad (8)$$

which could be written in terms of the amplifier noise figure F_n , as

$$\Delta\phi = \sqrt{\frac{F_n h \nu B_0}{4P_{in}}} \quad (9)$$

Here, n_{sp} is the spontaneous emission factor, B_0 is the optical bandwidth and P_{in} is the optical input power. Assuming that the EDFA phase noise distribution is Gaussian $G_\phi(\phi_n)$ [9], the random phase variation will affect each element of the antenna array differently. In fact each element

will experience an independent Gaussian phase variation which could be written as independent random variables in the array factor expression. In the context of white Gaussian noise, these Gaussian random variables are independent because the time delay necessary to achieve the phase shift between two successive elements is considerable compared to the time of fluctuation of the optical phase noise. The effect of EDFA phase noise on the array factor of an antenna array, shown in Fig.3., can be written as follows:

$$F_a(\theta, \phi) = \sum_{n=0}^{N-1} F_e C_0 e^{j(\varphi_n + n(k_0 d \cos \psi + \alpha d))} \quad (10)$$

where φ_n is a Gaussian random variable independent from any random variable φ_m for $m \neq n$. The plot is for $\phi = \theta = 0$. One can theoretically find the distribution of the array factor D_{F_a} due to the effect of phase noise. Mathematically, $F_a(\varphi_n)$ is a function of a continuous random variable φ_n . The mapping of F_a onto φ_n is not one to one i.e. F_a is not monotonous over the interval $[-\pi, \pi]$ over which it is defined. But if this interval could be partitioned into k mutually disjoint sets such that each of the inverse functions $w_k(F_a)$ is defined on a one to one basis, then the probability distribution of F_a satisfies the following, over each of the k disjoint sets [10], [11]:

$$D_{F_a}(F_a) dF_a = G_\phi(\varphi_n) d\varphi_n. \quad (11)$$

Equation (12) can be rewritten as

$$D_{F_a}(F_a) = G_\phi(\phi) \frac{1}{dF_a / d\phi} \quad (12)$$

Like the left hand side term, the right hand side term needs to be expressed in terms of F_a . This requires the knowledge of the inverse functions $w_k(F_a)$ that express φ_n in terms of F_a . Analytically, this could be done by solving for φ_n the following equation:

$$F_a(\theta, \phi) = \sum_{n=0}^{N-1} F_e C_0 e^{j(\varphi_n + n(k_0 d \cos \psi + \alpha d))} \quad (13)$$

The number of roots is given by the number of the intersections the function F_a has with the φ_n axis. The above expression could be solved using classical numerical techniques [12]. Numerically, it is straight forward to find the distribution of any function of a random variable using the method of the histogram [10]. A random variable with a normal distribution (Gaussian distribution) is generated and the function is calculated at each iteration. This maps the randomness of the variable to the randomness of the function. Plotting the histogram of the function shows the number of times each "event" (a value of the function) occurred. Then dividing by the total number of events (number of iteration in this case) would give the probability distribution of the function. This is shown in Figs. 5 and 6 for the case of $N=6$. This clearly illustrates that the array factor has its most probable values distributed symmetrically about the origin for small random variables i.e random variables with relatively small means e.g. $\mu \approx 0.02$ rd, while the distribution

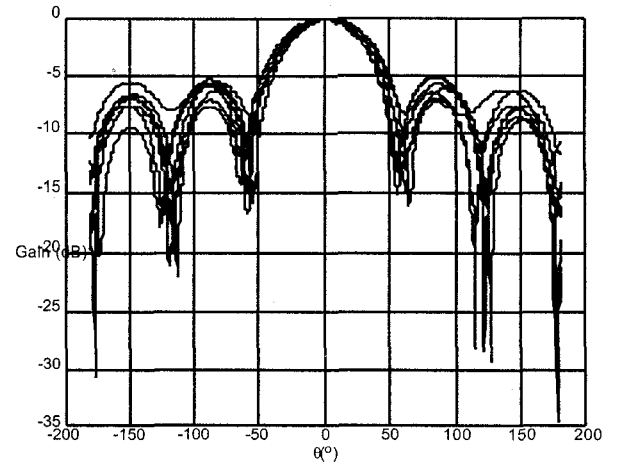


Fig.3. Effect of EDFA phase noise on antenna array radiation pattern ($N=6$).

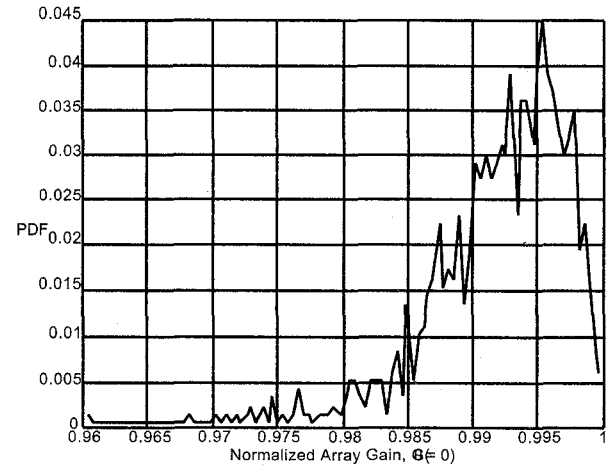


Fig.4. PDF of the antenna array radiation pattern $G(\theta=0)$, case $N=6$ and $\mu_\alpha = 0.05\pi$ rd.

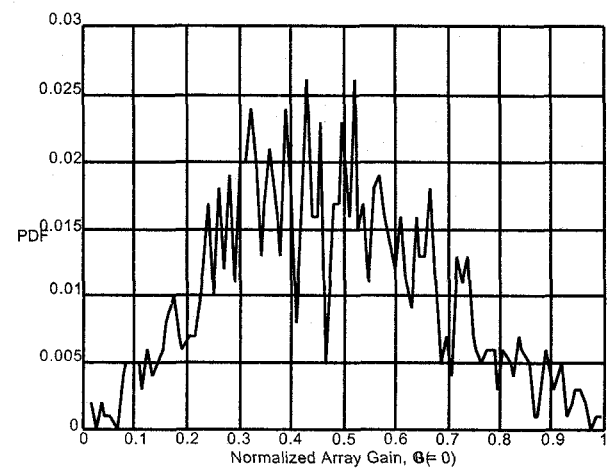


Fig.5. PDF of the antenna array radiation pattern $G(\theta=0)$, case $N=6$ and $\mu_\alpha = 0.5\pi$ rd.

experiences a positive skew for random variables with bigger means e.g. $\mu \approx 0.2$ rd.

CONCLUSIONS

Phased antenna arrays were shown to greatly help overcome some specific problems of CDMA wireless networks such as avoiding GPS signal jamming, dynamically serving hot spots and better accommodating emergency calls. Optical feed and amplification have enormous advantages over classical techniques. Optical fibers have loss as low as 0.2 dB/Km (at 1.55 μm), whereas the frequently used coaxial cables such as the 50- Ω , 1- Foam Dielectric LDF series cable [13] has a loss of 47.7 dB/Km around the PCS frequencies (~ 2 GHz). The use of optical amplifiers (EDFA) is necessary to compensate for the path loss and the splitting-induced power penalties. However, the use of optical amplifiers was shown to induce a random phase noise due to Amplifier Spontaneous Emission (ASE) which has a direct effect on the performance of the antenna array. The phase fluctuations make the main beam to jitter around a mean value directly related to the mean and the variance of the ASE induced random phase change. The bigger the mean, the more accentuated the main lobe jittering. With a more flat distribution of the random phase, the occurrence of a significant phase change is more probable. The use of higher optical signal would decrease the width of the distribution in a $1/\sqrt{P_{in}}$ fashion as shown in Eq.8. However, a considerable power increase would induce the fiber nonlinearity as its refractive index becomes intensity dependent. Nevertheless, the optical feed remains the best candidate for building smarter, compact and more efficient wireless systems.

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