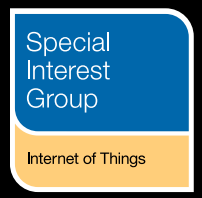

IOT
Internet of Things
Special Interest Group

A roadmap for interdisciplinary research on the Internet of Things

In mid-2011, the Technology Strategy Board started an integrated programme of work focused on the Internet of Things (IoT), which included strategic investment and the establishment of a Special Interest Group aimed at building and engaging a UK community of innovators and researchers in the IoT. As the portfolio of activities with businesses, academics and other stakeholders progressed, it became apparent to us that the community had a keen interest in taking a more concerted and deeper look at the fundamental research issues in the IoT and that a more interdisciplinary approach was needed.

Responding to this level of interest, the Technology Strategy Board joined forces with the Arts and Humanities Research Council, the Economic and Social Research Council, the Engineering and Physical Sciences Research Council and the Research Councils UK Digital Economy Programme and agreed to collaborate on an interdisciplinary R&D roadmapping activity, arguably the first of its kind in the UK.

The activity, led by Professors Rahim Tafazolli, Hamid Aghvami, Rachel Cooper, William Dutton and Dr Colin Upstill brought together insight from a wide group of leaders and culminated in a two-day 'meeting of minds' in Loughborough on 11 and 12 July 2012.

This report summarises the outcomes of the activity and makes important wide-ranging recommendations.

Dr Maurizio Pilu
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the Arts and Humanities Research Council, the Economic and
Social Research Council and the Engineering and Physical
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of Things Special Interest Group.

Contents

Introduction

This report summarises a unique collaborative effort between the Technology Strategy Board (TSB), the Arts and Humanities Research Council (AHRC), the Economic and Social Research Council (ESRC), the Engineering and Physical Sciences Research Council (EPSRC) and the UK Internet of Things Special Interest Group focused on developing an interdisciplinary understanding of the priorities for research and innovation in the IoT.

- **This section outlines the development of the IoT, emphasising the range of research challenges and issues that need to be addressed.**
- **'The methodology' describes the distinctive interdisciplinary approach to the roadmapping exercise.**
- **'Key recommendations' contains key high-level, far-reaching recommendations for the Research Councils and the Technology Strategy Board.**
- **'Priority research areas' summarises the key priority areas for research, grouped into six cross-cutting themes, highlighting important research challenges that need to be addressed.**

The Internet of Things (IoT) is one of the terms widely used for the set of technologies, systems and methodologies that underpins the emerging new wave of internet-enabled applications based on physical objects and the environment seamlessly integrating into the information network.

Some research estimates that the number of connected objects will reach 50 billion as early as 2020. The potential added value of services using the IoT is likely to reach hundreds of billions of pounds a year, with new business models, applications and services spanning all sectors of the economy (such as smart cities, intelligent transport, health monitoring and environmental control, to name but a few).

Today...

... the IoT landscape is already very complex and is typical of an emerging technology area. It is characterised by a large number of proprietary, sector-specific approaches, lack of interoperability and unclear business propositions in all but a few application areas.

In the next five to ten years...

… there will be wider-scale commercial deployments at a domain-specific level, with applications spanning several sectors. New business propositions for investing in IoT applications will begin to emerge, while greater user involvement together with surer handling of trust and privacy issues will increase end-user pull. As interoperable, standards-based and open solutions begin to emerge, costs and barriers to both deployment and the development of scalable services will be reduced, stimulating innovation by the developers' community.

Over the longer term …

… there will be a data and information-rich IoT ecosystem not unlike the one that exists today in the wider internet. A full understanding of the system-level complexity, cost reduction of key components driven by economy of scale, interoperability, standards and clear business propositions will drive wide-scale deployment and adoption of IoT applications and services. Investment in sensors, data and communications infrastructure will support this expansion. International governance frameworks will be in place and there will be a high level of choice and control in how people interact with and use a range of robust and reliable IoT services.

Complex research challenges need to be addressed to support this development. The immediate challenges are often perceived as technological – developing and supporting a global network of intelligent, interconnecting devices producing data at a scale not previously reached.

> "The scale of the IoT could dwarf that of the Internet of today. The potential scale of its societal implications is equally enormous."

The Internet of Things

But central to the development and success of the IoT is the role of people. In addition to bringing design and creative perspectives, people are themselves both sources of data and users of IoT-enabled applications and services, raising important social, ethical and legal issues (such as privacy and consent).

For the UK economy to benefit fully from the exciting opportunities offered by the IoT, a firm understanding of the business and regulatory issues needs to be developed. In an area where existing business and regulatory models may be hard to apply, there needs to be a willingness to learn from other disciplines and to identify where the value in the IoT lies and to make the case for investment. The complexity and scale of these challenges and their interlinked nature formed the rationale for this interdisciplinary effort, involving a wide community of researchers and practitioners, to create a roadmap for research.

"Sometimes the sheer difference of scale at which the IoT operates requires qualitatively different approaches from past internet innovations."

"The IoT holds out the promise of great opportunities – for the individual and for the economy as a whole."

The methodology

The methodology used for the roadmapping centred on a two-day interdisciplinary workshop bringing together over 100 invited experts from academia and industry. This was followed by an in-depth investigation of the findings, resulting in four white papers. These white papers contributed to the recommendations and research themes set out in this report.

The objective of the collaboration between the Research Councils and the Technology Strategy Board was to develop an understanding of the research issues related to realising the full potential of the IoT.

Central to the collaboration was a two-day roadmapping workshop held in July 2012 in Loughborough. Over 100 invited experts from academia and industry came together to build an understanding of future challenges and research opportunities around the IoT. The experts comprised researchers, industrialists and practitioners from the diverse fields of arts and humanities, business, social sciences, pure science, and technology.

The approach was based on exploring issues across disciplines as well as developing a sound understanding of the challenges within each discipline.

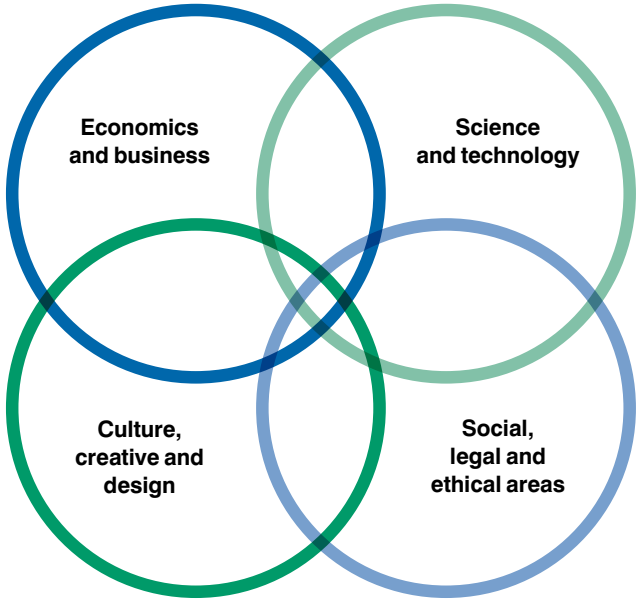
This was achieved through a format designed to stimulate new thinking with a series of short thought-provoking sector-based presentations on 'What needs to happen for the IoT to become a serious and valuable reality?'

"The workshop was a model of how people could interact on cutting-edge research topics."

Footage of the workshops

Photos: ImaginationLancaster

IoT issues were examined from four different perspectives, seeking to understand common as well as distinct challenges.



Breakout groups then considered and prioritised key issues and research questions from the following perspectives:

– science and technology
– culture, creative and design
– economics and business
– social, legal and ethical.

The groups explored specific challenges from their range of expertise, sectors and disciplines. Various challenges emerged from this process that the groups could then discuss with other groups, benefiting from the experience and expertise of those coming from other disciplines. These formed the basis for the interdisciplinary work.

Thinking and dialogue across traditional boundaries were maximised through the use of a modified form of 'field research', where participants were encouraged to extend their own understanding by mixing and collaborating with other groups (not necessarily related to their core areas of interest and expertise). This enabled questions and challenges identified within each discipline to be taken to the other three groups.

This process in itself had its own challenges, for example the use of different languages and terms, and different methodologies employed within different disciplines and areas of research. However, all four groups engaged with the challenges identified within the other groups, resulting in a valuable cross-disciplinary dialogue that generated a rich body of material.

Before a final plenary session, all participants returned to their 'home' group to share their findings and explore 'solutions', built on a much broader body of knowledge.

Lead academics in each of the four areas produced white papers, based on the workshop discussions, highlighting strategically important research areas that would help to shape IoT priorities over the coming years:

– A Roadmap for Interdisciplinary Research on the Internet of Things: Technology
– A Roadmap for Interdisciplinary Research on the Internet of Things: Culture, Creative and Design
– A Roadmap for Interdisciplinary Research on the Internet of Things: Economics and Business
– A Roadmap for Interdisciplinary Research on the Internet of Things: Social Sciences.

An expert group worked to study the white papers to develop an overarching set of recommendations and imperatives as well as priority research themes, which are presented in this report.

The research challenges summarised in this report are elaborated on further in the four white papers, which are available at:
tiny.cc/iotresearchculture
tiny.cc/iotresearcheconomics
tiny.cc/iotresearchsocial
tiny.cc/iotresearchtechnology

"I appreciated the overlap of disciplines to stimulate debate, share knowledge, question our terminology and discover how similar our areas of concern are."

Key recommendations

There are a number of imperatives for funders and the research community to advance the UK's position in the IoT:

- **Develop a coordinated national research and innovation programme**
- **Fund and sustain open experimental research spaces**
- **Fund the development and deployment of open experimental IoT platforms**
- **Fund interdisciplinary research**

Develop a coordinated national research and innovation programme

The Technology Strategy Board, the Research Councils and other relevant agencies should convene to take on board the outcomes and recommendations outlined in this report in order to develop a concerted action plan for investment in research and innovation in the IoT. It is essential that all of the priority research areas identified in this interdisciplinary roadmap form the basis for an ongoing research programme. An integrated, interdisciplinary approach must be taken. Furthermore, the nature of the evolution of the IoT will necessitate a dynamic approach to the detailed research agenda within each priority area, reflecting the rapid evolution of the IoT landscape, as set out in the introduction.

"The Internet of Things is evolving rapidly – we need a highly dynamic approach to research."

Fund and sustain open experimental research spaces

In order to investigate new usage paradigms resulting from the IoT, research spaces should be created in which it is possible to explore and 'play'. Environments need to be created for agile co-development and co-evaluation, supported by toolkits and expertise in technical knowhow, socio-cultural understanding, marketing and strategy. This activity should be supported by low-level, rapidly available funding that will foster new ideas and enable scaling of pilots and demonstrators.

These spaces should involve users, together with researchers, designers, artists, ethnographers and hardware and software developers working in an interdisciplinary research environment that encourages exploration of the interface between disciplines. Negotiations over the ownership of data, intellectual property, personalisation and localisation, and the gathering of data from complex objects that have multiple properties would need to be supported. Experimentation should be undertaken within a variety of community settings (for example, schools or with patient support groups) using different engagement models: brokering discussions and relationships, facilitating conversations, and holding workshops or creative labs to promote growth and innovation.

"There is a pressing need to create an interdisciplinary research community focused on the issues which have been identified in this report."

"We cannot predict disruption – we need to facilitate it."

Fund the development and deployment of open experimental IoT platforms

The UK can best differentiate itself from the rest of the world by pursuing integrated solutions rather than continued development of individual technologies. In order to explore such solutions, a small number of open experimental platforms specifically designed for IoT research need to be developed. It is imperative that these platforms include not only basic functionalities that are common to most applications, but also new and evolving functionalities that can be integrated and tested by the research community.

IoT platforms should not just be about capability, but should be deployed in demonstrators to prove value, lower cost or reduce risk. Such demonstrators must be developed in the context of specific use cases (such as health, transport, the built environment). They need to address the problems of scale and integration inherent in the IoT and enable the study of the interactions between different design approaches, algorithms, protocols and technologies proposed for disparate aspects of the IoT.

In conjunction with the experimental research spaces, these platforms and demonstrators would be invaluable in exploring how concepts and experiences developed in a small-scale environment could be scaled up for wider deployment. These platforms should also be accessible to non-technologists to support the development of new IoT services and applications.

Fund interdisciplinary research

The IoT inherently involves many areas of technology, economic, legal, ethical, social, creative and design disciplines. Funders and the research community must embrace a programme of research that crosses traditional boundaries within and across disciplines. Significant efforts should be dedicated to ensuring that practitioners from all these disciplines are included in the research agenda.

The disruptive nature of the IoT also means that traditional linear methods of scientific and technology research should be complemented with experimental and field research methodologies that emphasise co-production with users.

Priority research areas

Six themes cutting across the multiple disciplines addressed in the workshop were identified. Each theme contains a number of priority areas for research. While the important issues within each priority area will change over time, these will all remain significant areas for research over the next ten to fifteen years.

Priority areas within six cross-cutting themes

Governance

The complex ecology of the IoT includes aspects of governance that are poorly understood and need to be well researched over the coming years to inform policy makers and regulators. The expert group has identified six important priority areas pertaining to national and international coordination, regulation, policing and accountability.

G1 Ethical implications
G2 Accountability and liability
G3 Regulatory and standards issues
G4 Digital life and death
G5 Ownership and intellectual property rights
G6 Aligning local, national, regional and global practices and policies

Ethical implications (G1)

It is an open research question whether privacy, security and specific values or principles (such as moving control closer to the user) can be designed into IoT systems and services from the beginning rather than downstream. Indeed, what will be the norms around the use of the IoT (which may often generate very sensitive personal information)? Lessons from social media could potentially inform the development of appropriate guidelines in the IoT – and whether they can be voluntary or need to be imposed.

Accountability and liability (G2)

There will inevitably be failures, data breaches and costs associated with IoT services. There is a need to research and understand whether the IoT will increase or undermine and obscure accountability.

Devices that know and learn a great deal about their users potentially need to be either governed by rules, or allowed to reveal and disclose everything about their user. An 'anything goes' strategy might be appropriate during early experimentation but less appropriate as devices become more ubiquitous, with increasingly sophisticated functionalities and applications.

Control of actuators (which perform actions such as making adjustments to an operational system) may be just as sensitive as the question of control of sensors, with tensions between the goals of security and quality control and the goals of human autonomy and user-responsive technology. One can envisage, for instance, that smart city actuators could just as easily become a mechanism for citizen empowerment, or for infrastructure attacks, or for citizen disempowerment.

Regulatory and standards issues (G3)

Given the pace of new developments, issues of how to regulate the vast scale and scope of the IoT are constantly emerging. For instance, regulatory processes designed to cope with hundreds or thousands of transactions or service providers might not be able to cope with billions of connected things.

Challenges in regulation, legislation, compliance and standards of the IoT will span administrative and jurisdictional borders. Bottlenecks and barriers to interoperability across the IoT ecosystem (whether technical or otherwise) need to be investigated, and standards for interoperability need to be in place. Critical standards issues that need to be investigated include:

- What should be standardised?
- How should standards be developed and regulated, if at all?
- How open should standards be?
- Is there a need for global and/or regional harmonisation of standards?
- What are the preferred standards?

Digital life and death (G4)

Research is needed on the life-span of data. We create digital artefacts, archives and data, but who has the moral, ethical and legal authority to signify and ensure when data ceases to exist – the death of data?

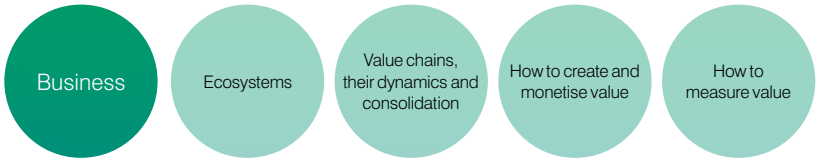
Ownership and intellectual property rights (G5)

There is a need for research into issues related to ownership and usage rights of IoT data. For instance, does IoT data belong to the device or system collecting the data, or to the thing to which the data pertains, or indeed to a person or organisation?

Aligning local, national, regional and global practices and policies (G6)

Policy developments in this area are emerging in the EU and other regions, but they are poorly understood. What are the policy dimensions of the IoT, and what should the policy agenda be? How should the UK's policy agenda be aligned with developments in policy and governance at local and global levels?

"With the longer-term development of international governance frameworks, there is a need for study of appropriate models for an IoT that can cope with the scale and pace of change in this area."



Business

The internet has disrupted traditional value chains and transformed business models – but it has also helped to build new markets, out of which have emerged opportunities for value and growth. The stakeholders involved in today's internet have gradually understood and found the correct incentives for their involvement. Early signs with the IoT suggest that these incentives are frequently unclear and not aligned. How will these incentives develop and eventually manifest themselves? What financial policies and regulations may be needed to underpin IoT services and transactions? And, ultimately, how can a financially viable and sustainable IoT be built?

Four priority research areas underpin the recommendations around the business theme.

B1 Ecosystems
B2 Value chains, their dynamics and consolidation
B3 How to create and monetise value
B4 How to measure value

Ecosystems (B1)

When data is made accessible across a potentially vast and open IoT ecosystem, there is a myriad of opportunities to create sustainable economic growth. Challenges arise around ensuring that data and information that lead to the creation of business opportunities and value can flow through the ecosystem as it evolves and that new players are stimulated to participate, contribute and innovate.

Value chains, their dynamics and consolidation (B2)

Theories, models and simulations of evolving value chains within this ecosystem need to be developed, tested and validated. A long-term goal is to understand trends about how value chains form and evolve, not only within the IoT ecosystem but also external to it. For instance, what new organisational partnerships will be required to support service innovations in the IoT and the business models behind them (for example, between insurance companies, in-car-navigation software providers and car telematics systems providers)?

How to create and monetise value (B3)

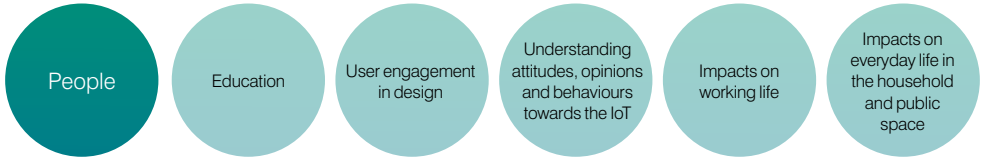
There is insufficient knowledge of the formal mechanisms that need to be deployed in the market to effectively unlock the potential of new business activities across the value chains of the IoT. A strictly economic approach to value may not be applicable to the IoT, but the monetisation of value is a shared concern.

How to measure value (B4)

How do we enable, measure and demonstrate the value of data and information as it flows through the value chain? This needs to be achieved in real time and in the context of potentially complex multi-level service agreements.

There is also a need for new data and information transaction models, together with tools for monitoring changing value.

> "Data providers from one sector will be asked to store and share their data with service providers from unrelated sectors. Where is the incentive for this?"



People

In addition to bringing design and creative perspectives, people are themselves both sources of data and users of IoT-enabled applications and services. In the race to solve technical challenges, there is also an imperative to research and understand how users will interact with objects and data and the developing role of people as participants in and users of the emerging IoT ecosystem.

Five underlying priority areas were identified.

P1 Education
P2 User engagement in design
P3 Understanding attitudes, opinions and behaviours towards the IoT
P4 Impacts on working life
P5 Impacts on everyday life in the household and public space

"With the introduction of self-monitoring devices in patient healthcare, institutions such as the NHS will need to respond organisationally in order to deliver different types of services. It requires an integrated approach between different stakeholders rather than a bolt-on approach."

Education (P1)

There is a vital need to foster collaboration between individuals, organisations and businesses that will use the IoT, to help them understand the value and specific aspects of IoT applications and services. Many inherent assumptions associated with the IoT (particularly in relation to privacy and data protection issues) are potentially distinctive from those of the internet and will require a reshaping of expectations among users. Involving businesses and people in pilots and demonstrator projects will increase understanding and ultimately drive adoption.

At a broader level, as new systems for collecting and using data and IoT services are introduced, it will be important to consider how these systems align with prevailing cultural or organisational practices. Is there a need to educate towards new practices?

User engagement in design (P2)

There is a need to understand how researchers, developers and end users can become involved in co-designing IoT services, especially with respect to information interfaces and seamless services. 'Living labs' could be instrumental in achieving this goal. Generating narratives and scenarios for communication, discourse and user engagement would enrich this activity.

People will be both producers of information in, and users of, the IoT. This interplay, together with the usage contexts, should be better understood, including in relation to social and cultural norms, for IoT products and services to be widely adopted.

Understanding attitudes, opinions and behaviour towards the IoT (P3)

To drive adoption, it will be necessary and critical to research and understand public attitudes to specific classes of IoT applications and services, and to identify where concerns may not be aligned with benefits or behaviours. For example:

- Should users be offered choice in their use of and involvement in IoT applications and services?
- Will there be an increase or decrease in choice?
- Who controls the use of data or systems?
- What are the demographics of the early adopters willing to trial new applications and services?

Impacts on working life (P4)

The IoT will have an impact on working life, changing business processes and the way in which we interact as employees and workers. Research is needed on how IoT products and services can enhance productivity and improve work–life balance.

Impacts on everyday life in the household and public space (P5)

IoT applications and services will reconfigure how we do things in households and public space. Meanwhile, threats to privacy and data protection must be considered to prevent the unintentional construction of a surveillance society. Who will control what functions? How will the so-called 'politics of the remote control' extend to control of the household?

Trust

Trust is a vital component for people and businesses to adopt IoT applications and services. Very little is understood about how trust will manifest itself in different contexts of use and application. For instance, 'unconscious exposure' to applications and services has implications in terms of consent and trust that are more central to the IoT than with many internet applications that are more consciously used by people. There is thus a need for substantial research into the technical, social, legal and ethical issues around developing a trusted IoT.

Four priority areas were identified.

T1 Empowering users and establishment of trust mechanisms
T2 Privacy and data protection
T3 Safety and protection of the public
T4 Reliability and dependability

Empowering users and establishment of trust mechanisms (T1)

All the various actors involved with the IoT are likely to err on the side of getting and harvesting more information than they need. This was a classic issue with management information systems in the earliest decades of data processing, and the IoT is now facing the same problem.

In this context, there is a need to understand how users can make informed decisions to judge the trustworthiness of information. In thinking about metrics of trust, research into objective measures and their semantic representations across different ecosystems and governance approaches is needed.

Liability and ownership, particularly when things go wrong in safety-critical systems, is another important aspect of trust. When data is constantly recombined and reused in new (and originally unintended) ways, who owns and who is liable for what?

Privacy and data protection (T2)

Much of the IoT data can, in one way or another, be associated with individuals. Attitudes and approaches to 'giving away' personal information vary widely. There is a need to carry out research both into attitudes to privacy in an IoT context and into technologies, solutions and methodologies to deliver peace of mind for users and businesses.

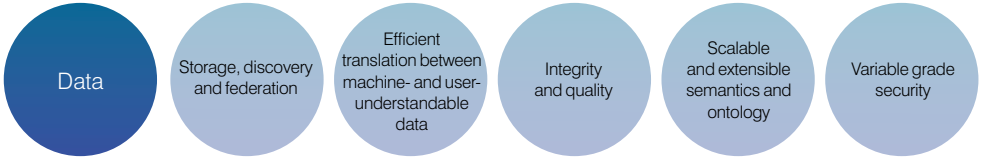
Safety and protection of the public (T3)

The IoT has great potential to enhance safety and protect the public, and its role needs to be better understood. An important aspect needing research relates to the fact that data collection may occur unknown to the individuals, and safety and protection applications may infringe personal rights. Patient monitoring is one of the best-known applications where this tension manifests itself.

Reliability and dependability (T4)

To ensure the viability and relevance of IoT applications and services, people must view IoT data and information as reliable. Current mapping examples show how easily trust can be undermined by inaccurate data on which people depend. There is a need for systems to be robust, dependable and secure, and considerable research is needed in this space.

"The IoT carries with it an inherent assumption that information will need to be shared across things, applications and possibly sectors in order to be most useful, such as in using energy meter readings to alert a family about the vitality of an elderly parent living alone. This data-sharing assumption might lead to the IoT having even more dramatic impacts on privacy and data protection than other information and communication technologies."



Data

Today's IoT applications tend to be highly vertically integrated – with often just one provider engineering the entire stack. The vision for how the IoT is going to develop is one of connection and interaction between billions of objects and devices, supporting multiple vendors and emergent services and applications centred around the flow of IoT data and information. Whilst a large body of knowledge exists, many of the issues to deliver this vision are poorly understood.

Five priority areas relating to data have been identified.

D1 Storage, discovery and federation
D2 Efficient translation between machine- and user-understandable data
D3 Integrity and quality
D4 Scalable and extensible semantics and ontology
D5 Variable grade security

Storage, discovery and federation (D1)

Today, most IoT applications are hard-wired to particular, often proprietary, mechanisms for publishing and searching datasets or datastreams (for example, the Common Open Service Market project). In the future, there will be a diverse array of IoT data sources, which could be highly distributed, heterogeneous and unreliable. New generic and scalable search-and-discovery mechanisms specific to IoT need to be researched and tested in complex, real-life deployments.

Efficient translation between machine- and user-understandable data (D2)

The IoT will be generating huge quantities of data. The value of this data depends on what is captured, where it is stored and how it is accessed. While much technology already exists to deal with large volumes of data, specific IoT research into technologies and methodologies is needed to make this data tangible, visible and understandable, in order to engender trust and drive usage.

Integrity and quality (D3)

A multitude of parties will be involved in the IoT, spread out physically and using different media, gateways and links. In such a variable environment, it is important to anticipate inaccuracy, incompleteness and flaws in the data. There is thus a challenge to define methods and standards for testing and declaring data quality. Overall, how can better methods and solutions for extracting high-confidence knowledge from multiple, distributed, low-quality IoT data sources (such as sensors monitoring water pollution) be developed?

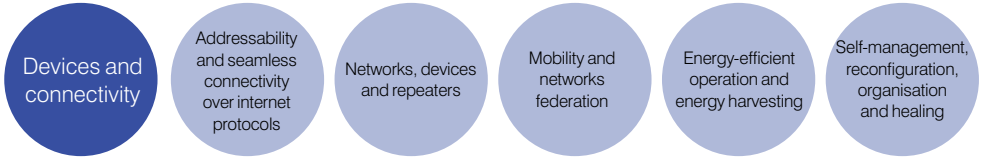
Scalable and extensible semantics and ontology (D4)

Currently, within many closed IoT implementations, the actual meaning of the data is application/domain specific. But research and experimentation is needed for an open IoT ecosystem, where different parts of the system designed by many different parties need a common interpretation of the data being exchanged. Semantic interoperability is needed to resolve differences in real time on an ongoing basis and to ensure that services are extensible and scalable.

Variable grade security (D5)

As well as being usable, data must be secure, and end-to-end security and privacy protection needs to be tuned to specific contexts, user experience, preferences and cost. For instance, the security context for a pacemaker will have several descriptor fields that will be different to those of a hallway thermometer. There needs to be research and development in approaches that deal with these specific situations in an IoT context.

"We see the challenge and opportunity to undertake far more work on the translation, visualisation and access to data in order to make data manifest, reduce its obfuscation and improve trust."



Devices and connectivity

Objects can be equipped with intelligence and connectivity; in the future, we will see the emergence of extensive self-managed networks of IoT devices with flexibility, self-management, scalability, high capacity, low energy consumption and low cost of deployment and maintainability. The technological challenges involved in realising such an infrastructure are substantial.

The research challenges identified comprise five priority areas.

- **C1 Addressability and seamless connectivity over internet protocols**
- **C2 Networks, devices and repeaters**
- **C3 Mobility and networks federation**
- **C4 Energy-efficient operation and energy harvesting**
- **C5 Self-management, reconfiguration, organisation and healing**

Addressability and seamless connectivity over internet protocols (C1)

There is a need to uncouple addressing and identification to facilitate mobility and generality of applications. A more dynamic, lightweight and less fragmented approach to naming objects and mapping them to their locations is required. Various approaches have been proposed but research and testing at scale is needed, together with renewed standardisation and interoperability efforts.

Networks, devices and repeaters (C2)

There is a need to research effective solutions and develop standards for IoT device and gateway management ('care and feeding'). This would make it possible for third-party IoT service providers to install, upgrade and configure devices as well as maintain them. Such solutions will have to cope with devices with widely different capabilities. For instance, most sensors do not have a keyboard or a screen for a user to enter a security key. In such cases, devices should automatically and securely pair themselves with each other without a central controller or intervention by a person. There is a need to research such self-configuration and security protocols.

"The IoT is regarded as a network of networks. Important enablers are RFID for identification of things, sensors for sensing physical changes around things and collecting data and wireless short links and communication networks for connecting things. The infrastructure is an integration of several networks."

Mobility and networks federation (C3)

Research is needed to handle islands of wireless sensor/actuator networks (WS/ANs), which may not be fixed in a specific geographical location. Islands could move and change their locations and become part of or merge, physically or virtually, with other islands to form larger WS/ANs.

Energy-efficient operation and energy harvesting (C4)

The range of feasible IoT applications becomes much wider as the devices that provide them use less energy. Furthermore, low energy has distinct environmental benefits: the energy consumption of vast numbers of devices communicating with cloud-based services could have a substantial environmental cost. There is therefore a need to research into devices, systems and networks for minimum energy consumption, particularly with respect to radio frequency design and signal processing.

Design of devices to harvest energy will also be important for specific applications (e.g. exploiting thermoelectric effects or body motion for body-mounted devices). The ultimate aim would be to make devices self-powered.

Self-management, reconfiguration, organisation and healing (C5)

Research must be carried out in realistic deployment scenarios on IoT applications and systems that are reliable, easy to deploy and use, self-organising, and able to operate in any circumstances, including in disasters or emergencies. They will need to be adaptable and responsive to different modes of operation and communication.

Another aspect inherent with tightly coupled systems that remove human intervention is an increased risk of vulnerability associated with system crashes or cyber-attacks, which could have serious business or safety impacts. Loosely coupled systems, such as the internet, might be more flexible and more capable of adapting to unexpected changes. The research community needs to provide novel and robust solutions and test them at scale.

Acknowledgements

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