Wireless Pers Commun (2013) 70:1221–1234
DOI 10.1007/s11277-013-1110-3

Out of the Shadow: Long Term Cost Development of Intelligent Sensor Networks

Erik Fledderus · Leon Kester · Karin van Kranenburg-Bruinsma

Abstract The paper addresses intelligent sensor networks (ISNs) as a special version of networked wireless robotics. The success of these networks is partly explained by the technical advances, but as well by cutting down costs of these networks. Using a functional breakdown of intelligent ISNs, the trends of the various functions are discussed. The analysis shows how individual sensor network component prices decline at an almost predictable speed. This is mainly a result of generic developments in technology. These developments sustain because an economy of scale is reached at the level of individual components. This makes the integration of these components the most important barrier to acquire large scale implementation of intelligent ISNs, both with respect to cost and needed R&D breakthroughs. Integration includes the need for standardization and interoperability between different standards. The paper illustrates its generic analysis in two use cases: cooperative driving and smart living.

Keywords Intelligent sensor networks · Costs · Trends · Communication · Computation · Standardisation · Integration

1 Introduction

Much of our today's ICT technology is well-hidden, behind displays and advanced user-interfaces. In some cases this is the result of a long development, involving miniaturization and integration and automation of functionalities. Technology is nicknamed a positive 'plug and play'—no hassle to install and operate. The downside of hidden technology is that we easily tend to accustom to its omni-presence—it should be there, it should work, always. And

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E. Fledderus (✉) · L. Kester · K. van Kranenburg-Bruinsma
TNO, Brassersplein 2, 2612 CT Delft, The Netherlands
e-mail: erik.fledderus@tno.nl

L. Kester
e-mail: leon.kester@tno.nl

K. van Kranenburg-Bruinsma
e-mail: karin.vankranenburg@tno.nl

we forget what is needed to make things work. It requires curious people to wonder and ask 'how stuff works'.

The current paper addresses intelligent sensor networks (ISNs) as a special version of (networked) wireless robotics. The small sensors appear as the often hidden 'deus ex machina' that do the job. As we will show sensors, and sensor networks, become more and more widely used. The success is partly explained by the technical advances, but as well by cutting down costs of these networks. The key assumption of the paper is that understanding the origin of the costs involved can lead to focused measures to decrease these costs, and thereby fuel the wide-spread adoption and use of ISNs.

But besides (reduced) cost as a relative advantage it is equally important to address clear examples of added value of ISNs. Rogers [1] and Moore [2] state that 'observability' of an innovation, e.g. the underlying essence of what makes stuff work, is a crucial element in the adoption of this innovation, and with that the (ultimate) widespread use of it. To illustrate this some concrete, recent and down-to-earth examples of the use of ISNs will be presented, together with a thorough analysis of the incurred costs.

These well-chosen examples that will return in the rest of the paper will be introduced below to illustrate more general concepts. We believe that the examples are model for the first areas where ISNs will be used to their full extend. After the examples, a global cost breakdown is presented, followed by the introduction of a functional model for ISNs. Cost development of the different system elements is described by applying a trend analysis. After that, we return to the cases that were introduced: what cost development do we expect for these particular examples? This will lead to the conclusions of this paper.

1.1 ISNs at Work: Cooperative Driving

Being mobile seems to be one of the unspoken basic human rights. The recent production of cheap cars in India only underpins this notion, and at the same time it identifies 'mobility' with 'driving a car'. Besides personal mobility, the transport of raw materials and (semi-)manufactures is an important factor that puts pressure on scarce resources such as energy (fuel, electricity), clean air (CO_2 emission, particulate matter), space (road space or *shy distance*) and time (travel time, transportation delay). Reducing this pressure is based on economical, safety and environmental arguments, and requires both technological and behavioural advances.

Specifically in busy urban areas, e.g. North Western Europe, the increased traffic load and multiple choices of travelling by car or public transport increases the complexity, and thus rules out straightforward solutions. Governments are struggling with advanced travel payment plans in order to smoothen out this traffic load, and look for ways to inform the traveller about the consequences of its travelling behaviour. A serious aspect that matters to travellers is (a reliable estimate of) the travel time.

An important part of the solutions in this complex domain may come from cooperative driving (See Fig. 1). In the broadest sense this represents the close cooperation between infrastructure, cars and drivers resulting in efficient, smooth, safe and clean driving. The challenge in this case is to make the infrastructure, the cars and the drivers more cooperative in this common goal. This can be achieved by applying ISNs.

- *Infrastructure*
  Sensors above, alongside or embedded in the road infrastructure can measure traffic condition and the condition of the road. The traffic condition, related to the traffic load, can be used to adaptively control traffic flow mechanisms, such as traffic lights, speed

Fig. 1 Cooperative driving

advice or the number of lanes that can be used. In addition, it can be used for a personalized traffic advice.

- *Cars*
  Currently, many cars contain more than 100 types of sensors [3]. Their important tasks include the monitoring of internal processes as well as to measure physical parameters of mechanical automotive components and actuators. Next to that there are sensors dedicated for the vehicle position, speed and acceleration with respect to the road and other cars and sensors that may detect dangerous situations. In particular the last category of information is interesting to exchange with other cars in the case of cooperative driving to enhance safety and to increase throughput. The limits of growth are determined by costs. Measured by the average gross earnings of an industrial worker, the price of a car has remained stable at 1 yearly gross income during the past 50 years [4].
- *Drivers*
  The driver interacts with the intelligent car though intelligent interfaces that on the one hand sense the preferences and needs of the driver and on the other hand present personalized sets of advices that can be used to reach the destination in the most suited way. Otherwise, sensors related to the driver involve measuring of e.g. nodding in case of fatigue.

In order to ensure safety and stability at high throughput, positions, velocities and accelerations of the neighbouring cars need to be provided at high update rates and with high probability of reception. This puts high demands on sensing, communication, information processing and control capabilities to ensure this under all possible conditions. Simply improving these capabilities with more and improved sensors, a larger bandwidth and more computing power will not be enough. The system must be able to reason about using sensors, communication and computation resources cooperatively in the most efficient way.

This system with sensors in the cars communicating with each other and the infrastructure can be viewed as an intelligent mobile sensor network.

1.2 ISNs at Work: Smart Living

Besides being mobile and ‘on the way’, we also spend considerable time at or around the home. Even more so, in several domains the focus on ‘local’ activities is prominent. Generating energy locally and contributing it to the grid, care at home while alleviating the pressure on expensive hospital care, safety and security of households, … these phenomena are partly explained as cost-driven, but can also be seen as a viable alternative to solve nowadays transport problems, or a way to increase social cohesion in neighbourhoods. An important enabler of this ‘smart living’ (‘living’ as a verb!) are ISNs.

The role of ISNs in the smart living case incorporates:

- measuring vital functions of residents, interpreting this, and taking adequate actions (communication to first line support, feedback as e.g. a health coach),
- measuring use and need of energy, balancing this with local and non-local supplies,
- measuring presence and behaviour of living beings, interpreting this with safety and security 'in mind', and taking adequate actions (communication to neighbourhood watch, professional support, …),
- and many others.

From an end-user perspective, it is not desirable to have multiple sensor-systems from the same type for different purposes, e.g. multiple camera systems for health and safety. Thus, re-use of capabilities for different applications will stimulate the uptake of ISNs at home.

1.3 Cost Breakdown

As stated above, cost, or more precise, the price of a product or service is an important adoption parameter. Cost is in most cases an important parameter to determine the price of a product or service. Lower cost will often cause a lower price, which will lead in turn to a higher market demand and result into a larger economy of scale. Economy of scale, in turn, will lead to lower costs (see Fig. 2). To stimulate adoption of ISNs, it is important to bring the flywheel into motion.

Technical development is important to lower cost of ISNs. For example, power harvesting may prevent expensive installation of wired electricity provisioning. In the next section a functional model of ISNs will be presented. The expected long term cost development of the different elements in this model will be analysed.

A more indirect way of influencing costs of ISNs is to influence *market demand*. By developing more application areas of ISNs, the potential market will be enlarged. For example cooperative driving includes a range of completely new applications that are enabled by ISNs. Technical development is necessary to make these applications possible. In this way, technical development is also an indirect way of influencing the costs of ISN, as illustrated by Fig. 2.

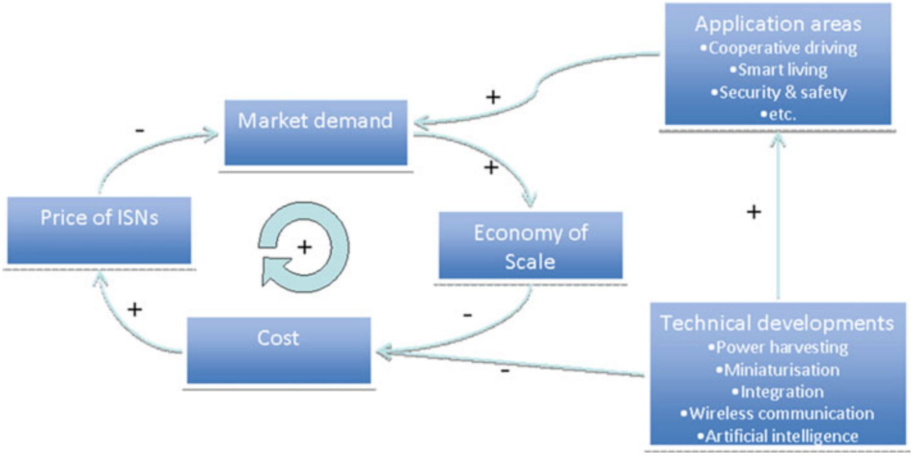


Fig. 2 ISN cost dynamics diagram

Before diving into the cost development of the different system elements, an overview of the most important cost drivers is given.

Costs consist of capital expenditure or investments (CAPEX) and operational expenditure or recurring costs (OPEX). Yearly costs can roughly be determined by dividing CAPEX through lifetime or depreciation period, and adding yearly OPEX. Financial indicators like cost of capital are left out of scope in this analysis.

Most important cost drivers for ISNs are:

- *CAPEX* material costs, production costs, installation costs, R&D costs and costs for product development;
- *OPEX* maintenance, consumption (i.e. energy, communication, etc.), support and licence costs.
- Other costs like marketing costs, project costs and office costs are not taken into account, because they are not relevant for this analysis.

2 ISN System Elements

Before we can address the costs of ISN we need a model or 'design pattern' of these types of systems that enable us to attribute specific costs to the different elements of the system.

For the definition of a system we refer to INCOSE [5]:

"A construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behaviour and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected".

Although from a system designers perspective there can be many views on the system our experience is that a functional view is most suitable to address the costs of the system. Since, according to the definition, people can be part of the system also the human elements are viewed in a functional way.

Although different in nature, both human and machine can perform similar functions and tasks like, sense the outside world, recognize objects or situations, act on the outside world and reason how to reach certain goals. Therefore, the approach taken here is to focus on modelling the system according to specific functional elements, postponing the decision if they should be performed by a humans or machines.

In Fig. 3 a high level model is presented for such a system. The functional elements we identify in this high level model are *Sense*, *Create Situation Awareness*, *Decide on action* and *Effect*. The system senses the physical environment with its sensors, both human and non-human, and transforms that into signals inside the system. The element *Create Situation Awareness* processes these signals to create an awareness of the situation that is most suitable for deciding what actions to take to reach the system goals. Finally these decisions have to be put into effect by the element effectors.

Next to that there are three 'supporting' elements: *Communicate, Compute* and *Provide energy*. In a traditional view on these types of systems the functions are static and the system is designed such that everywhere in the system enough energy, communication capabilities and computing power is available. In a modern service oriented approach functional elements have a service oriented relation which means that runtime services are provided to those elements

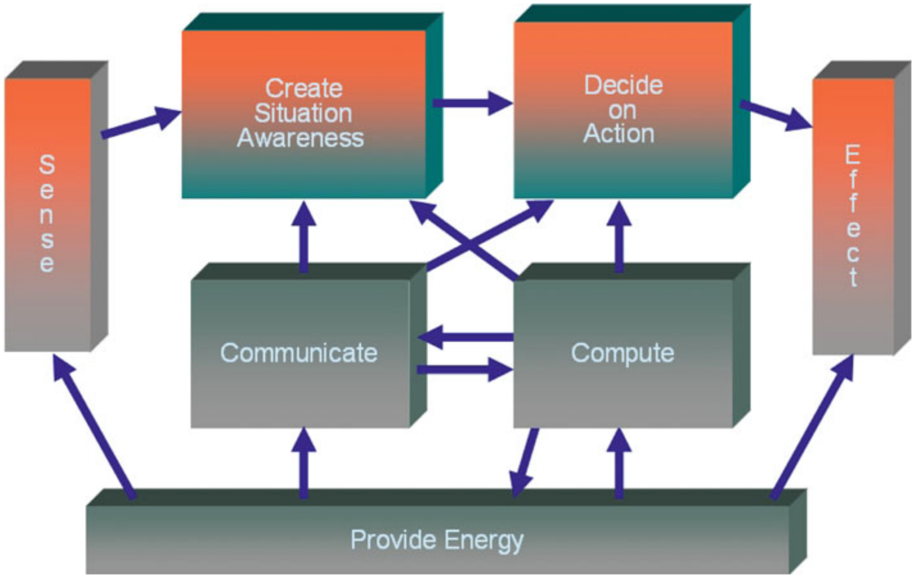
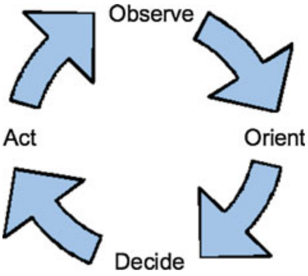


Fig. 3 High level functional on ISNs

Fig. 4 OODA model



that are in need of them. In this way resources can be used more efficiently, particularly in dynamic situations.

The arrows in the functional model represent those services. E.g. *Create Situation Awareness* needs communication, computation and signals from the sensors while communication needs energy and computation (for intelligent reasoning about optimization of the communication service). Vice versa communication is needed to optimize grid computing.

In the figure the colours indicate the typical nature of the element; grey stands for primarily hardware, green for primarily software and orange for primarily human.

Although this model is very useful for a generic approach on the cost aspects it is still a little too coarse for addressing the cost aspects of creating situation awareness and decide on action.

For these elements we would like to go one level deeper. For this purpose we use a model that, like our high level model, is applicable to both humans and machines.

A well-known and widely used model is the OODA loop (Fig. 4), which stand for Observe, Orient, Decide and Act. Typical functions that are attributed to the four stages are:

- *Observe* processing of signals from collectors to estimate states of physical entities
- *Orient* estimation of relationships among physical entities. This includes aggregates, intentions, relations, interactions among the entities, etc.
- *Decide* estimation of possible future developments and rewards of possible actions
- *Act* execution of actions on the situation

For discussing the generic trends in ISN elements we therefore use the high level model of Fig. 3 with *create situation awareness* separated into *observe* and *orient* and *decide on action* into *decide* and *act*.

3 Generic Trends for ISN Elements

In this paragraph generic cost trends for the different system elements will be discussed.[1]

3.1 Trends in Sensors

Similar to Moore's Law for computation there is a law for the development of some types of sensors, for example in the number of pixels/cm^2 in cameras. This will result in cheaper and smaller sensors with lower installation and maintenance costs. Since the sensors become cheaper we can afford to use more of them which results in more robust systems due to a certain redundancy.

Next to that also new types of sensors will become available that have new types of sensing capabilities e.g. ladars, 3D imaging radars and multi spectral sensors. Those sensors will be expensive but are expected to follow the same trend as the more conventional sensors.

3.2 Trends in Computation

A well-known measure for the trend in computation is Moore's Law. The original Moore's Law states that the number of transistors that can be placed on a transistor grows exponentially doubling typically every 1 or 2 years. For our analysis we are not so much interested in the development of the number of transistors that can be placed on a chip but in the development of the cost of computation. These costs can be separated in capital costs and operational costs. The capital costs are mainly driven by the cost of microprocessors, memory and system support like cooling. The operational costs are dominated by energy consumption and maintenance.

A good indicator for development in computation is the increase in computing power of supercomputers as tracked by 'TOP 500 supercomputer sites'. Although the number one in the list shows, as expected, a somewhat capricious increase in computing power, the sum of the computing power of the top 500 gives a steady indication of the development of this power that the society is able to bear in total cost, in CAPEX as well as in OPEX.

CAPEX is mainly determined by the number of microprocessors involved and the OPEX mainly by the energy consumption during operation. Since energy is becoming more expensive there is a shift towards OPEX and this is becoming more and more the limiting factor in supercomputing systems.

Two disclaimers need to be mentioned here:

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[1] Effectors will be left out in this analysis, because this paper focuses on *sensing*.

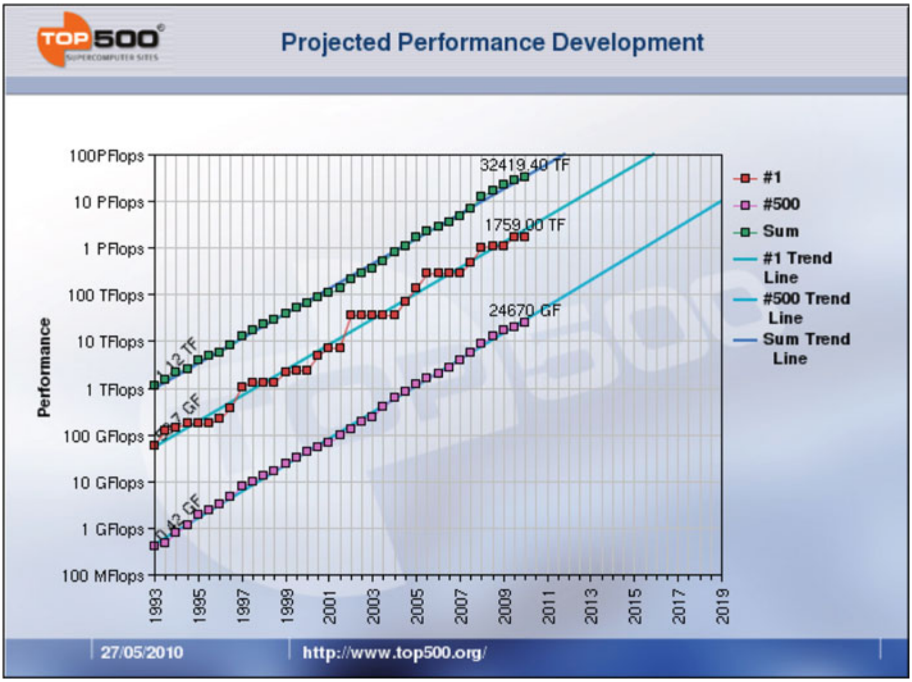

Fig. 5 Projected performance development of the world's most powerful computers

- The benchmarks that are used to measure the performance are intended for general purpose computing. For dedicated tasks such as parallel processing of huge amounts of complex sensor data the computing power is typically ten times as high while following roughly the same rate of change as general purpose computers.
- For those applications where power consumption is critical such as in smart phones the CAPEX is substantially higher but also in this case the rate of change in computing capabilities is similar to the rates in the other domains.

The rate of change in terms of cost is expected to continue for at least 20 years, expecting that when current technologies reach their limits new technologies will arise to continue the trend (Fig. 5).

3.3 Trends in Communication

Trends in communication have focused considerably on the 'battle' between wireless and wired telecom networks. But since many of the developments in ICs directly influence the realised speeds in communication networks, people have tried to fit 'exponential growth' curves through the data. Phil Edholm of AT&T has claimed [6] that for both wireless and wireline networks speed doubles roughly every 1.7 year—recently this number came down to 1.6 year (Fig. 6). The data comes from actually deployed networks, so Meijer [7] states that as a corollary in 1.7 (or 1.6 for that matter) years we will have about twice today's bandwidth at our disposal *at a price we are willing to pay*. This interesting fact shows that this growth in communication capabilities is directly translated into a premium for a specific price.

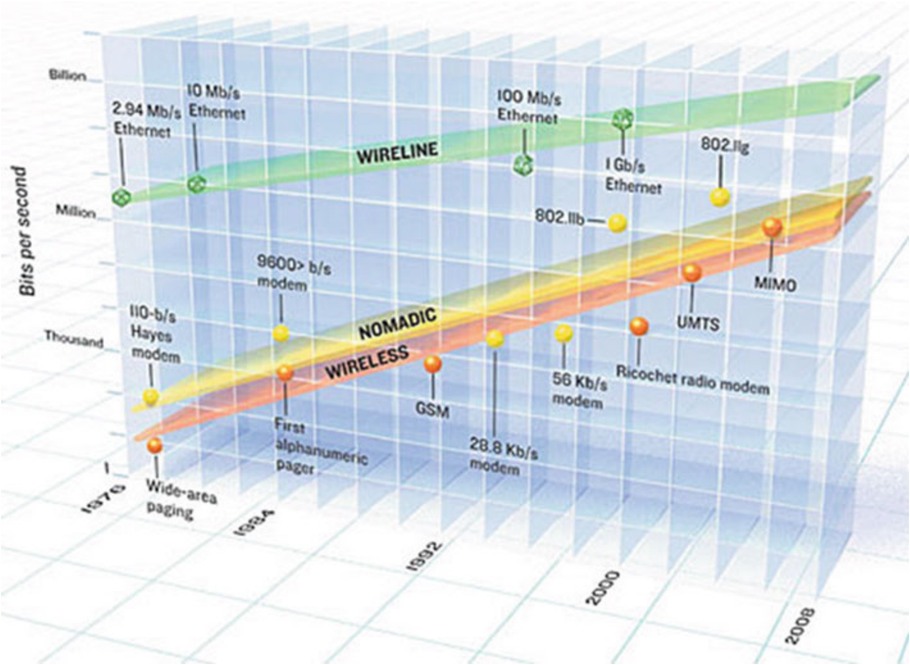

Fig. 6 Edholm's law for fixed, nomadic and wireless networks [6]

It is difficult to translate these results into *costs for an embedded radio*. The reason is that these costs are largely influenced by so-called downstream IPR-costs: the costs that need to be paid by the customer to have a radio module embedded in e.g. CE and IT devices, but also in cars, refrigerators, … There is not so much as a trend, as well as a difference between the 802.11-based standards (e.g. WiFi) and telecom-standards like GSM and UMTS: WiFi modules cost $5 to buy and integrate and have no downstream IPR costs. The cost of an embedded GSM radio is calculated as a percentage of the end-price of the product it is embedded in … [8], which means that an embedded GSM radio in a Ferrari will be very expensive.

3.4 Trends in Energy Supply

Traditional energy resources (i.e. oil, gas, coals) are depleted at a faster rate than that they are created [9]. Without alternatives, companies like Shell have to turn to fields that were originally left-aside because of their very high exploitation costs. This leads to higher operational costs for energy consumption. At the same time this trend drives the development of usage of alternative, renewable energy resources. Power harvesting techniques enable utilisation of energy from the environment, like sun, wind, but also temperature changes and vibrations for example. This energy can be stored in batteries that are becoming more powerful and are able to store energy for a longer time, over and over again. Power harvesting modules, combined with small batteries, offer a self-employed, wireless manner of energy supply. This makes it possible to supply sensor, communication and computation units with energy in all kind of places, without having to invest heavily in a wired energy supply.

3.5 Trends in Create Situation Awareness

3.5.1 Observation (Signal Processing)

Both the increase in the number of applied sensors and in the number of pixels per sensor results in a sharp increase in the amount of data that needs to be processed. At present most data is processed locally at each sensor while in the future more and more data will be correlated across sensors e.g. 3D reconstruction with multiple cameras. These correlation techniques increase the need for computation further. This will also dramatically increase the demand for communication. Since the computing costs decrease faster than the communication costs more computing power will be spent on intelligent algorithms that reason about exchanging only the most relevant data. Also data processing techniques will become more intelligent using more contextual or learned knowledge increasing even further the need for computing power. Lastly self-optimisation and self-organisation techniques will become more important for an efficient and effective operation of ISNs. This may decrease the need for computing power but may also increase the need for computing power when used for efficient and effective use of sensing and communication.

3.5.2 Orientation (Information Processing)

First of all at this level a major shift from human/user to computer is expected. Also, orientation capabilities will need more computing power to handle more detailed contextual information or learn that during operation. A huge demand on computing power is expected when intelligent algorithms shift from logical and rule based reasoning to probabilistic and fuzzy reasoning.

3.6 Trends in Decide on Action

3.6.1 Decision Making

In the case of decision making the shift from human to computer may even be more dramatic. The algorithms will be able to predict the possible outcomes of certain actions in more detail and further into the future. On top of that also for decision making probabilistic and fuzzy reasoning will more dramatically increase the need for computing power.

3.6.2 Act (Actuator Scheduling)

Similar trends as in observation play a role on the action side. The increase in need for computing power and communication is maybe slightly smaller since the complexity of the actuators in not expected to increase as dramatically as the complexity of the sensors.

4 Cost Analysis for Selected ISN Applications

4.1 Cooperative Driving

As stated before, cooperative driving may use sensors related to the road infrastructure, and sensors in the car. For road infrastructure sensors, cameras above the road and detection loops are most common. But technological innovation also makes it possible to apply small sensors within the road that measure vehicle location and speed. The price of these different types of sensors has dropped over time and will even drop further. But cameras and detection loops lead to installation and maintenance costs, and sometimes require occlusion of the road. Research is done to small sensors within the road, which can be installed during regular road maintenance, and requires no further maintenance [10].

Vehicles need to measure parameters like speed and acceleration and communicate these to other vehicles. Also their distance to other vehicles (i.e. with radar, laser or cameras) will be measured. Although the prices that car manufacturers account for these options are still significant, they have dropped considerably and will drop further when they become more widespread.

Costs for energy supply will be negligible with respect to in car systems. For systems along or above the road, in most cases, energy supply is already present. When applying sensors within the road, power harvesting solutions are needed.

Cars get more and more computing power on board. Cooperative driving will strengthen this trend. Computing power needed for *situation awareness* and *decide on action* will increase significantly but will always be limited to a small percentage of the price of the car. The same trend is expected for the roadside unit. However, since the cost of computing power with respect to the cost of the total infrastructure is negligible at the moment a larger increase is expected.

Costs for communication will depend on the requirements on response times and guarantees that messages arrive. A standard dedicated to wireless access in vehicular environments (WAVE), named 802.11p was developed and will suffice for cooperative driving, when requirements are not too high. When requirements become higher, which is in particular the case when cars drive closer together to increase throughput, the need for smarter management of information processing and communication capabilities becomes larger. To achieve this more computing power is needed but due to the price development of computing power this will hardly lead to higher costs.

Implementation for *create situation awareness* and *decide on action* is still in its infancy. They are in the R&D stadium, and hence will require considerable investments in R&D for the coming 10 or even 20 years. The service building blocks will become more intelligent over time, using higher update rates of state estimation information and resulting in smarter control decisions. During this evolution requirements on computing and communication and also precision of sensors will get higher. In particular communication capabilities will not be able to exchange all relevant information in time at reasonable cost. The faster decreasing cost of computation with respect to communication will result in the development of create situation awareness and decide on action service building blocks that are also capable of reasoning about the most efficient use of communication capabilities.

We can conclude that the development of *situation awareness* and *decide on action* will be most costly of the different components named above. Besides that, car manufacturers will account significant margins, especially as long as cooperative driving is not a widespread service.

We should however pay attention to another aspect, next to the prices of the different components: cooperative driving will require far-reaching standardisation and integration of the different components, and should be based on a well-thought architecture. Realising this will be a challenging and time consuming, and thus costly process.

4.2 Smart Living

From a technical perspective, Smart living is increasingly realized when various components (hardware, software, data) within the architecture have an open, standardised 'interface'.

- Hardware with open interfaces can create an eco-system with new manufacturers that specialize on particular functionalities; the computer, GSM and car industry to a certain extend are good examples.
- The success of open software, e.g. protocols, is surrounding us every day, with app stores on smart phones.
- Open-data can fuel the development of services that on their own can resolve issues that are other difficult to solve.

However, apparently there are reasons for stakeholders not to invest in open interfaces. The question is whether cost-considerations play a role.

Applying this to ISNs, companies have to consider e.g. a proprietary sensor or an open-interface multi-purpose sensor. This consideration is related to an existing, well-known market versus a partly unknown, non-existing market; this unknown market with companies that might want to use your multi-purpose sensor could have different options, and at the same time, your existing customers may not understand your move, and turn to a competitor. Furthermore, when your position on the market is a strong one, why would you consider something else as proprietary?

Similar arguments hold for software and data. These arguments show that open, standardized interfaces can be introduced successfully when the additional costs are low, and when there are clear indications of the eco-system that will provide additional return on investments. This involves coordinating efforts from industry fora and standardization bodies, combined with clearly articulated customer demands and stimulated by government policies. The recent efforts of ETSI, CENELEC and CEN to join forces in the field of smart living is encouraging; a joint team discusses narrowly defined standards for individual use cases, and identifies possibilities to move forward in a constructive fashion, with non-overlapping standards that constitute a high-quality framework.

When standardization is less likely, the process can be improved by making clear decisions from leading companies. An eco-system will only flourish when it can build on sound and stable decisions, about technology-choices, de-facto standards. Lewko [11], CEO of wireless industry partnership, discussed what mobile application developers—a good example of an eco-system—need. single APNs, (clear) choices and gate openers (not gate keepers) were high on her list, and still are. Google with the Android platform has probably been a clear example for her how it should work, but other examples can, or should follow. How is this related to cost? Lewko estimated that fragmentation is a 6 billion dollar cost to the industry, not being spent on innovation, and that 2–3 times more effort is being spent on developing applications in a fragmented world. This generic lesson is without doubt translated to smart living and ISNs.

5 Conclusions

The analysis shows how individual ISN component prices decline at an almost predictable speed. This is mainly a result of generic developments in technology. These developments sustain because an economy of scale is reached at the level of individual components. This makes the integration of these components the most important barrier to acquire large scale implementation of ISNs, both with respect to cost and needed R&D breakthroughs. Integration includes the need for standardization and interoperability between different standards.

Recently the European Commission expressed its worries on this issue. Via diverse projects the Commission wants to gain insight to what level actual interoperability exists between standards (deiure or de facto), when applied within different sectors but to similar use cases. One of these use cases is the home environment, where a.o. telecom, multimedia, energy and care come together. Preliminary conclusions are not very encouraging. This indicates that especially for ISNs there is space to gain. ISNs should be available in different sectors, and should be interoperable through a number of well-defined interfaces. This paper motivates a number of strategically chosen interfaces that are closely related to clearly defined functionalities. A follow up on this analysis should show to what extend the domains, demarcated by these interfaces, are attractive to market players. Sufficient market attractiveness demonstrates the feasibility of a fruitful ISN-ecosystem where suppliers can make a profit.

A relevant question is how the process of realizing high quality standards can be accelerated. In literature on innovation management theory this topic is described (preliminary designs). The phase where different preliminary designs coexist and where corresponding competing consortia or even ecosystems compete with each other is seen as necessary and fruitful. In this manner the market is tested and involved in the evolution of a winning design. A winning design can be the basis of different standards, as diverse examples from recent history have shown (automotive, PC industry, smart phones, …).

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Author Biographies

Erik Fledderus received his M.Sc. and Ph.D. in the field of Applied Mathematics. Starting in 1998 he worked with KPN Research, the research lab of the Dutch incumbent telecom operator. His main field was mobile networks, including propagation channel modeling, multi-user detection in spread spectrum systems, and UMTS network modeling. He was coordinator and principal architect of the European project Momentum. In addition, he was project leader of the Dutch project Broadband Radio@Hand, on MIMO and radio over fiber—this project has put forward the basics for the 802.11n standard and demonstrated as the first in the world a 3 × 3 system based on 802.11a ($\geq$162 Mb/s). Erik started in 2003 as part-time professor at Eindhoven University of Technology in the field of wireless communication networks, and also moved to TNO. Since 2011, Erik's interests have moved to cognitive principles for radio networks. In addition, he is now managing director of TNO's ICT activities, both business-wise and research-wise. He frequently audits European projects, and acts as advisor to Next Generation Mobile Networks (NGMN).

Leon Kester received his M.Sc. degree from the Delft University of Technology in 1988 and his Ph.D. degree from the VU University Amsterdam in 1993. From 1994 to 1998 he worked at ICT automation as a senior software engineer. Since 1998 he works at TNO in the Hague as senior scientist. His research started here on radar signal processing, tracking, sensor fusion and decision making. Currently his research focusses on efficient self-optimising and self-organising systems by combining proper techniques of artificial intelligence.

Karin van Kranenburg-Bruinsma holds a Master degree in Applied Mathematics (Delft University of Technology). From 1995 to 2003 she worked at the R&D division of Dutch telecom operator KPN, starting in the communication architectures department. In 1999 she shifted to the business modelling department. Currently she is a senior consultant at the Netherlands Organisation for Applied Scientific Research (TNO), where she combines her financial skills with her technical background to assess the economic feasibilities of innovative communication techniques.