RF Over Fibre Systems

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Abstract: *The expansion in mobile working has led to increased demand for wireless services, such as cellular radio and Wireless Local Area Networks (WLAN). The proliferation of such services and rapid evolution in coding and modulation standards has increased interest in Radio Frequency (RF) over fibre systems which distribute such services in their final modulated RF carrier form from a central site over optical fibre to antenna units which then convert the signal back to the RF domain. This paper reviews evolving technologies for such systems.*

Introduction

Development of the core optical communications network through dense wavelength division multiplex technology has led to massively increased transmission capacity, while increased interest in broadband applications, such as interactive video, has increased interest in broadband end to end capability. However the provision of fixed broadband (> 2 Mb/s bi-derectional) access has been relatively slow and expensive. Broadband wireless access through IEEE standards 802.11a/b/g and 802.16 has shown rapid growth in both private and public ("hot-spot") networks and is seen as a route to push forward broadband deployment. Such networks have been created by adding wireless transceivers to ethernet or similar wired networks. Changes in standards require corresponding changes in fielded transceivers.

Distributing broadband wireless signals over optical fibre has a number of advantages relative to traditional copper cabling. Because of the low transmission loss of optical fibre, the antenna units (AUs) can be located where coverage is required and remotely connected to the RF generation and detection hardware, which is centralised along with other telecommunications and network hardware in a single equipment room. In this case, the AU function can be simplified to just RF radiation/reception and electrical/optical conversion. Such a system can be made modulation format agnostic and therefore future-proof. When new standards and services are introduced, upgrades are only required to the centralised hardware in the equipment room, but not to the fibre infrastructure or AU. The wide bandwidth of optical fibre further allows different services such as Gigabit Ethernet, IEEE802.11a/g, 802.16, GSM and 3G to share the same infrastructure, making the wireless over fibre approach a truly multi-operator and multi-service technology.

In this paper the main technologies used for RF over fibre systems will be reviewed and promising approaches for future systems identified.

Passive Picocells

The concept of Passive Picocells was first proposed in 1997 by Wake *et al* [1] at BT Laboratories, who demonstrated that an unbiased waveguide electroabsorption modulator (EAM) would have sufficient performance to function as both optical modulator and photodetector simultaneously. When attached to an antenna, the EAM serves as a passive transceiver at the AU. An experiment was carried out in which the EAM was attached to an 8 dBi gain bow-tie type antenna and was placed in a Picocell (a 3m x 6m office). A 2.5 GHz commercial wireless LAN access point (AP) was located in the central station (CS) and after detaching its own antennas, the electrical input and output ports of this AP were converted to optical connections using a separate photodiode and a directly modulated laser. The AP in the CS was connected to the EAM transceiver in the Picocell with two optical fibres, one for the downlink direction (CS to AU) and one for the uplink direction (Picocell to AU) as shown in Fig. 1. To show that the EAM was functioning correctly as a remote Picocell transceiver, a notebook computer equipped with a wireless LAN adapter was brought to the Picocell office and a 3Mbit/s half-duplex network connection was successfully established between the computer and the EAM transceiver via a 2.5 GHz radio link, and thence via the two optical fibres to the AP in the CS.

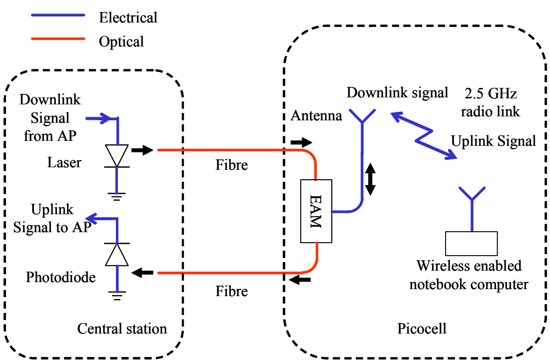

Fig. 1: Schematic representation of the Picocell experiment using a waveguide type EAM transceiver by Wake *et al*.

At UCL we have been investigating a different type of electroabsorption modulator for Picocell or broadband wireless over fibre applications. The modulator is an Asymmetric Fabry-Perot Modulator (AFPM) with an InGaAsP/InGaAsP Multiple Quantum Well (MQW) electroabsorbing region [2,3]. One key difference from the original passive picocell work is that the AFPM is a reflective device with a single optical window. The downlink optical signal is incident on the AFPM within the optical window.

The uplink optical signal on the other hand is simply the AFPM modulated reflection of the residual downlink optical signal through the same optical window. Because of the reflective nature of the AFPM, only one fibre is required for carrying both downlink and uplink optical signals. Compared to the waveguide type EAM, the AFPM also has a number of attractive features. Being a vertically addressed optical intensity modulator, the AFPM is polarisation insensitive because the electric field of the input optical signal is always in the plane of the MQW layers. Thus polarisation control is not required, in contrast to the waveguide type EAM. The optical insertion loss for the AFPM can be as low as 4 dB because of a relatively large (≈20μm in diameter) optical window which eases coupling to optical fibre compared to the typically small cross-sectional area of 1μm × 0.26μm of the waveguide InGaAsP/InGaAsP MQW EAM [4]. At UCL, a reliable air-bridge process has been developed which allows low-capacitance (< 270 fF) AFPMs to be fabricated. In this section, details of the application of the AFPM in RF over fibre systems and its characteristics are described.

Like the waveguide type EAM, the AFPM can be employed at the BS and function as a combined optical modulator and photodetector in a single device. Fig. 2 illustrates the role of an AFPM in a simplified wireless over fibre system.

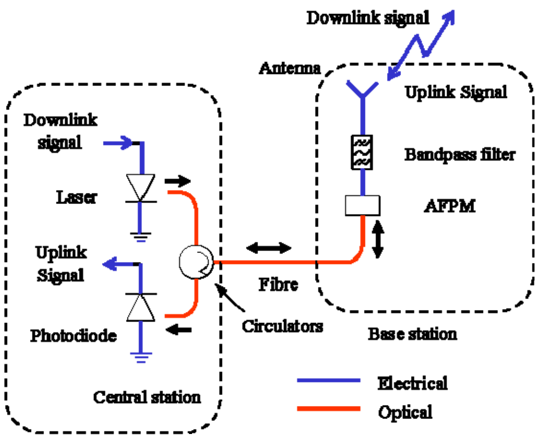

Fig. 2: A simplified wireless over fibre system concept involving an AFPM at the AU performing photo-detection for the downlink path and optical modulation for the uplink path.

The downlink signal is detected by the AFPM and radiated by the antenna. The radio uplink signal received by the antenna is fed to the AFPM which in turn modulates the residual light left from the downlink direction. This residual light, now carrying the up-link signal, is reflected by the AFPM back to the central station.

Fig. 3 shows a micrograph of the air-bridged AFPM developed and fabricated at UCL.

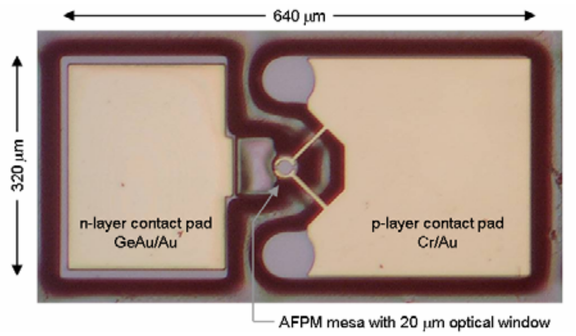

Fig. 3: Top microscopic view of a fabricated air-bridged AFPM.

The AFPM has a −3 dB modulation bandwidth of about 15 GHz which is more than sufficient for carrying the IEEE802.11a/b/g broadband wireless data as well as the cellular GSM and UMTS signals. This is the fastest long (1,550 nm) wavelength InGaAsP/InGaAsP MQW AFPM reported to date. Higher operation speeds have been reported for AFPMs using other material systems [5,6].

Bi-directional 5.2 GHz broadband 68 Mbit/s Differential Phase Shift Keying (DPSK) modulated wireless data transmission over a 12.6 km fibre has been demonstrated using an AFPM alternately as a modulator and a photodetector while keeping the device and experiment parameters same. Full details of the experiment can be found in [7].

Optical Analogue Link Performance Enhancing Techniques

Instead of employing an AFPM at the AU as a single electrical/optical transducer as in Fig. 2, the more traditional method would be to use separately a photodiode for the downlink and a directly modulated laser diode for the uplink. The BS can receive simultaneously both high- and low-power radio signals from nearby and distant users, respectively. Any non-linear components in the fibre-optic link such as a directly modulated laser can cause spectral re-growth (or broadening) of a strong input signal, interfering with any weak neighbouring channel. When a diode laser is directly modulated with two high-power modulated channels, strong inter-channel distortion products are also generated which can degrade a third neighbouring weaker channel or even render it undetectable.

At UCL a microwave frequency feed-forward linearisation scheme has been developed for directly modulated lasers [8,9]. It will be shown in this section that with such a linearisation scheme, the inter-channel distortion generated in the laser diode when driven by two high-power 11 Mega Symbols per Second (Msymb/s) Quadrature Phase-shift Keying (QPSK) modulated signals can be suppressed by at least 11 dB and a neighbouring low-power channel, which would otherwise have been buried under such distortion, can be recovered and detected successfully.

Fig. 4 shows the implementation of the feed-forward linearisation [10] and the experimental arrangement for triple QPSK modulated wireless signal transmission over fibre.

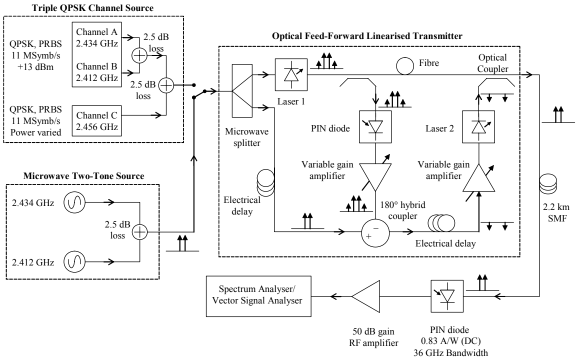

Fig. 4: Experimental arrangement for feed-forward linearisation and triple QPSK modulated wireless signal over fibre transmission.

Laser 1 had a wavelength of 1550 nm and was a commercially available fibre-pigtailed Distributed Feedback (DFB) diode laser. When directly modulated with two microwave tones, the non-linearity of Laser 1 caused third and higher order intermodulation distortion products as well as harmonic components of the two carriers to appear in the output optical intensity modulation spectrum. The detailed working principle of the feed-forward linearisation has been previously reported [11]. The key point is that the optical output of Laser 2 of 1570 nm wavelength replicates the distortion products generated by Laser 1 in anti-phase and without the main microwave tones. Therefore when the outputs from Lasers 1 and 2 are detected by the PIN type photodiode, the distortion products are cancelled, leaving only the linearised signal from Laser 1. The same principle applies when Laser 1 is directly modulated with two high-power QPSK channels. In the experiment the feed-forward could be enabled or disabled by simply connecting or disconnecting Laser 2 output from the optical coupler. The output from the optical feed-forward transmitter was transported over a representative 2.2 km length of Single Mode Fibre (SMF). Finally the linearised signal at the output of the photodiode was amplified and detected using a spectrum analyser and a Vector Signal Analyser (VSA).

A Vector Signal Generator (VSG) was used to provide two 11 Msymb/s QPSK modulated signals at 2.434 GHz (Channel A) and at 2.412 GHz (Channel B). Both Channels A and B had a fixed power level at +13 dBm throughout and were internally filtered with a root raised cosine function having a roll-off factor of 0.5 for reducing the occupied bandwidth. Another VSG provided Channel C which was an 11 Msymb/s QPSK modulated signal at 2.456 GHz. Channel C was internally filtered with a root Nyquist function having a roll-off factor of 0.5. A number of measurements were conducted with different Channel C power levels. All three QPSK channels were first combined using microwave combiners as illustrated in Fig. 4 before being fed to the optical feed-forward linearised transmitter.

With Channel C set at –23 dBm, the transmitted RF spectra with the feed-forward disabled and enabled were measured with a spectrum analyser and are shown in Fig. 5.

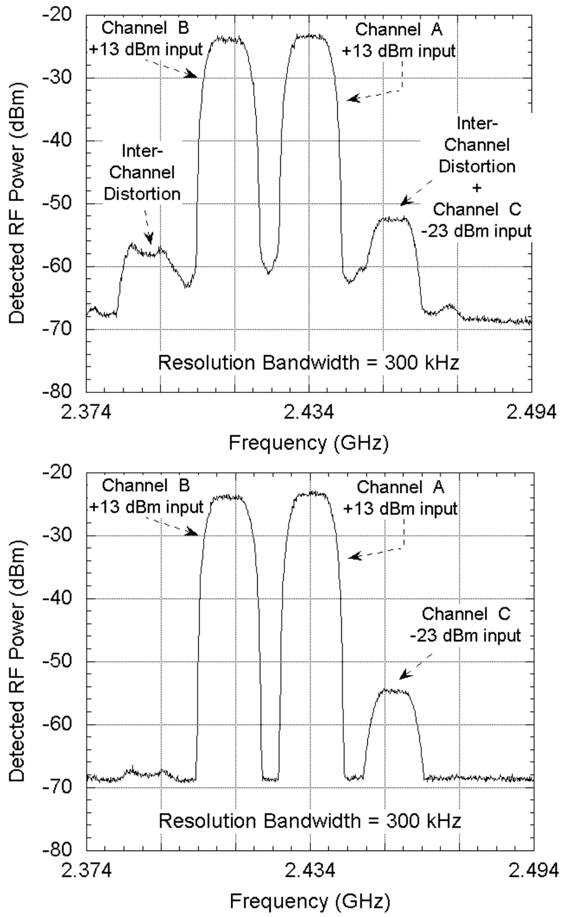

Fig. 5: Detected RF spectra of the three QPSK channels with feed-forward linearisation disabled (top) and enabled (bottom).

Under such a high-power input, particularly from Channels A and B, Laser 1 in Fig. 4 generated a significant level of inter-channel distortion as identified in Fig. 5 (upper plot) in the non-linearised case. The weaker Channel C was effectively buried under and could not be readily distinguished from such distortion products in the RF spectrum. With the feed-forward enabled, the inter-channel distortion was reduced by at least 11 dB and the spectrum of Channel C could then be clearly seen as in Fig. 5 (lower plot).

To assess further the impact of the inter-channel distortion on the weaker Channel C in the time domain and the effectiveness of the feed-forward linearisation, a VSA was used to measure the eye-diagram, the error-vector magnitude (EVM) and the signal-to-noise ratio (SNR) for Channel C. With the VSA tuned to the centre frequency of Channel C at 2.456 GHz and set to a 20 MHz channel filter bandwidth, the eye-diagrams with feed-forward disabled and enabled were measured and are shown in Fig. 6.

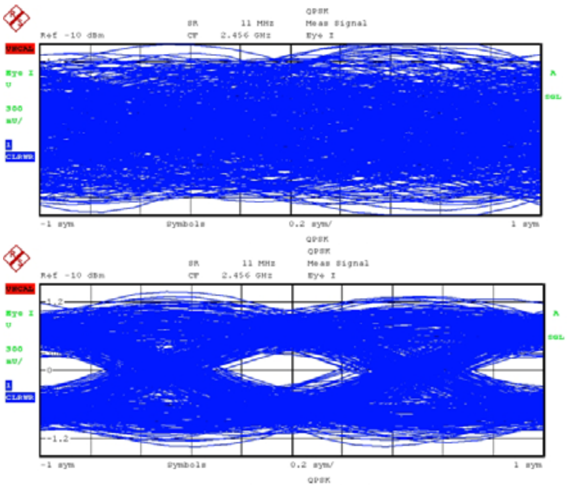

Fig. 6: Detected -23 dBm Channel C in-phase eye-diagrams with feed-forward disabled (upper) and enabled (lower). Channel filter bandwidth: 20 MHz.

When the feed-forward was disabled, no eye-diagram could be detected which suggests that the inter-channel distortion products from Channels A and B completely overwhelmed the weaker Channel C. When the feed-forward was enabled, a clear, widely open eye-diagram was obtained for Channel C. Such a dramatic difference in the quality of the received eye-diagrams illustrates how effective the feed-forward linearisation technique is in suppressing inter-channel distortion. In Fig. 6, only the in-phase eye-diagrams are shown since the corresponding quadrature-phase ones were very similar.

Finally the EVM and SNR for Channel C were measured as a function of channel input power and the results are plotted in Fig. 7.

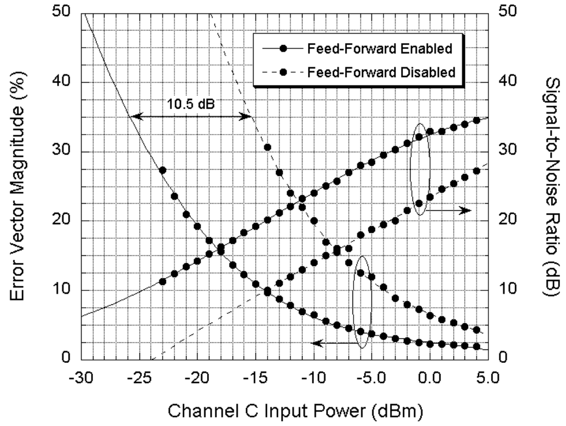

Fig. 7: EVM and SNR vs. Channel C input power. Channel filter bandwidth: 20 MHz.

The EVM decreased and SNR increased with increasing Channel C input power. At –14 dBm input power, the feed-forward linearisation reduced the EVM from 31 % to 10 % and increased the SNR from 10 dB to 20 dB. The IEEE 802.11b standard requires that the EVM not exceed 35 % and it can be seen in Fig. 7 that without feed-forward, Channel C would not be able to comply with this requirement for input levels below –15.5 dBm, whereas with feed-forward the specification is met for Channel C levels as low as –26 dBm, a power advantage of 10.5 dB.

Other researchers have also reported different analogue link performance enhancing techniques. Ackerman et al. [12] demonstrated an optical analogue link with RF noise figures ≤ 15 dB over the frequency range from 1.0 to 9.5 GHz with a laser RIN suppression technique which is illustrated in Fig. 8.

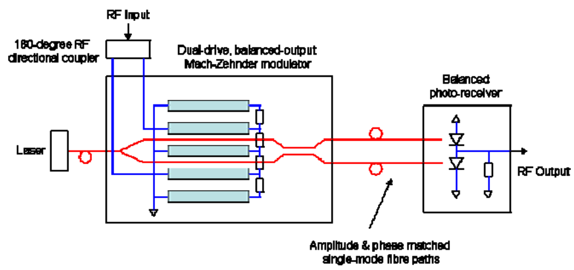

Fig. 8: Analogue optical link employing dual-drive Mach-Zehnder modulator and balanced photo-receiver for laser RIN suppression.

The key components in the optical link are the dual-drive Mach-Zehnder modulator (MZM) with balanced outputs and the balanced photo-receiver. The laser source is first split in two parts which are externally modulated in the two separate arms of the dual-drive MZM. Because of the 180-degree RF directional coupler, the modulation outputs from the MZM are in anti-phase. The two modulated optical signals are then transported to the balanced photo-receiver through two identical optical fibres having matched amplitude and phase response. The balanced photo-receiver produces an RF output which is the difference between the two photodetected signals. Since the two modulated signals are out of phase by 180 degrees, the original RF input signal is enhanced and delivered to the RF output. On the other hand, since the RIN is the same in two fibres both in amplitude and phase, it is suppressed by the balanced photo-receiver.

Darcie et al. [13] realised that the problems associated with the shot noise and the laser intensity noise in an analogue optical link are caused by the presence of a large DC optical power level in the transmission system. They demonstrated a technique for decreasing the DC optical power level, hence reducing the shot noise and laser intensity noise, by using two MZMs set up in a Class AB configuration analogous to that in transistor amplifier circuits. Fig. 9 shows the simplified experimental arrangement for this Class AB analogue optical link.

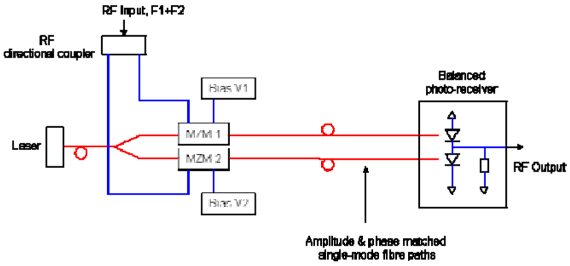

Fig. 9: Simplified experimental arrangement for the Class AB analogue optical link.

The key feature of this Class AB configuration is that the two MZMs are biased at $\pm V_{\pi}/6$ from the zero transmission, respectively. Therefore one of the MZMs is mostly transmitting in one half of the input signal circle and the other MZM mostly transmitting in the other half of the signal circle forming a Class AB configuration similar to that of a transistor amplifier circuit. The next effect is that the amount of average optical power reaching the balanced photo-receiver is reduced, lowering the effects of the shot noise and the laser intensity noise. Darcie demonstrated that the Class AB optical link shows a 5.7 dB reduction in shot noise compared to that achieved with a MZM conventionally biased at quadrature (50% transmission).

Wireless over Multi-Mode Fibre Systems

The work described so far has used single mode optical fibre which is invariably employed in long haul optical transmission systems. Most modern commercial buildings already have a multi-mode optical fibre (MMF) infrastructure for carrying Ethernet data. To provide cost-effective and reliable indoor cellular and WLAN coverage without dependence on the radio penetration from outside BSs, it is highly desirable that the same MMF infrastructure be used to carry these additional services between the equipment room and the remote AUs around the building.

MMFs were not previously regarded as being suitable for carrying modulated signals at microwave frequencies because they suffer from modal dispersion, limiting their bandwidth-distance products to between 500 MHz.km and 1 GHz.km at 1,300 nm wavelength. For cellular GSM1800 and UMTS systems, this would mean a maximum fibre length of around 500m while for IEEE 802.11a WLAN operating in the 5 GHz band, the maximum length is further reduced to less than 200m, which is not sufficient for large in-building installations. Commercial products for transporting cellular signals over fibre do exist which either transmit the signal over single mode fibre at the original RF, or transmit the signal over the MMF at a down-converted IF which is selected to be within the 3-dB bandwidth of the MMF. To provide in-building cellular coverage, the former method requires specialist and expensive fibre and component installation, because most installed fibres within buildings are MMF. The latter method requires complicated hardware, especially for the remote AUs since up-conversion from the IF to the original RF is necessary.

It was shown in 1998 by Raddatz *et al* [14] that transmission over MMF is possible over narrow bands of frequencies beyond the 3-dB bandwidth limit and this is because the impulse response of MMF contains a series of delta functions with different arrival times, which gives rise to high frequency components with considerable amplitude in the frequency domain.

UCL in collaboration with the University of Cambridge have investigated the transmission of cellular and broadband wireless IEEE 802.11b/g signals over MMF and the results so far are encouraging, sufficiently so that the work is now being exploited commercially [15]

To demonstrate that good quality broadband wireless signal transmission over multi-mode fibre can be obtained, experiments [16] experiments using 32-QAM modulation and demodulation were carried out. This complex digital modulation scheme requires a signal to noise ratio of more than 25 dB and is therefore a good test of the fibre performance. In the experiments a carrier frequency of 2 GHz and a symbol rate of 2 Ms/s were chosen, which corresponds to a transmission bit rate of 10 Mb/s.

Fig. 10 shows the constellation and eye diagrams for 32-QAM transmission. The left hand plots show results for a short coaxial cable link as reference and the right hand plots shows results for transmission over a 1km MMF (50 micron core and 125 micron cladding) with a specified bandwidth of 500 MHz. Comparable results were obtained using other similar fibre reels. It is clear that transmission over multimode fibre, at least up to a length of l km is not significantly degraded compared to the short coaxial cable reference.

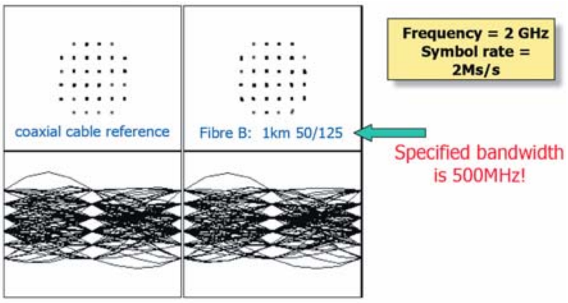

Fig. 10: Constellation and eye diagram for 32-QAM transmission at 2 GHz and 2 Ms/s. Left is coaxial cable (reference) and right is fibre reel B

To reduce the cost of in-building broadband wireless over fibre deployment even further, the use of uncooled, directly modulated lasers is highly desired. Transmission experiments using IEEE 802.11a/b signals over MMF have been performed using an uncooled 1,300 nm directly modulated laser [17]. Initially, the transmission performance of IEEE 802.11a/b wireless LAN signals over MMF was assessed using a VSA to determine the likely system performance. The received 11Mb/s 802.11b Complementary Code Keying (CCK) (similar to QPSK) constellation for a 2.41 GHz carrier frequency after 1km was clear with a measured error vector magnitude (EVM) of 1.21 %. The received 54Mb/s 802.11a 64-QAM constellation for a 5.35 GHz carrier frequency after 1km was also well defined with a measured EVM of 2.19 %. These are well within the maximum EVM specifications of 35 % for 802.11b and 5.6 % for 802.11a signals.

Conclusions

We have in this paper described a number of research projects which are relevant to broadband access using RF over fibre techniques, including using an AFPM as a single optical/electrical transducer for Picocell and wireline/wireless access applications, the feed-forward linearisation of directly modulated lasers, microwave signal transmission over low-cost multi-mode fibre and direct modulation of uncooled lasers.

Our experience has been that the take-up of such technologies is strongly dependent on applications drive. Specifically, we expect that ubiquitous in-building broadband wireless LAN (WLAN) coverage will be regarded as being as essential as coverage for the cellular systems such as GSM and 3G, and will be increasingly so when more and more people use their wireless enabled notebook computers or their handheld personal digital assistants (PDAs) not just for data applications but also for voice conversation instead of using the conventional mobile phone. Voice over IP (VOIP) is attractive as it allows people to make cheap (if not free) device to device or device to telephone calls conveniently and Skype, a piece of free software, has helped fuel the popularity of VOIP. As explained above, most commercial buildings have existing MMF infrastructure for carrying Ethernet traffic. It is also technically feasible to use MMF to carry other microwave signals beyond its 3-dB bandwidth limit. Therefore a strong case can be made that the existing MMF infrastructure be used for carrying a number of services, including WLAN, GSM, UMTS, TETRA and DECT etc. To provide such multi-service in-building coverage, the optoelectronic components involved must have high enough linearity, otherwise distortion products generated in them will degrade the system performance or even render one or more of the services unusable. In-building fibre infrastructure invariably uses direct modulation of semiconductor lasers to achieve the most cost-effective solution compared to other approaches such as external modulation. Although linearisation techniques for direct modulation lasers provide significant performance gains they require a number of extra components and are not sufficiently stable over time to be practical. We therefore expect that low-cost high-linearity direct modulation lasers will be the key to the success of future multi-service and multi-operator in-building wireless access networks. Given the difficulty in providing high data rate in-building coverage from outside the building, coupled with the need for comprehensive, rather than hot-spot WLAN coverage, to support VOIP we expect strong growth in the deployment of in-building wireless over fibre.

In conclusion, it is envisaged that the future of broadband wireless networks will depend on their ability to provide comprehensive multi-service and multi-operator coverage for buildings. Simple, practical and cost-effective technologies will be the key to success for suppliers to this market and there remains much scope for research on new devices and system architectures to assist this.

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