Integrating sensor networks into the future internet

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Abstract. We consider whether sensor networks should be included in discussions of the future internet, and the challenges they present. We conclude that the entire future internet would benefit from being regarded as being sensorised and adaptive, and suggest a search for a new "narrow waist" to facilitate innovation while promoting diversity.

1 Introduction

Sensor networks are rapidly achieving a major significance both in computer science and networking, and in experimental physical and biological sciences. Typically composed of small, low-power devices with (by modern standards) extremely limited computation, storage and communication resources, such networks clearly differ from the more familiar networks: even common consumer wireless networks offer massively superior reliability and capabilities.

A large body of work exists in the low-level techniques for such networks, including optimised routing protocols [1, 2] and operating systems [3]. Several important questions still remain, however: How should sensor networks be integrated into, and addressed from, the wider, future internet?, and what special challenges do they present to designers and implementers?

In this paper we present some views on these questions, drawing on experiences in sensor networks, autonomic systems, semantics, middleware and programming languages. Section 2 considers whether it is reasonable (and valuable) to regard sensor networks as part of the internet rather than simple as edge devices. Section 3 considers the factors that make sensor networks unique, and concludes that many of the features encountered might usefully be "pushed up" into the rest of the future internet. Section 4 proposes that we search for a semantic "narrow waist" around which to frame sensorisation and adaptation for the entire network.

2 Should the internet encompass sensor neworks?

Perhaps the internet's greatest innovation was to make its end-points networks in their own right, rather than terminal devices. The intention was to standardise and abstract-away from the details of the handling of long-haul traffic, while allowing edge-networks to optimise their own internal organisation. The "narrow waist" provided by the Internet Protocol (IP) maximises the opportunities for innovation in other parts of the protocol stack, avoiding the need for a lowest common denominator end-to-end – at the well-known cost of weakening end-to-end guarantees.

A sensor network can therefore be regarded simply as an edge network upon which the internet need make no further demands: as long as the boundary router can respond to IP traffic, the sensor network is free to use whatever techniques within itself that it wishes – for example optimised protocols for *ad hoc* routing and so forth. In this view, the future internet need make *no* statements about, or provisions for, sensor networks – or indeed any other special-purpose networks that may be connected.

There are a number of limitations in this view, however. Firstly, we believe that sensor networks are set to become ubiquitous. Many of the major scientific and social challenges of our times require large volumes of data for their solution: environmental sensing, security and healthcare are all "early adopters" of sensor networks. This suggests that the internet will interconnect a large number of sensor networks, and it seems a little short-sighted not to embrace these systems fully within the architecture.

Secondly, the ubiquity of sensor systems is not confined to sensor networks, but includes the sensorisation of the network itself. Modern core networks have become highly monitored, and the rise of autonomic communications [4] has increased its prominence as a way of informing adaptation. This suggests that the future internet will be substantially more adaptive than the current architecture at all levels, and viewing the sensor edge-networks as part of this opens-up the possibility for more thorough, global adaptations.

3 What are the challenges of a sensorised internet?

What, therefore, are the core challenges of integrating sensors across the future internet? This is a question whose scale almost denies answer, but several facets are immediately obvious.

Capturing meaning and purpose

If we believe that the future internet will be more adaptive to its environment and load, we must also accept the need to develop ways of capturing, modelling and reasoning with this context information [5].

One approach is to capture the semantics of *all* elements of the system: the environment, the network, the services running on top of it, and so on. This capture of broad semantic information is a goal of the semantic web initiative [6]. Although typically seen as a service-level concept, there is no reason that techniques such as the Resource Description Framework [7] cannot be used to integrate diverse information within a reasoning-based management framework.

The unavoidable environment

A sensor network – and indeed many consumer wireless networks, mesh networks and other systems that are undoubtedly part of the future internet – are intimately and unavoidable tied to the environment in which they are embedded. It is easy to forget exactly how isolated from the real environment the "main" internet is, but the techniques used do not often translate down to these wider systems.

We cannot design a network node that is robust against (for example) being trampled by cattle – a distressingly common phenomenon in much environmental sensing! We can however build a *network* that is robust (to some extent) against such events. The techniques required can perhaps be packaged and re-used across other scenarios: the point is that only by knowing and understanding the environment of a network can we take the steps necessary to give it the non-functional properties required for it to fulfil its mission.

Management

This leads to the challenges for network management – but also points towards a solution. Broadly-captured semantic information, properly encoded and combined with models of the environment, goals and characteristics of the network and its services, can perhaps be used to construct a reasoning-driven network management framework.

This is likely not to be a traditional policy-based management scheme, however. Most policy-based approaches do not lend themselves to analysis, and therefore to the ability to make definitive statements as to how they will behave. Given the increasing scientific and economic importance of the internet this is unlikely to be acceptable, and a better-founded approach to management – possibly drawing on intuitions from dynamical systems and other ideas – may well be needed. The important point is to combine information from various levels within a common framework, and the tools and techniques of the semantic web offer some hope that this can be accomplished.

Programming and re-purposing

A final challenge concerns programming – or perhaps its partial elimination. Reifying complex ideas as code has the advantage of performance – and this is perhaps the sole advantage. Once reduced to code in this way, further analysis becomes far more difficult, as does evolution and adaptation. A more effective strategy may be to keep as much network "code" as possible in the form of semantic rules and goals, and allow the network to reason over this knowledge. This becomes particularly important when one wants to analyse the behaviour of a particular component, or the impact of a change in constraints, or indeed to re-purpose the network wholly or in part to perform some alternative (or additional) task.

4 Conclusion

Rather than view a sensor network as something at the edge of the future internet, we believe that it makes sense to view the future internet as more-or-less sensorised from end to end, and to include in the architecture explicit and ubiquitous for sensing and sensor-driven adaptation.

Realising such a network suggests that we need to find another "narrow waist" – this time at the semantic level – that will allow disparate systems to innovate individually whilst retaining an overall compatibility. The substantial investment in semantic web technologies – including flexible knowledge description formats, ontologies, description logics and their associated high-performance reasoners – makes this seem like a realisable goal. A programme to apply such semantic technology to network design and adaptation would allow this investment to be capitalised upon.

Identifying the core adaptive structures is a further step towards this goal, and something we are keen to pursue in the future. Rather than construct networks, topologies, protocols and adaptive approaches *ex nihilo*, a shared toolkit of well-characterised components might be used to develop networks whose properties are guaranteed (wholly or in part) ahead of time. The interaction of such components with semantic descriptions and reasoners might give the future internet a sound and expandable footing for future expansion – replicating the success we owe to the original designers of IP.

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