An investigation on the benefits of DS-CDMA in fibre supported mm-wave radio systems supporting flexible capacity reconfiguration

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Abstract: *Prior to the successful deployment of fibre supported mm-wave radio systems (FSMS) over a wide area, two important architectural issues need to be considered. These are the development of multiple access techniques enabling FSMS to use a shared fibre infrastructure and that of architectures that support the flexible reconfiguration of radio capacity. This paper proposes an investigation on the benefits and usability of direct sequence code division multiple access (DS-CDMA) techniques in FSMS where the base stations transmit on the same wavelength.*

1. Introduction.

Research on fibre supported mm-wave radio systems (FSMS) has concentrated on developing appropriate mm-wave generation techniques, improving device performance and developing system concepts. Recently, fibre radio systems for in building coverage, operating in the 0.8 – 1.5 GHz have become available, moving fibre radio systems outside the laboratory.

The deployment of fibre radio systems over a wide area has mainly been restrained because mobile operators lacked an extensive optical fibre access network infrastructure and high costs prohibited them from implementing one. Also at present, fibre radio systems provide no added functionality vis-à-vis their more economic electronic counterparts.

However several emerging trends may catalyse the deployment of fibre radio systems. The shift towards a wireless broadband periphery is forcing operators to adopt a microcellular approach and for new proposals operating at mm-wave frequencies to be developed. While mobility and broadband make short term network capacity planning very difficult, strengthening the case for flexible capacity reconfiguration to be an important network O&M requirement.

The increased coverage of optical metropolitan area and access networks coupled with developments in wavelength division multiplexing technology should enable wavelength leasing to become available at this level, reducing the capital outlay required. While the high cost of UMTS licences in Europe has speared the formation of partnerships between operators to bid for the licence and to share the costs of the infrastructure roll out.

From the above discussion it may be concluded that prior to the widespread deployment of wide area fibre radio systems, two important architectural issues must be resolved:-

(i) the need for fibre radio systems to coexist on the same fibre infrastructure with other fibre radio systems or with other services; i.e. the development of suitable multiple access schemes;

(ii) the need for fibre radio architectures to inherently support and facilitate the flexible reconfiguration of the radio network.

There are essentially four basic multiple access techniques, Time division multiple access (TDMA), Wave division multiple access (WDMA), Sub-carrier multiple access (SCMA) and

Code division multiple access (CDMA). Hybrid techniques combining two or more of the above may also be used.
The high bit rates envisaged for FSMS make synchronisation between the different base stations sharing the same channel very difficult, putting TDMA at a disadvantage. The concept of flexible capacity reconfiguration on a WDMA/SCMA network has been demonstrated.[1] WDM based fibre radio networks merge well with the metropolitan area and access optical networks being developed. It may thus be safely assumed that WDMA will be used for FSMS. This paper concentrates on comparing the relative advantages and disadvantages of using SCMA or CDMA on a single optical wavelength, for FSMS.

2. Sub-carrier Multiple Access

The use of SCMA requires careful sub-carrier and optical wavelength planning since the remote base stations (RBS) need to be equipped with the appropriate lasers, optical and electrical filters, while radio signal interference must be avoided. A special case exists when the radio network also uses frequency division multiple access. In this case if the number of RBS supported on the same wavelength is equal to the number of cells in a reuse cluster, then one can use the radio frequency plan as the sub-carrier plan. A main design consideration is at what level to support the flexible capacity reconfiguration, whether at the SCMA or WDMA level or both. This decision cannot be taken in isolation from the specifics of the radio network transported and its support for dynamic channel allocation techniques. If supported at the WDMA level multiple lasers and filters need to be made available at each RBS so that the probability of blocking is reduced.

The use of RBS operating on nominally the same optical frequency increases the magnitude of Optical Beat Interference (OBI). OBI results from the square law characteristic of photodiodes. If some of the beat frequencies overlap an active sub-carrier channel, then the signal to noise ratio (SNR) of that channel is degraded.

OBI effects in directly modulated laser SCMA networks have been analysed by various authors.[2] A general case analysis where $N \geq 2$ showed that the worst case SNR due to OBI, which occurs when all the light sources have identical centre wavelengths may be given by [3] :-

$$SNR_{OBI}(N) = \frac{\pi}{4N(N-1)} \cdot m^2 \cdot \frac{\Delta f_{FWHM}}{B}$$

where Δf_{FWHM} is the full width at half maximum of the light source power spectrum, m the modulation index and B is the receiver bandwidth. It is clearly seen that OBI rapidly deteriorates the SNR as the number of nodes in the SCMA network increases.

Several solutions to reduce OBI have been proposed such as, increasing the modulation index to increase the line width of the light source or use LEDs, random polarisation of the interfering stream or using DS-CDMA as a way of reducing OBI.[4]

3. Direct Sequence Code Division Multiple Access (DS-CDMA)

DS-CDMA has been extensively studied in the context of mobile communication networks. DS-CDMA is based on spreading the information signal spectrum by multiplying it with a spreading code sequence in the time domain. By a proper choice of code the signals on the shared network can be made as mutually non interfering as possible. At the receiver the original signal is de-spread by correlating the received signal with the code used to spread the original signal. In the process any interference is spread.

DS-CDMA has been used to suppress the effect of interference due to jamming, interference from other users in the same channel and self interference due to multipath propagation. In optical networks this technique can be used to suppress the effect of intermodulation distortion caused by the laser non-linearity and optical beat interference. DS-CDMA has some disadvantages. It is difficult to acquire and maintain synchronisation (required to be kept within a fraction of a chip duration) between the locally generated code sequence and the received signal. In practice this limits the achievable processing gain. DS-CDMA also requires accurate power control to solve the near far problem. Current CDMA receivers are based on the RAKE receiver principle, which considers other users' signals as interference. Therefore an increase in the number of active users on the same carrier frequency brings about a graceful degradation of the performance of each user.

The use of DS-CDMA requires careful spreading code and optical wavelength planning since the orthogonality between the individual signals must be preserved. In theory a frequency and code reuse factor of 1 is allowed, but in practice this is not achieved because of inter cell interference. Adjacent cells either utilise different frequency carriers or different code sets, forming a cell reuse cluster.

A special case exists when the radio network also uses DS-CDMA. In this case if the number of RBS supported on the same wavelength is equal to the number of cells in a code reuse cluster using the same radio carrier frequency, then one can multiplex the received radio signals directly on to the optical network. This blends well with the concept of FCR. In principle the design capacity of a DS-CDMA system may be distributed as required among the RBS forming a code cluster with the proper assignment of codes. This reasoning assumes no dynamic range issues are present because of tight power control on the radio part.

Several authors have examined the impact of laser non-linearity on the transport of DS-CDMA signals in direct laser modulation systems and experimental systems have been demonstrated.[5,6] Others have analysed the performance of hybrid DS-CDMA/SCMA systems for suppressing the effects of laser non-linearities.[7,8] Kajiya et al used DS-CDMA to mitigate the effect of optical beat interference.[4] The outage probability and the number of connectable RBS were analysed and compared with those of a SCMA system. The results show that a processing gain of 10^3 equals the performance of an equivalent SCMA system, while a processing gain of 10^4 triples the number of RBS connected.

Koshy et al compared the error and outage probabilities of a directly modulated laser system using DS-CDMA or SCMA respectively.[9] Their model considered the combined effects of radio channel fading and laser non-linearities. They concluded that a DS-CDMA system is not a viable alternative to a SCMA system because it is inefficient with regard to spectrum utilisation (i.e requires high processing gains). Consequently they showed that a combined DS-CDMA/SCMA system can improve the system performance. Whilst Huang et al proposed a two stage cancellation technique to cancel both the multiuser interference and the non-linear distortion.[10] They show that for the same error probability the number of active users is increased by using the cancellation technique proposed.

4. MM-wave fibre radio systems exploiting DS-CDMA

An overview of the broadband wireless systems being developed and mm-wave fibre radio issues and potential architectures may be found in the following papers by O'Reilly et al and Kitayama. [11,12]

Whereas three term mm-wave generation techniques are very simple in concept, the effect of fibre chromatic dispersion on the optical signal leads to a cyclic variation of the generated power with fibre distance or frequency. Two term techniques rely on the E-field non-linearity of the photo-detector. The detector acts as a mixer that generates an electrical beat signal at a frequency equal to the separation of the two optical components. Using two term techniques the impact of fibre chromatic dispersion is minimised.

The impact of fibre chromatic dispersion on the performance of an externally modulated mm-wave fiber radio system incorporating a radio DS-CDMA scheme has been analysed by Smith et al.[13] They showed that the large amplitude variation normally experienced in externally modulated systems can be significantly reduced in DS-CDMA systems.

The impact of optical beat interference on the performance of mm-wave fibre radio systems employing a two term mm-wave generation technique is under investigation. The performance of SCMA is expected to be reduced compared to SCMA systems operating at lower frequencies because of the increase in the OBI due to the increase in the number of terms beating on the photo-detector. On the other hand the analysis should provide useful information on the ability of DS-CDMA to mitigate the effects of OBI in mm-wave fibre radio systems. The aim is to identify the system boundaries (e.g. processing gain range) within which DS-CDMA mm-wave fibre radio systems would be advantageous and achievable.

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