Institution: Newcastle University

Unit of Assessment: 11

Title of case study: Efficient Power Management in Consumer Electronics

Period when the underpinning research was undertaken: 2000-2020

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:**
Dr Victor Khomenko	Lecturer / RAEng & EPSRC Research Fellow / Lecturer / Senior Lecturer / Reader.	2003-present
Prof Maciej Koutny	Lecturer / Reader / Professor	1985-present
Prof Alexandre Yakovlev	Lecturer / Reader / Professor	1991-present
Dr Danil Sokolov	RA / Senior RA / Principal RA	2006-2020
Dr Andrey Mokhov	Lecturer / Senior Lecturer & Royal Society Industry Fellow	2009-2019

Period when the claimed impact occurred: 2014 - 2020

Is this case study continued from a case study submitted in 2014? N

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

Asynchronous electronic circuits have considerable advantages over traditional clocked circuits in the area of Power Management Integrated Circuits (PMIC) but are notoriously difficult to design correctly. Dialog Semiconductor PLC (a world leading electronic chip designer and, since 2007, the exclusive supplier of PMICs for the Apple iPhone, iPad, and Watch) has stated that Newcastle University research, implemented in the software framework WORKCRAFT, was a *[redacted]* of their PMIC design. Following researcher- provided training, the framework has been *[redacted].* By 2016, Dialog held close to 70% of the fast-charging smartphone and computing adapter market. In 2018 Apple Corporation, in their largest deal of its kind, bought Dialog's PMIC business and 3-years supply of PMICs for $600,000,000. The underlying technologies have also been applied by GitHub Inc. and Analog Devices Inc.

2. Underpinning research (indicative maximum 500 words)

Due to the widespread popularity of portable electronics such as smartphones and smartwatches, there is an increasing demand for integrated circuits which are smaller, more complex, more power-efficient, and yet cost-effective. This has led to a rise in the use of Analogue and Mixed Signal (AMS) systems, in which the analogue layer is "digitally enhanced" with its own "little digital" control [P1, P2] (as opposed to "big digital" which describes traditional computational electronics). Analogue and Mixed Signal (AMS) systems now play a vital role in monitoring a system's operating conditions, as well as distributing and regulating energy flows. However, "little digital" electronics is considered extremely hard to master, as the digital components must integrate seamlessly with the analogue parts, which are dynamic and notoriously hard to interface.

To satisfy the latency requirements, traditional synchronous AMS controllers need to operate at a high clock frequency, which results in inefficient use of energy and silicon area. In contrast, asynchronous AMS control operates at a pace that is determined by current operating conditions, while avoiding the overheads imposed by clocking.

Newcastle University pioneered research into “little digital” AMS controllers [P1, P2] and tackled the issue of how to use asynchronous digital circuits to control analogue parts. Novel electronic components (WAIT, WAITX, SAMPLE, etc.), called analogue-to-asynchronous (A2A) interfaces [P1, P2], were developed in collaboration with Dialog in response to their needs. The resulting design methodology draws on research into the use of Petri nets and causal representations of concurrent behaviour in electronic circuits, which can be validated by simulation, formally verified, and automatically synthesised into electronic circuits [P3]. This methodology increases the design productivity and the quality of circuits, with a much higher confidence in their correctness [P2].

When applied to PMICs, the developed “little digital” design methodology results in higher efficiency of power conversion, which translates into longer battery life and faster charging. The methodology is supported by WORKCRAFT (workcraft.org) – a visual framework for development of Interpreted Graph Models (e.g. Petri nets and digital circuits), including visual editing, (co-) simulation, formal verification and synthesis, all of which are crucial for industrial adoption. It allows the user to design a system using the most appropriate formalism (or even different formalisms for the subsystems), while still utilising the power of formal methods based on Petri nets and supported by software tools.

“Little digital” methodology offers a significant reduction in the chip area for small controllers. The area of a controller’s core logic is normally similar for asynchronous and traditional designs and is usually <10,000μm^2 for PMICs. However, to achieve the efficiency comparable to asynchronous power converters, the traditional synchronous design would in addition need a high frequency (3GHz) clock [P1,P2] and hence require, besides an RC oscillator (area approximately 10,000μm^2), a frequency multiplier implemented as a Phase Locked Loop (PLL) (area over 100,000μm^2). Hence, the total area of a traditional design would be approximately 120,000μm^2, compared to less than 10,000μm^2 for asynchronous designs. This translates to more chips per silicon wafer and thus better cost-efficiency.

Furthermore, the asynchronous control has very low latency (the response time is usually several gate delays as opposed to 2.5-3 clock cycles in synchronous designs), making it possible to use smaller inductors (coils), which are traditionally bulky and affect the dimensions of some consumer gadgets [P1,P2].

The research has been carried out jointly by Dr Victor Khomenko and Prof Maciej Koutny (School of Computing), and Prof Alexandre Yakovlev, Dr Danil Sokolov and Dr Andrey Mokhov (School of Engineering). The resulting methodology has been implemented in several software tools (such as PUNF, MPSAT and PCOMP), which have later been included into WORKCRAFT – a visual framework for development of Interpreted Graph Models. Research on algebraic graphs [P4] incorporated in WORKCRAFT was also made available as an independent open-source software library- `algebraic-graphs` [P5] for algebraic manipulations of graph models.

Industrial collaborations funded by Dialog for approximately £688,000 [G1,G2], demonstrated the significant advantages of “little digital” design methodology implemented in WORKCRAFT, in terms of improved reaction time, voltage ripple, peak current, and inductor losses, resulting in a higher efficiency of power conversion [P1, P2]. Collaborative work was significantly enhanced due to appointing David Lloyd, Dialog’s Senior Member of Technical Staff and a Digital System Architect for the Custom and Mixed Signal Business Group, a Visiting Professor of Practice at Newcastle University. This enabled the researchers to better understand the problems faced by industry, develop solutions, and provide suitable training to Dialog’s engineers, which helped the industry to adopt these new technologies and produce PMICs with enhanced power management capabilities. In 2020 one of WORKCRAFT’s developers, Danil Sokolov, now a visiting researcher at Newcastle University, joined Dialog to continue promoting the use of WORKCRAFT and to further enhance the collaboration between Dialog and Newcastle University.

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

[P1] D. Sokolov, V. Dubikhin, V. Khomenko, D. Lloyd, A. Mokhov, and A. Yakovlev. *Benefits of Asynchronous Control for Analog Electronics: Multiphase Buck Case Study*. Proc. of DATE'2017, IET Proceedings: Computers & Digital Techniques (2017) 1751-1756. DOI: 10.23919/DATE.2017.7927276.

[P2] D. Sokolov, V. Khomenko, A. Mokhov, V. Dubikhin, D. Lloyd and A. Yakovlev. *Automating the Design of Asynchronous Logic Control for AMS Electronics*. IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (2019). DOI: 10.1109/TCAD.2019.2907905. Print ISSN: 0278-0070. Online ISSN: 1937-4151.

[P3] V. Khomenko, M. Koutny, and A. Yakovlev. *Logic Synthesis for Asynchronous Circuits Based on Petri Net Unfoldings and Incremental SAT*. Special Issue on Best Papers from ACSD'04, IOS Press, Fundamenta Informaticae 70(1-2) (2006) 49-73. DOI: 10.1109/CSD.2004.1309112.

[P4] A. Mokhov and V. Khomenko: *Algebra of Parameterised Graphs.* Special Issue on Best Papers from ACSD'12, ACM Press, ACM Transactions on Embedded Computing Systems 13(4s) (2014). Article No. 143. DOI: 10.1145/2627351.

[P5] `algebraic-graphs` library. Available at http://hackage.haskell.org/package/algebraic-graphs.

Grants

[G1] 2014-2018, "Asynchronous Design for Analogue Electronics (A4A)", EPSRC, £574,524, EP/L025507/1; Dialog fully funded a PhD student (approximately £90,000).

[G2] 2017-20 "Tools for Asynchronous Logic" (approximately £505,266.60) fully funded by Dialog, and they in addition fully funded a PhD student (approximately £93,000).

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

The prevalence and pervasiveness of consumer electronics from smart phones to the Internet of Things has created a need for more efficient power management on devices where battery life and fast charging are important considerations. Before the impact period, the vast majority of *Power Management Integrated Circuits* (PMICs) used in consumer electronics employed synchronous (clocked) designs which are limited by their power conversion abilities – a bottleneck for the new generation of devices. Asynchronous designs, though more efficient, were not typically used in industry due to the difficulties in design and verification, and a lack of practically applicable tools [E1].

Newcastle University research implemented in the WORKCRAFT framework and industrial collaboration by researchers have been seen by industry as the *[redacted],* in particular PMIC. Specifically, novel techniques have been applied to the industrial production process resulting in PMICs capable of higher efficiency of power conversion. Electronic devices using new PMICs benefit from longer battery life, faster charging and smaller power management components which allows for greater flexibility in physical design. For manufacturers of electronic chips and devices, this translates to cost reductions and market advantage.

WORKCRAFT has also provided industry with tools that allow more rigorous verification. PMICs make millions of control decisions per second and so the responsiveness and robustness of PMICs are crucial, as a single misstep can short-circuit the battery and permanently damage the device.

Dialog Semiconductor PLC

Researchers have achieved impact through sustained industrial collaborations with multinational world leading electronic chip manufacturers, Dialog Semiconductor PLC and Analog Devices Inc. The impact of WORKCRAFT is evidenced by the growth of these manufacturers, and by the industry advantage gained by their customer organisations. The WORKCRAFT team have been recognised by industry as *[redacted]*. The benefits of enhanced power conversion also extend to manufacturers of mobile phones, smartwatches and other electronic devices containing asynchronous PMICs (in the form of market and business advantage), and to users of such devices (longer battery life and faster charging).

Dialog is the exclusive supplier of PMICs for Apple Corporation's iPhone, iPad and Watch, which represented 75-80% of Dialog's sales [E4]. Collaborations with Dialog began in 2014 through joint R&D programmes and training of over 80 engineers based in the UK, USA and Europe in the use of WORKCRAFT. The software has been *[redacted].* Dialog holds two patents based on these novel technologies [E5]. In 2016 Dialog reported that power conversion, one of their three main business segments, delivered a year-on-year growth of 54% [E6]. By then, Dialog's power conversion controllers held close to 70% of the fast-charging smartphone and computing adapter market. The importance of this technology to the industry is evident in the 2018 purchase of Dialog's power management business and 3-years supply of PMICs by Apple Corporation in a $600,000,000 deal [E3] – the largest deal of its kind by Apple.

Analog Devices Inc.

Another key pathway to impact on the industry is through USA-based world leading chip manufacturer Analog Devices Inc. who see asynchronous design important for the success their portfolio of over 45,000 products [E1]. In 2018, the company invested into training their engineers from the USA and UK in using WORKCRAFT. Due to this, they are able to conduct formal verification of correctness of analogue and mixed-signals electronics to identify all potentially problematic configurations and states – a task was *"virtually impossible to achieve"* previously [E1]. An important element of the impact is in engineering education which will continue to have impacts for the future electronics industry. Analog Devices acknowledge that formalised training for asynchronous logic design is *"extremely rare worldwide"* [E1], however it is essential for new technologies to be accessible to industry.

GitHub, Inc.

Research on algebraic graphs [P4] incorporated in WORKCRAFT was also made available as an independent open-source software library algebraic-graphs [P5] implemented by the researchers. GitHub deploys it in their semantic library (https://github.com/github/semantic) for parsing, analysing, and comparing source code across multiple programming languages. GitHub have stated [E7] that they use `algebraic-graphs` to *[redacted].* GitHub Inc., since 2018 a subsidiary of Microsoft, is the world's largest source-code hosting platform. It reports over 67,000,000 users and over 213,000,000 repositories and is the 74th most visited website according to Alexa ranking.

Widening accessibility

Workcraft has over the impact period been adopted into teaching at a number of universities: *MSc System on Chip* at Southampton University; *02204 Design of Asynchronous Circuits* at the Technical University of Denmark; and *CSC3324 Understanding Concurrency*, *EEE8043 Design of Asynchronous Low Power Systems, EEE8087 Real-Time Embedded Systems,* and *EEE8124 Low Power VLSI Design* at Newcastle University.

Workcraft is an open-source project that is available publicly at workcraft.org. Since 2014 there have been 32 public releases of Workcraft, which were downloaded approximately 20,000 times from approximately 4,700 unique IPs. The open-source library algebraic-graphs is also publicly available [P5] and was downloaded approximately 9,600 times since 2016.

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

[E1] Letter from Steve Martin, Battery Charger and PMIC Design Manager, Analog Devices Inc. 17 January 2019.

[E2] Letter from Hasan Khan, Vice President – Central Engineering. Dialog Semiconductor PLC. 15 April 2019.

[E3] (a) Dialog (2018). "*Dialog Semiconductor and Apple enter agreement*", Company announcement 11 October 2018. Available at https://www.dialog-semiconductor.com/press-releases/dialog-semiconductor-and-apple-enter-agreement [last accessed 03-02-2021]
(b) Reuters (2018) "*Apple gets critical iPhone technology in $600 million Dialog deal".* Available at https://uk.reuters.com/article/us-dialog-licensing/apple-gets-critical-iphone-technology-in-600-million-dialog-deal-idUKKCN1ML0IJ [last accessed 03-02-2021]

[E4] Investor's Business Daily (2016), "*Chipmaker's Strong Sales Seen as Positive For Apple*". Available at http://www.investors.com/news/technology/click/chipmaker-report-seen-as-positive-for-apple/. [last accessed 03-02-2021]

[E5] (a) D. Sokolov, V. Khomenko, A. Yakovlev: *"Asynchronous Circuit"*. US Patent: US10581435 (B1). Dialog Semiconductor (UK) Limited.

(b) D. Sokolov, V. Khomenko, A. Yakovlev: *"Tools and Methods for Selection of Relative Timing Constraints in Asynchronous Circuits, and Asynchronous Circuits Made Thereby".* US Patent US10839126 (B1). Dialog Semiconductor (UK) Limited.

[E6] Dialog Semiconductor Interim report Sept 2016. Available at https://www.dialog-semiconductor.com/sites/default/files/gb0059822006-q3-2016-eq-e-00.pdf

[E7] Letter from Patrick Thompson, Senior Data Engineer, GitHub Inc. 10 December 2018.