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Phil. Trans. R. Soc. Lond. A 2000 **358**, 2297-2308
doi: 10.1098/rsta.2000.0648

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Broadband wireless systems and networks: an enabling role for radio-over-fibre

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There has been a remarkable take up of wireless and mobile communications in recent years, such that in a number of countries the number of mobile phones now exceeds the number of fixed network connections. Alongside this, we are seeing dramatic growth in data on the network compared with voice: the so-called 'data wave'. While much mobile network traffic is currently voice there is increasing use of the available data facilities with these now being enhanced (e.g. via evolution of the global system for mobile communications and subsequently the introduction of 'third-generation' systems such as the universal mobile telecommunications system). Accordingly, there is considerable interest and activity in the research community concerning possible technologies exploiting yet higher frequencies where truly broadband future wireless networks may be realized. This paper will review some of the technology options currently available or under examination for millimetre-wave broadband wireless networks and will go on to consider in some detail a specific example of 'fixed-wireless' technology synergies exploiting radio-over-fibre techniques to achieve flexible, reconfigurable broadband wireless networks.

Keywords: broadband radio; fixed-wireless networks; DWDM

1. Introduction

There has been a remarkable resurgence in interest in wireless systems with the development of cellular radio networks, so much so that in some countries the number of mobile phones now exceeds the number of fixed connections. At the same time there has been dramatic growth in data communications, fuelled particularly by the Internet and World Wide Web. As a consequence there is increased pressure on the radio spectrum and demand for wireless data capabilities. To serve this demand spectrum allocations have been made at higher frequencies extending into the millimetre (mm)-wave region. In this paper we review first some of the evolutionary developments in mobile and wireless systems, and then note developments supporting wideband/broadband data. Finally, we explore ways in which optical fibre technology may play a part in facilitating the realization of broadband wireless networks based on mm-wave radio-over-fibre techniques.

2. Towards third-generation mobile networks

First-generation, analogue, mobile wireless networks have been followed by second-generation digital networks, such as the global system for mobile communications

(GSM). These support a larger number of customers, provide enhanced security and voice quality while providing the foundations of a data capability which made the introduction of value-added services possible. Currently, networks based on the GSM standards operate in the 800–900, 1800 and 1900 MHz frequency bands, utilizing a macrocellular and microcellular architecture.

In parallel we have seen considerable growth in take-up of the Internet, and this has led to efforts to effect a degree of merging/mutual support with mobile communications; there is considerable demand for improved mobile data capabilities. Within the framework of GSM Phase 2+, the European Telecommunications Standards Institute (ETSI) has developed two new data services—high-speed circuit-switched data service (HSCSD) and general packet radio service (GPRS)—which augment the current data capability of GSM of 14.4 kb s^{-1} per user.

HSCSD is based on the parallel use of several GSM channels. A maximum data rate of 57.6 kb s^{-1} can be achieved by using four time slots allocated for the duration of the call. Although the maximum data rate is increased, HSCD is still circuit switched in principle and therefore it does not handle bursty data connections efficiently.† The implementation of this service requires that changes be made in channel allocation, connection set-up, hand-over procedures and interworking to the fixed network.

GPRS was designed to cater for the inherent burstiness present in data communications. The number of GSM channels allocated to GPRS is adapted on demand to suit the prevailing traffic conditions. Furthermore, the up-link and down-link are used as independent channel resources. This offers a packet-switched service alongside existing circuit-switched data services, eliminating the need to replace current GSM services. Depending on the distribution of traffic offered to the network, GPRS is capable of achieving a maximum data rate of 115 kbit s^{-1}. Furthermore, it allows users to be always on line since they only consume resources when they are transmitting or receiving data. Significant restructuring is required in the GSM network in order to integrate a packet-switched backbone network. GPRS is being made available commercially during 2000 (Gotz & Bernhard 1997; Jian & Goodman 1997).‡

Another technique, called Enhanced Data Rate for GSM Evolution (EDGE), is being studied (Schramm *et al.* 1998; Olfsson & Furuskar 1998). This technique reuses the GSM carrier bandwidth and time slot structure, together with a modified air interface that enables the transmission of up to 384 kbit s^{-1}. The EDGE concept is being hailed as enabling networks operating in the 800, 900, 1800 and 1900 MHz frequency bands to provide third-generation capabilities (Furuskar *et al.* 1999).

In 1985 the International Telecommunications Union (ITU) formed a working group with the aim of evaluating and specifying requirements for future wireless standards. This led to the establishment of a third-generation standard now called International Mobile Telecommunication 2000 (IMT-2000). This aims at providing a global standard—or, rather, a set of standards—promoting a high degree of commonality of design world-wide, with a view to supporting global mobility, service portability and multimedia.¶

In Europe, within the broad framework of the IMT-2000 family of systems, ETSI is developing a third-generation mobile radio system called universal mobile telecom-

† ETSI GSM 03.34 1997-04 *High speed circuit switched data (HSCSD)*, version 5.0.1.

‡ ETSI GSM 03.64 1997-11 *Overall description of the GPRS radio interface*, version 5.1.0.

¶ See the IMT-2000 home page ('frequently asked questions') at http://www.itu.int/imt/7_faqs/index.html.

munications system (UMTS). Conceived as a global system employing a hierarchical cellular structure, covering picocells, microcells, macrocells and satellite coverage, UMTS allows terminals to roam from private cordless or fixed networks, into a pico/micro/macro cellular public network, then into a satellite mobile network with minimal break in communications. This allows terminals to cover all areas of application at home, in the office, en route, train and aircraft. Transmission of up to 2 Mbit s^{-1} when stationary, 384 kb s^{-1} when in pedestrian movement and 144 kb s^{-1} for vehicular communications is being targeted. UMTS will also allow roaming during an existing connection while supporting a virtual home environment.

3. Broadband wireless systems

The systems considered above are narrow band, or some, if generously interpreted, wide band. Today the major research challenge is to realize the promise of a ubiquitous, wireless multimedia network. Broadband wireless system initiatives span from wireless local area networks (WLANs), to fixed wireless access systems, to mobile broadband systems. In order to sustain the data rates planned, broadband wireless initiatives are evaluating the use of spectrum in the upper microwave- and mm-wave frequencies, out to *ca.* 60 GHz.

(*a*) *Wireless local area networks (WLANs)*

WLAN standardization initiatives have been undertaken by the IEEE 802 LAN/MAN standards committee, which specified IEEE 802.11, and ETSI, which specified HIPERLAN types 1 and 2.

The IEEE 802.11 standard specifies a medium access control (MAC) layer and several physical layers. Two physical layer standards are designed to operate in the 2.4 GHz ISM band: one uses a frequency hopping spread spectrum technique (FHSS) and the other a direct sequence spread spectrum technique (DSSS). A third physical layer standard is designed to operate in the infrared region. All three physical layer standards must support 1 Mbit s^{-1} transmission. Transmission at 2 Mbit s^{-1} is mandatory for the DSSS standard and optional for the others. The MAC protocol provides two services: an asynchronous service and an optional contention-free service. It is based on a carrier sense multiple access with collision avoidance (CSMA/CA) protocol.

Work has started on the specification of a 20 Mbit s^{-1} physical layer standard operating in the 5 GHz band, in cooperation with other international standardization bodies, and on an extension in the 2.4 GHz band enabling a data rate of up to 11 Mbit s^{-1}.

The ETSI high-performance radio LAN type 1 standard (HIPERLAN 1) operates in the 5 GHz frequency range and it uses the same modulation scheme as GSM, Gaussian minimum shift keying (GMSK). It enables a maximum of *ca.* 20 Mbit s^{-1} user throughput when using its most efficient packet structures.

HIPERLAN type 2 is a connection oriented WLAN offering quality of service support. It also operates in the 5 GHz frequency band. The physical layer utilizes orthogonal frequency division multiplexing (OFDM). A key feature is that several modulation and coding alternatives are provided that enable adaptation to the current radio channel quality. A maximum user data rate of *ca.* 25 Mb s^{-1} is possible.

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The standard is network and application independent, for easy integration with a variety of fixed networks (Martin 1999).

(*b*) *Fixed broadband wireless access networks*

The development of fixed broadband wireless systems has been catalysed by the requirements of new entrant operators aiming at bypassing the local loop. These systems typically use licensed microwave or millimetre frequencies to connect network nodes to fixed users through rooftop antennae. The different system configurations are as follows.

Point-to-point systems. Commonly deployed at bit rates from 2 to 155 Mbit s^{-1} and operating in the 17 or 38 GHz band, these systems are used to connect corporate sites to the backbone network via line-of-sight (LOS) links spanning few tens of kilometres.

Point-to-multipoint systems. Cellular systems employing multiple base stations, each of which serves a neighbourhood area. Many systems are being proposed, differing from each other in the frequency band used, cell radius, bandwidth capacity and asymmetry, and their ability to support differentiated services to customers. Among the most common systems are:

Multipoint microwave distribution systems (MMDSs). Systems that operate at *ca.* 2 GHz with a cell radius from 20 to 50 km. Originally installed as a TV distribution infrastructure, there is now a push to develop MMDS to support interactive services.

HiperAccess Urban/Rural. An ETSI broadband radio access network (BRAN) initiative, to standardize a point to multipoint system capable of 25 Mbit s^{-1} with a coverage of up to 5 km. Spectrum allocation is being discussed.†

Local multipoint distribution systems (LMDSs). These are systems that predominantly utilize the 26–30 GHz band. In early 1998 the FCC, subsequently followed by a number of countries, auctioned the LMDS spectrum. Standardization activities are being carried out by the IEEE 802.16 Broadband Wireless Access working group and the Digital Audio Visual Council (DAVIC). LMDS aims at providing a cell coverage of 3 km, using a cell sectoring technique based on different polarizations. Several issues related to line of sight limitations, foliage interference and depolarization are being studied. Local Multipoint Communication Service (LMCS) is an LMDS variant used in Canada.

Microwave video distribution system (MVDS). This is a cellular based system for video broadcasting and interactive services. In the UK it has been allocated the 40.5–42.5 GHz frequency band. Out of the two GHz of spectrum 100 MHz is currently allocated for the return channel. Experimental MVDS networks are reusing many of the digital video broadcasting specifications. MVDS suffers from the same disadvantages as LMDS albeit more severe.

Broadcast systems. The main systems here are wireless digital video broadcasting (DVB) and digital audio broadcasting (DAB) systems.

† ETSI BRAN homepage. See http://www.etsi.org/.

Satellite systems. Satellite systems using satellites at various orbital levels have also been proposed.

Stratospheric platforms. Stratospheric platforms in which the base station is mounted high in the atmosphere are gaining popularity. The two major existing proposals plan uncrewed dirigibles and crewed aeroplanes. Both seem to provide feasible solutions for metropolitan regions.

(*c*) *Mobile broadband wireless networks*

Technology and systems concepts for a mobile broadband system were investigated within the framework of the European RACE programme in the MBS project (Leonardo 1993). The concept is essentially to extend to mobile users access to the same range of broadband services being developed for fixed users. The broadband aspect of MBS typically addresses services above 2 Mbit s^{-1} up to *ca.* 155 Mbit s^{-1}.

Broadband mobile systems pose a new set of challenges in addition to those dealt with by the narrowband mobile systems. The high data rates envisaged by MBS require operation at higher radio frequencies, extending up into the 60 GHz band where a peak in attenuation due to oxygen absorption restricts cellular coverage to *ca.* 100 m (picocell), allowing a small frequency re-use pattern.

From an evolutionary point of view MBS may start as a WLAN technology and subsequently evolve to a fully integrated public network. However, considerable challenges exist to engineer a low-cost base station unit capable of being deployed in the numbers envisaged, together with the engineering of a transport network capable of interconnecting the base stations and supporting their broadband capacity requirements: an area where mm-wave radio-over-fibre techniques may offer a solution (O'Reilly & Lane 1994).

4. Millimetre-wave radio-over-fibre support for wireless networking

The topology of a typical fibre-supported mm-wave radio system (FSMS) is shown in figure 1. The data–optical interface needs to generate an optical signal that can be detected and processed to yield the required mm-wave signal. The optical network distributes this optical signal to a number of antenna units (AUs) where the optical to radiofrequency (RF) conversion occurs. The AU radiates the RF signal and the mobile equipment (ME) receives the signal. The optical network may make use of optical amplifiers to support a high split ratio, and may also use wavelength division multiplexing (WDM) in conjunction with wavelength routing devices to allow different signals to be radiated from different antenna sites.

As target requirements for an FSMS, the system should be

(i) able to deliver mm-wave signal to a remote antenna unit;

(ii) able to modulate the mm-wave signal;

(iii) transparent to the modulation format;

(iv) able to operate over an optical network; and

(v) able to provide capacity into area on an as-needed basis.

To meet these requirements, a number of optical mm-wave generation methods are possible, as discussed below.

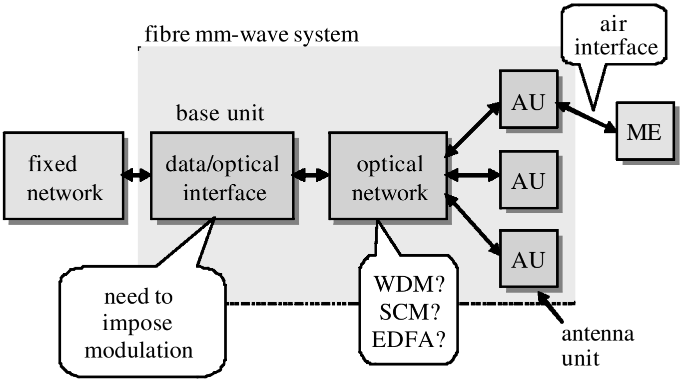

Figure 1. Reference architecture for a fibre-supported mm-wave radio system.

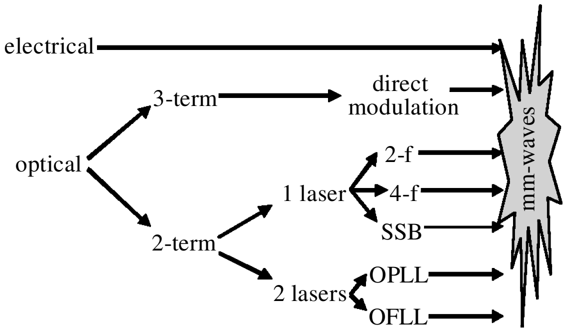

Figure 2. Roadmap of mm-optical wave generation methods.

(*a*) *Generation methods and performance*

Optical mm-wave generation methods can be divided into two broad classes: three-term techniques, corresponding to conventional amplitude modulation of the optical signal at the mm-wave frequency required; and two-term techniques, where the two optical components mix (heterodyne) on the photodetector to generate an electrical signal at a frequency equal to the separation of the two optical components. The relationship between these two broad classes is illustrated in the roadmap of generation methods shown in figure 2.

(i) *Three-term techniques*

The three-term approaches are very simple in concept since all that is needed is an optical intensity modulator that can operate at the mm-wave frequency. A major limitation though is the impact that fibre dispersion has on the generated signal. The phase change experienced by the three different components due to fibre dispersion can be viewed as a rotation of the three phasors representing the signals. This leads to a cyclic variation of generated power with fibre distance or frequency. At the frequencies of interest here, this effect limits the usefulness of three-term techniques to fibre reaches of only a few kilometres.

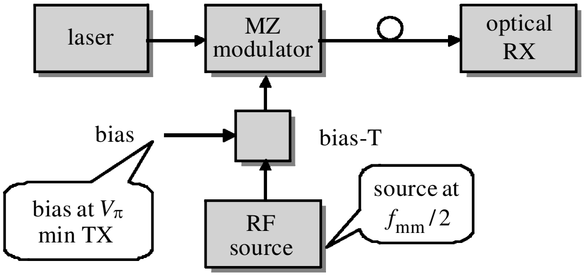

Figure 3. 2-f generation method. RX, receiver; MZ, Mach–Zehnder modulator.

(ii) *Two-term techniques*

The two-term techniques rely on the E-field nonlinearity of the photodetector. The detector acts as a mixer that generates an electrical signal at a frequency equal to the separation of the two optical components. The advantage of this method is that the dispersion induced rotation of the phasors representing the two optical components only leads to a change in the generated mm-wave signal, which is not an issue of any concern.

(*b*) *Specific two-term generation methods*

(i) *Two-laser techniques*

The simplest two-laser method is the optical frequency locked loop (OFLL). Generation of a high spectral purity mm-wave signal requires very narrow linewidth lasers. A variant on this method is the optical phase locked loop (OPLL) where a phase detector is used to generate an error signal depending on the phase error between the lasers. This latter method can generate very narrow electrical linewidths since the slave tracks the phase noise of the master laser.

(ii) *Single-laser techniques*

Single-laser methods rely on the generation of two optical components from the single laser through modulation. One technique, referred to here as the 2-f method, uses a Mach–Zehnder modulator biased at minimum transmission. Driving the modulator with a sinusoid around this point generates a double-sideband-suppressed carrier (DSB-SC) signal with two optical components separated by twice the microwave/mm-wave drive frequency. This method is shown in figure 3.

(*c*) *System issues*

An important issue associated with the use of two-term generation techniques is how to impose service signals. Modulation can be imposed on to both optical components or onto just one of the components as indicated in figure 4.

The first approach is simplest to implement since no optical filter is required, while the second yields better tolerance to dispersion but needs the optical diplexer to track the frequency of the laser.

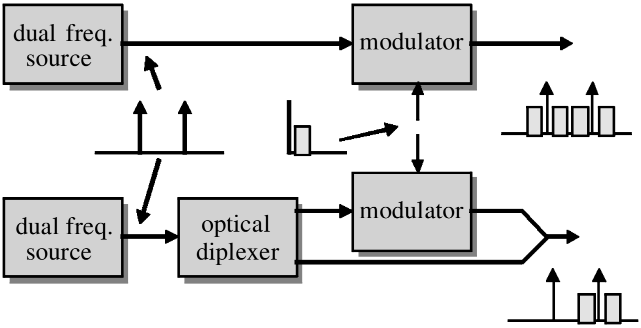

Figure 4. Imposition of modulation onto a dual-frequency optical source.

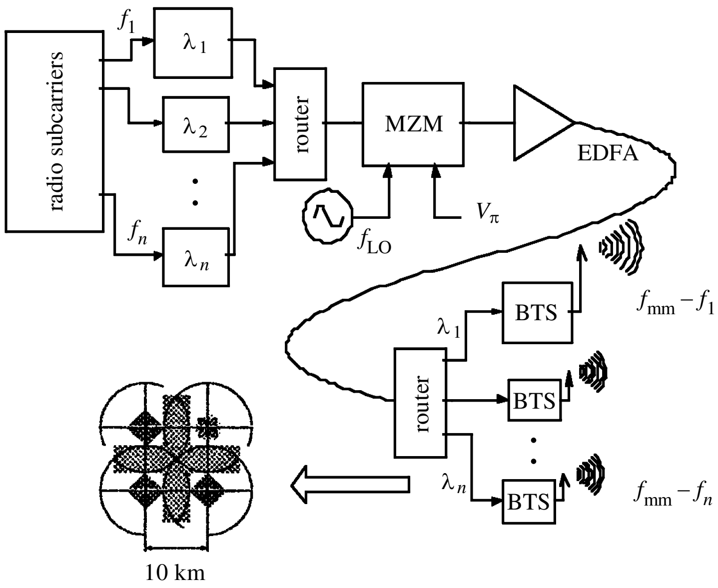

Figure 5. Optical mm-wave/DWDM overlay providing service differentiation. EDFA, erbium-doped fibre amplifier; BTS, Bose transceiver station.

5. Combining radio-over-fibre and dense wavelength division multiplexing (DWDM)

FSMSs have the potential to offer huge flexibility in terms of providing capacity on an 'as-needed' basis. To realize this potential, research now needs to be concentrated on systems and network deployment issues to identify architectures and topologies best suited to achieving flexibility supporting reconfiguration of network capacity.

The application of DWDM techniques provides a promising approach to achieving this. A likely cellular access system will comprise overlapping cells of radius *ca.* 5 km, each of which is divided into multiple sectors. The introduction of DWDM will allow data from the central office (CO) to be targeted to a particular cell sector, providing service differentiation and hence efficient use of radio spectrum.

DWDM could be applied using multiple optical mm-wave sources, but a particularly attractive approach is the optical mm-wave/DWDM overlay shown in figure 5.

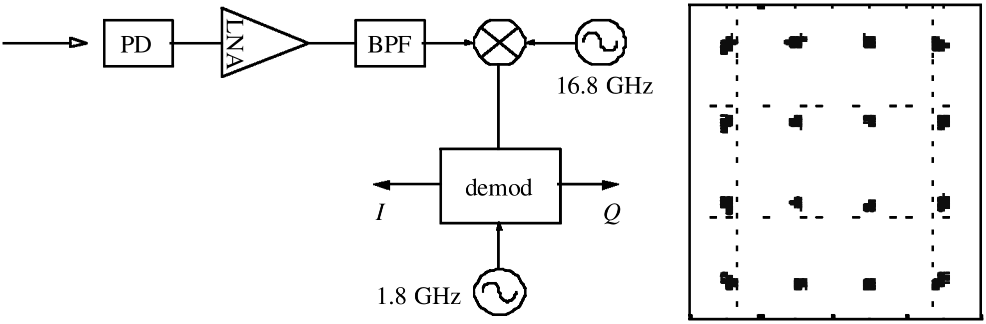

Figure 6. Experimental system and associated 16-QAM signal constellation. PD, photodiode; BPF, band pass filter.

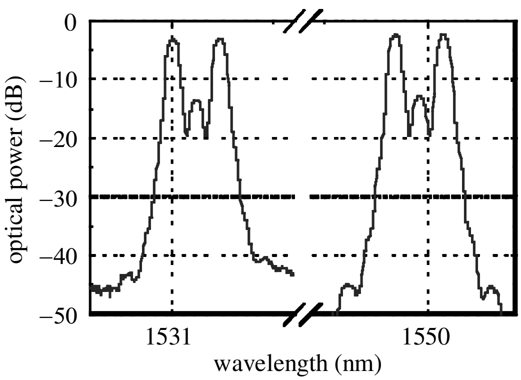

Figure 7. Optical spectra for simultaneous modulation of two widely spaced sources.

In this approach, radio subcarriers are applied directly to DWDM sources, the multiple wavelengths are multiplexed and the composite signal is upconverted to mm-wave frequency using a Mach–Zehnder modulator (MZM) to perform suppressed optical carrier (SOC) modulation (Sauer *et al.* 1998; Griffin *et al.* 1999*a*). This approach allows the use of standard DWDM sources, can span tens of kilometres of standard single-mode fibre, and employs only a single high-speed modulator/driver/local oscillator.

Modelling of system performance for the DWDM overlay produces extremely promising results. An experimental arrangement and associated 16-QAM† signal constellation is illustrated in figure 6, while figure 7 illustrates simultaneous SOC upconversion at 30 GHz of two sources separated by *ca.* 20 nm, demonstrating the wavelength transparency necessary for an optical mm-wave/DWDM overlay.

Figure 8 shows predicted bit error rate (BER) performance for a 16-wavelength system spanning 20 km. Based on these results, which account for the link power budget, optical-to-RF phase noise conversion and laser chirp-induced intermodulation distortion, a single central office may support broadband access over *ca.* 200 km^2. A serious obstacle to implementation of such a scheme, however, is the impairment which may result from optical cross-talk, and this is the issue which we address here.

† Quadratic amplitude modulation.

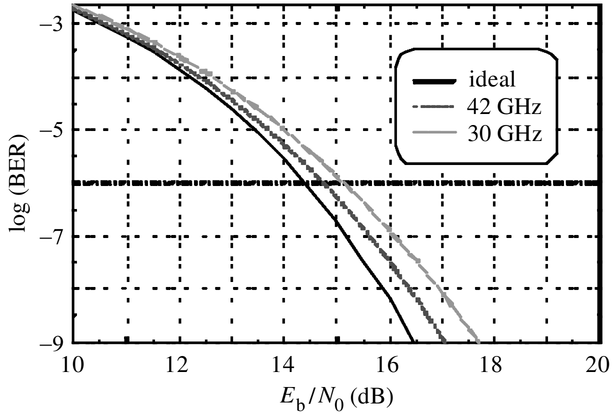

Figure 8. Simulated bit error rate (BER) performance for a 16-channel optical mm-wave/DWDM overlay transmitting multiple 16-QAM carriers with an aggregate data rate of 1 Gb s^{-1} per wavelength.

(*a*) *Cross-talk considerations*

Dense WDM is proving extremely successful for high-speed, long-haul fibre spans transmitting baseband binary signals. For radio-over-fibre applications, however, optical spectra are broad due to high carrier frequency, and tolerance to cross-talk is reduced. There are several router non-idealities that may impact system performance. For 100 GHz channel spacing, the optical bandwidth of the mm-wave signal may approach or exceed the router bandwidth, resulting in loss of optical power. Due to finite extinction and roll-off of the band-edges of the router, power from adjacent optical channels will leak into any given channel, giving rise to cross-talk. Potentially the most serious problem arises from the nonlinearity inherent to the MZM, which can generate spurious components in adjacent channels, and is problematic even for ideal routers. With relative wavelength drift between adjacent wavelengths, a worst case may occur where a large beat term coincides with the data band, resulting in system outage. Careful system design must be carried out to ensure that spurious components are sufficiently small to avoid significant penalties. However, detailed modelling and associated experimental studies have established that these difficulties are surmountable and the required performance is realizable, as illustrated in figure 9. Further enhancement of the operating margins is possible by exploiting polarization interleaving for alternate DWDM channels (Griffin *et al.* 1999*b*), a subject of on-going investigation.

6. Concluding remarks

This paper has reviewed recent developments in wireless network technologies with an emphasis on progression towards truly broadband operation. This led to the observation that radio-over-fibre techniques offer potential for realizing flexible network architectures. A range of options for the remote delivery and generation of modulated mm-wave signals through the use of optical techniques was indicated. Methods for the imposition of modulation onto the mm-wave signal were described. Finally, the prospects for combining radio-over-fibre and DWDM techniques as a means of

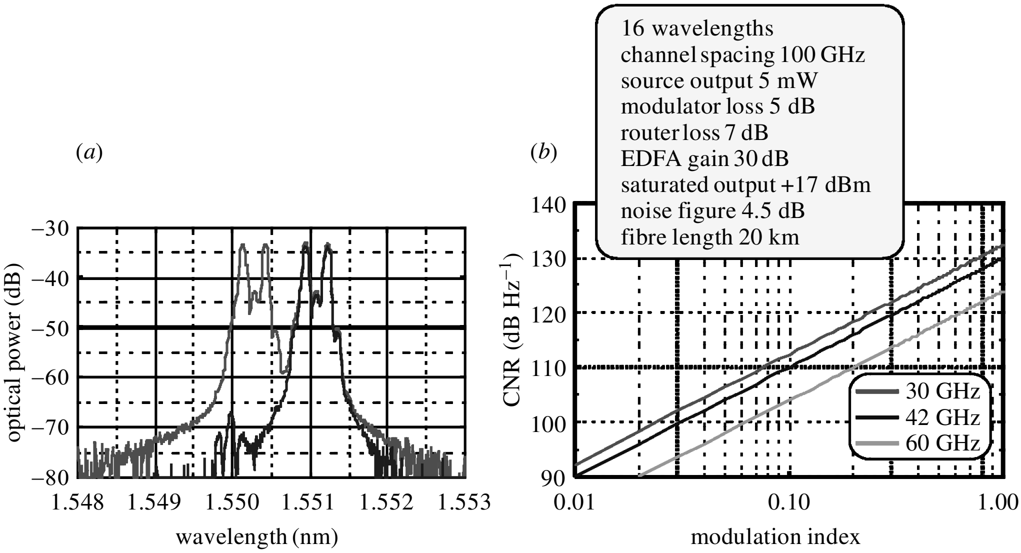

Figure 9. Impact of cross-talk between adjacent channels on system power budget, quantified in terms of attainable carrier-to-noise ratio.

enhancing service differentiation and offering flexible network capacity allocation were outlined. Preliminary performance results were presented indicating the practicability of this arrangement. It is suggested that further research is appropriate aimed at developing deployment concepts that will allow the flexibility potentially offered by these systems to be realized.

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