Coherent Optical Wireless Communications; a Key Technology to Obtain a Denser WDM Access Connectivity

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Abstract: - The recent progress in the optical wireless communications systems with direct detection makes them appear as an important alternative to the conventional wireless (and wired) communication systems. An important application of such systems could be the called “last mile” connection. Nevertheless, in order to take full advantage of the extremely huge wide bandwidth of the optical channels it will be necessary to use coherent detection instead of direct detection. In this paper, we describe several key issues needed to implement a practical coherent wireless communications system.

Key-Words: - coherent detection, optical wireless systems, optical synchronization, pointing, tracking, acquisition.

1 Introduction

The optical wireless systems are capable of working at higher bit rates with smaller antennas than the conventional radio frequency systems [1]. In addition, the use of optical wireless systems would reduce the present problem of the radio-electric spectra saturation in the RF bands. The optical wireless communications systems have an important number of potential applications, such as: a) broadband communication networks in campus and between buildings, b) HDTV broadcasting, c) satellite links, d) a faster implementation of broadband networks for emergency situations and/or natural disasters, e) high security communications systems, f) “last mile” broadband connectivity, among others [2,3,4,17,18,20,21]. Currently, there exist in the market several wireless optical communications systems that use the direct detection technique [5, 6, 19], however, to the best of our knowledge, there is no commercial system that make use of the optical coherent detection.

2 Optical Wireless Communications Systems

The optical wireless communications systems can be classified as [8]: a) direct detection systems, and b) coherent detection systems. Currently, the direct detection systems (see figure 1) are the systems with greater commercial use way due to their relative simplicity of implementation. In these systems the amplitude of the optical field $E_{sd}(t)$ is modulated directly or through an external modulator obtaining the signal:

$$E_{sd}(t) = E_{sod}\, m(t) \sin(2\pi f_s t + \varphi_s(t)) \quad (1)$$

with:

$$m(t) = \sum_{k=-\infty}^{\infty} m_k rect\left(\frac{t-kT}{T}\right) \quad (2)$$

where:

E_{sod} : amplitude of the optical field without modulation
$m(t)$: binary data signal,
$f_s, \varphi_s(t)$: frequency and phase of the optical carrier respectively
T: is the period of the data signal

with:
$m_k = 0,1$ (3)

The modulated optical carrier signal is injected, in this case, through an optical antenna to the communications channel (free space). This signal, after traveling a distance that can vary from a few hundreds of meters to several kilometers (depending on the application) inevitably will be affected by a diversity of random disturbances such as scattering and attenuation among others [13]. The disturbed signal arrives at the reception stage where it is photo-detected and demodulated by means of a quadratic process according to the following equation:

$$i_s(t) = M\Re P_s(t) \quad (4)$$

where:

$i_s(t)$: is the photodetector's current
$M \geq 1$: photodetector's gain (normally is used an APD in which case M is greater than 1)
$\Re$: photodetector's responsitivity
$P_s(t)$: is the power of the incident optical field,

where:

$$P_s(t) \propto E_{sd}(t)^2 \quad (5)$$

Replacing the equation (1) in (5) and taking into account that the optical frequencies are much greater than the electrical bandwidth of a photodetector, we obtain the following equation:

$$i_s(t) = M\Re \frac{(E_{so}m(t))^2}{2} + n(t) \quad (6)$$

From the equation (6) is evident the name of direct detection since the information is recovered directly from the optical to electrical conversion, although, of course, a regeneration process is used to reduce the effects of the additive amplitude noise $n(t)$, which in this case is due to the contributions of the shot and thermal noises, the environment and dark noises, in addition to the disturbances caused by the communications channel (fog, haze, etc..). A spatial synchronization control can be used to maintain aligned the receiver with the transmitter. Although this control is not always included, its utility is evident. On the other hand the coherent optical communications systems (see figure 2) have superior advantages over the direct detection systems, such as greater wavelength selectivity (at the cost of a much more complex design and implementation) in addition to a greater sensitivity in the receiver. In this case, the optical carrier signal can be modulated in amplitude (acting over $m(t)$), phase or frequency (acting over $\varphi_k(t)$), obtaining the signal:

$$E_{sc}(t) = E_{soc}m(t)\sin(2\pi f_s t + \varphi_s(t) + \varphi_k(t)) \quad (7)$$

where:

E_{soc}**:** amplitude of the optical field without modulation.

Unlike the systems with direct detection, in this case, the information signal must be combined in the receiver with a local optical oscillator signal $E_{lo}(t) = E_{lo}\sin(2\pi f_{lo}t + \varphi_{lo}(t))$ that has to be spatial and frequency synchronized (and phase synchronized in the homodyne case, $f_s = f_{lo}$) with the received signal, besides to have the same state of polarization of the information signal. If all these conditions are met, the photodetected electrical signal obtained is:

$$\begin{aligned} i_{sl}(t) &= n(t) + \Re[Ps + P_{lo} + \\ &+ 2\sqrt{P_s P_{lo}}\cos(2\pi(f_s - f_{lo})t + \varphi(t) + \varphi_k(t))] \end{aligned} \quad (8)$$

In the heterodyne case ($f_s \neq f_{lo}$) $i_{sl}(t)$ is input to a demodulation stage, whereas in a homodyne system ($f_s = f_{lo}$) this signal is at base band and it only has to be regenerated. From equation (8) we can see an important advantage of the coherent systems with respect to the direct detection systems; there exists a noiseless gain provided by the local oscillator. Although this advantage has been despised in the fiber optical communications systems, mainly due to the appearance of the optical amplifiers, in the wireless systems is very important because it allows an improvement in the sensitivity of the photoreceiver. On the other hand since the demodulation is made (for the heterodyne case) at an intermediate electrical frequency using electrical filters instead of optical filters, the frequency selectivity is enhanced due to a significantly better quality factor of the electrical filters. This improvement is essential to implement a higher density WDM system. These additional advantages allow to greater distances for the optical wireless systems with a denser wavelength division multiplexing [7, 8]. Although the advantages of the coherent optical wireless communications systems are very attractive, their practical implementation faces important difficulties that must be solved with high quality engineering designs for spatial acquisition as well as with systems of extremely fine optical carrier synchronization [9,10].

3 The “last-mile” problem

The 'last mile' defines the link between a customer's equipment and the local phone company's central office. The “last-mile” is not necessary a mile, because this link can vary up to several miles. A more correct term is local loop. Currently there is a growing necessity to digitalize the local loop so that high speed end-to-end networks perform efficiently. The new public network requires an updated broadband infrastructure with very high capacities, and multichannel services that can accommodate voice, data and video streams. At the moment, there exist several potential solutions to this problem, such as: a) DSL technology, b) unlicensed wireless RF, c) millimeter wavelength technology, d) optical wireless systems, e) W-band technologies, f) hybrid optical wireless systems with direct detection and millimeter wavelength technology [22]. Although none of them has been fully accepted it seems that the last one (hybrid technology) is the best solution because optical wireless systems mitigates the weaknesses of millimeter wavelength technology and vice versa. However, as mentioned above, the capacity of the optical wireless systems can be improved if coherent detection is used instead of direct detection, but there exist the important problems of spatial and optical carrier synchronization to be solved.

4 Spatial Synchronization

In order to establish an optical communications wireless link it is required in the first place to suitably point the optical transmitter signal towards the receiver (this is what is called “the pointing process”). The receiver at the same time has to be able to know the direction of arrival of the transmitter beam (acquisition process). Once the receiver has acquired the optical transmitter signal, it also has to be able to follow any frequency variation of the same one (tracking process). The combination of all these events is called spatial synchronization [12]. This synchronization process is affected by random disturbances to the optical field (attenuation, change of the state of polarization, phase fluctuations among others) produced by the optical communications channel (free space) [13]. The optical wireless communication systems that use direct detection compensate the attenuation of the optical beam signal using for example a multilaser signal [14]; nevertheless, in the optical coherent systems it is essential to compensate the variations of the polarization state as well as of the phase noise of the optical carrier in order to have a useful signal needed for the subsequent detection and demodulation stages [7]. Currently we are working in the design and implementation of a spatial synchronization system that will be tolerant (at least to a certain minimum level) to this type of disturbances; for example, we are designing a system that detects and controls the state of polarization of the optical information signal.

5 Optical Carrier Synchronization

In order to obtain the greater sensitivity of the coherent wireless communications systems we have to make use of a synchronous detection scheme [7] and at the same time we need optical carrier synchronization at the receiver stage [7, 10, and 15]. Several schemes originally used in the RF domain have been proposed and tested in optical fiber communication systems [7, 8, and 11]. However, the optical carrier synchronization is a complex problem that in the case of the free space has additional complications due to the randomness of the disturbances of the phase of the optical carrier and its state of polarization as well as of its amplitude. Currently, we are working in developing an optical carrier synchronization scheme that will use the maximum – likelihood theory and will take into account the diverse disturbances introduced by the free-space as a communications channel [10, 16].
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6 Conclusion

The recent progress in the optical wireless communications systems with direct detection makes them appear as an important alternative to the conventional wireless (and wired) communication systems. An important application of such systems is the so called “last mile” connection for access connectivity to the subscriber. Nevertheless, in order to take full advantage of the extremely huge wide bandwidth of the optical channels it will be necessary to use coherent detection instead of direct detection. In this paper, we have described several key issues needed to implement a practical coherent wireless communications system such as the spatial and optical carrier synchronization process that we are currently working on.

References:

[1] J.H. Franz, V.K. Jain, *Optical communications, components and systems*, CRC Press, 2000.

[2] H.Willebrand, B.S.Ghuman, *Free-space optics: enabling optical connectivity in today's networks*, Sams Publishing, 2000.

[3] Aoptix Technologies, Introducing the AO-5000 Free Space Optics Transmission System, *Internal Report*, April 2002.

[4] I. Kim, M.Achour, Free-space links address the last-mile problem, *Laser Focus World*, June 2001.

[5] Cablefree Solutions: Optical Wireless Laser Infrared Communication Systems.

[6] FSO Insight.

[7] Kazovsky, L. y Benedetto, S., *Optical Fiber Communications Systems,* Artech House, Inc. 1996.

[8] G.P. Agrawal, *Fiber-optic communication systems 3rd edition*, Wiley-Interscience, 2002.

[9] S. G. Lambert, W. L. Casey, *Laser communications in space*, Artech House, 1995.

[10] A.Arvizu, F.J.Mendieta, Optimum estimation of a phase modulating Wiener process with applications in coherent detection systems, published on the book *Recent Advances in Signal Processing and Communications*, World Scientific and Engineering Society Press, 1999.

[11] Betti, S., De Marchis, G. y Iannone, E., *Coherent optical communications systems*, John Wiley and Sons, 1995.

[12] Gagliardi, R.M., *Optical Communications*, John Wiley & Sons, Inc.,1995.

[13] L.C. Andrews, R. L. Phillips, *Laser beam propagation through random media*, SPIE Optical Engineering Press, 1998.

[14] T.H. Carbonneau, SONAbeam™ Optical Wireless Products, *Proceedings of SPIE Free-space laser communication Technologies XII symposium*, January 2000, San Jose, CA, USA.pp.45-51.

[15] Meyr, H., *Synchronization in digital communications Vol.1*, John Wiley and Sons, 1990.

[16] Van Trees, H.L., *Detection, Estimation and Modulation Theory Part I*, John Wiley and Sons, 1968.

[17] T.Tolker-Nielsen, J.C.Guillen, SILEX: the first European optical communication terminal in orbit, *ESA Bulletin* 96, November 1998.

[18] E.J.Lerner, Free-space communications struggles to find its niche, *Laser Focus World*, June 2002.

[19] L.Wirbel, Lucent teams with TeraBeam on broadband free-space optics, *Eetimes*, April 12, 2000.

[20] T.Greene, Free-space lasers shining as obstacles are overcome, *Network World Fusion*, January 15, 2001.

[21] J.Mendieta, E.Pacheco, A.Arvizu, R.Muraoka, Optical communication payload for an experimental microsatellite in low Earth orbit, *Proceedings of SPIE Free-space laser communication technologies XIII*, January 2001, San Jose, CA; USA.

[22] S. Bloom, W. Seth Hartley, The Last-Mile Solution: Hybrid FSO Radio, *AirFiber, Inc*., May 2002.

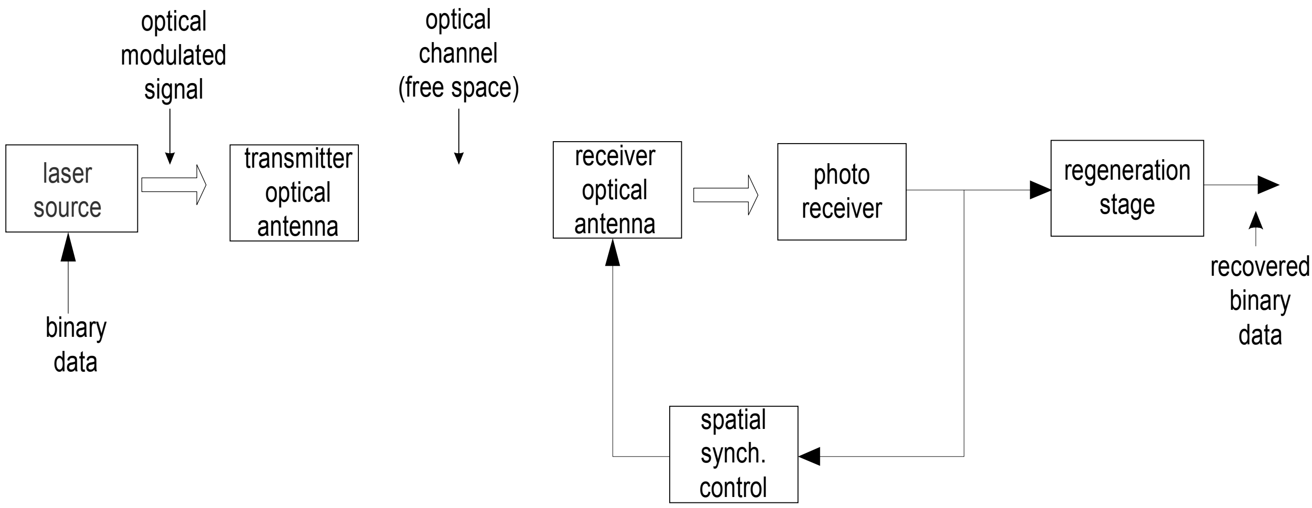

Figure 1. Block diagram of an optical wireless communications system with direct detection.

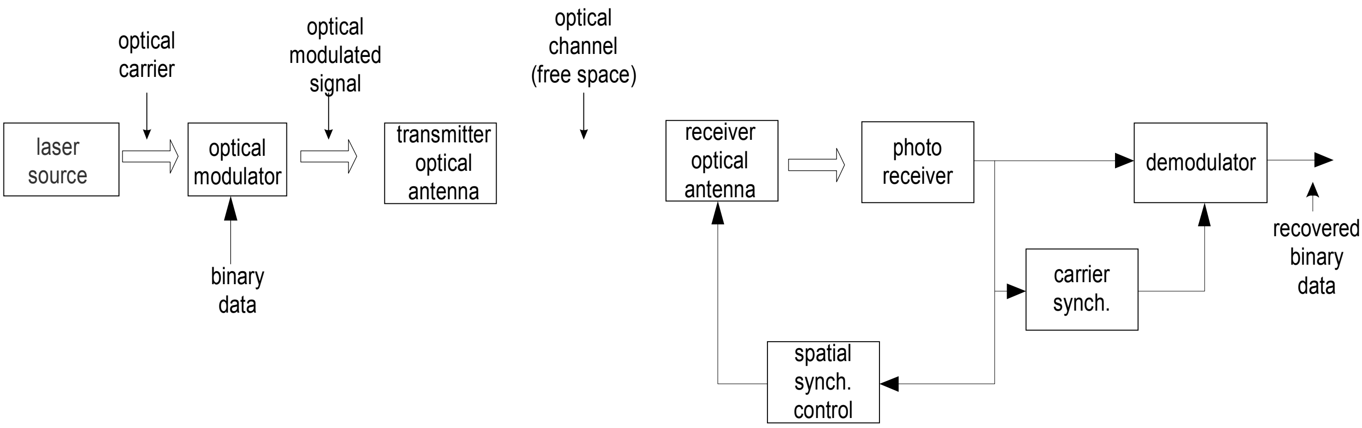

Figure 2. Block diagram of an optical wireless communications system with coherent detection.