Towards Self-Adaptable, Scalable, Dependable and Energy Efficient Networks: The Self-Growing Concept

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***Abstract*— In next generation systems and networks, the incorporation of mechanisms achieving robust, predictable and self-adaptive behavior with minimum cost will be a key requirement. Towards this goal we introduce the notion of the “self-growing network”. The latter, in its initial deployment stage, is limited to a single dedicated purpose (energy-efficient networking, spectrum efficient communications, control and surveillance use, etc) but can evolve/grow into a multi-purpose, versatile infrastructure, that serves a broader range of applications by utilising combinations of self-x and cooperating features. The self-growing network paradigm considers (i) mechanisms for energy efficient interaction of the wireless network elements and (ii) mechanisms for the reliable and efficient evolvement towards later lifecycle phases. The Self-growing system incorporates the network(s) as well as user services and applications thus creating self-growing solutions applicable to wide range of purposes and impacting various beneficiaries, such as providers, consumers and end users.**

Keywords-self-growing; self-adaptation; cooperation, distributed systems; low energy

I. Introduction

In future large-scale distributed systems, the emergence of mechanisms achieving robust, predictable and self-adaptive behaviour will be an important evolution step. At the same time, as systems get more complex in terms of scale and functionality, reliability and dependability are getting increasingly important and self-adaptation techniques for achieving dependable system operation under cost and energy constraints will be a key concept. In this context, key challenges lie in the efficient cooperation of heterogeneous elements in order to provide advanced problem solving capabilities and improved as well as reliable services.

Furthermore, innovations for low energy are considered a fundamental parameter in the efforts to combat climate change and to achieve sustainable economic growth. Low energy solutions create an attractive business case by offering significant benefits in terms of operational cost, long-term product reliability, sustainability, and increased lifetime of wireless or mobile elements. For this purpose, a promising path lies in the study and development of energy-aware distributed and cooperating systems for monitoring and control, in particular based on wireless networks for providing radio and environmental context information.

Current wireless network development is driven by horizontal mass-markets (“one size fits all”). Vertical markets and niche applications demand for (costly) dedicated configurations or developments. Consequently, the evolution of a wireless network often demands for infrastructure and terminal replacement. Extending system and network capabilities, switching services or switching the purpose of an operational network usually requires costly (manual) reconfigurations and upgrades, while usually results in temporary unavailability of system services. Promising solutions for these problems are expected to require foundational multi-disciplinary research, leading to an integration of next generation technologies. Such integration is leveraging on capabilities for spontaneous ad-hoc cooperation between objects, self-adaptive behaviour, exploitation of dynamic information, predictability of non-functional properties (e.g., energy consumption), etc.

Furthermore, the constantly rising complexity of such dynamically changing network infrastructures can only be managed and maintained by highly trained professionals – making the requirements for self-growing and self-adapting wireless infrastructures an absolute must in order to ensure a large scale deployment.

As a summary, *energy efficient and dependable operation at the level of cooperating wireless elements, network compartments and networks as a whole is becoming an increasingly difficult objective, given the ever-increasing complexity in heterogeneous telecommunication environments*. In this context, the evolution of mechanisms to cope with energy-aware and dependable cooperation of wireless elements becomes a fundamental enabler for future heterogeneous large scale distributed systems.

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The rest of the paper is organized as follows. The concept of the self-growing network is introduced in Section II. Section III presents the considered uses cases and elaborates on the potential benefits for every use case. Finally, Section IV concludes the paper.

II. THE CONCEPT OF THE SELF-GROWING NETWORK

In order to provide tangible solutions for the challenges discussed in the previous section, it is necessary to progress in two major research directions:

- Solutions for optimised energy consumption, adaptability and dependability in a small scale, purpose-driven network through balancing autonomic and cooperative approaches,
- Mechanisms for the self-evolvement of the network/system, towards a large-scale, multi-purpose network/system.

At the beginning of its lifecycle, defined in this paper as the progression through a series of differing stages of development which can potentially provide different services, a **self-growing network** (Figure 1) is set up on-demand, dedicated to a single purpose. Relevant use cases might be for example monitoring and/or controlling applications with a focus on distributed and cooperating systems, including construction sites, delivering wireless services within a complex home/office environment requiring network parameter negotiation with a multitude of neighbouring networks, etc. These applications usually have strict requirements in terms of energy consumption, thus *solutions for optimised energy consumption* are exploited. During the self-growing networks' lifecycle, it can evolve to serve several different objectives as needed utilizing *mechanisms for self-evolvement.*

The considered evolution may include for example providing general voice and data communications, integrating sensor networks in the vicinity, or supporting safety of life applications under exceptional situations. In the course of this it may coexist and cooperate with other wireless networks of distinct owners and interest groups evolving in the deployment area towards using or augmenting existing capacity. The sensor networks in particular may serve a multitude of purposes, including environmental sensing, radio parameter sensing, etc. Interoperability with existing network infrastructures and wireless standards enables geographical and/or functional on-demand extensions. Towards the end of its lifecycle, the self-growing network may still remain active and serve as a dedicated purpose network or as a failover for applications associated with other networks sharing the same area.

The self-growing concept incorporates both **collaborative** and **autonomic** aspects. Specifically, cooperative behaviour and problem solving is critical in the self-growing initial stage, the small-scale network, as well as in the evolvement to a larger scale network, able to serve different purposes and larger systems. For example, the combination of cooperation paradigms with the inherent redundancy of monitoring and control functionalities in distributed wireless networks not only allows the objects to dynamically adhere to the most energy efficient pattern but also provides error resiliency features, graceful performance degradation in the presence of faults, as well as efficient utilisation of redundancy for fault tolerance that are very important for large scale networks.

Moreover, autonomic capabilities constitute key enablers for self-growing network paradigms. In this context, the degree of autonomicity in an object (network device, network compartment/cluster, as well as a network and the system as a whole) is balanced against the requirement for efficient cooperation in order to maximize the gains in both energy efficiency and dependability. At the end of the day, the mechanisms and the enablers for the self-growing concept from the small scale to the large scale might form a complete toolbox that can be applied to a wide range of application areas or network purposes. It is expected that self-growing capabilities coupled with autonomic and self-adaptation features will pave the way for scalable, energy efficient heterogeneous wireless networks thus impacting various beneficiaries spanning from value providers to end users.

The proposed approach pursues to increase *dependability***,** *cost* and *energy efficiency*, and also *flexibility*, *resilience*, and *robustness* of a heterogeneous wireless network by utilizing reconfigurable wireless communication nodes and distributed cooperative control functions. In contrast, existing solutions that are optimised for a single purpose are expensive and lack flexibility; flexibility would for example allow creating hybrid solutions without significant effort for incorporating additional network and service gateway functions to achieve interoperability.

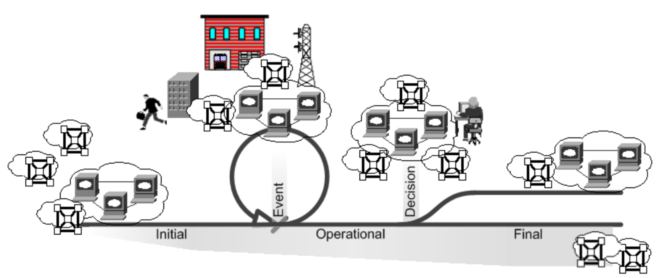

Figure 1: Self-Growing Network Life Cycle.

Regarding **self-evolvement**, the envisaged methodology resembles the structure and approach discussed in the context of self-growing neural networks presented in e.g., [1],[2]. This concept allows initiating a learning process from a very limited training space and supports response to an extension of the training space later on by "growing" the capacity or number of decision elements. A practical implementation of this concept could be repository/ontology based by providing a database of decision making capabilities that is dynamically composed of contributions of participating networks. A similar approach has been presented in the context of self-growing robot control software to respond to changes in service requirements [3]. Leveraging on these notions we will identify and develop a suitable cognitive architecture that will enable participating networks to reconfigure their topologies and optimisation goals on

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demand. Furthermore, we will develop and formalize the decision making framework as well as its related baseline functions in order to enable describing, planning and controlling the targeted behaviour of participating networks in the process of self-growing in a concise and scalable way.

III. USE CASES

Three major uses cases are given next to emphasize on potential benefits by applying the approach in certain scenarios and to provide concise examples of possible implementations of the approach. These use cases intend to underline the toolbox nature of the approach mentioned earlier. It is shown that the use cases given here can benefit even though the approach may be applied only to a limited extend.

A. Construction Sites

The first use case addresses both wide-area and in-facility construction sites as well as moving work zones. Network evolution is achieved by deploying heterogeneous equipment and by continuously updating operational policies. This is an example where the network grows by cooperating, collaborating and integrating with neighbouring networks. Network deployment and purposes can be planned and optimised prior to start deploying equipment. Moving work zones are considered a special application of this concept in that they usually rely on short-living configurations with respect to a given geographical area. Road, railway or inland waterway construction scenarios may apply, explicitly requiring the use of mobile nodes and networks. Additionally, first-responder or military scenarios apply where autonomous vehicles pave the way deploying sensors and communication repeaters on their path.

In the initial stage of the deployment of the self-growing network, network equipment is deployed whenever needed for the given purpose and provides sensor network and surveillance services as well as a first step towards a large scale, distributed sensor network. Equipment is mostly dedicated to linking sensor (and actuator) functions, or to provide simple point-to-point and broadcast communications. In case of moving work zones nodes may need to support focused environmental monitoring in addition to RF and network monitoring.

In intermediate stages of deployment, the network is augmented by voice and data communication, positioning, machinery monitoring and control services and supports safety of life applications, e.g., for construction site workers or emergency teams. This can be achieved by integrating with, for example, neighbouring wireless local area networks or even microcells (by spontaneous ad-hoc cooperation between objects). Moving work zones will demand for more network flexibility in terms of environmental or radio scene adaptation capabilities since planning may not be possible to the same degree as applicable to permanent sites.

In the final deployment stage, network equipment might be left embedded in buildings and may provide wireless repeater functions (e.g., through elevator shafts), or may provide sensor network functionality to support facility management and monitoring. The infrastructure released by moving work zones may be utilized later on by other networks evolving in the vicinity or by vehicular networks for example. Network-centric computing with dynamic resource discovery and management will enable a seamless evolution of the network environment whenever new networking components are added.

Expected benefits of the self-growing concept in this use case include the reduced development cost for network nodes, the increased sustainability and flexibility of the system, the sharing of deployment cost, the extended lifecycle of the network, as well as the potential for less effort in planning and managing.

B. Embedded Incident Area Network

This use case addresses the deployment of a network in a limited geographical area utilizing for example a reconfigurable picocell and femtocell infrastructure as a pre-planned implementation of the self-growing network concept. In contrast to scenarios previously discussed that start from a main purpose associated with wireless sensor net functionality, this scenario starts from a general voice and data communications use case serving off-the-shelf end-systems. The network then grows with upcoming requirements from the deployment area. In case of an exceptional event on demand reconfiguration capabilities allow to switch to a purpose focusing on safety of life. The temporary switch of purpose then will designate the network, part of the network, or single network nodes to implement an incident area network until the incident is resolved. This interruption of planned operation will leave the network in a potentially undetermined state and thus requires self-adaptation for returning to pre-planned operation.

In the initial deployment stage nodes provide general voice and data communications only. The network may need to support mesh configurations (e.g., as a wireless backhaul) considering the potential need to cover larger areas with singular attachment points to a wide-area communications infrastructure. Intermediate deployment stages may extend the network into sensor nets and/or safety applications. In this direction, a continuous deployment of (heterogeneous) nodes either providing sensor/actor or communication capacity allows to optimise the coverage of the area in terms of placing functionality where it is needed to, for example, monitor dynamic geological phenomena with a suitable spatial resolution.

Under normal conditions, safety functions in this use case are mainly used in locating/tracking personnel, in health monitoring of personnel, in area monitoring (e.g., detecting a landslide) or in providing emergency call capacity where needed. In an incident case, the network can be reconfigured to guide emergency teams within the area. The reconfiguration might be flexible depending on the type of incident (e.g., focused on the location of the incident) and might be initiated manually by a network management action or automatically triggered by sensors in this location (e.g., after detecting sensor nodes going dysfunctional).

The use of off-the-shelf end-systems is beneficiary especially for this use case: safety functions are gaining from geo-location features provided by state-of-the-art handsets,

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and in an emergency situation the network may be allowed to actively place a call, causing an acoustic signal to guide emergency response teams more accurately even in difficult environments. In the final stage of the deployment, the general voice and data communications capacity of the network can be reused, e.g., by transferring it to an operator for establishing a new managed (commercial) infrastructure, or by setting up the initial phase of a new use case scenario, for example a construction site as discussed above.

Expected benefits of the self-growing concept in this use case include the support of service centric, on-demand adaptation capabilities to respond – potentially without requiring human user interaction – to changing application requests. Furthermore, this is achieved without imposing additional cost for network development/deployment to support safety-of-life applications.

C. Self-Growing Home and Office Environment

This use case addresses the deployment of a heterogeneous wireless network in a limited geographical area, such as a home and office environment. The objective is that such a network guarantees the provision of voice and data communication services, but also acts as a large scale, distributed and cooperating system for monitoring and control, possibly incorporating Wireless Sensor Networks. The utilisation of a network entity in a home or office environment may vary a lot during a normal day, for example it may not be used at all when there is no one at home or in the office. The energy efficient parameterisation of the corresponding network is a key challenge, due to both the variation in usage and the high percentage of households that are expected to apply the corresponding concepts in the future. However, this potentially great number of adopters also implies that the inherent potential for energy savings is huge. A further challenge lies in the efficient inter-network parameterisation, to support spontaneous ad-hoc cooperation between objects and exploit network-centric computing paradigms with dynamic resource management.

In practice, the deployment of such a network is expected to be done in various stages. In an initial stage of deployment, households and/or offices will deploy a network designed for an initial estimate of capacity and Quality of Service requirements. For cost reasons, typically common-off-the-shelf equipment is employed without any consideration concerning potential needs for a future evolution of such networks. Also, its integration taking into account corresponding deployments of distinct owners and/or interest groups in the vicinity is typically not considered in such an early phase.

In an intermediate deployment stage, the initial deployment evolves with needs for higher Quality of Service and the interconnection of a constantly increasing number of devices, partially building of novel radio components (for example, UWB components on top of an available WLAN and cellular network environment). The need for an overall network integration becomes apparent taking corresponding deployments in the vicinity into account. This furthermore includes a required evolution towards a distributed and cooperating system being able to support monitoring and control, incorporating wireless sensor networks. Self-growing networks are expected to provide a framework meeting both challenges, through the optimised integration of novel devices into a given network and the efficient overall system configuration taking the overall networking environment in the vicinity into account. Specifically, the approach will provide algorithms that lead to an automated parameterisation of all network components in the managed environment as well as in its vicinity; in particular, an overall change of the network configuration is considered if novel radio components are deployed.

In the final deployment stage, the home/office environment reaches a stable level of a high-density heterogeneous network deployment. The self-growing and self-optimised evolutionary approaches have lead to a stable network deployment, ensuring a low level of overall energy consumption and an optimum exploitation of the available system capacity. Typically, such stable stages exist for some time but eventually the network evolves further, and the network thereby enters the “intermediate stage” again.

Expected benefits of the self-growing concept in this use case include the seamless evolution of a home/office network without any user involvement together with the minimization of efforts to be spent for planning and maintenance. At the same time, the proposed mechanisms facilitate an overall low-power and high capacity optimization of the network taking device deployment and parameterisation in the vicinity into account.

IV. CONCLUSION

In future large-scale distributed systems, the emergence of mechanisms supporting robust, predictable and self-adaptive behaviour will be an important evolution step. Towards this goal we have introduced the notion of a self-growing network that during its lifecycle, can evolve (grow) to serve different objectives. The CONSERN project aims at defining and developing the required mechanisms for realizing the self-growing network paradigm. From the analysis of three major uses cases it is clear that the number of affected entities (e.g. users, operators, manufacturers) is considerable and the potential impact is very significant.

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