Institution: Cardiff University, School of Engineering
Unit of Assessment: UoA 15
Title of case study: Practical Waveform Engineering – Reshaping Today's Communication Systems
1. Summary of the Impact

Practical Waveform Engineering, developed at Cardiff, is having a major impact on how modern-day microwave power amplifiers are designed, delivering real competitive advantages for global communications companies such as Nokia-Siemens-Networks and M/A-COM.

Economic impact is through reduced time-to-market and lower design costs, leading to high-performance power amplifier products. Examples include $40M revenue and employment of additional staff for M/A-Com, and the successful spin-off company Mesuro Ltd., generating revenue in excess of £2.5M.

Impact on practice is through successful demonstration of new device technologies and amplifier architectures, the introduction of PWE-based CAD models, and most significantly, the introduction of the "Cardiff Model" into mainstream simulation tools.

Environmental Impact is by improving the efficiency of power amplifiers and significantly reducing the carbon contribution of mobile communications systems, translating into savings of approximately £2.5M/year and a 17 kiloton reduction in CO_2 emission for a typical EU network.

2. Underpinning Research

Radio Frequency (RF) and microwave power amplifiers (PAs) are critical components used to boost signal levels in all mobile and satellite communications networks, including military and security systems. Traditional approaches to power amplifier design are non-optimal, iterative and labour-intensive, and so the research focus of the Centre for High Frequency Engineering (CHFE) has been to address this issue by transforming the way in which power amplifiers are designed.

Practical Waveform Engineering (PWE) is a technique developed by Prof Tasker of Cardiff, and is the ability to modify or "engineer" voltage and current waveforms at the terminals of an amplifier or transistor, allowing near-theoretical, optimum performance within a practical system [3.1]. The integration of measurement and waveform engineering capabilities enables PWE and is unique, leading to a number of patents that have now been transferred to a spin-off company, Mesuro. PWE provides the major commercial advantage of streamlining development of both the PA modules and the underlying transistor technology. Using PWE to "emulate" the complex harmonic load environment within a PA and around a transistor significantly reduces reliance upon prototyping and enables optimal, "first-pass" design success [3.2].

The following research developments have led to impact:

Hardware developments enabling PA "emulation"

- PWE measurement systems were developed to address the needs for increasingly complex and realistic stimulus signals, including modulated and pulsed signals at higher frequencies and powers [3.1, 3.3]. This resulted in the establishment of University's spin-out Mesuro Ltd. by Profs Benedikt and Tasker, and recent funded lectureship and product development with National Instruments led by Prof Benedikt.

Concept development and utilisation

- PWE has uniquely demonstrated how real transistors can support near-theoretical signals, and hence realise "state of the art" performance in terms of output power and efficiency [3.4]. This is very important for the assessment of new semiconductor technologies, and has increased Mesuro's sales (such as to Miyoshi and Infineon).

- PWE has provided new insight into transistor operation that has transformed PA theory, leading to the invention of "continuous amplifier modes" [3.5] by Profs Tasker and Cripps. This has been recognised by industry as a major and timely breakthrough in wide-band PA design.
- A number of PA demonstrators have been realised that meet industry's challenging design specifications in terms of power, efficiency and bandwidth, without the need for extensive prototyping and costly design iterations.
- PWE has allowed complex RF/microwave PA architectures to be analysed and realised for the first time, most notably including harmonic injection PAs pioneered by Prof Benedikt, as well as broadband push-pull, class-J and continuous mode PAs by Profs Cripps and Tasker.

CAD integration and behavioural modelling

- A measurement-based behavioural modelling approach has been developed by Prof Tasker, allowing PWE data to be fully exploited within the computer-aided design (CAD) environment [6], allowing the most recent and promising device technologies to be quickly adopted.

Key staff contributing to the research are Prof PJ Tasker (1996- , Founder and Director of CHFE), Prof J Benedikt (PhD 1997-2000, research associate 2000-2004, academic staff 2004), Prof SC Cripps (2008-) and Dr J Lees (PhD 2001-2004, research associate 2005-11, academic staff 2011).

PWE has attracted research income in excess of £3.5M: from EPSRC (EP/F033702/1, £2.5M jointly with Bristol University, 2008-13), UK MoD (EMRS DTC, £346k, 2004-09), EU (FP7 NoE TARGET IST-1-507893-NOE, £317k, 2004-06) and industry contributions of more than £1.25M. Research outputs linked to PWE involves over 20 international journal papers, over 100 international conference papers and 3 patent applications.

3. References to the Research

3.1 **Benedikt J., Gaddi R., Tasker P.J.** and Goss M. (2000) High-power time-domain measurement system with active harmonic load-pull for high-efficiency base-station amplifier design, *IEEE Transactions on Microwave Theory and Techniques*, Vol. 48 No. 12 pp. 2617–2624. 10.1109/MWSYM.2000.862249

3.2 **Wright P., Lees J., Benedikt J. Tasker P.J.** and **Cripps S.C.** (2009) A Methodology for Realizing High Efficiency Class-J in a Linear and Broadband PA, *IEEE Transactions on Microwave Theory and Techniques*, Vol. 57, No. 12 pp. 3196–3204. 10.1109/TMTT.2009.2033295

3.3 **Williams D.J.**, Leckey J. and **Tasker P.J.** (2002) A study of the effect of envelope impedance on intermodulation asymmetry using a two-tone time domain measurement system, , *Microwave Symposium Digest*, IEEE MTT-S International, June 2002, pp. 1841–1844. 10.1109/MWSYM.2002.1012221

3.4 **Roff C., Benedikt J.** and **Tasker P.J.** (2007) Design Approach for Realization of Very High Efficiency Power Amplifiers, , *Microwave Symposium Digest*, IEEE MTT-S International, June 2007, pp. 143–146. 10.1109/MWSYM.2007.380310

3.5 **Cripps S.C., Tasker P.J., Clarke A.L., Lees J. and Benedikt J.** (2009) On the Continuity of High Efficiency Modes in Linear RF Power Amplifiers, , *IEEE Microwave and Wireless Components Letters*, Vol. 19 No 10 pp 665-667. 10.1109/LMWC.2009.2029754

3.6 **Hao Q., Benedikt J.** and **Tasker P.J.** (2009) Nonlinear Data Utilization: From Direct Data Lookup to Behavioral Modeling , *IEEE Transactions on Microwave Theory and Techniques*, Vol 57 No 6 pp 1425–1432. 10.1109/TMTT.2009.2019996

4. Details of the Impact

Economic Impact

Cardiff's PWE has achieved global economic impact since 2008, with world-leading companies applying it to develop new products. PWE has resulted in a successful spin-off company, Mesuro

Ltd. [5.1], attracting industrial funding of over £1.25M from Selex, LabTech, Milmega, Copham, M/A-COM, Freescale, Agilent and QinetiQ.

The streamlined development and emulation capabilities afforded by PWE reduce the need for prototyping, minimises time-to-market and provides competitive edge. PWE, according to M/A-COM, plays a *"significant role in developing and optimising the circuit used in the final design"* [3.2] [5.2]. This was recognised from the outset by key players in the mobile communications industry, e.g. from 2004-2007 Nokia provided financial support of £400k and benefited from reduced development time and costs by using PWE to evaluate device technologies for next generation mobile communications systems [3.1] [5.3].

M/A-COM is an excellent example of a beneficiary that has achieved time/cost savings and major competitive advantage. It used PWE [3.3] to develop a high-performance PA product for satellite telephones ahead of competition, *"to successfully secure the design win"* [5.2]. This product alone has directly generated over $40M revenue and employment of eight additional staff in 2009-2013. PWE has enabled additional amplifier products with expected revenue of $15M for 2013-2018 [3.2] [5.2]. Furthermore, QinetiQ (2008) and WIN Semiconductors (Taiwan) (2012-13) have used PWE for rapid optimisation of their gallium nitride (GaN) technology [3.1],[5.4].

The successful demonstration of a system based upon fundamental PWE concepts [3.1] at the International Microwave Symposium in 2008 (the largest such exhibition, attracting over 200 exhibitors and 15,000 attendees) indicated its potential for direct commercialisation. After raising an initial investment of £1M from three investors (Fusion IP, Invest Wales and ERA Foundation), the Cardiff University spin-off company Mesuro [5.1] was established in 2009.

Mesuro supplies PWE systems directly to the relevant industries, e.g. mobile communications, semiconductor foundries, military and satellite systems, and has exploited PWE to establish a successful market presence and leadership. It currently employs 7 FTE staff. In 2010-11 it secured investment of £450k and revenue of £220k, with revenues for 2011-12 and 2012-13 rising to £700k and £1.5M, respectively. This includes sales to Infineon and M/A-COM in the USA, and Miyoshi (Mitsubishi) in Japan.

In 2009, and as a result of the success of PWE, Welsh Government funding (£370k) enabled the "Green Communications Centre" within the Knowledge Transfer Centre (KTC), which increased technological capabilities and improved business access; it is now part of Cardiff School of Engineering's "Business Gateway". To date, this industry-focussed, PWE-related activity [3.1] has generated £160k from customers including EADS-ASTRIUM, Cobham CTS, UMS, TNO, Plextek, WIN-Semiconductors and Analog-Devices.

Impact on Practice

CREE, currently the world –leading company in the RF-power semiconductor sector, used PWE to successfully demonstrate the potential of their GaN technology for very efficient PAs (2008) [3.1], [3.3]. CREE have introduced PWE-based CAD models for mainstream simulation tools, for their newest 50V GaN technology (2013) [5.5]. This new generation of models gives circuit designers unique access to PWE by displaying the internal voltage and current waveforms within CREE transistors – *"a technique driven by the published work and activities of the Cardiff CHFE group*" [5.5]. Similar work was undertaken for Freescale on its LDMOS technology (2008) that translated into two funded PhD studentships (£100k).

In his plenary presentation at the 2013 IEEE Radio and Wireless Week, the President, CEO and Founder of National Instruments (NI) highlighted PWE's impact on their new products [3.6],[5.6]. The "Cardiff model" has now been integrated into NI's mainstream microwave simulation tool (AWR Microwave Office). NI is also providing £250k of funding (2013) to support device-modelling aspects of PWE research at Cardiff in addition to funding a NI Lectureship post (2013).

Since 2008, industrial engagement with PWE has been promoted through 16 EPSRC CASE and other industry-funded studentships with M/A-COM (x2), QinetiQ (x2), Selex (x2), Freescale (x2), Alcatel-Lucent, Copham, Millmega, Roke Manor, Labtech, Mesuro, NXP and EADS. International PhD funding from Agilent (USA) is a direct result of Cardiff's reputation for working with industry on a wide range of challenging practical areas. The impact of PWE is also promoted through the

targeted recruitment of Cardiff PhD graduates to relevant industries, including three students into Alcatel-Lucent (UK) in 2009 and one into Ericsson (Sweden) in 2010.

Environmental Impact

Emerging communication systems must minimize their environmental impact through improved energy efficiency. In collaboration with Alcatel-Lucent, Nokia-Siemens-Networks, France Telecom - Orange, Freescale and other members of the OperaNET-2 consortium, Cardiff is using PWE to improve efficiency of power amplifiers and so reduce the carbon footprint of mobile communications systems [5.7]. A 20% efficiency improvement in a typical (2013) 3G base-station power amplifier translates into savings of approximately £2.5M/year and a 17 kiloton reduction in CO_2 emission for a typical EU network (with 12,000 base-stations).

5. Sources to Corroborate the Impact

5.1 Confirmation of Cardiff's role in establishing successful spin-out Mesuro Ltd (http://www.mesuro.com/index.php/about/history).
5.2 Confirmation from Engineering Manager M/A COM UK of advantages of using PWE in design and development and resulting revenue in excess of $40 million.
5.3 Confirmation from Chief of RF Technology (Radio Platforms), Nokia Siemens Networks, of reduced development time and cost benefits from using PWE for next generation mobile communication systems.
5.4 Confirmation from Associate Vice President (Technology), WIN Semiconductors (Taiwan) that they have used PWE for rapid optimisation of their GaN technology.
5.5 Confirmation from Strategic Business Development Manager CREE that CREE has introduced PWE-based CAD models, underpinned by Cardiff research, for mainstream simulation tools for their newest 50V GaN technology.
5.6 Confirmation from Vice President (Europe) National Instruments of PWE impact on product development.
5.7 Confirmation of OperaNET2 consortium objective of improving efficiency of PAs and reducing CO_2 emissions - http://projects.celticplus.eu/opera-net2/.