Institution: Edinburgh Research Partnership in Engineering

(ERPE: Edinburgh and Heriot-Watt Universities joint submission)

Unit of Assessment: UoA12 Engineering

Title of case study: pureLiFi: The first LED light-based communication system

Period when the underpinning research was undertaken: August 2007 to January 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:
Harald Haas	Chair of Mobile Communications	01/06/07 - 18/07/20
Mostafa Afgani	Research Fellow	08/03/10 - 04/01/12
Sinan Sinanovic	Research Fellow	25/06/07 – 02/01/13
Stefan Videv	Experimental Officer, LiFi R&D Centre	08/03/17 – 01/08/17
	Engineering Director, LiFi R&D Centre	01/10/18 - 02/08/20

Period when the claimed impact occurred: September 2013 to December 2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact

ERPE researchers, led by Prof Harald Haas, invented and developed a wireless system that transmits data via LED lighting, using light fidelity technology (LiFi). This extended the available capacity of the electromagnetic (EM) spectrum for dense short-range wireless communication beyond the existing limits of radio frequency (RF) and exploited, as a platform, the ongoing proliferation of light emitting diode (LED) lighting. Following the formation of a spin-out company, called pureLiFi Ltd (pureLiFi), the major impacts arising from the ERPE research in the return period include:

(A) - International investment of USD28.9M into pureLiFi to commercialise the technology;

(B) - A series of world-first innovative products delivered to the market;

(C) - Extensive global business growth through partnerships involving trials of 200 applications in 23 countries across healthcare, education, defence and telecoms sectors;

(D) - Registration of 34 patents and 2 trademarks [5.8] and leadership of the international industry LiFi task force developing the global standard IEEE 802.11bb;

(E) - Multiple industry awards to pureLifi; and

(F) - Global public engagement including 2,800,000 views of a 2015 TED talk.

2. Underpinning research

ERPE research by Professor Harald Haas and colleagues at the University of Edinburgh (UoE), funded by EPSRC (P1, P3) resulted in pioneering breakthroughs in data communication systems using LED lighting (LiFi). There were two primary combined research drivers and opportunities:

- Future annual growth of Wi-Fi communications usage would quickly overcrowd, and be restricted by, the limited capacity of the radio-frequency (RF) spectrum; and
- The accelerated uptake of LED lighting across many applications, environments and markets provided a pre-existing and adopted technology platform into which this new communications technology could be integrated.

Haas and ERPE staff delivered the enabling research to develop LiFi via LED lighting as a future global communications medium for diverse applications. These included:

Ensuring that Orthogonal Frequency Division Multiplexing (OFDM) could be adapted and optimised for use within LiFi.

OFDM is the primary signal coding technique that underpins many modern RF communication systems such as 4G, 5G and Wi-Fi. OFDM is an efficient method of encoding information and data on the amplitude *and phase* of a radio wave. But in LiFi, the *phase* property of the light wave is not available for data transmission. Consequently information can only be encoded on the light *intensity* (akin to using a data stream to rapidly yet invisibly change the brightness of a light source). Haas and colleagues identified and exploited key changes [3.1] to adapt OFDM into a new format and enable it to be used in LiFi, for the first time, to transmit data in the visible light part of the EM spectrum, while retaining all of its other benefits.

The new format was initially developed assuming that all components in a LiFi system would have a linear response. However, LED LiFi was initially found to have a non-linear behaviour, which degraded and limited its performance - measured by an increase in the Bit Error Rate (BER). Research described in [3.2] developed a model that accurately described how the BER metric was determined by component non-linearities. This allowed the input parameters of the LiFi design to be adapted to ensure and maintain an acceptably low BER and unlock the technology for commercial development.

Optimum LiFi input signal parameters to achieve maximum data-rate using 'real' LEDs.

The amount of 'dc-bias' applied to the data signal defines the 'operating point' in the design of a LiFi system. This is a critical choice for optimum performance. [3.3] reported a mathematical analysis that was able to model and define the optimum dc-bias level. Further analysis [3.4] described and quantified the resulting degradation in data-rate when a LiFi system is operated on either side of the optimum point, and provided a framework and algorithm to ensure optimum system performance and data-rates based on [3.3].

Enabling close-to-zero dc-bias without data-rate loss for LiFi uplink.

In a conventional RF-based wireless communication system, an OFDM signal amplitude has both positive and negative values. However, because light intensity can only be positive the maximum data rate reduces by half. [3.5] discovered that, by setting the operating point close to the absolute minimum value required to illuminate the LED, the data rate could be restored to nearly the original value, which also saved energy. [3.6] elaborated on this enhanced-Unipolar OFDM (eU OFDM) method, which is based on super-position modulation combined with a unique OFDM frame structure to create a 'layered modulation'.

3. References to the research

[3.1] **Conference**. Elgala, H., Mesleh, R. and Haas, H. (2009) "Practical considerations for indoor wireless optical system implementation using OFDM," 10th International Conference on Telecommunications, Zagreb, pp. 25-29. https://ieeexplore.ieee.org/document/5206382

[3.2] **Journal**. Elgala, H., Mesleh, R. and Haas, H. (2010) "An LED Model for Intensity-Modulated Optical Communication Systems," in IEEE Photonics Technology Letters, Vol. 22, (Issue 11), pp. 835-837. https://doi.org/10.1109/LPT.2010.2046157

[3.3] **Journal**. Dimitrov, S., Sinanovic, S. and Haas, H. (2012) "Clipping Noise in OFDM-based Optical Wireless Communication Systems", IEEE Transactions on Communication, Vol. 60, (Issue 4), pp. 1072–1081. https://doi.org/10.1109/TCOMM.2012.022712.100493.

[3.4] **Journal**. Dimitrov, S. and Haas, H. (2013) "Information Rate of OFDM-Based Optical Wireless Communication Systems With Nonlinear Distortion," IEEE/OSA Journal of Lightwave Technology, Vol.31, (Issue 6), pp.918-929. https://doi.org/10.1109/JLT.2012.2236642

[3.5] **Conference**. Tsonev, D. and Haas, H. (2014) "Avoiding spectral efficiency loss in unipolar OFDM for optical wireless communication," 2014 IEEE International Conference on Communications (ICC), Sydney, NSW, pp. 3336-3341. https://doi.org/10.1109/ICC.2014.6883836

[3.6] **Journal**. Tsonev, D., Videv, S. and Haas, H. (2015) "Unlocking Spectral Efficiency in Intensity Modulation and Direct Detection Systems," in IEEE Journal on Selected Areas in Communications, Vol. 33, (Issue 9), pp. 1758-1770. https://doi.org/10.1109/JSAC.2015.2432530

Related Research Project Funding

P1 – Haas (PI): Spatial Modulation, EPSRC Grant EP/G011788/1, EPSRC, (GBP308,693) May 2009 - April 2012

P2 – Haas (PI): D-Light, Scottish Enterprise, Proof-of-Concept Programme, (GBP400,000) January 2010 - January 2012

P3 – Haas (PI): EPSRC Established Career Fellowship: "Tackling the looming spectrum crisis in Wireless Communication", EP/K008757/1, (GBP1,344,142) February 2013 – January 2018

4. Details of the impact

The significance of the underpinning ERPE research carried out at the University of Edinburgh to all of the pureLiFi products [3.1, 3.2], was described by pureLiFi's Chief Technology Officer [5.1] as "*laying the foundations for pureLiFi's Technology and helped us to develop and commercialise LiFi solutions*" to be "*a key differentiator in the market*". Outputs [3.3, 3.4] helped pureLiFi to "*develop dimmable solutions…across a whole range… to maximise the data rate*" [5.1], and [3.5, 3.6] led to a "*technique for improving power efficiency*" [5.1]. This has resulted in the following major impacts:

(A) National and Global Investment in Commercialisation

Scottish Enterprise proof of concept funding led to the formation of the spin-out company pureLiFi Ltd, led by Prof Haas and staffed by research colleagues. Within pureLiFi, Haas serves as Chief Scientific Officer and, in the REF return period, pureLiFi has secured major external investment year-on-year from investors [5.2] to commercialise the technologies arising from the underpinning research. This involved securing approximately USD28,900,000 (as of Oct-2020) - involving USD1,9000,000 in 2015, USD9,000,000 in 2016 and USD18,000,000 in 2019, including international inward investment from Singapore investment company Temasek. pureLiFi has approximately 40 employees including software engineers, light communication engineers and design and innovation specialists.

(B) World Firsts in Innovative Products to Market

The original research by pureLiFi [3.1-3.4] has led to a series of new products [5.3] entering the market, including:

1. The first ever commercial LiFi light communications product (Li-1st, Sept 2013) utilising 'off the shelf' LED technology;
2. The first mobile wireless communications LiFi product (Li-Flame, Dec 2014), providing far superior data densities than those available from existing state of the art Wi-Fi; and
3. The first high-speed LiFi pc and laptop dongle (LiFi-X, March 2016).

Further prototype products developed by pureLiFi [5.4] with industry partners included mobile devices embedded with a LiFi optical module (or Light Antenna) to deliver gigabit download speeds approximately 20 times faster than the current UK average.

(C) Business Growth and Key International and UK Partnerships

In 2016 Business Wire reported [5.5] that pureLiFi had recorded '*year-on-year quarterly revenue increases of over 300%*' since autumn (Q3, 2013) and significantly grown its

international customer base around the world to support market mainstreaming. The company secured and led international partnerships with companies such as French lighting manufacturer Lucibel and Indian IT consultancy Wipro [5.4]. Other industry partnerships for new products and network systems development have included O2 Telefonica, Liberty Global, network infrastructure vendors such as Cisco, [5.4, 5.5] and Rolls Royce [5.5]. Both Cisco and Rolls Royce partnerships stemmed from Innovate UK funding.

The first LiFi LED commercial luminaire in the world to reach the market was jointly developed by Lucibel and pureLiFi in September 2016 [5.3, 5.6]. In Dec 2017 Christophe Jurczak, Lucibel Chief Scientific Officer stated in the industry Lucibel White Paper "*pureLiFi is Lucibel's technical partner [5.6, p2]…The Technology has reached maturity.. and over 50 Lucibel clients have built projects with a large variety of use cases and [5.6,p1] ..implementing LiFi provides a powerful complement or alternative to Wi-Fi and 4G [5.6, p9]".*

The advantages of LiFi over conventional Wi-Fi include improved security of communications because of LiFi's focused "line of sight" and that it does not travel through solid objects such as walls. In 2018 the second generation Lucibel-pureLiFi lighting luminaire was launched [5.3]. Applications for Lucibel client secure environments and pureLiFi partnerships included sectors such as Defence, Banks and R&D Centres. pureLiFi products are uniquely deployed in normally restricted RF zones including hospitals (e.g. MRI facilities), pre-kindergarden schools and EMI sensitive industrial facilities [5.6, p9].

By April 2020 more than 200 projects had been delivered in over 20 countries [5.7]. Further commercial exploitation has taken place with major companies such as:

- O2 Telefonica signed deal in August 2018 [5.7],
- BT Defence communications [5.7],
- Babcock Engineering [5.7] for conditioned based monitoring, and
- Disaster response communications with Nokia and Versizon [5.7].

Jeffery Schweitzer, Chief Innovation Architect, from Verizon commented "*pureLiFi demonstrated that LiFi solutions could perform under real life operations and enable critical communications during response missions in chaotic and disastrous environments*." The Solari Spa healthcare project [5.7-06] included both geofencing and geolocation services provided by the pureLiFi system. This led to "*enhanced operational efficiency*" and offered *"acute management of an individual user's access to data*" [5.7-04].

(D) Patents and New Global IEEE Standards

The intellectual property of pureLiFi arising from the underpinning research includes 34 registered patents and two registered trademarks [5.8]. To enable and support international standardisation and future growth of the LiFi sector the Institute of Electrical and Electronics Engineers (IEEE) established a new Topic Interest Group (TIG) in 2016. This was followed by the IEEE 802.11bb international industry LiFi task force to develop the global standard. This includes major industry members such as Osram and Huawei. The international task group is led and chaired by a staff member of pureLiFi [5.9], formerly an ERPE researcher.

(E) Industry Awards to pureLiFi

The underpinning research leading to the developments in technology and growth of pureLiFi have been recognised by major industry awards [5.3, 5.10] including:

- Crystal Cabin 2018;
- Edison LightTrade Award 2017;
- Mobile World Congress 2017 'Cool Tech' award;
- 'Commended Innovation', Institute Of Physics Business Innovation Awards 2017;
- Scottish Business Technology Company of the year 2015.

In October 2020 pureLiFi was listed as the 'Most Innovative Company' by Business Cloud's Scotland Tech 50 rankings. ERPE research led by Haas established 'LiFi' as the universally adopted term for visual light communications.

(F) Public Engagement

Public visibility and engagement extends from LiFi being used for the first time in a secondary school classroom [5.11], International Science Festival 2014 (Tam Dalyell Prize) free public lecture and invited talks at many industry events. The 2015 TED Talk explaining the pureLiFi technology, function and capabilities has had 2,804,378 views (as of Nov, 2020) [5.12].

5. Sources to corroborate the impact

[5.1] Letter from pureLiFi by Chief Technology Officer explaining the foundations and products of pureLiFi stem from the underpinning research at UoE. (Feb, 2020)

[5.2] Combined external investment approx. USD29,000,000 to pureLiFi (2015 -2019)

- 5.2a USD1,900,000 (2015) https://www.prnewswire.com/news-releases/purelifi-raises-15m-valuing-lifi-leader-at-over-14m-289011761.html
- 5.2b USD9,000,000 (2016) https://techcrunch.com/2016/07/15/purelifi-scores-7m-series-b-to-commercialize-pulsating-light-based-wi-fi-alternative/
- 5.2c USD18,000,000 (2019) https://tech.eu/brief/scottish-startup-purelifi-raises-18-million-to-bring-its-new-wireless-technology-to-mobile-devices/

[5.3] Company key history chart – pureLiFi website – company timeline and products graphic

https://purelifi.com/company/#history (sourced summer 2020)

[5.4] 'Herald' newspaper article explaining pioneering technology (April, 2020)

https://www.heraldscotland.com/business_hq/18386083.scottish-lifi-technology-pioneer-targets-mass-market-rollout/?ref=twtrec

[5.5] Article in Business Wire - Relating to external investment, company growth and partnerships (July, 2016).
https://www.businesswire.com/news/home/20160715005046/en/pureLiFi-Closes-Series-Commercialize-LiFi-Technology

[5.6] Lucibel White Paper: LiFi: Enlightening Communications by Christophe Jurczak, Lucibel Chief Scientific Officer, Palo Alto, California (Dec, 2017).

https://www.lucibel.io/wp-content/uploads/2020/01/LiFi-White-Paper.pdf

[5.7] Sector case studies (during REF period) of applications and partnerships including defence, health and major disaster response https://purelifi.com/case-studies/

[5.8] Crunchbase sector briefing on pureLiFi, patents and trademarks listed by 'IPQwery' (Dec, 2020). https://www.crunchbase.com/organization/purelifi/technology

[5.9] IEEE – News of the new global standard committee being chaired by pureLiFi (2018).

https://purelifi.com/lifi-is-getting-a-global-standard/

[5.10] Awards/nominations for pureLiFi (2015 onwards) https://purelifi.com/category/awards/

[5.11] World first use of LiFi by pupils at a secondary school (Aug, 2018).

https://www.insider.co.uk/news/purelifi-kyle-academy-paul-wheelhouse-13151142

[5.12] Sept 2015 Ted Talk by Harald Haas demonstrating LiFi, 2.8 Million views (Dec, 2020).

https://www.ted.com/talks/harald_haas_forget_wi_fi_meet_the_new_li_fi_internet