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Trends in the development of communication networks: Cognitive networks

Carolina Fortuna *, Mihael Mohorcic

Department of Communication Systems, Jozef Stefan Institute, Jamova 39, Ljubljana, Slovenia

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ABSTRACT

One of the main challenges already faced by communication networks is the efficient management of increasing complexity. The recently proposed concept of cognitive network appears as a candidate that can address this issue. In this paper, we survey the existing research work on cognitive networks, as well as related and enabling techniques and technologies. We start with identifying the most recent research trends in communication networks and classifying them according to the approach taken towards the traditional layered architecture. In the analysis we focus on two related trends: cross-layer design and cognitive networks. We classify the cognitive networks related work in that mainly concerned with knowledge representation and that predominantly dealing with the cognition loop. We discuss the existing definitions of cognitive networks and, with respect to those, position our understanding of the concept. Next, we provide a summary of artificial intelligence techniques that are potentially suitable for the development of cognitive networks, and map them to the corresponding states of the cognition loop. We summarize and compare seven architectural proposals that comply with the requirements for a cognitive network. We discuss their relative merits and identify some future research challenges before we conclude with an overview of standardization efforts.

1. Introduction

The area of information and communication technologies is one of the fastest changing areas, with related services and applications having enormous and almost immediate impact on diverse aspects of the modern society, including inter-human relations, economy, education and entertainment. In this respect the development of reliable and robust yet flexible and future proof communication infrastructure capable of real-time, secure and cost effective delivery of data is of utmost importance to increase the user's perceived quality of life by facilitating human-to-human as well as human-to-machine communication almost anywhere and anytime, providing services such as e-health, e-learning and e-payments. Future networks will be ever more complex, extending towards ubiquitous communications, and will provide a broad range of other services and applications, from remote managing of an intelligent house to advanced real-time navigation systems.

In spite of the increased complexity, future networks should be easily maintainable and their capabilities should be continuously improved and upgraded by relying as little as possible on human intervention. In order to meet this demand, the networking research community proposed a new paradigm for networking: the cognitive network [1–3]. Architectures that fall under this paradigm include a cognitive process that can sense current reality, plan for the future, make a decision and act accordingly. It is generally agreed that cognitive networks have the ability to think, to learn and to remember [2,3].

* Corresponding author. Tel.: +386 14773114.
E-mail addresses: carolina.fortuna@ijs.si (C. Fortuna), miha.mohorcic@ijs.si (M. Mohorcic).

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The capabilities of a cognitive network can be highly distributed or extremely centralized depending on the engineering tradeoffs for each specific network. In general, a cognitive network is formed of a set of distributed cognitive entities (agents), which are somehow "smart" in the way that they have certain reasoning capabilities and are connected in a network. In this network the cognitive entities interact with each other; they can cooperate, act selfishly or a combination of the two. While functioning in this environment, the cognitive entities are able to learn and take decisions in such way as to reach an end-to-end goal (or optimize a set of end-to-end goals). These end-to-end goals are dictated by the business and user requirements [4,3]. Developing and maintaining such a network is an extremely challenging task and has enormous potential, especially in the area of network management

A cognitive network needs to evolve over time: its set of technologies has to be updated by removing deprecated and adding new ones; its set of tools that help managing complexity should be added and removed in a plug and play fashion. Thus, the architecture of the cognitive network should be flexible and should lead to a modular and highly scalable infrastructure. Furthermore, the cognitive network must be self-aware: it should be able to know what is happening inside, what it must do; it must be able to determine appropriate actions to achieve goals and to learn while doing all these. It should be self-configuring, self-optimizing, self-healing and self-protecting in a *cognitive* way. Developing of such a network necessitates state-of-the-art knowledge and tools from various fields of science carefully engineered into a complex and efficient system.

In this paper, we analyze some recent trends in the development of communication networks and investigate in more detail the concept of cognitive networks. Cognitive networks are promising to be the major step towards efficient and autonomic management of increasing complexity of communication networks. In Section 2, we briefly discuss the current necessities from user's and network operator's point of view and provide an objective analysis of trends for the future, carried out using an ontology editor. Section 3 presents the five approaches of the research community towards developing communication networks, paying special attention to two of them that fit in the concept of cognitive networks. Section 4 provides a conceptual overview and the definition of cognitive networks as well as enabling technologies and tools, while Section 5 summarizes different architectures for cognitive networks proposed in the literature and discusses their relative merits. Current standardization activities are briefly mentioned in Section 6 while Section 7 concludes the paper.

2. Current necessities and research directions

In the history of telecommunications, development has always been driven by humans' need to communicate, i.e. reliably transmit ever increasing amount of information across increasing distances. Over time this resulted in the current landscape of telecommunications characterized by large variety of technologies that are offering various ways to connect users with other users or with application servers. Worldwide standardization efforts are enabling interoperability and integration of legacy, new and emerging technologies. However, communication networks became increasingly complex and more difficult to manage, requiring increasingly specialized tools and human operators for their maintenance, configuration and optimization.

From the user's point of view the necessities in the world of telecommunications, as it is today, are: higher bandwidth or alternative solutions (since the full bandwidth of a link is scarcely used at full capacity) capable of accommodating the traffic; QoS for the wide range of applications that fixed/mobile terminals support and services that network operators deliver; more flexibility in choosing service providers and access technologies; security; reliability; and low costs. These necessities derive from the users' thirst for digital content.

From the network operator's point of view, some of the main necessities are: complexity management; security; scalability; fault tolerance; fast integration of new technologies; and a good business model [5]. The network operator has to create adequate premises for delivering the digital content.

These user's and network operator's necessities are actually forming the basis for research activities currently underway in the area of cognitive networks, as we show in the following. In general, research directions in communications can be classified in eight broad categories: theory, signal processing, networks, software, user satisfaction, security, management, and new/next generation protocols and architectures. In an attempt to obtain an objective big picture of the trends in research areas as well as a quantitative estimation of the ongoing work, we used Ontogen, a semi-automatic ontology editor [6], to analyze the conference proceedings of IEEE Globecom 2006 and 2007, totaling 2011 papers. Fig. 1 presents a topic map which is a 2D visualization of the IEEE Globecom papers based on processing paper titles and abstracts. Papers addressing similar issues are positioned close to each other, thus forming clusters which represent the main topics approached by the papers within this particular conference. The keywords that appear on the map are the most descriptive for the cluster of papers projected in the corresponding area.

Two main clusters can be easily distinguished on top left side of Fig. 1, transversally disposed, one on the upper side of the figure and the other on the lower side. The upper cluster of papers on system and network level aspects is described by relevant keywords such as *networking, sensor, wireless, node, routes, mobile, protocol, algorithms, scheme* and *scheduling*. The relevant keywords describing the lower cluster of papers on propagation channel and radio interface aspects are *code, channels, estimates, MIMO, OFDM, receiver, frequency, systems, fading* and *antenna*. The density of the two clusters decreases towards the left where a merger between them can be also noticed (see zoomed area in Fig. 1). In this area, keywords such as *relay, cooperative* and *cognitive* can be found denoting emerging trends in wireless relay, cooperative and cognitive networks. The content of these documents is somewhere between the two main, and traditional, areas of research: low layers such as physical and data link and