Institution: 10007857 – Bangor University

Unit of Assessment: UoA 13

Title of case study:
Optical OFDM Transceiver Development and Commercialisation

1. Summary of the impact (indicative maximum 100 words)

Pioneering research at Bangor on the advanced communications technology termed Optical Orthogonal Frequency Division Multiplexing (OOFDM) has enabled industrial impact with global implications. OOFDM was a candidate technique for the ITU-T G989.1 NG-PON2 and the IEEE 802.3bm standards and is currently under consideration by the IEEE 802.3 400Gb/s Ethernet Study Group. Supported by 8 patent families and first-phase funding of £1.1M, in 2013, the pre-revenue Bangor University spin-off company Smarterlight Limited, was established. Smarterlight has deployed services to several international telecommunications companies to develop advanced solutions for access optical networks and data centres.

2. Underpinning research (indicative maximum 500 words)

Driven by emerging bandwidth-hungry services, end-users' demand for bandwidth increases >70% year-on-year. British Telecom has predicted that each subscriber will require >1Gb/s by 2016. Existing copper cable-based access networks have become the main obstacles to providing the ultra-wide bandwidths required. Passive optical networks (PONs) offer an attractive means for meeting the defined requirements. Cost effectiveness and flexibility are the key challenges for wide deployment of PONs. Great research and development effort has therefore been directed at identifying effective, "future-proof" technologies to meet predicted end-user requirements.

On his appointment to a lectureship at Bangor on 01/01/2005, and following his world-first proposal of OOFDM (OFC/NFOEC Paper OFP3, 2005), Tang initiated a vigorous research programme which led to publications detailing investigations of the transmission performances of OOFDM signals over Multi-Mode-Fibre-based Ethernet links and Single-Mode-Fibre-based PON systems [3.1,3.2] This work established the strengths of OOFDM inherent advantages including highly spectral efficiency, excellent cost-effectiveness, great system flexibility and performance robustness, as well as digital signal processing (DSP)-enabled rich transceiver/network intelligence. The area of research has grown rapidly since 2005 such that over the past five years, OOFDM related research papers represent approximately 10% of the total number of communications-related papers published in world-leading journals and major international communications conferences.

Tang's research group (currently having 15 full-time researchers) includes a key member of staff Dr Roger Giddings (PhD student at Bangor since 05/2008, Lecturer since 2012) and has made pioneering contributions to diverse aspects of OOFDM including fundamental operating principles [3.1], cost-effective modulation/demodulation [3.1,3.2], high-speed DSP algorithms [3.3], high-capacity and intelligent transceiver designs/implementations [3.3], simple, accurate, high-speed and low-overhead system/network synchronization [3.4], effective linear/nonlinear component/system impairment reduction], high-speed transmission over SMF and MMF-based systems, as well as bidirectional, point-to-multipoint PON networks [3.5]. Since 2005 Bangor has published more than 150 OOFDM papers including 3 invited papers in international-leading journals, given more than 10 invited tutorials/presentations in major international communication conferences, and secured 14 research grants of total value £4M.

Research at Bangor has, in particular, generated extensive "know-how" for addressing difficulties associated with the implementation of highly complex, computationally intense and high-speed DSP algorithms with sufficient precision. Using that know-how Bangor was able to make the world first experimental demonstration of a series of end-to-end real-time intelligent OOFDM transceivers at record-high speeds of up to 30Gb/s (ECOC2013, P.6.7.5) and corresponding networks, utilising

low-cost and "off-the-shelf" optical/electrical components. Our recent investigations have indicated that 4GS/s-enabled 40Gb/s real-time multi-band OOFDM transceivers are also achievable.

Since 2005, Bangor has filed eight patent families covering all core features of OOFDM ranging from DSP algorithms, transceiver architectures, point-to-point systems and point-to-multipoint networks [3.6]. Technical inventions which have been protected include high-speed/adaptive transceiver designs, system/network synchronisation techniques, low-cost intensity modulator-based optical conversion, simplified network architectures and techniques for improving the upstream network performance.

Three Bangor-patented synchronisation techniques and intelligent transceiver designs capable of automatically adapting to component/system/network imperfections have been built into Bangor's world-only real-time test-beds of multiple access OOFDM PONs. The test-beds have also been equipped with sufficient networking intelligence supporting fully end-user-controlled channel add/drop functions, which are a revolutionary feature for realising future elastic optical networks. Bangor's extensive research has shown that OOFDM is feasible for mass deployment in cost-sensitive application scenarios.

Bangor's OOFDM work has received significant international interest from both the academic and industrial sectors and has led to fruitful international research collaborations with major system vendors, service providers, transceiver manufactures and universities European Commission including the current €3.07M FP7 PIANO+ Project (2011-2014) , "Optical OFDM for Cost-Effective Access Networks (OCEAN)" coordinated by Tang.

3. References to the research (indicative maximum of six references)

1. J.M. Tang P.M. Lane and K.A. Shore, "High-speed transmission of adaptively modulated optical OFDM signals over multimode fibres using directly modulated DFBs," IEEE/OSA J. Light. Tech.,24, pp.429-441, Jan.2006 DOI: 10.1109/JLT.2005.860146
   First paper detailing the operating principles of the OOFDM technique and its applications in simple multi-mode fibre-based Ethernet systems. 58 WoS citations.

2. J.M.Tang and K.A.Shore, "30Gb/s signal transmission over 40km directly modulated DFB-laser-based single-mode-fibre links without optical amplification and dispersion compensation," IEEE/OSA J. Lightwave Technol., Vol.24, No.6, pp.2318-2327, June 2006 DOI: 10.1109/JLT.2005.874557
   First paper detailing the applications of the OOFDM technique in single-mode fibre-based PON systems. 61 citations.

3. R. P. Giddings, X. Q. Jin, E. Hugues-Salas, E. Giacoumidis, J.L. Wei and J. M. Tang, "Experimental demonstration of a record high 11.25Gb/s real-time optical OFDM transceiver supporting 25km SMF end-to-end transmission in simple IMDD systems," Optics Express, Vol.18, No.6, pp.5541-5555, 15 March 2010.
   First paper reporting record-high speed, real-time single-band OOFDM transceivers with adaptive power loading using low-cost optical/electrical components. 52 citations. Submitted to REF 2014 (REF Identifier 1330)

4. X.Q. Jin, R. P. Giddings, E. Hugues-Salas and J.M. Tang, "Real-time experiments demonstration of optical OFDM symbol synchronization in directly modulated DFB laser-based 25km SMF IMDD systems", Optics Express, Vol.18, No.20, pp.21100-21110, September 2010.
   First paper reporting real-time experimental demonstrations of the Bangor patented automatic OOFDM synchronisation technique that plays a key role in the practical implementation of the technique. 9 citations. DOI: 10.1364/OE.18.02110.

5. E. Hugues-Salas, R.P. Giddings, X.Q. Jin, J. L. Wei, X. Zheng, Y. Hong, C. Shu and J.M. Tang, "Real-time experimental demonstration of low-cost VCSEL intensity-modulated 11.25Gb/s

optical OFDM signal transmission over 25km PON systems," Optics Express, Vol.19, No.4, pp.2979-2988, Feb.2011. DOI: 10.1364/OE.19.002979. Submitted to REF 2014 (REF Identifier 1339)
First paper reporting the feasibility of utilising extremely low-cost directly modulated VCSELs as intensity modulators in ONUs. The work has established a solid base for further reducing the cost of OOFDM transceivers. 24 citations.

6. Filed Bangor Patents : PCT/EP2012/056244,PCT/EP2011/069487, PCT/EP2011/057684, PCT/EP2010/066475, GB1208016.4, PCT/EP2010/066463, PCT/EP2010/066471, PCT/EP2010/066467. Copies of filing receipts of these patents are available on request

4. Details of the impact (indicative maximum 750 words)

The strong growth of interest in OOFDM following research initiated by Tang in 2005 has led to OOFDM being extensively explored world-wide by major telecommunication equipment/system vendors, service/network providers, telecommunication research institutes and universities. In view of the large commercial potential of this technology, Bangor has identified three principal means to maximise the industrial and economic impact of its OOFDM research and expertise: 1) promoting OOFDM to standards bodies; 2) establishing the Bangor spin-off company Smarterlight 3) providing design services to international telecommunications vendors/ manufacturers.

Since 2008, Bangor has used its research-based expertise to actively promote OOFDM technology to various standards bodies by: working closely with major international telecommunications companies; participating in and co-ordinating FP7 projects; delivering seminars at companies; hosting industrial visitors and working with companies involved in standards task groups. Since 2010 the Full Service Access Network (FSAN) Next-Generation PON (NGPON) task group consisting of leading network providers and vendors worldwide considered OOFDM as a strong candidate for NG-PON2 (ITU-T G989.1) standards [5.1]. However in 07/2012 the FSAN adopted time-wavelength division multiplexing (TWDM) as the primary technology for NG-PON2. In addition, since 2012 the IEEE 40Gb/s and 100Gb/s Fibre Optic Task Force group has also considered OOFDM as a candidate technology for high-speed Ethernet systems (IEEE802.3bm standards) [5.2]. In a group meeting in 05/2013 no consensus was reached concerning the candidate technologies and thus a new IEEE 802.3 400Gb/s Ethernet Study Group was subsequently formed, which recommends OOFDM as a candidate technology [5.2].

In order to further the impact of Bangor OOFDM research, the Bangor University spin-off company, Smarterlight Limited (07813373) was registered on 18 Oct 2011. Smarterlight is dedicated to using its protected OOFDM technology to develop portable, "future-proof", cost-effective transceivers offering end-users with >20Gb/s symmetrical download/upload speeds with guaranteed quality of services at price levels currently applied to 20Mb/s services. Smarterlight is in receipt of a total of £1.1M first phase funding: In 07/2012, Smarterlight secured a £600k commercialisation grant plus a 5-year rental-free office space of 500m^2 from Xiamen City Council, China [5.3], which has established a hi-tech incubation and innovation platform to promote technology transfer to address the central government strategy of "Broadband China and Optical City" announced in 2011. In 2013 Finance Wales agreed to make a first phase investment into Smarterlight of approximately £500k [5.4]. In addition, Xiamen City Council has agreed to provide total funding up to £2.3m when Smarterlight meets defined performance targets [5.3]. At present, 8 people are working on Smarterlight projects with a revenue stream of £200k having been identified in 2013 [5.5].

In 2012, Smartlight was engaged by Huawei (the biggest global telecommunication equipment vendor) 1) to develop OOFDM multiple access PON solutions for the Advanced Technologies Department of Access Optical Networks in Shenzhen, China [5.6], and 2) to investigate the feasibility of utilising OOFDM to upgrade installed 10Gb/s metropolitan networks to 40Gb/s for the Huawei's R&D Centre in the US [5.7]. The successful completion of these projects will lead Huawei to develop corresponding commercial product lines. Since September 2012 we have impacted technological advancement in respect of Fujitsu Labs (Atsugi, Japan) new product lines addressing

400Gb/s data centre interconnections [5.8].

5. Sources to corroborate the impact (indicative maximum of 10 references)

Documents listed here all can be made available on request

Evidence of OOFDM impact on standards:

1. News coverage on OOFDM being considered by the standards is available at: http://www.gazettabyte.com/home/2012/4/4/fsan-close-to-choosing-the-next-generation-of-pon.html
2. Presentation by Fujitsu on OOFDM as a recommended option is available at: http://www.ieee802.org/3/400GSG/public/13_07/takahara_400_01_0713.pdf (where OOFDM is termed DMT)

First-phase funding of Smarterlight

3. Terms and conditions of the grant offer made by the Xiamen City Council, July 2012
4. Head of Terms of Finance Wales investment in Smarterlight Limited, Feb. 2013

Evidence for deployment of services by Smarterlight:

5. **Smarterlight Design Services**: Terms and conditions of agreements between Huawei and Bangor, 2013
6. **Smarterlight Design Services** "Real-Time 40Gb/s Downstream and 10Gb/s Upstream Multi-Band Optical OFDM Multiple Access IMDD PONs with Adaptability and Single Upstream Wavelength-Supported Colourless ONUs", Technical agreements, June 2012
7. **Smarterlight Design Services** "40Gb/s over 40km SSMFs in IMDD systems using DMLs with 3-dB bandwidths of approximately 8GHz", technical agreements, July 2012.
8. **Smarterlight Design Services** "Multi-band Optical OFDM Multiple Access PONs (MOON)" Technical agreements with Fujitsu, September 2012.