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Gliese, Ulrik Bo; Nielsen, Søren Nørskov; Nielsen, Søren Nørskov

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Limitations in Distance and Frequency due to Chromatic Dispersion in Fibre-Optic Microwave and Millimeter-Wave Links

U. Gliese, S.N. Nielsen and T.N. Nielsen†

Center for Broadband Telecommunications, Electromagnetics Institute
Technical University of Denmark, Building 348, DK-2800 Lyngby, Denmark
Phone: +45 42 88 14 44, Fax: +45 45 93 16 34, E-mail: ug@emi.dtu.dk

†Now with AT&T Bell Laboratories, Murray Hill, USA

Abstract

Chromatic dispersion significantly limits the distance and/or frequency in fibre-optic microwave and millimeter-wave links based on direct detection due to a decrease of the carrier to noise ratio. The limitations in links based on coherent remote heterodyne detection, however, are far less significant, and are primarily due to an increase of the phase noise.

Introduction

The effect of chromatic dispersion is well described for both direct detection and coherent detection fibre-optic communication systems for transmission of digital baseband signals (see [1], [2] and references herein). It has, however, not yet been treated in sufficient detail for neither direct detection (DD) nor coherent remote heterodyne detection (RHD) fibre-optic microwave and millimeter-wave (MW) links. Such links are subject to a still increasing interest, and in this paper it is shown that the chromatic dispersion cannot be disregarded. It significantly limits the transmission distance and carrier frequency that can be used in the links.

In the DD links, the dispersion results in a carrier to noise ratio (C/N) penalty on the detected MW signal. In the RHD links, it results in a C/N penalty as well as an increase of the phase noise on the detected MW signal. The C/N penalty in RHD links has been treated previously [3], but the dispersion induced phase noise, that turns out more dominant, has not yet been investigated. In this paper we present results concerning all of the dispersion effects both considering standard fibre-links with a dispersion of 17 ps/km·nm and dispersion shifted or compensated fibre-links with a dispersion close to zero. The obtained results are of great value as they enable proper selection of the fibre depending on the chosen link configuration, the MW frequency and the desired transmission distance.

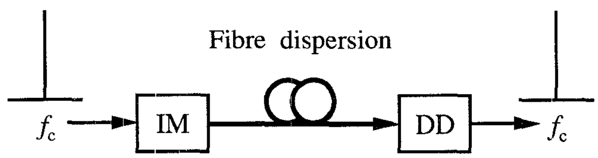

Figure 1: Principle of intensity modulated direct detection fibre-optic MW links.

DD Links

In the DD links, c.f. Fig. 1, the MW signal is intensity modulated (IM) onto the optical carrier from a laser. The optical signal is then transmitted through the optical fibre, and the MW signal is

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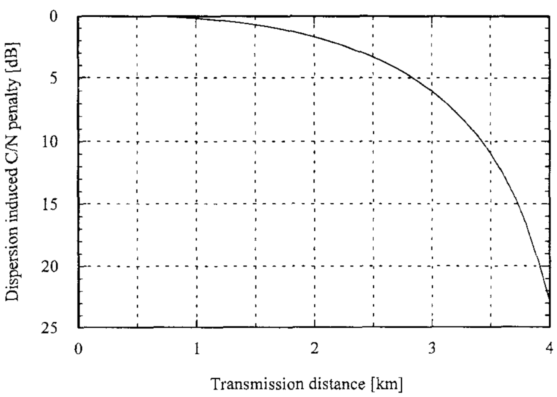

Figure 2: Dispersion induced C/N penalty as a function of transmission distance for a wavelength of 1550 nm, a chromatic fibre-dispersion of 17 ps/km·nm and a carrier frequency of 30 GHz.

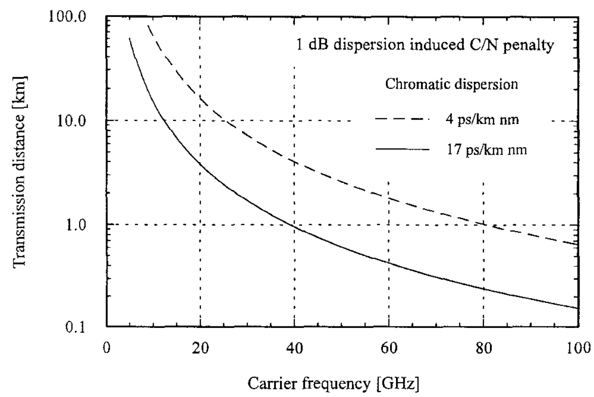

Figure 3: Obtainable transmission distance as a function of carrier frequency at a wavelength of 1550 nm for a 1 dB dispersion induced C/N penalty and with the chromatic fibre-dispersion as parameter.

recovered by DD in a photo diode. The MW signal is carried as a lower and a upper side band on the optical carrier. Due to the dispersion and the large frequency offset between the side bands and the optical carrier, the phase of each of the spectral components of the transmitted optical signal has experienced a differential change. After detection, this results in a power reduction on the recovered MW signal and thereby a decrease of its C/N.

As shown in Fig. 2, for a MW carrier of 30 GHz, a dispersion of 17 ps/km·nm results in a significant decrease of the C/N as the transmission distance is increased. This severely limits the obtainable transmission distance in IM-DD fibre-optic MW links using standard single mode fibre.

The amount of dispersion induced C/N penalty that is tolerable in any given link naturally depends on the required link budget and the available margin in each specific case. To generalize the transmission distance investigation, however, a dispersion induced C/N penalty of 1 dB is chosen as acceptable. This value ensures a minimal influence of the dispersion on the entire system performance in terms of C/N. The dependance of transmission distance on carrier frequency is shown in Fig. 3. It is seen that an increase in carrier frequency significantly limits the obtainable transmission distance. At 60 GHz, the distance is limited to less than 500 m on standard single mode fibre. When longer distances or higher frequencies are required, it is necessary to use fibre with much lower dispersion such as dispersion shifted fibre or dispersion compensated fibre. It is seen that the transmission distance for the 60 GHz MW signal can be increased to approximately 2 km by reducing the dispersion from 17 to 4 ps/km·nm. In general the increase in distance scales with the square root of the decrease in dispersion.

RHD Links

In the transmitter of RHD links, c.f. Fig. 4, two phase-correlated optical carriers are generated with a frequency offset equal to the carrier frequency of the MW signal. This transmitter con-

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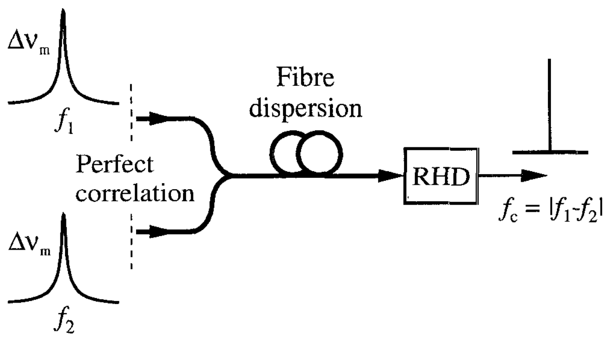

Figure 4: Principle of remote heterodyne detection fibre-optic MW links.

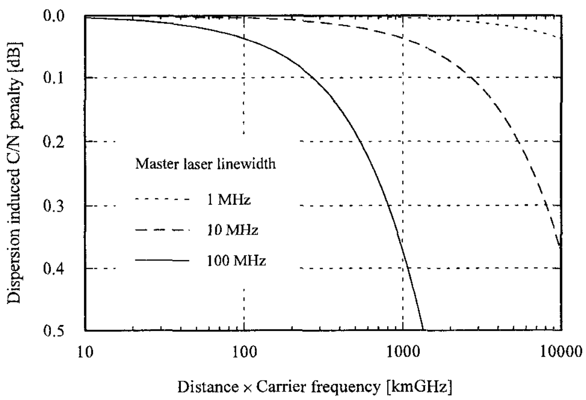

Figure 5: Delay induced C/N penalty as a function of transmission distance times carrier frequency for a wavelength of 1550 nm and a chromatic fibre-dispersion of 17 ps/km·nm and with the master laser linewidth as parameter.

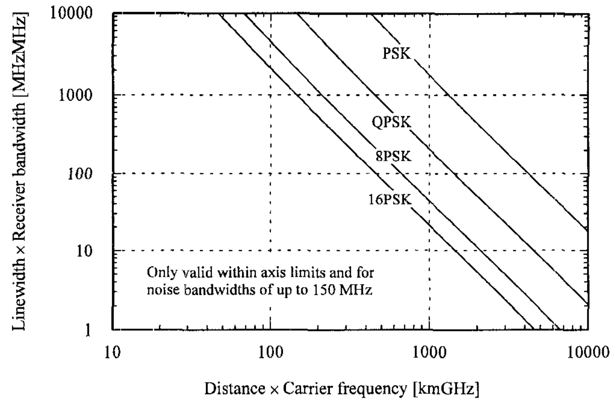

Figure 6: The maximum transmission distance times carrier frequency as a function of the master laser linewidth times the receiver noise bandwidth for different types of systems.

cept can be implemented by various schemes [3]-[6], but the link principle is the same for any of these. The two optical carriers are transmitted through the optical fibre, and the MW signal is recovered by heterodyning of the two optical signals in the remote photo diode.

With any of the transmitter schemes, one of the optical carriers can be regarded as a master laser signal with a Lorentzian 3 dB linewidth $\Delta\nu_m$. The other optical carrier is then regarded as a phase-correlated replica. For a perfect transmission the two optical carriers are also phase-correlated at the remote detector where the heterodyning takes place. Therefore, the resulting beat signal is a highly phase-stable MW signal. However, due to chromatic fibre-dispersion, the two optical signals become partially de-correlated as they travel the fibre. This results in a decrease of the C/N and an increase of the phase noise, both dependent on the dispersion, the transmission distance, the carrier frequency and the master laser linewidth.

The dispersion induced C/N penalty is shown in Fig. 5 for a dispersion of 17 ps/km·nm. As seen, only a small C/N penalty, of far less than 0.5 dB, is induced even for large distances or frequencies and wide master laser linewidths. Consequently, the dispersion induced C/N penalty is considered insignificant in RHD fibre-optic MW links using standard single mode fibre.

Only a limited amount dispersion induced phase noise can be tolerated on the MW signal. As the dispersion induced phase noise should only constitute a fraction of the total allowable phase noise, a value of 10% of the typically allowed values in

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standard MW systems is chosen as acceptable. The dispersion induced phase noise depends on the transmission distance, the carrier frequency, the master laser linewidth as well as the microwave receiver noise bandwidth. The interplay between these parameters is shown in Fig. 6, for a dispersion of 17 ps/km·nm, based on the 10% phase noise values of M-ary PSK systems. It is seen that the obtainable transmission distance times carrier frequency product decreases as the master laser linewidth or the receiver noise bandwidth increases. If, as an example, a 150 Mbit/s QPSK microwave signal, which is received in a single sided bandwidth of 45 MHz [7], is transmitted over a remote heterodyne fibre-optic link using a master laser with a linewidth of 10 MHz, then the obtainable distance times carrier frequency product is 640 km·GHz, e.g., a transmission distance of approximately 10 km for a carrier frequency of 60 GHz. From this it is seen, that the influence of the dispersion is far less significant than in IM-DD links, and that standard single mode fibre can be employed in most cases.

Conclusion

In the IM-DD links, chromatic dispersion results in a C/N penalty on the transmitted MW signal. This effect is independent of the modulation format of the MW signal as well as on the laser linewidth, and, therefore apply equally for any type of MW signal. The effect is severe and necessitates the use of dispersion shifted or compensated fibres in many cases.

In the RHD links, chromatic dispersion results in a C/N penalty as well as an increase of the phase noise on the transmitted MW signal. Of these, the phase noise increase proves far the most dominant. Further, it is dependant on both the master laser linewidth and the modulation format and bandwidth of the MW signal. The dispersion effects, however, are not severe, and standard fibre can be used in most cases.

In conclusion, both direct detection and remote heterodyne detection fibre-optic microwave and millimeter-wave links are limited in transmission distance by chromatic dispersion when operating in the above 20 GHz range. The effect in IM-DD links is severe and necessitates specialized fibre whereas it is tolerable in RHD links even for standard fibre.

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