Analysis of Wireless Broadband Systems employing Optical Fiber Links

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Abstract

In this paper we analyze the performance of fiber optic links for wireless broadband communication systems. Non-linear distortions arising from the laser source and noise contributions coming out from both transmitter and receiver are taken into account. With respect to the previous literature, a complete analysis of the optical link performance has been accomplished.

Keywords

FTTA system, millimeter-wave band, sub-carrier multiplexing, non-linear distortions, clipping, chirping

1 INTRODUCTION

New subscriber distribution systems, called FTTA (Fiber To The Area), uses millimeter-wave radio band to connect subscribers with base station, and optical fiber to connect base station with control station, in order to obtain broadband transmission. In these systems, rainfall attenuation is the main source of signal degradation in the radio link, while the optical link is affected by several causes such as clipping due to the threshold characteristics of the laser source (assuming direct modulation that is the cheapest solution), the intermingling of laser chirping and fiber dispersion, and the signal distortion due to laser resonance frequency. While sufficient literature is available to characterize the radio link, an analysis of the simultaneous effect of the impairment occurring in the optical link of this type of system still has not been investigated. The aim of this paper is to present some figures about such effects on the system performance.

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2 THE FTTA SYSTEM

The basic concept of an FTTA system is depicted in fig. 1 [1].

In this system each zone radius is 300 in order to enhance the spectrum utilization efficiency and to reduce transmitter power of both subscribers and base station. Base station receives RF signals from subscribers and converts them in optical signal by means of SCM (Subscriber Multiplexing) to transmit the control station through optical fiber. Then, the control station converts optical signal into RF signals, demodulates these signals, assigns each signal to channel and connects it to public switched networks.

The transmission, in this kind of system, can be schematized in a radio link and in an optical link.

The use of radio communication system with millimeter-wave is quite efficient in spectrum utilization, since it can cover small service zone with line-of-sight transmission and little co-channel interference. This radio transmission system is flexible for changing number of subscribers and it is easy to apply for high capacity mobile communications. On the other hand, the use of millimeter-wave band is limited by rainfall attenuation. In fact, if the rainfall induced attenuation exceeds a given threshold, outage occurs on radio channel.

The choice of carrier frequency for a radio system is usually dictated by its bandwidth and by the wave propagation characteristics (related to the extension of the coverage area), although antennas can pose restrictions as well (because of their size compared of the required gain). Thus, the study of wave propagation is an important task when developing a wireless systems. In this paper, we assume the use of 50 GHz as carrier frequency-band., for the radio transmission between subscriber and base station.

At this frequency band, modeling of wave propagation can be done on the basis of geometrical optics by using ray theory; at the millimeter wave band in particular, the diffraction phenomenon can be neglected the sum of the direct ray with reflected ones is enough to describe the propagation channel behavior with a reasonable degree of accuracy [2].

Figure 1. The concept of a Fiber-To-The-Air (FTTA) system

Definitely, the crucial parameter that has to be considered is the permissible attenuation due to rainfall, Z_a (dB). This can be evaluated according to the following relationship:

$$Z_a = P_T + G_R + G_T - L_f - KTB F - \gamma_{QAM} \quad (1)$$

where the terms on the right hand side represent the transmission power from subscriber, the subscriber antenna gain, the base station antenna gain, the free-space loss, the noise from the receiver, and the required carrier-to-noise ratio (CNR), respectively.

In particular a relation exists between the required CNR values relating to 2^{2n} QAM signals transmission and to QPSK signal transmission:

$$\gamma_{QAM} = \frac{1}{3} (2^{2n} - 1) \gamma_{QPSK} \quad (2)$$

where γ_{QPSK} is the required CNR when QPSK is used. For instance, the value of γ_{QPSK} which guarantees that bit error rate is less than 10^{-6} is 13.8 dB [1].

The percentage of time in which the attenuation of the radio link exceeds the permissible attenuation Z_a represents the system outage. The evaluation of the outage probability can be carried out by evaluating such a percentage of outage time. Of course this value depends on the geographic location of the systems. Anyway this calculation is above the scope of the present paper.

3 ANALYSIS OF THE OPTICAL FIBER LINK

The radio-frequency (RF) signal transmitted from subscriber is converted into an optical signal, in the base station, by using a direct intensity modulation of a laser diode (LD). At the end the optical signal is transmitted to control station where it is converted into RF signals by a PIN photo-diode (PIN-PD).

The dynamics of a single mode laser diode can be modeled by the laser rate equations [3], which describe the interactions among photon density $p(t)$, carrier density $n(t)$, and an equation describing the phase of the electric field $\phi(t)$ behavior:

$$\frac{dp(t)}{dt} = \Gamma G(t) [n(t) - n_0] p(t) - \frac{p(t)}{\tau_p} + \frac{\beta \Gamma n(t)}{\tau_n}. \quad (3)$$

$$\frac{dn(t)}{dt} = \frac{I_p(t)}{q V_a} - G(t) [n(t) - n_0] p(t) - \frac{n(t)}{\tau_n}. \quad (4)$$

$$\frac{d\phi(t)}{dt} = \frac{\alpha}{2} \left[\Gamma v_g a_0 [n(t) - n_0] - \frac{1}{\tau_p} \right]. \quad (5)$$

In these equations Γ is the mode confinement factor, n_0 is the carrier density at transparency, τ_p is the photon lifetime, β is the spontaneous emission coupled into the lasing mode, τ_n is the carrier recombination time, q the electron charge, V_a is the active layer volume, v_g is the group velocity, a_0 is the gain coefficient, and α is the linewidth enhancement factor. The saturable gain $G(t)$ can be expressed as:

$$G(t) = \frac{v_g a_0}{1 + \epsilon p(t)}. \quad (6)$$

being ϵ the gain compression factor.

The input current $I_p(t)$ can be expressed as:

$$I_p(t) = I_{bias} + \sum_{n=1}^N m \cdot (I_{bias} - I_{th}) \cdot \cos(2\pi f_n t + \theta_n). \quad (7)$$

where m is the optical modulation index of the single channel, I_{bias} and I_{th} are the bias and threshold currents, respectively, f_n and θ_n are the n^{th} carrier frequency and random phase, respectively.

The current $I_p(t)$ represents the electrical signal consisting of N frequency division multiplexed channels, and is generated by reverse fast Fourier transform (FFT) of N randomly phased tones. These signals represent generic broadband channels whose bandwidth varies between 20 and 150 MHz. We also consider a number of channels varying from 10 to 30.

The optical spectrum can be derived through FFT of the output intensity, which is directly derived by the photon density. Moreover, since the distortion is strongly dependent on the particular phases of the tones, we average the results of (20) sets of random phases.

Finally the spectrum of the signal, after passing a single mode standard fiber, is easily obtained by using the fiber transfer function reported in [3].

The optical signal transmitted from base station is transmitted to control station. In control station the optical signal is converted into RF signals by PIN-PD with sensitivity η and demodulate. When the number of input signal to LD is plural, intermodulation distortion (IMD), occurs by the combinations of input signals. Therefore, in control station, the received carrier to noise ratio is given as follows

$$\text{CNR} = \frac{\frac{1}{2} m^2 I_{ph}^2}{(RIN \cdot I_{ph}^2 + 2 \cdot e \cdot I_{ph} + \langle I_{th}^2 \rangle) \cdot B + \text{NLD}} \quad (8)$$

where the noise terms in the denominator represent the relative intensity noise contribution from the laser, the shot noise term, the thermal noise from the receiver, and the equivalent noise accounting for non-linear distortion as a whole, respectively. In particular:

B : bandwidth per carrier

e : electron charge

RIN : the relative intensity noise for the laser diode

I_{ph} : average current received in control station

$\langle I_{th}^2 \rangle$: equivalent input noise current density in optical receiver

NLD : non-linear distortion power

m : optical modulation index

The term NLD accounts for all system contribution to non-linear distortions, such as laser clipping, chirping-fiber dispersion, and distortions due to the laser resonance frequency. While all the other noise contributions are calculated separately by their analytical expressions, NLD is calculated by simulation. In fact, the simulation allows the total spectrum at the receiving end to be evaluated. Consequently, the noise falling in the RF bandwidth of a

given channel is integrated numerically to provide the value of NLD. The worst case value of NLD is calculated and put in (8).

4 RESULTS

Figures 2 - 4 show the transmission performance of the system in terms of the CNR versus the optical modulation index (OMI) of the single channel.

It is worth noting that the increasing of the signal power, related with the OMI, produce an increasing of the CNR, until non-linear distortions become significant. This explains why there is an optimum value of the OMI allowing the highest CNR to be reached.

The impact of the number of RF carriers on the performance is depicted in figure 2, where the performance are reported for different values of the number of carriers, assuming a double-side bandwidth of 150 MHz for any single channel. In fact, it can be noticed that the CNR decreases with the increasing of the number of carriers. Basically, two reasons can be individuated for this: 1) the overall bandwidth of the RF signal increases and, consequently, the noise contributions grow; 2) the probability of clipping events (e.g. the clipping induced total distortion) increases when there are more carriers [4].

From these results it is possible to derive a first conclusion concerning the system design. Since the required CNR values, to obtain an error probability of 10^{-6} , using QPSK or 16 QAM modulation schemes, are 13.8 and 18.8 dB, respectively, we could say that it is possible to transmit up to 30 carriers using such modulation schemes. On the other hand, if the 64 QAM modulation is desired, the required CNR of 34.8 dB pose restrictions on the number of carriers and requires a limited range of value of the OMI (with 20 carriers the OMI should be in the range $-26 \div -13$ dB).

To investigate the impact of the single channel bandwidth on the system performance, figure 3 shows the CNR versus the OMI for three different values of the channel bandwidth, for 20 RF carriers. It is evident as the increasing of the bandwidth leads to an increasing of the noise contributions.

Taking into account the required values of CNR for the QPSK and 16QAM modulation schemes reported before, we could say that at least 20 broadband signals can be favorably transmitted in this kind of system.

In order to evaluate the effect of source chirping (in commingling with fiber dispersion) and of the resonance frequency of the laser on the system performance, it is useful to observe

figure 4. Here we assume to transmit 20 carriers. It is also presumed a fiber optic link length of 30 km. The RF signals comb, received from the antenna, is down shifted near the baseband (200 MHz) in one case, and to 1 GHz in the other case. In both the cases the performance are evaluated either considering the chirping effect and not.

By comparing the curves relating to the comb initial frequencies of 200 MHz and 1 GHz, respectively, we can observe a difference of few dB (3 in the worst case). This is due to the fact that the resonance frequency of the laser introduces further distortions when the laser operates to higher frequencies (the comb starts at higher frequency).

It is also to be highlighted that the impact of chirping effect is absolutely not negligible, since it brings about a penalty on the CNR of more than 13 dB. Again, considering the required values of CNR for QPSK and 16 QAM modulation schemes, we could say that, in this case, just a limited range of values for the OMI is admissible, considering a transmission of 20 carriers.

In order to provide some information about the feasibility of the system as a whole, it is worth while giving some information on the performance of the radio link too.

Assuming a transmitting power of 18 dBm, table 1 reports the outage probabilities for two different values of the cell area radius, and for the two considered modulation schemes, considering the meteorological statistics of the city of Roma, Italy [5].

5 CONCLUSIONS

An analysis of a fiber-to-the-air system has been carried out. The system performance is mainly affected by rainfall attenuation, concerning the radio link, and by noise contribution and non-linear distortions, regarding the optical link. In particular, optical non-linear distortions are due to non-linear characteristics of the laser source and to the intermingling of laser chirping and fiber dispersion.

The analysis revealed that this kind of system allows the transmission of some tens of broadband carriers, using two relevant modulation schemes: QPSK and 16 QAM.

In general, we could say that a tradeoff exists between the number of carriers and the channel bandwidth. Furthermore, the impact of chirping could be significant. The design of such a type of system must take into account all these effects. The model presented here allow the different effects to be taken into account.

Figure 2. Carrier-to-noise ratio versus the optical modulation index, for different numbers of carriers. The RF comb starts from 200 Mhz, and the single channel bandwidth is 150 MHz.

Figure 3. Carrier-to-noise ratio versus the optical modulation index, for different values of the channel bandwidth. The RF comb starts from 200 Mhz, and the number of carriers is 20.

Figure 4. Carrier-to-noise ratio versus the optical modulation index, for different values of the start frequency and showing the chirping effect. The number of carriers is 20 and the channel bandwidth is 150 MHz.

OUTAGE PROBABILITY

Modulation	Cell radius: 300 m	Cell radius: 1 km
QPSK Modulation	10^{-6}	10^{-3}
16 QAM Modulation	10^{-5}	10^{-2}

Table 1. Outage probability as a function of the cell radius and of the adopted modulation scheme.

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