Section A

Institution: University of St Andrews

Unit of Assessment: UoA 11: Computer Science and Informatics

Title of case study: Evolving the Internet with ILNP

Period when the underpinning research was undertaken: 2006 - 2019

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:**
Saleem Bhatti	Professor	01 January 2006 - present

Period when the claimed impact occurred: 01 August 2013 - 31 December 2020

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

Section B

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

The Identifier Locator Network Protocol (ILNP), developed at St Andews, is a radical approach to an architecture for next generation Internet systems and services. Within the global communications technology community, ILNP has changed the thinking and conversation about Internet architecture and future generation networks. ILNP has been **recommended for standardisation by the Internet Research Task Force (IRTF) as a communication protocol** for global, Internet-wide usage. It has **influenced future technology development** for two of the largest, global communication companies, Cisco and Ericsson. The **formation of two high-profile Silicon Valley start-ups**, Lispers and Quantonium, was in direct response to the ideas put forward by the ILNP research conducted at St Andrews. An ILNP **derivative produced by Quantonium is used globaly** by Facebook (approximately 2,500,000,000 people (users) worldwide) in its datacentres. A global cloud service provider, Fastly, supporting hundreds of millions of users worldwide, has based its datacentre management on ideas from ILNP. ILNP is supported in commercial DNS products and services, including BIND, a necessary component of Internet applications and is used by many Internet service providers worldwide.

2. Underpinning research (indicative maximum 500 words)

The current Internet Protocol (IP) architecture has been expanded over decades with new functionality through incremental updates, resulting in a complex engineering landscape, one that does not scale well. ILNP, for which Professor Saleem Bhatti has led development and research since 2006, defines a radical and disruptive change to the core Internet Protocol architecture: a modification of the way that addressing and naming is used, removing the use of the IP addresses, and replacing them with two new datatypes, an Identifier and a Locator [R1, R2]. However, judicious engineering with open source platforms means that only end-systems – those under the control of individual users and system administrators – need to be updated with new software, leaving the existing, core network infrastructure untouched. This allows easy, incremental deployment at scale, which has always been a challenge for new network-level upgrades to the Internet. Software updates for ILNP with new and improved functionality can be achieved through the regular "over-the-air" updates that are common to all major operating systems today, for desktop, enterprise, and mobile devices.

ILNP can provide: (i) operation for resilient communication with enhanced security and privacy [R1]; (ii) improved models for management of datacentre compute resources [R3]; (iii) the ability to support existing applications – applications that are unaware of ILNP – without needing re-design, re-engineering, or re-compilation, demonstrated through challenging mobility scenarios [R4]; and (iv) the first solution to a long-standing challenge of seamless connectivity for ubiquitous computing [R5], for supporting future Internet of Things (IoT) systems.

Additionally, ILNP provides a vastly improved and harmonised model for packet-level security at the Internet protocol level [R3, R6]. ILNP also has direct provision for location privacy and identity privacy for end-users, which is especially important for mobile applications and ubiquitous computing [R2, R5].

The full body of research output for ILNP, full technical specifications (which were subject to global peer-review), and an open-source code-base with ILNP enhancements to the Linux operating system kernel, are all freely available at https://ilnp.cs.st-andrews.ac.uk/.

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

[R1], [R2], and [R4] were published in peer-reviewed, international journals. [R3], [R5], and [R6] were presented at, and published in the proceedings of, peer-reviewed, mature, international conferences. R1 & R2 were submitted to REF2014, and R4 & R5 to REF2021.

[R1] R. Atkinson, S. N. Bhatti, S. Hailes. Evolving the Internet Architecture Through Naming. *IEEE JSAC – IEEE Journal of Selected Areas in Communication*, vol. 28, no. 8, pages 1319-1325. Oct 2010. DOI: 10.1109/JSAC.2010.101009

[R2] R. Atkinson, S. N. Bhatti, S. Hailes. ILNP: mobility, multi-homing, localised addressing and security through naming. *Telecommunication Systems*, vol. 42, no. 3-4, pages 273-291. Dec 2009. DOI: 10.1007/s11235-009-9186-5

[R3] S. N. Bhatti, R. Atkinson, Secure & Agile Wide-Area Virtual Machine Mobility, *31st IEEE Military Communications Conference (MILCOM2012)*, Orlando, FL, USA 29 Oct - 01 Nov 2012. DOI: 10.1109/MILCOM.2012.6415716

[R4] D. Phoomikiattisak, S. N. Bhatti. End-To-End Mobility for the Internet Using ILNP*, Wireless Communications and Mobile Computing (WCMC)*, vol. 2019, no. Article ID 7464179, pages 29. Apr 2019. DOI: 10.1155/2019/7464179

[R5] R. Yanagida, S. N. Bhatti. Seamless Internet connectivity for ubiquitous communication. *PURBA2019, Pervasive Urban Applications Workshop (UBICOMP 2019)*. London, UK. Sep 2019. DOI: 10.1145/3341162.3349315

[R6] S. N. Bhatti, D. Phoomikiatissak, R. J. Atkinson. Fast, Secure Failover for IP. *33rd IEEE Military Communications Conference (MILCOM 2014)*, Baltimore, MD, USA. Oct 2014. DOI: 10.1109/MILCOM.2014.50

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

ILNP, as a result of the research described in section 2, has re-shaped thinking and technology development for networked systems globally: influencing two start-ups, three global companies, and standards development.

The full body of research output, and full technical specifications, including an open-source code-base using extensions to the Linux operating system kernel, are freely and publicly available at https://ilnp.cs.st-andrews.ac.uk/.

ILNP recommended for standardisation as an Internet communication protocol

ILNP design and develoment has been led by Prof. Bhatti, working with colleagues (a former PhD student and supervisor at UCL, but mainly his own PhD students at St Andrews). The ILNP web site (https://ilnp.cs.st-andrews.ac.uk/) contains links to approximtaley 200 pages of freely-available technical description, in 9 documents, which specify ILNP as an Experimental Internet Protocol. The acceptance and publication of those documents involved a highly rigorous, global, open review process, over 3 years, with scrutiny and feedback from multiple industrial and academic experts.

ILNP, after being assessed against 13 other proposals including LISP (see below), was recommended above the others for international standardisation; from Section 17 in RFC6115 [S1], the final recommendations of a key working group from the global Internet Research Force (IRTF):

"*We [the working group co-chairs] recommended ILNP because we find it to be a clean solution for the architecture. It separates location from identity in a clear, straightforward way that is consistent with the remainder of the Internet architecture and makes both first-class citizens. Unlike the many map-and-encap proposals, there are no complications due to tunneling, indirection, or semantics that shift over the lifetime of a packet's delivery.*" [S1, p. 65]

RFC6115 also references the ILNP web site at St Andrews, and cites numerous ILNP research papers [S1, pp. 67-70].

ILNP is now an "Experimental" status protocol, on the path to standardisation, which is a long process taking, many years, e.g. IPv6 (the most recent version of the Internet Protocol) took approximately 19 years to move from experimental specfications to a full standard.

Further progress on standardisation of ILNP, based on demonstrations at the Hackathon events and meetings of the Internet Engineering Task Force (IETF) was expected, at events in March 2020 and July 2020. However, both events were scaled-down and moved to online attendance only, due to COVID-19 restrictions, and so those activities were not possible.

ILNP has influenced the technology development of two of the largest, global communication companies, Cisco and Ericsson.

Cisco (USA) is one of the main suppliers of routers and switches for Internet connectivity worldwide. Overall, the key concepts in ILNP have influenced investment and the development of LISP-related products in Cisco [S2]. It was one of the first companies to provide Internet routers globally. Based on the key ideas of using *Identifer* and *Locator* values presented in ILNP, Cisco have produced their own version of the architecture called *Locater Identifier Separation Protocol (LISP),* included in their current products. The first full LISP specifications [S2] (Jan 2013) were based on ideas in ILNP, but were limited in scope. By Dec 2020, the LISP specification was still being extended to offer functionality in the same key areas as ILNP, including mobility and datacentre resource management, after the relevant ILNP research in this area was published [R1, R2, R3]. In keeping with Cisco's business model of selling core-network equipment, LISP implements their own flavour of the Identifier-Locator model in routers, in contrast to ILNP's focus on user (end-system) devices. LISP uses a specific implementation and deployment mechanism which adds complexity to the network engineering landscape, and was specfically considered a disadvantage (see "**Standardisation recommendation for ILNP**" above).

Ericsson (USA), one of the world's two main suppliers of equipment for mobile networks (3G, 4G, and emerging 5G systems), and a provider of large-scale IT services, has filed four patents for its products based on the use of ILNP [S3, S4, S5] (Apr/Jul/Aug 2014), [S6] (Nov 2018). Ericsson's interest in ILNP is across a range of capability, but especially in seamless mobility, as well as in large-scale systems, e.g. datacentres, and systems security. All of Ericsson's patents appear after publication of much of the core research describing the relevant functionality in ILNP, as well as after the core ILNP specification documents were published in 2012.

Influencing technology direction of two high-profile Silicon Valley start-ups

Lispers (https://www.lispers.net/) was formed in 2013, by engineers who had been working on LISP at Cisco, LISP being based on concepts from ILNP (please see above). Lispers developed an open-source version of LISP, for use in communication networks. The Lispers web-site claims over 20 customers and partners, including global companies such as Deutsche Telekom, Huawei, and HP.

Quantonium (https://www.quantonium.net/) was formed in 2015, and has co-defined and co-implemented, with Facebook, a direct derivative of ILNP called *Identifier Locator Addressing (ILA)* [S7, pp. 3, 4, 11, 35]. This is for use in managing computer resources in large-scale datacentres, an idea based on ILNP work published in 2012. ILA has been used by Facebook in their datacentres since approximately 2016 (see below). A version of ILA is currently implemented as a module for the Linux kernel, and is freely available. [text removed for publication]

ILNP derivative in global use

Facebook (https://www.facebook.com/) has been using the ILA derivative co-developed with Quantonium (see above) in their datacentres since about 2016. Facebook worked with Quantoium on the original specification. The most recent version of the public specification of ILA was made available in 2018 [S7, p. 1]. That version (as well as earlier versions) cites directly the ILNP specification documents from 2012, from which ILA is derived, with Saleem Bhatti listed specifically in acknowledgements [S7, p. 35]. As with many companies, Facebook and Quantonium have exploited the public review and feedback mechanism of Internet Drafts, but then it is not clear if the final specification of their system is public. However, two public videos – "Internet scale virtual networking with ILA" [S8] in 2016, and "Internet scale virtual networking using IPv6 ILA" [S9] in 2017 – record a network engineer and co-developer of ILA [S7], an employee of Facebook, explaining how ILA is derived directly from ILNP, and how it is used by Facebook. As ILA is used in Facebook datacentres, it is being used to support services for over 2,500,000,000 people (users) worldwide (user numbers from Facebook's own investors' report at https://investor.fb.com/investor-news/press-release-details/2020/Facebook-Reports-First-Quarter-2020-Results/default.aspx).

FD.io (https://fd.io/), is also using the ILA derivative in their products. The FD.io product is an opensource, high-speed router / switch codebase, and aims to improve secuirty, speed, and scalability of networking and storage in datacentres – "The World's Secure Networking Data Plane". FD.io are sponsored by The Linux Foundation, and so their work is publicly available (https://docs.fd.io/vpp/16.09/plugins_ila-plugin_ila.html). FD.io works with popular commercial systems platforms, such as OpenStack (https://www.openstack.org) and Docker (https://www.docker.com), both used globally by large and small enterprises.

ILNP ideas influencing global cloud services

Fastly (https://www.fastly.com) is a global cloud service provider, with customers such as BuzzFeed, GitHub, deliveroo, Shazam, Boots, The Guardian, Ticketmaster, and Vimeo (https://www.fastly.com/customers/), who, in turn have hundreds of millions of users worldwide. The core ideas in ILNP (such as in [R3]) have, since 2017, directly influenced the design and development of the datacentre intrafstructure and worldwide content distribution network (CDN) built by Fastly to support its customers, as explained in a publicly available video of a talk [S9].

Global DNS support

The Domain Name System (DNS) is an essential component of the global Internet infrastructure. DNS acts as a global directory service for the Internet, mapping user-friendly names to numerical values for use by devices and systems software. Internet applications cannot work without DNS support. There has been direct support and deployment for ILNP in commercial DNS products and services since 2014, with estimated global authoritative server deployment numbers from a Czech national service provider in their 2019 report https://stats.nic.cz/reports/2019/index.html#authoritative_dns_servers:

- BIND DNS https://www.isc.org/downloads/bind/ (more than 6,000)
- Knot DNS https://www.knot-dns.cz (more than 300)
- Unbound / NSD https://www.unbound.net (more than 80)

BIND DNS is *de facto* the world's reference implementation of DNS, used by many Internet service providers worldwide. KnotDNS and Unbound are also widely used by Internet Service Providers (ISPs).

Changing global standards and practitioner community

ILNP has influenced global industry thinking and vocabulary for next generation networks. The International Telecommunications Union (ITU), the creator of global standards for the world's telecommunication operators and equipment providers, published Recommendation Y.2022 (2011), "GLOBAL INFORMATION INFRASTRUCTURE, INTERNET PROTOCOL ASPECTS AND NEXT-GENERATION NETWORKS" [S10] This document from Jan 2014 use terminology, definitions, and architectural concepts that had been published in ILNP research papers from 2006 onwards [e.g. R1, R2]. However, whilst using many of the same terminology that ILNP defines, the Recommendation document makes no reference to any documents from the research community.

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

These are all publicly available sources – URLs checked on 04 Dec 2020.

[S1] T. Li (Editor), Recommendation for a Routing Architecture, Feb 2011. https://tools.ietf.org/html/rfc6115

[S2] D. Farinacci, V. Fuller, D. Meyer, D. Lewis. The Locator/ID Separation Protocol (LISP). RFC 6830 (Experimental), Jan 2013. https://tools.ietf.org/html/rfc6830

[S3] Method and system of frame based identifier locator network protocol (ilnp) load balancing and routing, Apr 2014, https://patents.google.com/patent/US20140115135A1/en

[S4] Methods and systems for seamless network communications between devices running internet protocol version 6 and internet protocol version 4, Jul 2014, https://patents.google.com/patent/US20140189160

[S5] Method and apparatus for enabling data path selection in a virtual home gateway, Aug 2014, https://patents.google.com/patent/US20140226642

[S6] Local identifier locator network protocol (ilnp) breakout, November 2018, https://patents.google.com/patent/WO2018207006A1/en

[S7] T. Herbert (Quantonium) and P. Lapukhov (Facebook). Identifier-Locator Addressing for IPv6. Internet-Draft draft-herbert- intarea-ila-01. IETF Secretariat, Mar. 2018. https://tools.ietf.org/html/draft-herbert-intarea-ila

[S8] P. Lapukhov (Facebook). Internet scale virtual networking with ILA. NANOG 68 (North American Network Operators Group). Oct. 2016. https://youtu.be/wZnAHDOshZo (relevant discussion starting at 3m16s) and Internet scale virtual networking using IPv6 ILA. Network@Scale2017. May 2017. https://youtu.be/AZ1gRPUyklw (relevant discussion starting at 4m10s)

[S9] João Taveira Araújo (Fastly). Addressing IPv6 : A CDN perspective. RIPE71, May 2017. https://ripe74.ripe.net/archives/video/62/ (relevant discussion starting at 19m 30s, and page 65 on the presentation PDF)

[S10] ITU-T Recommendation Y.2032 SERIES Y: GLOBAL INFORMATION INFRASTRUCTURE, INTERNET PROTOCOL ASPECTS AND NEXT-GENERATION NETWORKS - Future networks - Configurations of node identifiers and their mapping with locators in future networks. Jan 2014 https://www.itu.int/rec/T-REC-Y.3032-201401-I/en