Institution: Loughborough University

Unit of Assessment: B13 Electrical and Electronic Engineering, Metallurgy and Materials

Title of case study: Signal Processing Solutions for the Networked Battlespace

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

The Advanced Signal Processing Group at Loughborough University has, since 2007, changed significantly the awareness and understanding of technical staff at QinetiQ, Malvern, a world leading defence and security company, in relation to signal processing for Polynomial Matrix Decompositions, Game Theoretic Methods and Cooperative Communications and Beamforming. This has helped QinetiQ, Malvern, to develop state-of-the-art products and solutions for the networked battlespace with unique performance advantages. This impact is being extended through a five-year £4.5M project awarded, in 2013, by the EPSRC and Dstl to Loughborough University, to aid in implementing the UK's Defence Technology Strategy for the 21st Century.

2. Underpinning research (indicative maximum 500 words)

Research Team: The Advanced Signal Processing Group (ASPG) within the School of Electronic, Electrical and Systems Engineering at Loughborough University has been led by Professor Jonathon Chambers FREng CEng FIET FIEEE, Professor of Communications and Signal Processing, since July 2007 with support from Professor Sangarapillai Lambotharan, Professor of Digital Communications, over the same period. The technical members of staff working in signal processing at QinetiQ, Malvern, included Professors John McWhirter FRS FREng, Ian Proudler and Malcolm Macleod.

Polynomial Matrix Decompositions: Professors Chambers, Lambotharan and McWhirter supervised Dr Joanne Foster and Dr Martin Davies through the support of QinetiQ Industrial CASE Awards to PhD graduation in 2008. They spent secondments at QinetiQ Malvern in order that research findings could be immediately translated into industrial solutions. On the basis of their PhD research findings a three-year EPSRC project entitled "Novel Polynomial Matrix Decompositions with Application to Broadband MIMO Communications Signal Processing" [**G3.1**], was secured in June 2008 by Professors Chambers, Lambotharan, McWhirter and Proudler. ***The teams developed fundamentally new methods for calculating polynomial matrix singular value and QR decompositions [3.1] and applied these techniques to MIMO communication systems. The related algorithms were transferred to QinetiQ for application in battlefield communications.***

Game Theoretic Methods: Funding was provided in the project held by Professors Chambers, Lambotharan, McWhirter and Proudler [**G3.1**] supported by the EPSRC and QinetiQ to allow Dr Amod Anandakumar to undertake research in applying game theoretic methods to mutli-user resource allocation. This work undertaken between June 2008 and May 2011 developed a ***robust rate-maximization game under bounded channel uncertainty [3.2] and provided the basis for new interaction with the Defence Science and Technology Laboratory (Dstl) in a collaborative project in the area of game theoretic privacy-preserving collaborative data mining from May 2012 -> April 2013, which has transferred expertise from the ASPG to Dstl.***

Cooperative Communications and Beamforming Professors Chambers and Macleod acted as the co-supervisors of the PhD programme of Dr Matthew Hayes in the area of distributed wireless communications. Dr Hayes was a QinetiQ employee and received a QinetiQ ICASE Award and graduated in 2012. During the course of this interaction Professors Lambotharan, Chambers and Proudler secured a three-year EPSRC funded research project in convex optimisation based robust spatial multiplexing techniques for downlink multiuser wireless systems **[G3.2]** which ran from Dec 2008 -> Nov 2011. As a result the ASPG has developed internationally leading expertise in convex optimization techniques for the design of electronic beamformers [**3.3, 3.4**] with multiple constraints such as power and interference leakage. ***The novel methods developed at Loughborough include second order cone programming based robust designs to tackle channel uncertainties in the propagation environment. These techniques now transferred to QinetiQ are candidates for application in both military wireless systems for secure***

directional transmission and in commercial cellular wireless networks to manage/mitigate interference and to perform spatial multiplexing for enhancing overall spectrum efficiency.

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

The research funding in [G3.1] and [G3.2] below was secured in open competition with the top tier universities in the UK; the full research papers were published in the foremost international journals in their respective fields after thorough assessment by world-leading referees in terms of the level of contribution and scientific rigour.

3.1 J. Foster, J.G. McWhirter, M.R.Davies, and J.A. Chambers, "An Algorithm for Calculating the QR and Singular Value Decompositions of Polynomial Matrices", IEEE Trans. Signal Processing, Vol. 58(3), pp. 1263-1274, 2010.
3.2 A.J.G. Anandkumar, A. Anandkumar, S. Lambotharan and J.A. Chambers, "Robust Rate-Maximization Game Under Bounded Channel Uncertainty," IEEE Trans. Vehicular Technology, vol. 60, pp. 4471-4486, 2011.
3.3 K. Cumanan, R. Krishna, L. Musavian and S. Lambotharan, "Joint Beamforming and User Maximization Techniques for Cognitive Radio Networks Based on Branch and Bound Method," IEEE Trans. Wireless Communications, vol. 9, pp. 3082-92, 2010.
3.4 L. Musavian, S. Aïssa and S. Lambotharan, "Effective Capacity for Interference and Delay Constrained Cognitive Radio Relay Channels", IEEE Trans. Wireless Communications, vol. 9, pp. 1698-1707, 2010.

G3.1 J.A. Chambers (PI) and S. Lambotharan (CI) (Loughborough Uni.) and J. McWhirter (CI) (QinetiQ/Cardiff Uni.) and I. Proudler (QinetiQ), EPSRC F065477/1, EPSRC contribution £376,962, "Novel Polynomial Matrix Decompositions with Application to Broadband MIMO Communications Signal Processing," June 2008->May 2011.
G3.2 S Lambotharan (PI) and J.A. Chambers (CI), (Loughborough Uni.) and I. Proudler (QinetiQ). EPSRC G020442, EPSRC contribution £238,316, "Convex Optimization Based Robust Spatial Multiplexing Techniques for Downlink Multiuser Wireless Systems," Dec. 2008->2011.

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

Drawing upon extensive technical knowledge and intellectual property, QinetiQ provides technical support, training, test and evaluation, and know-how to customers in the defence, aerospace, and security markets primarily in the United Kingdom and North America. Innovation, deep domain knowledge, rigorous independent thinking and technical expertise underpin QinetiQ's success and mirror the values of the ASPG. The company employs over 10,000 people worldwide and is one of the UK's largest research and technology organisations and recognized as a world leader in defence and security. Much of QinetiQ's business is conducted with high levels of confidentiality therefore it is ***not possible to provide exact names of customers and details of products in which the new signal processing solutions have been or will be exploited*.**

Since July 2007 Professor Chambers as the first QinetiQ Visiting Fellow (awarded for his previous seven years of successful interaction with QinetiQ) and the Head of the ASPG at Loughborough University, has worked closely with engineers and scientists from QinetiQ, Malvern, to ensure they have awareness and understanding of the latest advances in the field. His role as a Senior Area Editor (unique in the UK) for IEEE Trans. Signal Processing, the world's leading academic journal in signal processing, demonstrates his international technical standing.

The novel research findings developed by Professors Chambers and Lambotharan, also since July 2007, within the ASPG at Loughborough University have provided new capability to the technical staff at QinetiQ Malvern which have allowed them to advance the state-of-the-art in signal processing solutions for the networked battlespace [**5.1**]. This activity has also benefitted the training of research students and postdoctoral assistants at Loughborough University, as listed in Section 3, who have since taken up positions in industry in the UK.

This interaction underpinned the formulation of the Loughborough, Surrey, Strathclyde, and Cardiff (LSSC) Consortium bid, led by Professor Chambers, to the EPSRC/Dstl Call, December 2011, on

"Signal Processing in the Networked Battlespace". This work is nationally important as it ensures that EPSRC's target to grow the UK's capability in digital signal processing and to attain an intelligent information infrastructure are met; and is helping to ensure the Defence Technology Strategy for the 21st Century is implemented [**5.2**]. The impact of the work of the LSSC Consortium can also be judged by the breadth of the six industrial partners spanning international companies to SMEs: QinetiQ, Thales, Selex-Galileo, Texas-Instrument, Steepest Ascent and PrismTech. This consortium was one of the two successful consortia, the other is from Edinburgh and Herriot Watt Universities, awarded ahead of other consortia from across the UK including one led by Imperial College with partners from Bristol, Cambridge and UCL.

In summary, the ASPG at Loughborough University has significantly changed the awareness and understanding of the technical staff at QinetiQ, Malvern, in relation to the very latest signal processing techniques for Polynomial Matrix Decompositions [**3.1**]; Game Theoretic Methods [**3.2**] and Cooperative Communications and Beamforming [**3.3, 3.4**]. This transfer of technical skills has helped QinetiQ, Malvern, to develop state-of-the-art products and solutions for the networked battlespace with unique performance advantage. The reach of this impact is being extended to other industrial organisations through the LSSC consortium and Dstl.

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

5.1 Chief Scientist, C4ISR Division, QinetiQ, Malvern, Worcestershire, WR14 3PS.
5.2 Technical Director, Dstl, Porton Down, Wiltshire, SP4 OJQ.