
A simple survey of knowledge plane approaches for future cognitive wireless networks

Vitor Guerra Rolla*, Alexandre Miguel Pinto and Marilia Curado

Department of Informatics Engineering,
University of Coimbra,
Pólo II – Pinhal de Marrocos,
3030-290, Portugal

E-mail: vitorgr@dei.uc.pt

E-mail: ampinto@dei.uc.pt

E-mail: marilia@dei.uc.pt

*Corresponding author

Abstract: The knowledge plane (KP) paradigm proposes the evolution to a cognitive network, where the devices learn, decide, and act to achieve end-to-end goals. This emerging paradigm is clarifying a set of new cognitive-based protocols and algorithms that optimise wireless network's performance. This work presents a survey of the most relevant research about wireless network techniques that employ KP concepts. Open issues that should be addressed by an applicable cognitive wireless network are identified.

Keywords: knowledge plane; cognitive wireless networks.

Reference to this paper should be made as follows: Rolla, V.G., Pinto, A.M. and Curado, M. (2012) 'A simple survey of knowledge plane approaches for future cognitive wireless networks', *Int. J. Mobile Network Design and Innovation*, Vol. 4, No. 4, pp.179–184.

Biographical notes: Vitor Guerra Rolla is a PhD student at the University of Coimbra, Portugal. His research interests include the use of artificial intelligence tools to solve routing problems in heterogeneous wireless networks. He received his MSc in Computer Science from IME, Rio de Janeiro, Brazil.

Alexandre Miguel Pinto is an invited Assistant Professor at the Department of Informatics Engineering, University of Coimbra, Portugal. He received his PhD in Computer Science from the New University of Lisbon. His research interests include, among others, knowledge representation and reasoning, computational logic, cognitive science, and semantic web.

Marilia Curado is an Assistant Professor at the Department of Informatics Engineering, University of Coimbra, Portugal, where she received her PhD in Informatics Engineering on the subject of quality of service routing. Her research interests are quality of service, mobility, routing, and resilience.

1 Introduction

Within the last few years the internet has morphed into a demanding network exchanging massive flows of information. The explosion of wireless mobile computing, the exponential growth of users, and the endless propagation of eclectic services, introduced new scale and distribution problems in different layers of the traditional open systems interconnection (OSI) model (Zimmermann, 1988). In order to manage this complexity, a new paradigm, the knowledge plane (KP), has been proposed. This new paradigm promises an evolution of the internet into an intelligent communications system capable of learning and improving its own performance and availability, resulting in decreased network access costs. Intelligent devices (e.g., smartphones, tablets and notebooks) that can make proactive decisions

(e.g., choose the cheapest network available) based on learning, reasoning, and cooperation, can help improve performance and coverage of wireless mobile networks.

According to Thomas (2007), cognitive networks are data networks that use artificial intelligence to learn and reason varying network conditions to optimise end-to-end goals. In order for a network to be cognitive it must be self-aware, and that means the agents (intelligent devices) in the network should be conscious of themselves, as well as the network. Research about cognitive networks is almost always related to the KP (Clark et al., 2003). Several different KP-based approaches have been proposed. This work addresses cognitive solutions for wireless networks that employ KP concepts.

The evolution to a KP is presented in Section 2. A survey of KP approaches for cognitive wireless networks appears in Section 3. Section 4 concludes with open issues and KP future.

2 The evolution to a KP

Various fields of research emerged to improve performance of the internet and the OSI model proposing cross-layer designs (Dougherty, 2005) and cognitive networks (Thomas, 2007). Cross-layer designs proposed (for the first time) that a specific OSI layer be designed concerning performance problems from another OSI layer (Srivastava and Motani, 2005). A cross-layer solution adapts the network stack allowing communication or sharing of internal information between layers. The information processing of each layer may occur implicitly, explicitly, or vertically.

In implicit cross-layer designs, one layer is designed taking into account a specific process performed by a fixed layer, no new interface has to be created. Implicit cross-layer design does not fully optimise the network stack due to architecture impositions (Dixit, 2003), limiting network flexibility and upgradeability. If several layers are designed this way, it would be impossible to describe the behaviour of the network, given the large number of variables (Giambene and Kota, 2006).

In explicit cross-layer designs, the information processing occurs by splitting or merging layers. Splitting a layer preserves outer interfaces and creates others between the new sub-layers. Examples of splitting layers are media access control (MAC) and logical link control (LLC). MAC and LLC resulted from the split of data link layer of the OSI model (Tanenbaum, 1988). Merging layers keeps the outer interfaces and does not create new ones. A great example of a merging physical layer and a LLC sub-layer can be found in wireless networks to improve spectral efficiency (ElBatt and Ephremides, 2002). Splitting and merging layers tends to optimise single goals and these approaches have difficulties adapting to changes (Giambene and Kota, 2006).

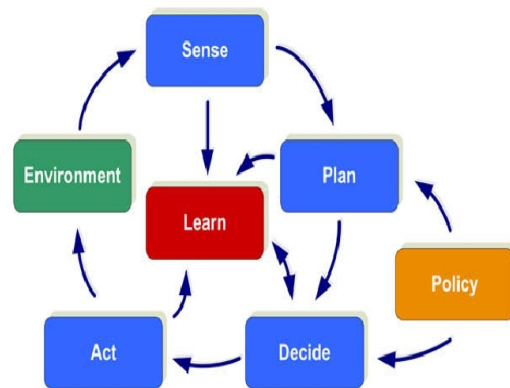
Vertical calibration attempted to establish certain rules regarding how layer interactions and information sharing occurs. A common shared database is proposed to avoid direct communication between layers combined with a structured method for accessing parameters, controlling, and sensing the status of each layer (Mahmoud, 2007). Vertical calibration is based on the idea that solid architectural designs lead to proliferation and longevity like the TCP/IP and the OSI models (Kawadia and Kumar, 2005). Unlike the KP, in cross-layer design solutions, the layers started to interact but there is no intelligence, learning, or pro-active adaptation.

The KP paradigm is responsible for bringing cognition to the OSI model with the introduction of artificial intelligence concepts. This paradigm is giving rise to a set of new intelligent network solutions (algorithms and protocols) which optimise wireless network performance.

At the abstract level, KP is a system for gathering observations, constraints and assertions, to generate useful knowledge about the network environment. At the physical level, KP is a system built out on the agents (intelligent devices) within the cognitive network. The agents are capable of making proactive decisions based on learning, reasoning and cooperation to improve performance and coverage.

The KP proposes a new objective for computer network research building fundamentally different network tools (algorithms and protocols) that can drive its own deployment and configuration, that can diagnose its own problems, and make defensible decisions about how to solve such problems. It assumes that experiences are all available at the environment, and the learning process transforms these into knowledge. Such continuing experiences can be summarised by a cognitive loop, as shown in Figure 1. The cognitive loop senses the environment, learns, and transforms experiences into knowledge to improve performance by acting in the environment.

Figure 1 Cognitive loop (see online version for colours)



Source: Fortuna and Mohorcic (2009)

3 KP approaches for cognitive wireless networks

Two fundamental aspects must be considered when building a cognitive wireless network that employs the KP concepts:

- 1 knowledge representation, how the network agents (intelligent devices) learn, represent, store and distribute knowledge
- 2 reasoning over knowledge, how the agents make use of learned knowledge.

3.1 Stack manager

The stack manager (SM) (Sutton et al., 2006) reconfigurable cognitive network platform consists of agents capable of changing each specific operation as necessary based on a component configuration inventory. The components can be

linked together to form a dynamic configuration network stack, where the layers, protocols and algorithms are represented as individual components, with varying levels of granularity.

Given an available wireless network, the SM constructs and initialises the required components of the network stack and controls its operation. The SM is responsible for deciding and reacting to any events signalled by the components as well as performing any reconfiguration required.

This proposal uses a XML file as a semantic knowledge representation to store the inventory of components and the well-known available wireless networks. A cognitive loop is proposed to think based upon the collected knowledge.

3.2 Cognitive resource manager

The cognitive resource manager (CRM) (Mahonen et al., 2006) interacts with the network and enables autonomic optimisation of the communication stack as a whole. The authors argue that cognitive techniques and the KP are alternatives to traditional cross-layer optimisation, which has proven to be more problematic than the initial upbeat works.

The solution is composed of a policy repository, a toolbox, and a direct interface. The repository dictates policies through supervised learning that should be followed by the CRM. The construction of a toolbox with a set of knowledge representation and reasoning tools is proposed, for example, simulated annealing, neural networks, colouring, bayesian reasoning, statistical learning theory and time series. A direct interface between the CRM and the application layer negotiates quality of service (QoS) requirements.

The CRM is aware of the spectrum usage, the quality of available links, the application layer traffic information, and the other agents participating in the cognitive network. Since it requires knowledge from the higher-layers, the authors suggest that CRM is a solid candidate to solve well known wireless problems. For instance, the interactions of transport control protocol (TCP) over wireless links. TCP does not explicitly account for complex interference in static multi-hop wireless routes leading to starvation and unfairness (Zhuang, 2012).

3.3 Intelligent handover management

The intelligent handover management (IHM) (Ahmed et al., 2010) presents a knowledge-based handover anticipation scheme. The authors propose the deployment of a multi-agent system (MAS) for handover decisions intended to reduce the data loss and to improve the handover delay. The intelligent agents are responsible for collecting information for sustaining the KP, and consequently, the handover decision and the network selection processes.

The information collection and the handover anticipation are based on two fundamental assumptions. First, the handover behaviour of any mobile user is more or less

similar to the mobile users that came from the same previous cells, and second, the mobile users have the same mobility pattern in the current cell in order to predict the future handover. Thus, it is possible to determine the next attachment point of a mobile user and estimate its handover time by using a history of observations in each network cell. Bandwidth, cost, user preferences, and user mobility pattern are examples of observed parameters.

The knowledge is represented by the agents through the use of an ontology that defines the network knowledge (e.g., QoS parameters, network coverage and monetary cost), and the agent knowledge (e.g., running applications, terminal status and user preferences). The collected information combined with the exchanged information from the other agents constitutes the local view of the agent. To determine whether a handover is necessary or not, the agent uses simple if-then conditions.

3.4 SmartA

SmartA (Fortuna and Mohorcic, 2008) is a KP-based solution that uses cognitive methods to represent QoS knowledge for efficient service delivery in heterogeneous wireless networks. The solution is composed of the assignment engine, the SM, and the resource manager.

The assignment engine is the component of the architecture that is responsible for optimally assigning layer two radio access services. This assignment is not specifically defined, but the authors suggest it should depend on the definition of an optimisation problem. For instance, the assignment could be performed by either minimising the cost of wireless access or maximising user satisfaction. The SM considers the application layer QoS requirements and the context information exchanged with the other agents and the network environment. The solution holds a semantic knowledge representation of QoS, that is represented by an ontology. The resource manager makes use of a cognitive loop to decide the best assignment based on previous experience.

3.5 Personal router

The personal router project aims to offer customised wireless services in an open market to provide ubiquitous access through a personal router device. The end-to-end goal is to offer the best and most convenient access service.

As part of the research, in Lee et al. (2004) a cognitive personal agent for wireless access service selection is proposed. The agent interacts with the wireless environment by continuously monitoring new available networks, and interacts with the user by retrieving feedback with respect to his/her satisfaction (supervised learning). The agent learns the user's preferences and selects the network that best fits these preferences in an autonomic and continuous fashion. In Faratin et al. (2002), reinforcement learning and collaborative filtering are used as knowledge acquiring methods.

Table 1 Summary of KP approaches

<i>KP approaches for cognitive wireless networks</i>				
<i>Protocol</i>	<i>Knowledge representation</i>	<i>Reasoning over knowledge</i>	<i>End-to-end goal</i>	<i>Publication year</i>
Stack manager (Sutton et al., 2006)	XML file	Cognitive loop	Optimisation of network stack and agent reconfiguration	2006
CRM (Mahonen et al., 2006)	Numeric (e.g., simulated annealing or neural network)	Bayesian reasoning	Autonomic optimisation of network stack	2006
IHM (Ahmed et al., 2010)	Ontology	Simple if-then conditions	Handover decision and network selection	2010
SmartA (Fortuna and Mohorcic, 2008)	Ontology language for encoding semantics	Cognitive loop	QoS knowledge for efficient service delivery	2008
Personal router (Lee et al., 2004)	Reinforcement learning and collaborative filtering	Utility functions	Convenient network selection	2004
ALBA (Sawma et al., 2008)	XML file	Simple if-then conditions	Relieve congestion by redistributing agents around overloaded fixed access points	2008
AMA (Latré and Simoens, 2009)	Numeric (neural network)	Cognitive loop	Optimisation of video quality of experience	2009

Utility functions enable the agent to comprehend the quality and cost of services in different network contexts. The authors argue that the construction of such a function is the core of the service selection problem.

3.6 *Autonomic networking and load balancing*

The autonomic networking and load balancing (ALBA) (Sawma et al., 2008) solution contains detailed runtime knowledge about the network load and channel utilisation, as well as the connection speed, the spatial distribution, and application QoS requirements of each wireless agent. Its main objective is to exploit the unused network resources to relieve the congested fixed access points while ensuring that eventually low rate stations will not degrade the QoS of the other existing connections. This is achieved by redistributing the agents around the overloaded fixed access points according to a wave-like pattern.

The authors propose a semantic knowledge representation of the current state of resources, the available fixed access point and the list of neighbours agents. This knowledge is used by ALBA to choose the best wireless agent to leave and re-join the network when the load must be redistributed to maintain global network QoS requirements. The agent comprehends the environment through simple if-then conditions. The solution was evaluated on an OPNET network simulator with a specific voice over wireless network application.

3.7 *Autonomic management architecture*

The autonomic management architecture (AMA) (Latré and Simoens, 2009) proposes the optimisation of the quality of experience (QoE) in multimedia wireless access networks using a cognitive loop. The solution is based on three different components: a monitor plane which monitors the

network and builds up knowledge about the neighbourhood environment, a KP that analyses and determines the ideal QoE actions, and an action plane that enforces these actions into the network.

The authors designed two knowledge representation formalisms that are part of the KP component. Using an analytical set of equations and a three layer neural network, AMA can optimise the QoE of video services in wireless multimedia networks by applying forward error correction to reduce the packet loss on a specific link and switching to a different video rate to avoid congestion.

AMA was tested in terms of the packet loss ratio and the peak signal noise ratio metrics using a modified version of the ns2 simulator and a practical testbed. The results show that both knowledge representation formalisms are capable of increasing video quality and lowering packet loss ratio.

3.8 *Summary*

Cognitive solutions for wireless networks attempts to address the challenges imposed by future wireless networks with large numbers of dynamic agents and multiple heterogeneous devices.

In this survey, the most relevant cognitive wireless networks that employ KP concepts were presented. Table 1 is a summary of these approaches. The research community addresses the issue from different perspectives, therefore intelligent solutions with different end-to-end goals have been proposed. The SM and the CRM proposals are concerned with the optimisation of the network layer stack. The IHM and the Personal Router projects are concerned with the network selection and the handover problems. Finally, the ALBA, the AMA and the SmartA solutions are concerned with QoS, QoE, and congestion problems.

4 Conclusions

A new active and expanding field of research employing KP concepts in cognitive wireless networks holds the promise of evolving into an intelligent communication system capable of improving the performance requirements in different types of wireless networks [e.g., wireless mesh networks (WMN), wireless community networks (WCN), mobile ad-hoc networks (MANET), vehicular ad-hoc networks (VANET), and delay-tolerant networks (DTN)].

The necessity of an intelligent computer network is rapidly growing alongside the implementation of information technology. In future cognitive wireless networks, intelligent devices must be able to organise themselves to take advantage of any communication opportunity to achieve end-to-end goals. Given today's internet demand, it is important to understand how intelligent devices can make proactive decisions which can help improve the performance and coverage of wireless mobile networks, and consequently the end user experience.

4.1 Open issues

The KP paradigm is clarifying a set of new cognitive-based protocols and algorithms that optimise the wireless networks performance on all layers of the OSI model. However, a number of end-to-end goals at different layers of the network stack still must be addressed to improve throughput, channel reliability, service provision, and obviously, data security (both in terms of transmission and data storage). For instance, at the transport layer the TCP does not explicitly account for complex interference in static multi-hop wireless routes leading to starvation and unfairness. At the MAC layer the hidden and exposed agent problems lead to low network performance. At the network layer the routing protocols must deal with the issues in heterogeneous environments that may lack continuous network connectivity. For more detailed information, see Zhuang (2012).

4.2 KP future

In the future, intelligent KP characteristics paired with the increase in mobile device density will trigger a communications revolution. Intelligent devices will work with each other to create an alternative spectrum. This new spectrum will stimulate the creation of an open and competitive market in which the intelligent devices can assemble themselves to offer customised wireless services, reassemble themselves as requirements change due to mobility, and switch to an alternative available network when something goes wrong.

Such new cooperative behaviour removes an individual's co-dependence of an internet service provider and places the control in the hands of the intelligent wireless devices themselves, which shall lower the cost of the internet for cooperative end users. Quite possibly, in the

not so distant future, a text message will travel through the streets jumping into and out of intelligent wireless devices all for free.

Acknowledgements

Fundação para Ciência e Tecnologia (FCT) User Centric Routing (UCR) Project (PTDC/EEA-TEL/103637/2008). The authors would like to acknowledge Ms. Sabrina A. Arlotta for her grammatical corrections.

References

- Ahmed, A., Boulahia, L.M., Gaiti, D. and Amoud, R.R. (2010) 'Towards a knowledge-based intelligent handover in heterogeneous wireless networks', *IEEE Local Computer Network Conference*, pp.284–287.
- Clark, D.D., Partridge, C. and Ramming, J.C. (2003) 'A knowledge plane for the internet', in *SIGCOMM*, pp.3–10.
- Dixit, S. (Ed.) (2003) *IP Over WDM: Building the Next-generation Optical Internet*, Wiley-Interscience, New York, NY, USA.
- Dougherty, N. (2005) 'Cross-layer design: a survey and the road ahead', *IEEE Communications Magazine*, December, pp.112–119.
- ElBatt, T. and Ephremides, A. (2004) 'Joint scheduling and power control for wireless ad hoc networks', *Wireless Communications, IEEE Transactions on*, Vol. 3, No. 1, pp.74–85.
- Faratin, P., Wroclawski, J., Lee, G. and Parsons, S. (2002) 'The personal router: an agent for wireless access', Technical report, AAAI '02.
- Fortuna, C. and Mohorcic, M. (2008) 'Advanced access architecture for efficient service delivery in heterogeneous wireless networks', in *Communications and Networking in China, ChinaCom 2008, Third International Conference on*, pp.1173–1177.
- Fortuna, C. and Mohorcic, M. (2009) 'Trends in the development of communication networks: cognitive networks', *Computer Networks*, Vol. 53, No. 9, pp.1354–1376.
- Giambene, G. and Kota, S. (2006) 'Cross-layer protocol optimization for satellite communications networks: a survey', *International Journal of Satellite Communications and Networking*, Vol. 24, No. 5, pp.323–341.
- Kawadia, V. and Kumar, P.R. (2005) 'A cautionary perspective on cross layer', *IEEE Wireless Communication Magazine*, Vol. 12, pp.3–11.
- Latré, S. and Simoens, P. (2009) 'An autonomic architecture for optimizing QoE in multimedia access networks', *Computer Networks*, Vol. 53, No. 10, pp.1587–1602.
- Lee, G., Faratin, P., Bauer, S. and Wroclawski, J. (2004) 'A user-guided cognitive agent for network service selection in pervasive computing environments', in *PERCOM '04: Proceedings of the Second IEEE International Conference on Pervasive Computing and Communications (PerCom '04)*, IEEE Computer Society, Washington, DC, USA, p.219.
- Mahmoud, Q. (2007) *Cognitive Networks: Towards Self-Aware Networks*, Wiley-Interscience.

- Mahonen, P., Petrova, M., Riihijarvi, J. and Wellens, M. (2006) 'Cognitive wireless networks: your network just became a teenager', in *Proceedings of the INFOCOM*, Barcelona.
- Sawma, G., Aib, I., Ben-El-Kezadri, R. and Pujolle, G. (2008) 'Alba: an autonomic load balancing algorithm for IEEE 802.11 wireless networks', in *Network Operations and Management Symposium*, NOMS 2008, IEEE, pp.891–894.
- Srivastava, V. and Motani, M. (2005) 'Cross-layer design: a survey and the road ahead', *Communications Magazine*, IEEE, Vol. 43, No. 12, pp.112–119.
- Sutton, P., Doyle, L.E. and Nolan, K.E. (2006) 'A reconfigurable platform for cognitive networks', in *Cognitive Radio Oriented Wireless Networks and Communications*, 1st International Conference on, pp.1–5.
- Tanenbaum, A.S. (1988) *Computer Networks*, 2nd ed., Prentice-Hall, Inc., Upper Saddle River, NJ, USA.
- Thomas, R.W. (2007) *Cognitive Networks*, PhD thesis, Blacksburg, VA, USA, Adviser-Dasilva, Luiz A.
- Zhuang, W. and Ismail, M. (2012) 'Cooperation in wireless communication networks', *Wireless Communications*, IEEE, Vol. 19, No. 2, pp.10–20.
- Zimmermann, H. (1980) 'Osi reference model-the iso model of architecture for open systems interconnection', *Communications*, IEEE Transactions on, Vol. 28, No. 4, pp.425–432.