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# A Future Internet Embracing the Wireless World

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**Abstract:** In this paper we describe several approaches to address the challenges of the network of the future especially from a mobile and wireless perspective. Our main hypothesis is that the Future Internet must be designed for the environment of applications and transport media of the 21st century, vastly different from the initial Internet's life space. One major requirement is the inherent support for mobile and wireless usage. A Future Internet should allow for the fast creation of diverse network designs and paradigms and must also support their co-existence at run-time. We observe that a pure evolutionary path from the current Internet design is unlikely to be the fastest way, if at all possible, to address, in a satisfactory manner, major issues like the handling of mobile users, information access and delivery, wide area sensor network applications, high management complexity and malicious traffic that hamper network performance already today. We detail the scenarios and business use cases that lead the development in the FP7 4WARD project towards a framework for the Future Internet.

**Keywords:** Future Internet, Network Architecture, Network Virtualisation, Self-Management, Information-centric Networking.

## 1 Introduction

Driven by the encouragement for new approaches from some of the "fathers of the Internet" (e.g. [4], [7]) and early experimental testbeds (see e.g. [14]), the discussion on the "Network of the Future" is gaining in intensity due to increasing concerns about the inability of the current Internet to address a number of important issues affecting present and future services and to the impetus provided by "clean slate design" research initiatives launched in the US, Europe and Asia. Many problems, arising from mobile and wireless perspectives, with the current network architecture have been recognized for a long time but have not received a satisfactory solution (see e.g. [1]). The issues like security, manageability, dependability, mobility, etc. result both from initial design flaws as well as the wide set of applications over the Internet that could not be envisioned from the beginning. In this paper, we present the approach taken within the 4WARD project (www.4ward-project.eu) to address these problems by researching different aspects of the Future Internet design.

In section 2 we first discuss societal and business forces that must guide our technical choices. Section 3 introduces our ideas on the key technical components for a Future Internet consisting of an architectural framework, network of information, flexible transport paths, network virtualisation and self-management. We end the paper with a short conclusions section.

# 2 Motivation and scenarios for the Future Internet

The Internet was initially developed for a limited number of trusted nodes interconnected by copper based transmission technology implemented supporting applications like file transfer and message exchange. The initial architecture developed for this purpose was essentially simple but open for new applications. Its evolution has led to a tremendous success – the Internet as we know it today. It is however far from clear that it is still the optimally evolvable solution, able to meet the challenges of fibre optics and radio transmission technology, real-time multimedia and file-sharing applications and exposure to an untrustworthy world. Furthermore the Internet, starting as a simple set of protocols and rules, has over the decades reached a state of high complexity with regard to interoperability, routing, configuration and management.

Within the research community the need for change is largely acknowledged although there is not yet agreement on how this change should take place. Some propose a *clean slate* approach, which aims at investigating new architectural concepts with new requirements in mind and which initially doesn't need to consider legacy, while others are advocating an evolutionary approach, introducing new solutions incrementally. It seems likely that both approaches will migrate current Internet technologies towards a Future Internet.

## 2.1 Scenarios for the Future Internet

The identification of key drivers is one of the most difficult prerequisites in the development of the Future Internet. By analysing the key driving forces and challenges in the Future Internet business environment, the 4WARD scenarios were built. These scenarios cover aspects of technical as well as non-technical areas.

The general frame for the scenarios can be summarized as follows:

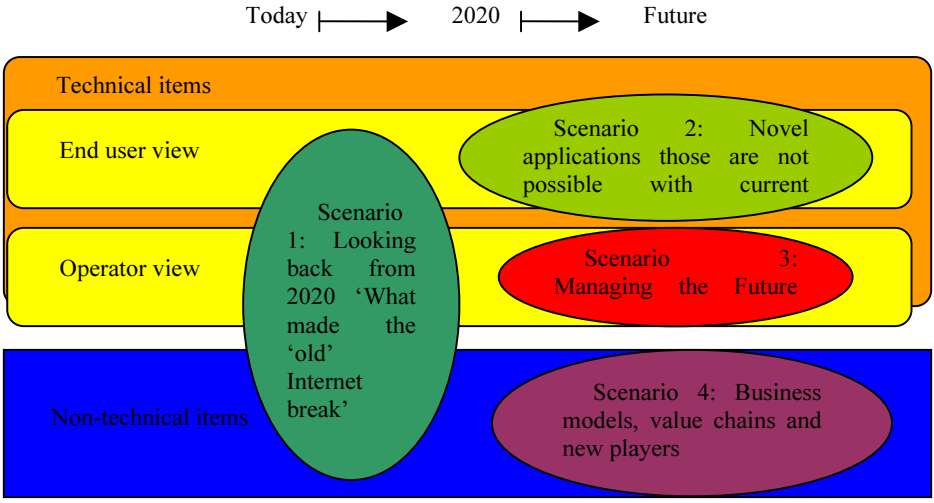
4WARD addresses the worldwide potential telecommunication market in 2020

Time frame for upcoming technologies: it should be possible around 2015, it should be widely used in 2020

Maintain an end-to-end view with respect to service, usage, business and technology development

Within this section four scenarios are described which focus on different aspects of the possible future evolution of the Internet. The following figure gives an overview on the potential areas of the scenarios.

**Fig. 1.** Scope of 4WARD scenarios and temporal horizon




The rest of the section presents the main conclusions of the different scenarios. The scenario 1 "Looking back from 2020 'What made the 'old' Internet break" outlines which technical and non-technical developments will have been decisive for the understanding that the smooth evolution of the existing Internet concepts will no longer be applicable in the communication world. This includes the analysis of infrastructure problems, innovation restrictions and the limitations in economic incentives.

The second scenario "Novel applications that are not possible with current Internet" identifies and evaluates from end user view which challenges will be posed from conceivable new applications to the Internet and how they overstrain the existing Internet concepts. This includes enablers for more user orientation, mobility support and augmentations. Some examples are networks that fit perfectly to users' likes, dislikes, preferences, and so on, even if users temporarily use someone else's terminals, the integration of the real world and the Internet, the potential of having a better support of non-continuous access to the Internet and asynchronous communication and the services for individual's life kernel (SILK), e.g. for health monitoring, control of house appliances, personal identification and interaction and how these services are not supported by today's Internet infrastructure. Sometimes they are possible only 'in principle', but wide-spread adoption is not possible due to complexity or scalability issues, lack of usable devices or other restrictions.

Scenario 3 "Managing the Future Internet - Benefits for operators" concentrates on network management issues which come up with the broadening of the traditional one-stop-shop operator to an environment with several partly competing, partly collaborating network operators and a multitude of service providers. Major themes covered are the blurring boundaries between operators and other players in a future Internet, the growing complexity of infrastructure and services and the associated need to find new ways of network/service management, the new capabilities provided to operators, based on innovative future Internet technologies. The separate document D.4-1 [17] details the problems and presents more in depth results.

**Business models, value chains and new players**

The last scenario focuses on the non-technical aspects of the Future Internet. It evaluates the impact of social, economic and political trends on the telecom business to work out the most

decisive elements which will govern the future business environment. The most important questions are:

1. Will the Internet arena be dominated by a limited number of big players or is it, on the contrary, more feasible that a multitude of specialized small companies will satisfy the increasing demand for individual services?
2. Will centralisation (e.g. big server farms) or decentralisation (peer-to-peer networks) determine the direction of future developments?
3. What will be the main inhibition of growth: regulative intervention, compatibility problems of technical solutions or a mismatch in market power?
4. How can the global usage and accessibility of the Internet be assured under different market environments without global regulation?
5. Will heterogeneity in technology accelerate or retard technical innovation? Is the coexistence of multiple heterogeneous platforms (may be operating on the same physical system but separated by virtualisation) a good alternative?

First answers on these questions have led to two opposite borders, called elephant and gazelle scenario. The figure below shows the borders of the scenario framework.

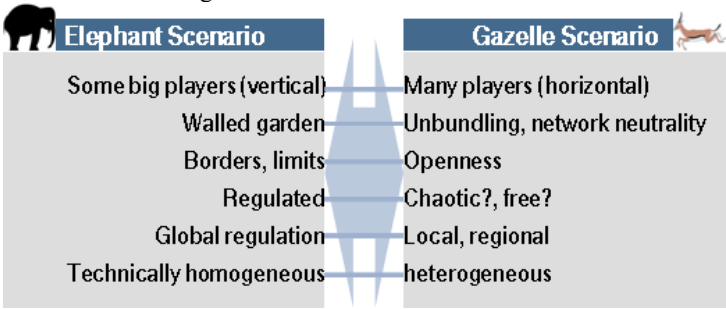



**Fig. 2.** Extreme Scenarios characterized by six drivers with uncertain development

### 2.2 Use cases

Based on the four scenarios, a set of different use cases was developed. Each use case covers a precise technical or business related topic. In order to reduce the complexity in the detailed analysis, a set of mandatory business topics were defined. These are the following:

General description including a basic technical overview (provide a basic overview how the use case could be implemented in the future)

Business player (including the analysis of a value proposition, the target market description, principle revenue model, resources and processes as well as the potential impact of the 4WARD technology, and the three non-technical aspects as described above)

Customer (focus is on the potential value and the impacts from technical and non-technical area)

Rivalry (based on the idea of Porter's Five Forces [15] and its analysis principles for competitors, suppliers, substitutes, new entrants and buyers. The model's limitations are understood and it has been extended to overcome these limitations).

After several evaluation rounds, five major use cases remained for detailed analysis:

1. Enhanced connectivity in the user communication space
2. End-to-End Quality of Service
3. Virtualisation
4. Identity Provider
5. New ways of information delivery

The idea of "Enhanced connectivity in the user communication space" is to separate the service connection from the network and holding an interaction between both layers. For example, a user is allowed to freely shift his communication from one terminal to another one without loosing the connection (e.g. in case of power failure of a terminal or arriving at a location with a better suited or connected terminal). Furthermore, enhanced security and the communication representation (the bit streams) will adapt to the connectivity and device constraints of the new terminal. This could change the service usage in principle and enable customers integrated service mobility in the future.

In the use case "End-to-End Quality of Service", the focus lies on the interprovider connections at the example of Quality of Service (QoS). This includes aspects like assuring QoS service levels by leveraging network state aware routing, provisioning of connections with guaranteed QoS levels across borders of different providers. The business view is the reduction of overprovisioning of networks and the associated optimisation of costs as well as the possibility for better service delivery and potential increase in revenues.

With (network hardware) virtualisation, the idea of virtualisation in the server area is applied for network optimisation. The implications could change the whole business logic in today's telecommunication environment and adapt to the more open Internet approach. This implies changes in the ecosystem containing now the three potential players Infrastructure Provider, Virtual Network Provider and Virtual Network Operator. In addition, other areas are interfaced like service delivery and usage or regulation. Key target is the optimisation of costs and possibility to retain profitability in the infrastructure business.

Exploration of the business opportunity arising from a combination of 4WARD concepts Network of Information and Generic Path is the focus of the use case "New ways of information delivery". It evaluates the prospects of deploying respective technologies, trying to identify a number of services they will enable in a Future Internet and who will be the stakeholders for these services.

The two use cases "virtualisation" and "New ways of information delivery" are analysed in more detail and documented in [16].

### 2.3 Migration Issues

4WARD has taken a research approach that is called "clean slate approach" that means that from research point of view we start the research as if the Internet does not exist. In the end we will have to take a migration approach that is applying results from research into the real network.

This can basically be done in 3 ways.

One is to incrementally enhance the existing internet paradigm by adding extension to present protocols and functions without compromising current implementations; an example could be Mobile IP. By this there will be no fundamental change of Internet and the problems with the current Internet will remain.

Another approach is to make use of overlay or underlay techniques which have been used for many years in traditional telecom as well. An example of overlay techniques could be SIP for VOIP or different access technologies like Ethernet or radio as examples of underlay techniques and hereby placing functionality either on top of or below the current Internet. Although this approach solves more problems than the previous one, we are still faced with that this approach is relying on the functionality of the current Internet. There is a risk for more overhead but also fragmentation due to that applications might need to implement same or similar functions per application rather than using an underlying common support functions.

A third option would be making use of network virtualization techniques and by this separating the network into virtually independent "slices". This means that based on a common

physical infrastructure one can have several network architectures operating in parallel, and which for example could interoperate at gatewaying points. This would allow for having networks serving different needs e.g. sensor networks, enterprise networks or even public networks, and where some could be based on new technologies.

There is of course another possibility to deploy a completely new network in parallel with the current Internet. We do not believe that this is a viable commercial option due to the immense success of Internet and its installed base. For this reason we will not pursue this approach further.

# 3 Key Components for a Future Internet

To realise those scenarios and business propositions, we have to develop a consistent set of key components for a Future Internet that we present here in the following subsections.

## 3.1 The architecture framework of a Future Internet

To enable innovation and rapid deployment of new networking solutions, the development of new architectures suitable for a specific environment (e.g. a LAN or a new type of radio access network or a specialised application), should be facilitated and the reuse of common components made possible. We develop a new **architecture framework** that must be able to accommodate changes in business and technology environments. Such agility is emerging in the software area with service oriented architectures and design patterns. We plan to extend and generalize these approaches, and develop an architecture framework by which different network architectures, which are tailored for various purposes and environments, can be derived and implemented. The aim is to end up with lean and dedicated instantiations of network architectures that remain **interoperable and evolvable**.

The interoperability that has been solved naturally by IP becomes a concern without the universal presence of design principles. Without such principles, it will in the long run be hard to interconnect and to interoperate the resulting networks. The design principles need to express aspects and properties that pertain to naming, addressing, routing, QoS, (self-) management, security, as well as overall performance objectives. Given the coexistence of heterogeneous network environments and different (and still unknown) technologies, it is very important to carefully analyse gatewaying principles for interconnecting networks having implemented different network architectures. It is likely that a modular and scalable approach to gatewaying should be considered.

The design of an architecture framework started with defining common requirements as well as a set of invariants. They must generally concern the performance objectives, scalability, extensibility, as well as the consistency and coherency of communication systems throughout the lifetime of the architecture framework. Implicit invariants usually emerge by overloading functions intended for other purpose(s), making the adaptation/replacement of these functions impossible. Indeed, according to Ahlgren et al. [6], if invariants are not explicitly defined, the design will be deficient in the long term, despite its superficial flexibility. The properties and aspects that, for instance, a specific sensor network and a MAN, or any other network of the future, will have in common, still need to be identified and investigated. Through the architecture framework it should be possible to instantiate, e.g. a very light-weight network architecture suitable for low-energy networks, with a very limited set of features implemented. Similarly, one should be able to instantiate a network architecture suitable for a MAN, for example, with built-in features such as security, privacy, QoS, and mobility.

Reconciling such diverse aspects as discussed above will be a challenge. Thus, explicit invariants, principles, properties, and design patterns shall be carefully designed into the

architecture framework. They are, by definition, the specific characteristics that determine the options as well as limitations for how network architectures can develop and evolve over time. The first results on architecture framework can be found [18].

### 3.2 Moving from networking of nodes to networking of information

The traditional role of networking has been to interconnect remotely located devices like computers or telephones. This function is increasingly recognised to be ill-adapted and inadequate for the information-centric applications that currently generate the vast majority of Internet traffic.

In 4WARD Networking of Information (NetInf) we take a different approach. Instead of the traditional *node-centric* paradigm, we adopt an *information-centric* paradigm. In this paradigm, the communication abstraction presented to applications is based on the transfer of application data objects instead of end-to-end reliable byte-streams as used today.

The current semantic overload of the IP-address as both node identifier and locator, indicating the current point of attachment in the network topology, is replaced by a clear separation of information self-certifying object identifiers and locators. Several models for abstracting the location and focusing on networking between (mobile) hosts have been proposed, (e.g. [7], [3], [9], [10]). 4WARD builds on this prior work and by taking it one step further; we are able to design a networking architecture where mobility, multihoming and security is an intrinsic part of the network architecture rather than add-on solutions. It also allows users to gain increased control over incoming traffic enabling new possibilities for defending against denial of service attacks. The self-securing property also intrinsically facilitates possibilities for effective content protection and access rights management.

The increasing number of overlays created for the purpose of information dissemination (e.g., Akamai CDN, BitTorrent, Joost) clearly shows the need for an information-centric approach. These overlays massively distribute information and move the load away from any central server, scaling automatically to any group size. 4WARD integrates much of the functionality of these overlays, including caching. This is done in a common and open information networking service that integrates networking and storage and is generalised for use by applications.

4WARD extends the networking of information concept beyond “traditional” information objects (e.g., web pages, music/movie files, streaming media) to conversational services like telephony, and store-and-forward services like email. Special attention is paid to how services can be made to work in an environment with a heterogeneous and disruptive communication infrastructure. Furthermore, we investigate how networking of information can extend to include real world objects, and by this enabling new types of services. Our initial results in the NetInf area can be found in [20].

### 3.3 Networking with the Generic Path

The construction of a path as a sequence of relaying nodes in a network takes currently place on multiple layers. In fact, a port of an IP router in the backbone will today typically be connected to an SDH or Ethernet layer on top of an optical layer. GMPLS has been introduced as control plane for multi-layer networks [11]. Here, for the first time, the otherwise lower-layer agnostic IP routers may perceive the notion of a changeable topology, leading away from pure overlay networks with separate control to an integrated and possibly distributed management of data transport. Our approach is to define the notion of a "Generic Path", able to efficiently realize "networking of information" by exploiting cross-layer optimization and multiple network paths.

We define a Generic Path (GP) as "means to organize the accessibility of a sufficient number of parts or copies of information objects stored in a group of hosts." See also [21]. Incorporating the paradigm of *information-centric networks* means that a GP is actually hiding the physical location of information objects. Wherever chunks or copies of information are stored, the GP takes care of delivering it to a sink.

Because cross-layer information is available, new transmission techniques can be used inside a GP. This is especially interesting for the introduction of network coding into fixed and wireless networks. Here, multipath routing needs to be combined with specific capabilities of nodes (e.g., bit-wise XOR of two frames).

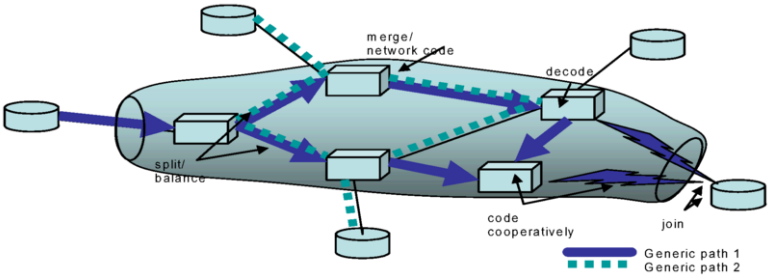



**Fig. 3** The Generic Path as a hull organizing data transport over multiple paths and layers.

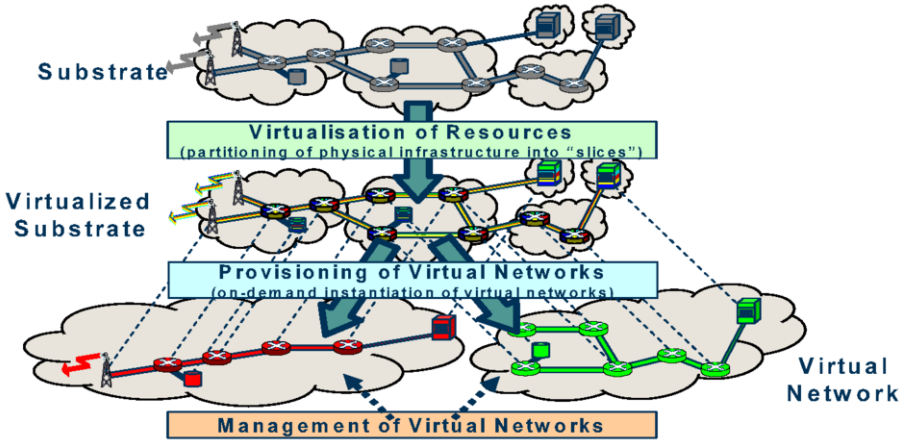
Generic Paths can thus be seen as a "hull" that is filled with information. One advantage of this concept is that mobility of information objects and hosts becomes conceptually equivalent and is dealt with by the GP internally.

There are a number of open questions that are addressed inside 4WARD to bring this concept to reality: routing and interaction of generic paths, the control plane for network coding, enhancement of mobility management and, importantly, the definition of a generic path API that allows the instantiation of a GP similar to today's sockets. The GP thus appears as the fundamental information channel in the future Internet that is sufficiently flexible to adapt to different requirements and available network technologies. A description of the GP mechanism can be found in [22].

### 3.4 Towards lean and innovative networks through virtualization

To introduce clean slate solutions like information-centric networking and generic paths we have to allow them to coexist with existing and other new approaches. Virtual networks can enable new protocols and architectures to be deployed independently without disruptions. Virtualization has been used in test-bed environments and is now being proposed as the basis of commercial networks (see also e.g. [10]).Virtual networks are ideally suited to allow the coexistence of different network architectures, legacy systems included. Virtualization is thus not only the enabler for the coexistence of multiple architectures, but it is also a smooth path for the migration towards evolutionary approaches. The goal is hence to develop a systematic and general approach to network virtualization. The virtualization of individual resources is the basis of the framework as depicted in Fig. 4 below.

**Fig. 4** Virtualization Framework




While the virtualization of many types of resources, such as servers and links, is well-known and already widely used today, we aim for a generalized approach that allows the use of a broad diversity of resources with higher flexibility and security. Virtualization of both wireless and wireline resources is expected to play a key role in the Future Internet. In particular, the secure, flexible, and efficient exploitation of wireless spectrum resources and wireless infrastructure is expected to significantly improve cost-effectiveness and utilization of expensive wireless infrastructures.

Virtualization allows an evolution of communication technology while largely reusing deployed infrastructure; thereby it reduces the economic barrier for technical evolution. It further provides a general framework for *network sharing*: providing different networking services of different network service providers on a common physical infrastructure. This is particularly beneficial in network domains where the deployment costs per network user are predominant and an obstacle for frequent technology replacement.

A key concern for owners of infrastructure resources and the operators of virtual networks using these resources is security and trust. The virtualization framework must ensure the protection of the physical resources, as well as the strict isolation of concurrent virtual networks from each other. Furthermore, virtualization may significantly change the business environment for infrastructure owners and operators' business models and incentives for use in a commercial setting need to be carefully considered. Our draft approach to Virtualisation can be found in [19].

### 3.5 InNetworkManagement: A new network management paradigm

The diversity of technologies and business models envisioned in previous sections can only be supported in operative networks if adequate management functions are integrated to initiate and maintain the network infrastructure. Management capabilities in current networks typically reside outside the network. Research has focused on solutions for self-management but so far these are mainly algorithms solving specific problems. Most of these solutions lack scalability, imply considerable integration costs with central management stations and – most important – are not suitable to cope with the complexity and dynamicity of tomorrow's networks.

In order to address these issues, the 4WARD project follows a new paradigm to network management. The basic concept of the new paradigm that we call *InNetworkManagement* is (1) to have network management functions as *embedded* 'default on' management capabilities of

network devices and (2) to allow these devices to interact in a peer-to-peer fashion to enable network-wide management functions. We envision management functions as inseparable capabilities of the device and the network itself. This leads to a novel, strongly decentralized architecture where management operations are localized in the network components. As a consequence, faults can be identified more quickly and isolated using cross-layer techniques, and control loops can be enforced more efficiently than in traditional management architectures. Benefits from this approach are to access embedded functions to cope with diverse technologies, different business models and the rich mix of services instead of adding complex management systems into the networks. We believe that InNetworkManagement is particularly beneficial in large-scale, dynamic network environments. A number of these issues have been described in [17].

The new embedded management functions are accessed through a *management plane inside the network* that organises itself and automatically adjusts to different network sizes and configurations. It executes a set of distributed, self-stabilising protocols for monitoring and control, enabling a range of self-management functions inside the network. This is accomplished first of all through the definition of models of interactions between network components and the inclusion of self-organizing algorithms inside network devices. Secondly, the behaviour and objectives of the network as a whole is studied and modelled. This includes outer control loops between different components and operators' interfaces to support network-wide processes, including monitoring of aggregated states and policy enforcement.

The development of protocols for the management plane can draw on current research on the computability of distributed functions under cost constraints, sensor networks and probabilistic protocols for distributed systems [13]. However, application to network management calls for progress beyond this research, in order to take into account the particular constraints regarding operational overhead in the management plane, the richer functionality of management operations and the potentially large number of concurrently executing management functions. Therefore, a systematic analysis of network working conditions is required, in order to assess the effectiveness of management operations in different situations and scenarios. Such an analysis identifies the trade-offs for management operations, including protocol overhead, accuracy of monitored data, timeliness of self-healing actions and frequency of self-optimization actions, which should become tuneable in real-time. (See [12] for an example). In addition, mechanisms are developed that provide control over the relationship between decision quality and the cost of achieving a specific level of situation awareness in the management plane. Our concept of INM is described in [23].

# 4 Conclusions

Considerable research effort is clearly necessary to address the challenges raised by the design of a Network of the Future. This effort is currently underway with many Future Internet activities across the world. The main thrusts of 4WARD, *a new architectural design*, the *information-centric paradigm, the generic path network virtualization and embedded self-management,* provide candidate solutions, which, after careful evaluation, should be appropriately incorporated into the architecture of the Future Internet. A major issue will be the integration of the various approaches within a common architecture framework. Results of this work are expected over the coming years.

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