Institution: University of Leeds		
Unit of Assessment: UoA12		
Title of case study: Radio Frequency Power Combiners for Mobile Communication Systems		
Period when the underpinning research was undertaken: 2000 – 2018		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Ian Hunter	Senior Research Fellow, Reader, Professor	01/08/1998 – 31/12/2018
Roger Pollard	Lecturer, Senior Lecturer, Professor	01/09/1974 – 30/09/2010
David Rhodes	Professor	01/04/1975 – 09/10/2003
Period when the claimed impact occurred: 2014 – 2020		
Is this case study continued from a case study submitted in 2014? No		

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

Research at the University of Leeds has underpinned the development and manufacture of radio frequency (RF) power combiners by Radio Design Ltd for use in mobile communication systems. Radio Design industrialised the Leeds research, training design engineers in the new technology, and designing devices for volume production. [text removed for publication]

2. Underpinning research (indicative maximum 500 words)

Since 2000, the University of Leeds developed a new research activity in the School of Electronic and Electrical Engineering led by Professor Ian **Hunter** FREng on the development of microwave filters for the rapidly expanding mobile communications market. As cellular networks became deployed more widely, there was a need for interference rejection filters for base stations with bandwidths of <1 MHz at centre frequencies of 1–4 GHz. **Hunter** conducted research into the development of filters with significant dissipation loss, and non-uniform Q filters. This new technique took low-Q structures into account, avoiding reduction in skirt selectivity, and this was then extended to transmission-mode filters with elimination of the requirement for a circulator [1]. Based on this research, Leeds received funding from two Technology Strategy Board projects with TWI (Cambridge) to develop filter designs ('Adept-Sip' Ref. 461348, £398,401, 1/05/2006–31/10/2009; and, 'PPM2' Ref. 475416, £325,000, 1/06/08–31/11/11), as well as research grants with the Defence Technology Centre for Electromagnetic Remote Sensing to support applications in the defence sector.

In response to the development of LTE and 4G systems by cellular radio operators, there was a growing need to develop directional channel combining filters. **Hunter** commenced a collaborative research programme with Radio Design Ltd in 2010 following their recognition of the commercial significance of **Hunter**'s work on cascaded directional filters in providing the theoretical concepts underpinning new filtering technology. Radio Design Ltd furthermore supported and co-funded **Hunter**'s appointment to a Royal Academy of Engineering Research Chair in 2012, and is currently employing him on a part-time basis following his retirement from the University in 2018.

Working with Radio Design Ltd, **Hunter** developed a theoretical synthesis technique for the design of directional filters for 4G power combining systems showing that parallel connected networks could be implemented with non-uniform Q filters [2], enabling transversal directional filters to be realized for channel combining [3]. This new design approach enabled a device called a 'four port combiner' to be constructed, which allows two radio frequency channels to be combined onto a single antenna, even if the two channels are very close in frequency. The four port combiner enables two cellular operators to share a single antenna by integrating their base stations to such a combiner, or a single operator to combine two different cellular systems (e.g. 4G and 5G) to the same antenna. This enables considerable savings in both cost and the infrastructure required for base stations, as well as reducing the consequential environmental impact. Ref. 3 reports a miniaturisation of the combiner by a factor of two or more in volume. The research was subsequently extended to the synthesis of multi-band filters [4].

This work was patented by Radio Design Ltd with **Hunter** [5,6], and used to underpin the series of successful products described in section 4.

Pollard and **Rhodes** both retired from the University during this period, but contributed to the research presented in Refs. 1 and 2, respectively, in collaboration with **Hunter**.

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

[1] A C Guyette, I C Hunter and R D Pollard, 'The design of microwave bandpass filters using resonators with non-uniform Q', *IEEE Transactions on Microwave Theory and Techniques* 54, 3914–3922 (2006). https://doi.org/10.1109/TMTT.2006.884627

[2] M Meng, I C Hunter and J D Rhodes, 'The design of parallel connected filter networks with non-uniform Q resonators', *IEEE Transactions on Microwave Theory and Techniques* 61, 372–381 (2013). https://doi.org/10.1109/TMTT.2012.2230021

[3] I C Hunter, E Musonda, R Parry, M Guess, P Sleigh, M Gostling and M Meng, 'Transversal directional filters for channel combining', *IET Radar, Sonar and Navigation* 8, 1288–1294 (2014). http://dx.doi.org/10.1049/iet-rsn.2013.0330

[4] E Musonda, R A Paradkar, I C Hunter, 'Synthesis of multi-band filters by linear optimization', *IEEE Transactions on Microwave Theory and Techniques* 67, 4764–4772 (2019). https://doi.org/10.1109/TMTT.2019.2945755

All of the above journals are internationally recognised with rigorous review processes and international editorial boards. The quality of the underpinning research being at least 2* is demonstrated by all four references.

Underpinning patents granted to Radio Design Ltd that include **Hunter** as an investigator.

[5] R Parry, P Sleigh and I Hunter, GB2507668—Apparatus for Allowing Radio Frequency Selectivity and Method of use Thereof (2013) https://patentscope.wipo.int/search/en/detail.jsf?docId=GB137556750

[6] R Parry, P Sleigh and I Hunter, GB2513724—Apparatus for Allowing Radio Frequency Selectivity and Method of use Thereof (2013) https://patentscope.wipo.int/search/en/detail.jsf?docId=GB137564553

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

Radio Design Ltd designs and manufactures single- and multi-band RF filters and combiners for cellular radio systems, focusing on: inter-operator and technology sharing; tower mounted amplifiers; interference reduction; and, the provision of test equipment. The company currently has around 470 employees, mostly in the UK and India, with a turn-over of ~£28M per annum.

In 2010, Radio Design Ltd. recognised the commercial significance of **Hunter**'s RF filter research at the University of Leeds and, in particular, its application to the development of miniaturised combiners that allow two radio frequency channels to be combined onto a single antenna, even if the two channels are very close in frequency.

Radio Design Ltd subsequently industrialised the Leeds research, training their design engineers in the new technology, upgrading their in-house filter design software and designing devices for volume production. Since 2015, [text removed for publication] products have been shipped based on the designs and simulations undertaken by **Hunter** and his group at the University of Leeds [text removed for publication] [A].

Specifically, these products comprise [B]:

- RD0569 800 MHz same band combiner with 5 MHz bandwidth
- RD0615 800 MHz same band combiner with 10 MHz bandwidth (adjacent spectrum)
- RD0630 900 MHz same band combiner with 5 or 10 MHz bandwidth
- RD0730 800 MHz same band combiner with 10 MHz bandwidth (non-adjacent spectrum)
- RD0784 1800 MHz same band combiner

The 5 MHz bandwidth products have a narrower guard band than the 10 MHz bandwidth products. In all cases, the combiner guard band is less than the unoccupied spectrum between adjacent carriers.

[text removed for publication]

Two granted patents associated with products RD0569, RD0615, RD0630 and RD0784 list Professor Ian **Hunter** among the inventors [5, 6]. Radio Design Ltd have a further patent application for product RD0730 (GB2566182) awaiting examination [text removed for publication] [A].

The University of Leeds has not only supported the design of new products at Radio Design Ltd, but has also provided highly skilled PhD-trained engineers from **Hunter**'s research group who have been recruited by the company. [text removed for publication].

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

[A] Letter from the Engineering Director, Radio Design Ltd., Wharf Street, Shipley, West Yorkshire, BD17 7DW, UK, 27 November 2020.

[B] 'Same Band Combiners', https://radiodesign.eu/same-band-combiners/#RD0569, Accessed 19 January 2021.