Radio over MMF Techniques, Part I: RF to Microwave Frequency Systems

Nathan J. Gomes, *Senior Member, IEEE*, Anthony Nkansah, and David Wake, *Member, IEEE*

***Abstract*— Recent work on radio over multimode fiber transmission, for the support of wireless LANs and current cellular systems operating at below 6 GHz, has shown that excellent performance (e.g. spur-free dynamic range well in excess of 100 dB.Hz2/3) can be achieved. However, here it is shown that for multi-system operation, spurious emissions may be more of a restriction than meeting good signal quality requirements (such as low error vector magnitude). Initial results are reported for error vector magnitude and adjacent channel leakage for UMTS transmission over a radio over multimode fiber link with a multi-system remote antenna unit, with conformance to standards being demonstrated.**

***Index Terms*— radio over fiber, multimode fiber, wireless communications, distributed antenna systems**

I. Introduction

THERE has been considerable recent interest in using radio over multimode fiber (MMF) for in-building distributed antenna systems (DAS) [1-8]. Generally, DAS offer improved radio coverage and lower emitted radio powers from the remote antenna units (RAUs), individually compared to standard access points/base stations, and in total [9]. There is also a lower power requirement on the mobile devices, extending battery lifetimes. Radio over fiber for supporting DAS has been investigated as the fiber bandwidth allows for multiple signals from different systems and operators to be transported, as shown conceptually in Fig.1, resulting in the possibility of deploying infrastructures based on "neutral host provision" and "base station hotels" [10 – 12]; the deployment can be low-cost by removing digital processing functions to a central location and is thus transparent to the precise coding etc. used. Indeed, the key requirement for such radio over fiber infrastructures is low cost: low-cost RAUs are essential due to the fact that they may be numerous to provide coverage, which in turn leads to the requirement for low-cost optical/electrical and electrical/optical radio over fiber transceivers.

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N. J. Gomes, A. Nkansah, and D. Wake are all with the Broadband and Wireless Communications Group, Department of Electronics, University of Kent, Canterbury, CT2 7NT, UK (phone: +44 1227 823719; fax: + 44 1227 456084; email N.J.Gomes@kent.ac.uk, A.K.A.Nkansah@kent.ac.uk, D.Wake@kent.ac.uk).

With the interest in low-cost radio over fiber solutions, the use of MMF has become of greater interest. A number of cost benefits can be identified. First, there is a need for much lower cost optoelectronic components: in particular, VCSELs are eminently suitable for use with MMF, and possess the electrical bandwidth required for direct modulation radio over fiber links operating in the frequency ranges of current, commercial mobile/wireless systems. Further, the majority of large in-building networks use MMF; MMF certainly dominates over single-mode fiber for link lengths up to 300 m, and continues to do so for such new installations [13], as improvements in MMF manufacture have continually enabled the requirements of higher speed Ethernet systems to be met.

This paper will concentrate on RF/microwave radio over fiber systems, certainly those operating below 6GHz, where currently used wireless (e.g. WiFi) and mobile (e.g., GSM, 3G) systems operate. Its companion paper [14] will examine techniques for higher frequency systems, the possible use of plastic optical fiber and digital-radio over fiber convergence issues. In the following section we review the important techniques that have made it possible to consider MMF for radio over fiber systems. In Section III, we review the experimental link demonstrations of RF/microwave radio over fiber systems; from these we draw general conclusions on the suitability of different types of configuration, and summarize the limitations that can be expected. Section IV, reviews the architectural considerations for MMF-fed DAS and presents conclusions on how cells can be overlaid in a multi-system environment. In Section V, we present measurements on an RAU designed for multi-system operation, which contrasts significantly to the design philosophy used in our previous work [4]. Finally, we conclude and discuss future work in Section VI.

II. Overcoming Bandwidth Limitations with MMF

Although, extensively used, especially for datacomms in Local Area Networks, MMF suffers a significant bandwidth limitation compared to single-mode fiber (SMF) due to modal dispersion. In the time domain, the effect can be seen as the different modes experiencing differing delays through the fiber link [15]. As many modes have similar group delays they are often assigned into mode groups. The observation of the delay spreads from these mode groups has become more apparent with the increased use of lasers for higher bandwidth links, as fewer mode groups are excited. In general, the bandwidth of MMF cannot be separated from the launch conditions of the light into the fiber (and therefore the specific source and coupling arrangement used) [6, 16, 17]. It was common to use the overfilled launch (OFL) condition to specify the bandwidth-distance product when LEDs were used [18], but with lasers other measures have been introduced such as restricted mode launch and minimum effective modal bandwidth [18, 19], to take into account the fewer modes excited. It is problematic: for edge-emitting lasers an axially aligned launch can enable a wide bandwidth, but a small misalignment can cause the bandwidth to be significantly reduced [16]. Thus, offset launching techniques were introduced, purposely launching the light into a region where good bandwidth was achievable with a reasonable tolerance to alignment accuracy [16]. With VCSELs, annular launches (e.g., sometimes, through vortex lenses[1]) are now often used to enable good and reasonably consistent bandwidth [20].

Although the time domain observations of modal dispersion can predict the bandwidth, they also predict that, much as in wireless systems where the multipath signals experiencing different delays cause fading, there will be peaks and troughs in the frequency response of any MMF link [21, 22]. Fig. 2 shows an example of such a measured MMF frequency response together with the corresponding impulse response obtained from an inverse fast Fourier transform – major mode groups are identified in the latter. For digital systems, this led to an interest in subcarrier multiplexing (SCM) with the data modulated onto subcarriers at frequencies corresponding to the passbands observed in the MMF response [21, 22]. This, effectively, was a move towards radio over fiber for datacomms. Again, the dependence on the launch conditions means that the spectral passbands in a MMF are not predictable in practical situations, but one can implement SCM or OFDM solutions in digital systems which would adapt to each particular link (as ADSL does over variable copper links). In radio over fiber systems, however, the radio frequencies are fixed by the wireless/mobile systems being transported, unless some adaptive frequency translation were to be used, which would add to cost and complexity. On the other hand, the limited bandwidth of current mobile/wireless systems is such that modal dispersion effects are less significant than in high data-rate digital systems [23].

At the time when the use of SCM for digital systems and offset launching were being investigated, typical bandwidth-distance products for typical graded-index MMF were of the order of 100MHz/km at 850nm. With the emergence of Gigabit (Gb) Ethernet and 10Gb Ethernet, enormous advances were made in MMF technology. Today, commercial MMF with bandwidth-distance products of several GHz.km is commonly available. It is also commonly optimized for 850 nm lasers [20]. This type of MMF can easily cater for the indoor distribution of the wireless systems considered in this paper. Although legacy, installed fiber must always be considered, it is such improvements in MMF which seem to guarantee its continued dominance in short-distance links, for the next few years, anyway.

[1] II-VI Infrared vortex lens data sheet: online, at: http://www.iiviinfrared.com

III. RF/Microwave MMF-Fed Wireless Systems

In this section, we will examine the experimental demonstrations of wireless system transmission over MMF, concentrating on the current and near-term mobile systems (GSM, UMTS) and wireless LANs (and, generally, OFDM systems). These systems operate at frequencies below 6 GHz. The system performance can be characterized in a number of ways. First, there are the measures of simple analog link performance [24] characterized by noise figure, compression and intermodulation product intercept points – leading to specifications such as compression dynamic range or spur free dynamic range (SFDR). The performance for the different modulation schemes used in the wireless/mobile systems is then often characterized by the error vector magnitude (EVM) observed from the multilevel signal constellation diagrams – the wireless system standards specify EVM requirements [25]. Characterization by bit-error ratio and packet-error ratio is also possible [26]. The performance can also be characterized by actual data transfer with throughput measurements [1 - 4], or more specifically for different applications (e.g., video or voice quality measures) [1, 3]. Finally, the wireless systems also specify requirements for minimizing interference with other systems, and conformance with these needs testing [25, 27].

Although the SFDR, for example, is a good indicator of link performance, the actual system dynamic range will be limited according to the EVM requirements of the modulation scheme, noise/interference and the conformance to requirements on spurious emissions. It should also be stated that many experiments characterize unidirectional fiber links, without wireless paths. Sometimes, this is necessary for testing in the licensed bands. We have found it important to test bidirectional links with wireless paths to ascertain a fuller understanding of the system dynamic range limitations [4].

Extensive measurements of VCSEL-MMF link dynamic range were carried out in [6]. Using multimode VCSELs SFDR in excess of 100dB.Hz$^{2/3}$ was found for frequencies in the range of 2 and 5 GHz for lengths of MMF up to 500m. The SFDR using newer, higher bandwidth fiber was generally several dB greater than with older MMF. This dynamic range approaches that found for DFB laser-MMF links, although in [28], for example, the SFDR (of better than 103dB.Hz$^{2/3}$) was measured over a frequency range of 1 - 20 GHz, and with 1km of older MMF.

EVM measurements were also carried out in [28]. In [1], measurements were carried out demonstrating that higher bandwidth MMF enabled lower EVM values to be obtained. This general dependence is also exhibited in the results presented in [5] and [25] where EVM for different fiber types with the transmission of 802.11g signals is reported; in the former case EVM results for GSM, UMTS and DECT packet radio service schemes are also presented. Generally, it is difficult to compare quantitatively EVM results for different links; typically, as only conformance is required, experimental work will consider how long the MMF can be, or what wireless range is achievable. However, when linearization techniques are applied, it is clearer to see the relation between dynamic range and low EVM. In [29], by injection-locking VCSELs, their resonance frequency is increased, leading to a reduction in dynamic nonlinearity and increase in link gain; this led to a 6dB improvement in carrier to third-order intermodulation product ratio. It was shown that the EVM was correspondingly, dramatically improved for 802.11b at 2.4 GHz for 0.25 and 0.5 km links. In [30], feedforward linearization was used to improve SFDR by 15dB; significant corresponding improvements in EVM for 16-QAM and 64-QAM at 5.8 GHz were also observed.

Spurious emission measurements for radio over MMF links have been carried out in [31], [25], and [27]. In [31] and [25], different VCSEL-MMF downlink measurements of UMTS adjacent channel leakage ratio (ACLR) were reported and confirmed conformance over a 12dB signal range. In [27], conformance against the spectral mask for 802.11b/g transmissions for VCSEL-MMF links has been confirmed by measurement at the RAU antenna port.

The range of measurements carried out indicate that MMF links are now capable of providing the required performance for radio over fiber systems to support current cellular and wireless LAN applications. This is the case for VCSEL based links which now approach the performance measured for DFB-MMF links, but may enable lower cost RAUs. Of course, further cost reductions may be possible through direct integration of photonic devices and antennas [32], which may also lead to power requirement reductions, and the possibilities of optical powering [27]. For the simplified RAUs, there is generally a trade-off with reduced dynamic range, SFDRs of around 90dB.$Hz^{2/3}$ being measured in [32], for example.

IV. MMF Radio over Fiber DAS Architectures

The need for higher data-rates to each, individual wireless user leads directly to the need to deploy picocellular architectures, which reduce the numbers of users per cell. Picocells also improve coverage, by reducing shadowing effects, for example, and result in lower overall radio emission levels. However, picocellular architectures do not necessarily imply the use of DAS or RoF. In local area networking, for example, one can simply deploy more wireless LAN access points (APs). There are limits to how small the cells can be (and therefore how many need to be deployed), especially at the 2.4 GHz band because of the lack of non-overlapping bands, but in principle this method can be used, and could involve the use of ultra-low-cost, consumer products for Ethernet and WiFi. For the mobile communication systems, conventional base stations are not so inexpensive; however, distributed radio architectures using UMTS remote radio heads[2] (with digital baseband links to the base stations) or GSM picocellular base stations using IP backhaul[3] are distinct alternatives to the use of DAS or RoF. Therefore, the use of RoF must provide other advantages.

Several advantages come from centralization; fewer radio channels are required to provide a given quality of service due to increased trunking efficiency, dynamic allocation of radio channels becomes possible and co-location of equipment leads to lower maintenance costs. In the wireless LAN scenario, signals from single APs can be remoted to multiple RAUs to improve coverage, or signals from multiple APs can be remoted to single RAUs to improve capacity in certain locations. For mobile communication systems, there is now significant interest in making use of spatial diversity for improving system data throughput; RoF links provide the centralized processing functions access to these diverse radio signals. There are also advantages in deployment in that operators can use a shared infrastructure (with neutral host installations); to the multiplexing of the operators' signals, can now also be added WLAN signals, providing a common infrastructure for all wireless communications systems.

Such advantages arise from the transparency of RoF to the particular signals being transported, and this also means that upgrading may be less disruptive. As has been mentioned before, for in-building infrastructures the RoF distribution should be implemented using MMF. In considering the architectures for in-building deployment, the above-mentioned factors need to be taken into account.

Recently, Sauer et al. [1] demonstrated a picocellular WLAN using radio over MMF. The demonstration was of 14 picocells (i.e. the RAUs for each picocell were associated with different APs); at the 2.4 GHz band this required much frequency re-use with only 3 available non-overlapping channels, while at the 5 GHz unlicensed band 12 channels could be used. Operation with ZigBee and RFID operating at the same unlicensed bands was also demonstrated, and the fiber-fed WLAN continued to provide 20 Mb/s throughput (typical of IEEE 802.11g operating under good channel conditions). With multiple users, only voice over IP results are reported (this is not a bandwidth hungry application). The authors also demonstrated successful handoff between picocells.

Crisp et al [3] used a set of distributed antennas from a single AP to demonstrate improved coverage and reduction of overall emission power. Throughput of approximately 20 Mb/s was again demonstrated. The authors also considered that with multiple RAUs from a single AP, the hidden node scenario in WLANs could be more problematical. A demonstration of the request-to-send/clear-to-send (RTS/CTS) mechanism in alleviating this problem was performed by connecting the RAU antenna ports to "wired" clients, emulating the actual scenario.

[2] See, e.g., Open Base Station Architecture Initiative, Available: http://www.obsai.org and Common Public Radio Interface co-operation specifications, Available: http://www.cpri.info

[3] See, e.g., IP Access, Available: http://www.ipaccess.com

In [2], the different WLAN medium access control (MAC) mechanisms, including RTS/CTS, were studied theoretically and experimentally. Here, it was shown that because of the added protocol overhead of RTS/CTS, it may only improve throughput when the channel conditions are good, allowing high bit-rate transmissions, and when there are more hidden nodes. For in-building distribution, the fiber delay is still significant enough to cause an increase in collision probability. Theoretical work [33] has shown that RTS/CTS will reduce the frame collisions, generally (even with no hidden nodes), but that this still needs to be balanced against the increased protocol overhead. The use of new MAC mechanisms in 802.11e may also improve the relative performance of WLAN over fiber systems [34].

For the mobile communication systems, we have said that a considerable advantage is gained when multiple systems operate simultaneously using the same RoF links. This type of link using higher-performance components and SMF has been commercialized and is used in many deployments. The shift to lower cost RAUs and multimode fiber is more problematic, although there are commercial moves there too[4]. A number of experimental demonstrations of multiple system operation over MMF links have been carried out. In [35] different pairs of GSM1800, DECT packet radio service (DPRS, at 1900 MHz), UMTS and 2.4 GHz 802.11g were transported over 300m VCSEL-MMF links and wireless paths of several meters, with EVM measured within the system requirements. A similar experiment was carried out for the radio over MMF link only (but with the personal handyphone – PHS – system instead of DPRS) in [36], with a system dynamic range of 20dB achievable while all systems were within EVM requirements. In [37] and [36], simultaneous operation of 4 systems was demonstrated with uncooled DFB-MMF and VCSEL-MMF links, respectively. The experiments demonstrate the potential of radio over MMF for multi-carrier, multi-system operation. However, the authors have found no reports on spurious emission conformance for multi-system operation.

In [4], whereas the throughput performance was experimentally verified using WLAN transmission, the radio path distances possible for different systems (including cellular mobile) were theoretically predicted. It was clear that the radio range for the OFDM modulated 802.11g signals was most limited, due to the much more stringent linearity demands of OFDM systems. On the other hand, the GSM signals (modulated using Gaussian Minimum Shift Keying) which do not suffer significant impairment from nonlinearity, were predicted to have the greatest radio range. The RAU in [4] used the same amplifier paths for all systems for simplification and cost reduction. A commonly considered alternative is to optimize each system's performance – an RAU designed along these lines is reported in Section V. However, the deployment scenario should also be considered, as shown in Fig.3. It might be perfectly desirable for GSM and UMTS signals to be distributed to/from fewer RAUs while still providing coverage (and utilizing spatial diversity) whereas the WLAN signals are distributed to/from many RAUs to enable capacity for high data-rate applications. As shown in Fig.3, more than one WLAN access point can be linked with an RAU in areas needing more capacity. As can be seen, this type of overlaying would also mean that not all systems are distributed to/from each RAU, lessening the performance requirements on the RoF links.

[4] See, e.g.: ZinWave, online: http://www.zinwave.com/

V. Performance of a Multi-System RAU

In [4] we designed, constructed and investigated a RAU with broadband operation covering the GSM and UMTS mobile communication systems bands and the 2.4 GHz WLAN band. The common, broadband amplification and common antennas (one transmit and one receive antenna, each covering all systems' bands) resulted in a simple RAU. However, this results in difficulties in optimizing the performance for each particular system. Here, we present experimental results on a RAU with separate amplification paths for each system and separate antennas. A block diagram for the RAU, and the corresponding components required at the central unit is shown in Fig.4. In the RAU, it can be seen that the separate amplifiers in the downlink follow one common preamplifier following the photodiode. In fact, due to component availability, broadband amplifiers were used but were made narrow band using bandpass filters. Diplexers were used to separate the downlink and uplink mobile communication systems signals which used common antennas (one per system), while the WLAN transmission used separate downlink and uplink antennas. Filters were also required at the central unit to separate the uplink signals; otherwise power combiner/dividers were used in both central unit and RAU to combine and split the signals.

Measurements were carried out for EVM and ACLR of all mobile systems, and of throughput for the WLAN, while the systems were operating individually and together. It was found that the GSM900 signal fed to the central unit VCSEL could be reduced to a level 8dB below the other signals (the other signals were at the same level) to provide similar performance for all systems. We will report more fully on these measurements, together with the design considerations used for the RAU in the future. Here, we concentrate on UMTS measurements as an example of the performance obtained.

Fig. 5 shows the measured EVM for the downlink UMTS signal (QPSK modulated) when three other signals (a GSM900, GSM1800 and an IEEE 802.11g) were present. The EVM of the signal prior to the central unit VCSEL is shown for reference. At low input powers to the VCSEL it can be seen that there is some EVM degradation due to the increased system noise, and at high input powers degradation due to VCSEL nonlinearity. With the MMF inserted, the increased overall noise figure again causes an EVM degradation at lower input powers. Nevertheless, the transmitted signal would meet UMTS EVM requirements (< 17.5%) [38] over the whole of the measured range. Similar link quality can be expected in the RoF uplink; this should enable the RAU to handle a range of received powers from mobile users, and thus offer a reasonable wireless range (see below).

Fig. 6 shows the measured ACLR for the UMTS signal (measured at the input to the transmit antenna) when no other signals are present. It can be seen that the RAU meets the requirement for low spurious emission at both 5 MHz and 10 MHz offsets over a range of input powers to the central unit VCSEL below 2.5dBm. When the other signals are present, however, as shown in Fig. 7, the ACLR requirements are more difficult to meet due to the reduction in signal levels necessary to accommodate the other systems (without overdriving the VCSEL). The 5 MHz offset requirement is met only at drive signal levels below -3.5dBm. It should be noted that in Figs. 6 and 7, although all curves appear to fall below the required ACLR at low input drive powers to the VCSEL, in this region noise is being measured rather than signal leakage from the central channel. As the effects of noise are rather different than signal leakage, different requirements are set. For UMTS, within 30 MHz offset, the requirement translates to an emitted noise level of -76 dBm/Hz. With drive levels to the VCSEL below -8 dBm, where we can expect the noise in the adjacent channels to dominate over signal leakage, we can confirm that even when the RAU amplifier gains are set such that -2 dBm UMTS radio power is emitted, the emitted noise level is 39dB below the requirement.

Conformance with the ACLR requirements is only important for the system downlink. It is clear that the ACLR requirement, especially with multichannel operation, is more stringent than the EVM requirement, so the operating point of the downlink must be carefully set with regard to it. In this case, an operating point with a UMTS signal drive level of -4 dBm to the central unit VCSEL will satisfy the requirement while allowing for the three other signals to be present. With this drive level to the VCSEL, the amplifier gains in the RAU can be increased to provide more output power, as long as they do not lead to the ACLR or noise output power requirements being violated. As stated above, we have confirmed that this is the case when the UMTS signal at the antenna is amplified to -2 dBm. In Table I, predictions of the radio range of the UMTS signal for different transmit power levels are given following a similar analysis to that presented in [4]. It is assumed that the other signals are present, thus the drive level to the central unit VCSEL is limited to -4dBm. The calculations assume that the path loss exponent is 3, and use the UMTS standard specifications of mobile device sensitivity of -107dBm assumed to be for QPSK with a required EVM of 17.5% [38] (and SNR of 15.1dB). For higher data rate transmissions composite signals that include 16-QAM may be used, with the EVM specification set as no worse than 12.5% [38] - this can lead to a SNR requirement of 18.1dB (3dB higher). In both cases, for the results presented, it is assumed that an extra 6dB signal level is required to combat multi-user interference. Nevertheless, the results show favorable values compared to those in [4]. The ranges of the other systems will depend on the optimization of their transmit power levels while conforming to noise and spurious emission and crosstalk requirements. This will be dealt with in future work.

VI. Conclusion

We have reviewed progress in low-cost radio over multimode fiber distribution of current cellular and wireless LAN signals, operating at below 6 GHz. It is clear that good performance can be achieved when single signals/systems are transported. For the transport of multiple signals, further work is required, particularly on conformance to spurious emissions. In this paper, we have also presented initial results on spurious emission testing for UMTS transmission with simultaneous transmission of other signals (GSM, WLAN), as well as confirmation of EVM performance, to initiate work in this area. We have also discussed architectural considerations for radio over fiber support of current systems: here, it is important to bear in mind the advantages that radio over fiber can bring in comparison with competing technologies when proposing system configurations. In future work, we will report more completely on the design and performance of the multi-system RAU. In general, work on radio over MMF needs to focus on architectures that can benefit from RoF distributions, such as the support of multiple-input multiple-output (MIMO) distributed antennas, and on further simplification and cost reduction of RAUs.

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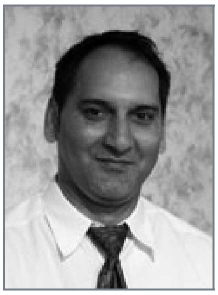

Nathan J. Gomes (M'92 - SM'06) received the BSc degree from the University of Sussex, UK, in 1984 and the PhD degree from University College London in 1988, both in electronic engineering.

From 1988 to 1989 he held a Royal Society European Exchange Fellowship at ENST, Paris. Since late 1989, he has been a Lecturer, and since 1999, a Senior Lecturer, in the Electronics department at the University of Kent. His present research interests include radio over fiber systems and networks, the photonic generation and transport of millimeter-wave signals, and photoreceivers for such applications.

Anthony Nkansah received the B.Eng. (with honors) degree in electronic engineering, the M.Sc. degree in broadband and mobile communication networks and Ph.D degree in electronic engineering from the University of Kent, Canterbury, U.K., in 2000, 2001 and 2007, respectively. His research interests include low-cost microwave and millimeter-wave radio-over-fiber networks and their deployment within premises.

David Wake (M'02) received the B.Sc. degree in applied physics from the University of Wales, Cardiff, U.K., in 1979, and the Ph.D. degree from the University of Surrey, Surrey, U.K., in 1987. He is currently a Senior Research Fellow with the University of Kent, Canterbury, U.K.

From May 2003 to February 2005, he was Director of Research and Development and Chief Scientist with Microwave Photonics Inc., a startup company based in Los Angeles, CA, which was formed to develop a product set for the mobile communications industry based on novel radio-over-fiber technology. In 2002, he cofounded Zinwave Ltd., a startup company aimed at exploiting innovative radio-over-fiber technology for the mobile communications industry. He has been involved in the radio-over-fiber research topic for approximately 17 years, initially with BT Laboratories, where he was the Program Manager for the microwave photonics research domain and then with University College London as a Senior Research Fellow.

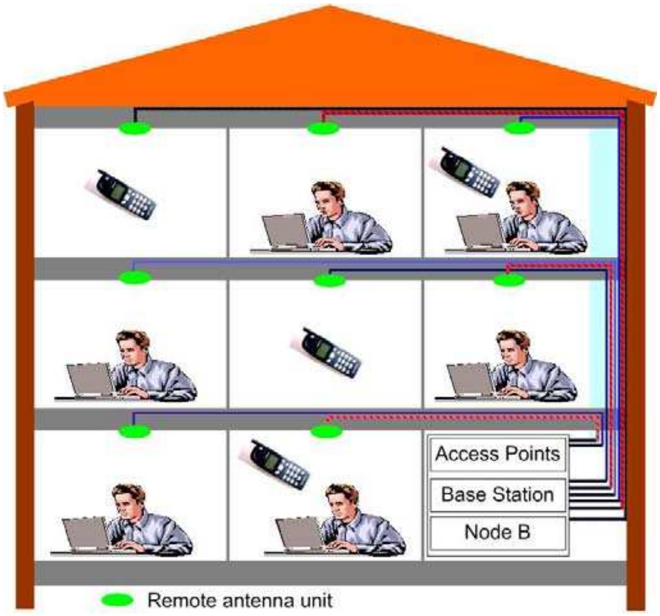

Fig. 1 Concept of an in-building distributed antenna system providing for wireless LAN and mobile telephony systems over the same (fiber) infrastructure.

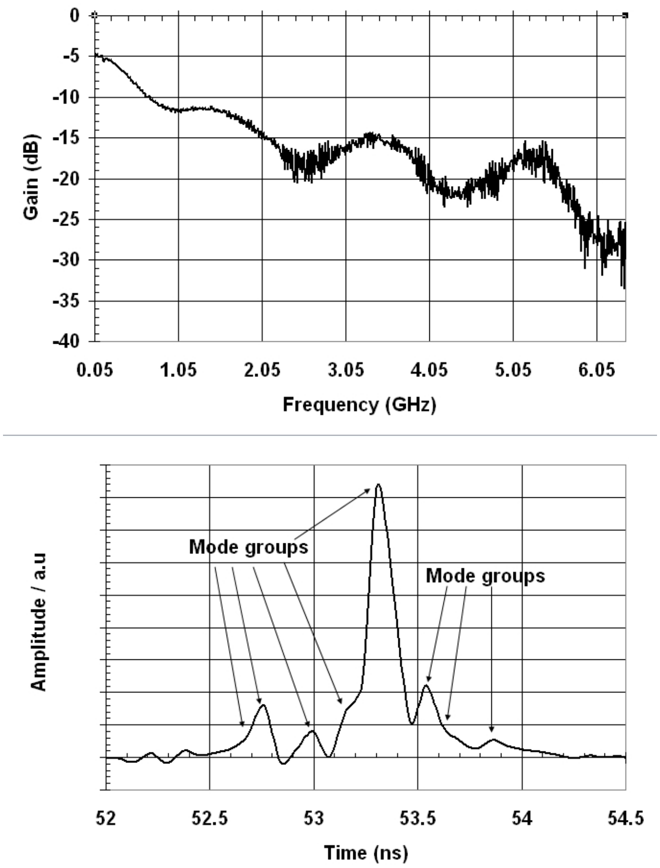

Fig. 2 Example, measured MMF frequency response (top) and its corresponding impulse response obtained through inverse fast Fourier transformation (bottom). The measurement was of 600m of 62.5µm diameter MMF, using an approximately axially aligned Honeywell VCSEL.

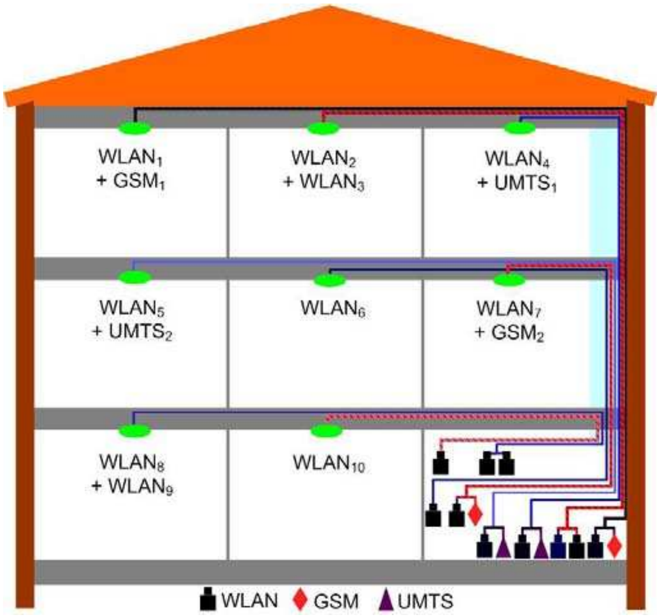

Fig. 3 Overlaying of systems: GSM and UMTS signals are transported to/from fewer RAUs because the radio range achievable from them is longer; WLAN signals are transported to/from all (or nearly all) RAUs as the radio range achievable from each is limited. To provide increased capacity each RAU may be connected to/from more than one WLAN access point.

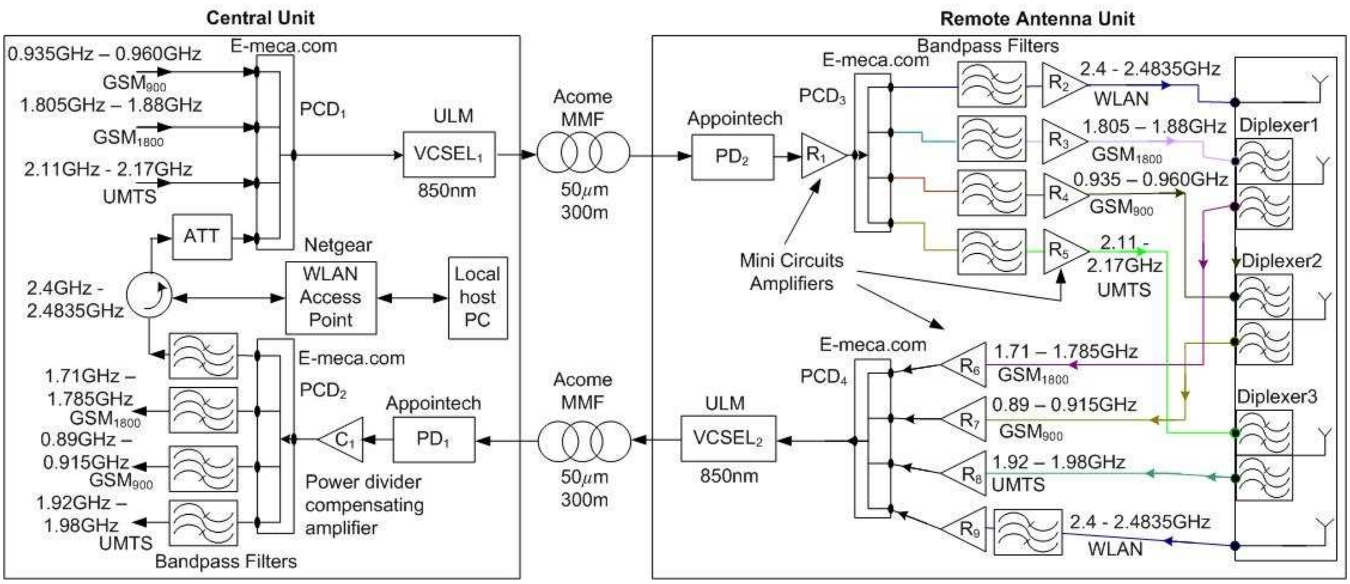

Fig. 4 – Experimental setup of simultaneous transmission of GSM_{900}, GSM_{1800}, UMTS and WLAN over an MMF link. PD=Photodiode, R_1 – R_8 = RAU amplifiers, C_1 = CU amplifier, PCD= Power combiner/divider, ATT=Variable Attenuator

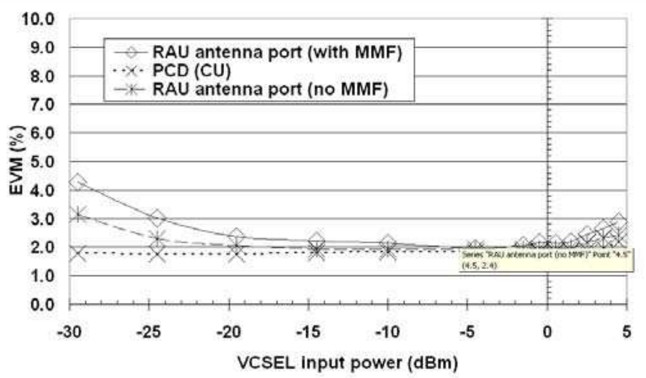

Fig. 5 - Measured EVM of UMTS (with GSM_{900}, GSM_{1800}, and WLAN present) at; input of CU $VCSEL_1$, and antenna port of diplexer 3 (with and without MMF) of Fig.4. Note that all signal sources were at equal power levels apart from GSM_{900} at a power level 8dB below the others. PCD=Power combiner/divider to $VCSEL_1$..

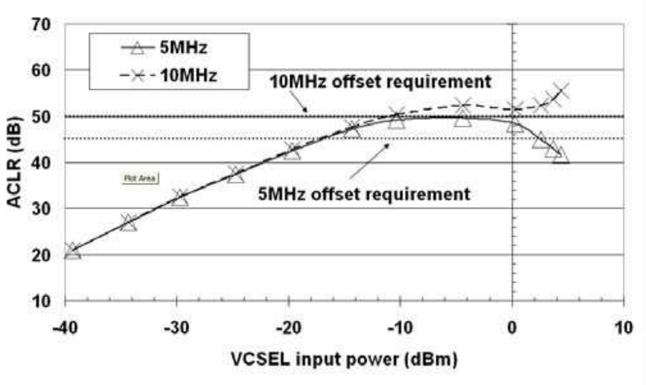

Fig. 6 - Measured ACLR of UMTS (with no other signal sources present) at RAU amplifier R_1 (but without MMF) of Fig.4.

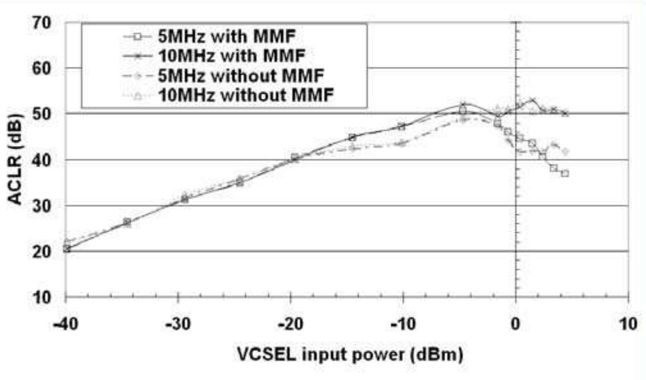

Fig. 7 - Measured ACLR of UMTS (with GSM_{900}, GSM_{1800}, and WLAN present) at amplifier R_1 (with and without MMF) of Fig.4. Note that all signal sources were at equal power levels apart from GSM_{900} at a power level 8dB below the others. PCD=Power combiner/divider to $VCSEL_1$.

TABLE I
POSSIBLE WIRELESS RANGES FOR UMTS WITH DEVELOPED RAU

Transmit power	Level below requirement of transmitted noise	Range (QPSK)	Range (16-QAM, QPSK)
-25 dBm	-64.8 dB	17 m	14 m
-14 dBm	-52.8 dB	40 m	32 m
-2 dBm	-38.8 dB	101 m	80 m

Wireless path loss exponent assumed to be 3. UMTS mobile device sensitivity is -107 dBm, but an extra 6dB is assumed to be required to combat interference from other users. The sensitivity for composite signals, e.g. when including 16-QAM, is degraded.