Survey on Signaling Techniques for Cognitive Networks

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Abstract— **Network evolution towards self-aware autonomous adaptive networking aims at reducing the burden of configuring and managing networks, which leads to performance degradation. In order to optimize network operations, the introduction of self-awareness, self-management, and self-healing into the network was proposed, leading to a novel paradigm in networking - known as cognitive networking. This paper surveys the state-of-the-art, in cognitive networking - identifying fundamental techniques and basic building blocks enabling cognition. Following an overview of existing methods for cross-layer signaling, the paper identifies the most appropriate approaches to be used for cognitive network implementation outlining advantages, drawbacks, and provides guidance for usage of each signaling method.**

Keywords- Cognitive networks, signaling

I. INTRODUCTION

The evolution of communication technologies, especially in the wireless domain, introduced a paradigm shift from static to mobile access, from centralized to distributed infrastructure, and from passive to active networking. Technological advances have brought networking a step forward towards the goal of service provision on an "anytime, anywhere" basis, while ensuring instantaneous and secure communications. However, such innovation is bound by the constraints included in the original Internet (and TCP/IP) design. The fundamental reason for performance inefficiency is the difficulty in configuring and managing networks [1].

Self-awareness, self-management, and self-healing characteristics have been proposed in order to optimize network operation, reconfiguration, and management, as well as to improve data transfer performance by bringing "intelligence" into the network, thereby creating a new paradigm known as cognitive networking, which is expected to become a key part of 4th generation wireless networks (4G) [2].

The term cognitive is related to the ability of a network to be aware of its operational status and adjust its operational parameters to fulfill specific tasks, such as detecting changes in the environment and user requirements. Cognition requires support from network elements (routers, switches, base stations, etc.), which should host active tasks to perform measurements to reconfigure the network.

The ability of cognitive network to think, to learn and benefit from past experience requires communication between cognitive elements. Cognitive network implementation can be highly distributed or tend towards centralized solutions. Common cognitive network is composed of the set of cognitive engines which may reside inside a certain protocol layer, be implemented between different layers, or be distributed between different nodes in the network. A detailed survey on cognitive networks is presented in [11].

Each cognitive agent operates locally but it also contributes into global goals by interfacing with other cognitive agents. As a result, efficiency of cognitive network operation depends on the efficiency of communication between the agents. Depending on the scope, inter-layer, intra-layer, or at the network level, different communication technologies are used which put additional constraints in terms of speed and delay of information exchange. These constraints cannot be neglected and should be taken into account during the design of cognitive network architecture and its agents.

II. SIGNALING TECHNIQUES

Initially, most of the signaling techniques appeared to overcome different limitations of the standard TCP/IP protocol reference model. Depending on the scope signaling techniques can be divided into two broad categories: node-level signaling and network-level signaling (see Table I).

A. Node-level Signaling

Node-level signaling techniques provide the means for information exchange between different layers of the TCP/IP stack initially designed to be standalone and separated.

Interlayer signaling pipe is one of the first approaches used for implementation of cross-layer signaling [3], to allow the propagation of signaling messages layer-to-layer along the packet data flow. Signaling information, included in an optional portion of packet headers, follows the packet processing path within the protocol stack, either in a top-down or a bottom-up manner. An important property of this signaling method is that signaling information can be associated with a particular packet incoming or outgoing from the protocol stack.

Interlayer signaling pipe can be implemented using encapsulation of signaling information into packet headers, for example into an optional portion of IPv6 header [4], or using packet structures allocated by the protocol stack internally.

Generally, signaling method using packet structures is more favorable due to lower processing overhead, flexibility, and simplicity of access or modification of encapsulated information at any protocol layer.

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TABLE I. COMPARISON OF SIGNALING APPROACHES

	Signaling Method	Scope	Type of Signaling	Signaling latency	Communication overhead	In-band / Out-of-band	Direction of signaling	Packet Association
Node-level Signaling	Interlayer signaling pipe	Node	Indication	Medium	High	In-band	Path dependent	Maintained
	Direct interlayer communication	Node	Request/ Response	Low	High	Out-of-band	Path independent	Not maintained
	Central cognitive plane	Node	Indication/ Request/ Response	Low	Medium	Out-of-band	Path independent	Not maintained
Network-level Signaling	ICMP messages	Network	Indication/ Request/ Response	High	High	Out-of-band	Path independent	Not maintained
	Packet headers	Network	Indication	High	Low	In-band	Path dependent	Maintained
	Explicit Notification	Network	Indication	High	Low	In-band	Path independent	Not maintained
	WCI	Network	Indication/ Request/ Response	High	High	Out-of-band	Path independent	Not maintained
	Cross-talk	Node/ Network	Indication/ Request/ Response	High	Low	In-band	Path dependent	Maintained

Direct Interlayer Communication (DIC), proposed in [3], aims at improvement of Interlayer signaling pipe method through the introduction of "signaling shortcuts" - performed out of band. DIC allows non-neighboring layers of the protocol stack to exchange messages, skipping processing at every adjacent layer. Along with reduced processing overhead, DIC avoids insertion of signaling information into packet headers, which makes it suitable for bidirectional communication.

Despite the advantages of direct communication between protocol layers and a standardized way of signaling, the ICMP-based approach involves operation with heavy protocol headers (IP and ICMP), as well as significant protocol processing overhead. Moreover, it appears to be limited to request-response actions, while more complicated signaling should be adapted to handle asynchronous events. To this aim, a mechanism employing callback functions at the node level can be proposed. Such mechanism allows a given protocol layer to register a specific procedure (callback function) with another protocol layer, whose execution is triggered by a certain event at that layer.

The Central Cognitive Plane, implemented in parallel to the protocol stack, is probably the most widely proposed interlayer signaling architecture. Each protocol layer is extended with a tiny interface allowing exchange of information and configuration commands to/from the layer. These interfaces are interconnected with a cognitive engine using a common bus.

Implementation of this signaling method could be as simple as a shared database accessed by all the layers [5], while more advanced implementations introduce signaling interfaces as each protocol level internally providing an access to the internal protocol layer parameters and functions [6].

B. Network-level Signaling

Most of the existing cross-layer signaling proposals employ signaling between different layers within the protocol stack of a single node. However, as emphasized in [7], true cognitive networking should maintain a network-wide scope - with the cognitive process operating on end-to-end goals. Consequentially, cognitive networks require signaling approaches capable of signaling information delivery between different nodes in the network in an effective way.

Packet headers can be used for propagation of signaling information between different nodes of the network. Nowadays, many protocol headers of TCP/IP family, like TCP or IPv6, are extended with optional fields. Signaling information transmitted in these optional fields propagate along the packet flow and can be assessed at every router as well as end nodes. Such signaling methods keeps overhead at the minimum while allows signaling information be associated with a particular network packet. On the other hand, disadvantage of signaling using packet headers is in limitation of signaling direction to the packet flow. However, this drawback can be resolved with the use of ICMP messages for signaling.

ICMP messages constitute the default signaling method from the early days in networking. Signaling information, encapsulated into ICMP and IP headers, can be directed and processed by the destination in the way ordinary IP data packets are routed in the network. Moreover, with a few exceptions ICMP messages are processed at the protocol stack kernel level rather than in the user application domain.

Signaling using ICMP messages is desirable when instant communication should be performed out of the regular data flow direction. In order to maintain association of signaling information with a particular packet an explicit reference to this packet should be included.

ICMP messages consume network bandwidth and influence delay resources of other flows corresponding to a heavy overhead solution. Thus, they should be used as a complimentary signaling scheme to packet headers.

Explicit notification schemes, like Explicit Congestion Notification (ECN) presented in [8], is another example of network-level signaling. ECN signaling is performed in-band by letting network routers to mark in-transit TCP data packets with a congestion notification bit. Then, at the receiver this marking is turned back in TCP acknowledgement directed to the sender node.

The main advantage of explicit notification schemes is a low overhead. The drawbacks are in the limitation of signaling propagation to the data packet paths, requirement for maintaining signaling loop through the receiver, as well as requirement of all network routers to support signaling and traffic generation functionalities.

The WCI (Wireless Channel Information) is an example of adaptation of the Central Cognitive Plane architecture to network-level signaling [9]. It is accomplished using specifically dedicated network service able to collect current wireless channel characteristics at the link and physical layers. Then, WCI information is aggregated and provided back to the mobile stations allowing them to adapt better to constantly changing channel conditions. In this method, network communication is performed using standard TCP/IP protocols such as SNMP, HTTP over TCP and other.

Cross-Talk is a unique combination of node- and network-level signaling [10]. CrossTalk consists of two cross-layer optimization planes: one is responsible for the organization of cross-layer information exchange among protocol layers of a single node, and the other plane is responsible for network-wide coordination (considering aggregation of information provided by the local plane). Most of the signaling is performed in-band, using the packet headers method, making it accessible not only at the end host but at the network routers as well. Cross-layer information received from the network is aggregated and then can be considered for the optimization of local protocol stack operation based on global network conditions.

C. Comparison and Relevance for Cognitive Networks

In this section we compare available signaling approaches by the comparison of their individual characteristics like type of signaling, scope, signaling latency, communication overhead, in-band or out-of-band type of signaling, direction of signaling and whether signaling information can be associated with a particular packet flowing in the network.

As pointed later, there is no optimal choice of signaling scheme performing well both for node- and network-level signaling in all the considered scenarios. For that reason, several signaling methods should be employed in cognitive networks at the same time to ensure efficient functionality of cognitive algorithms.

A comparison of different characteristics of signaling methods is presented in Table I.

Scope defines the boundaries of signaling method operation. Solutions limiting their operation to a single protocol stack tend to be more flexible in the choice of signaling techniques: they can use internal protocol stack techniques such as packet structures or callback functions, thus avoiding processing related overhead and the need for standardization effort.

Solutions operating at the node are suited for signaling between reconfigurable elements of cognitive network injected inside the protocol layers. In case only several protocol layers are concerned by a cognitive network implementation signaling is typically performed using direct interlayer communication methods. However, in case of many protocol layers concerned, either interlayer signaling pipe or central cognitive plane are the desired solutions.

Type of signaling corresponds to the communication primitives supported by each signaling method. Approaches encapsulating signaling information into packet structures, like interlayer signaling pipe, packet headers, and explicit notification, are limited to indication primitive. While other approaches performing out-of-band signaling transmissions can perform wider range of communication types including request-response actions.

According to the type of signaling the choice of appropriate approaches depends on the actions required to be performed between cognitive agents. At the node level, cognitive engine performing blind monitoring of the environment can be connected with the cognitive engine core using methods supporting indication primitive only. This will allow low-overhead communications. However, in case a cognitive agent should follow setup comments request-response actions become unavoidable requiring the use of heavier signaling approaches.

Signaling latency parameter describes the delay associated with signaling message delivery. It becomes essential for signaling performed across the network, where the delay corresponds to the delay of communication links and time messages spend in router buffers. For local signaling methods, the delay is usually several orders of magnitude lower than for network-level cross-layering. However, signaling using interlayer signaling pipe method is slower than direct interlayer communications due to layer-by-layer processing. Moreover, interlayer signaling pipe can only afford asynchronous reaction to the event occurred, while direct communication allows instantaneous reaction.

Overall, propagation latency is an important parameter defining efficiency of cognitive network implementation and influencing its architecture design. It defines information aggregation and reporting intervals for cognitive engines performing monitoring, specifies the speed the decision is taken by the cognitive engine, and corresponds to the delay of the reaction taken for a given change in networking dynamics.

Communication overhead parameter is more important for network-level communications. It describes the amount of network resources required for signaling. Encapsulation of signaling information into packets headers does not require any additional network resources in case reserved fields are used, or corresponds to just minor increase in case optional packet header fields are involved. On the contrary, ICMP messages require a dedicated effort for their delivery from the network, consuming considerable amount of network resources – including also protocol (ICMP and IP headers) overhead. The communication overhead for local signaling corresponds to the amount of operations (CPU cycles) required to deliver the message from one layer to another. This parameter is different from processing overhead, which includes message encapsulation and processing. The highest communication overhead for local communications is associated with interlayer signaling pipe due to subsequent processing at several protocol layers before message delivery.

The lowest communication overhead corresponds to signaling methods relying on existing data flow a signaling bearer, like packet headers method. Other signaling methods, like using ICMP messages or WCI, require standalone transmission of signaling information encapsulated into heavy protocol headers, and thus consumes network bandwidth resources.

Communication overhead should be taken into account during design and tuning of cognitive network algorithms. It could happen that the bandwidth consumed by signaling could ruin all the benefits coming from cognitive optimization if cognitive engine reporting interval is chosen inappropriately.

In-band / Out-of-band parameter shows whether existing data traffic flow is used as carrier for signaling information (in-band) or signaling information is sent on its own (out-of-band). In-band signaling methods do not add any significant overhead in term of network bandwidth and routing resources. However, the main drawback of in-band signaling, like packet headers, explicit notification, or Cross-talk, is in type of signaling limited to indication primitive only and relatively high latency of message delivery. On the other hand, out-of-band signaling is not constrained in signaling type and allows the fastest information delivery between ends. However, this is done at expense of network resources.

Direction of signaling is an important characteristic which defines the applicability of the signaling approach to the chosen cross-layer optimization scheme. The out-of-band signaling schemes are packet path independent and can provide a faster reaction to an event. This reaction can be performed also in synchronous way, while packet path dependent signaling provides only asynchronous reaction. The speed and flexibility of path independent signaling comes at the expense of the additional communication resources. Nevertheless, path independence cannot be only considered as an advantage as it does not allow packet association.

Packet association shows whether signaling information can be associated with a specific packet transmitted through the network. Such property is required by many optimization approaches. For example, at the network level ECN signal sent along with a TCP data packet and echoed back with TCP acknowledgement by the receiver indirectly carries information related to TCP flow for which ECN signal is sent. At the node level information monitored at the physical layer (SNR or BER) is typically required to be associated with a packet it was measured for.

In-band signaling techniques maintain indirect association with between transferred signaling information and the packet used to carry it. On the other hand, if out-of-band signaling is used such association can be inserted explicitly. A good example is when "Time Exceeded" ICMP message sent by a router for a packet dropped due to expired TTL includes the copies of protocol headers of the packet dropped.

III. SIGNALING IN COGNITIVE NETWORKS

A. Available Cognitive Network Solutions

Research on cognitive networks was embraced by several efforts, both in the United States [12] and in Europe, being relevant within the European Sixth and Seventh Research Framework Programmes (FP6 [13] and FP7 [14]).

The E2R project is funded by European Commission and aims at providing reconfigurability capability to networks.

Architecture: The goal of E2R is the construction of an all-IP network fully integrated with reconfigurable equipment [16]. E2R includes many existing and upcoming radio access technologies like 2G, 3G, WLAN, WMAN, and DVB. However, the main focus of the project is biased towards cellular network architecture. In this framework, reconfiguration is considered almost in all the functional blocks for every network element. At the node level, reconfiguration starts at the radio modem and propagates up through the protocol stack.

Signaling: The E2R project proposes the development of end-to-end reconfiguration management along with optimal partitioning of intelligence between cognitive network core and reconfigurable elements. When deployed, this architecture should be mapped on elements of legacy systems.

Taking into account that reconfiguration is mostly concerned at the bottom layers of the E2R protocol stack responsible for spectrum allocation, scheduling, and inter-cell optimization the most appropriate for this case signaling architecture is a simplified version of the Central Cognitive Plane extended with an inter-node signaling interface.

m@ANGEL was designed to provide as autonomic management platform for offering seamless cognitive connectivity [17].

Architecture: the focus of m@ANGEL platform is exclusively devoted to bring cognitive functionalities into beyond-3G access networks. Most of the reconfiguration and cognitive functionalites are concentrated at the base stations located in multiple Radio Access Technology (RAT) networks.

The structure of the access network consists of two planes: the infrastructure plane, which includes reconfigurable elements (such as hardware transceivers, base stations, and the network core) and the management plane, composed of m@ANGEL entities. Each m@ANGEL entity is responsible for monitoring, resource brokerage, goals management, and reconfigurable element control functionalities.

Signaling: m@ANGEL defines a set of protocols for information and command exchange between the platform entities responsible for resource brokerage, profiles, goal agreements, monitoring, discovery, context acquisition, configuration, negotiation, selection, and implementation. An essential property of m@ANGEL platform is related to cooperation between the platform elements, which involves corresponding signaling.

Sutton at el. proposed a reconfigurable platform for development of cognitive networks developed at Trinity College Dublin [19].

Architecture: node reconfiguration can be requested by the cognitive engine and performed by the Stack Manager component, which is the core of the reconfigurable node architecture. The stack manager builds a customized protocol from the layer components provided by the Component Inventory. Layer components are the software modules implementing functionalities of an entire protocol layer or a part of the layer. They aim at interconnection with other layer components and communication with the stack manager.

This approach relies on the making the cognitive node capable of modifying or adjusting its protocol stack as a function of the dynamics of network environment.

Signaling: at the node level, the Stack Manager is a centralized entity where reconfiguration decisions are taken. The logical separation of the cognitive network primitives, such as learning or decision making outside reconfigurable nodes (into cognitive engine), can potentially limit the benefits from local optimization and it can increase the amount of signaling traffic in the network.

TABLE II. COMPARISON OF COGNITIVE NETWORKS PROPOSALS

Approach	Reconfigurable elements	Cognitive process	Signaling Requirements	Appropriate Signaling Methods
E^2R	Whole protocol stack	Centralized or partially distributed	End-to-end signaling using dedicated control protocols, however, mostly localized in cellular network core.	Direct Interlayer Communication/ ICMP messages
m@ANGEL	Lower protocol stack layers	In access network	Dedicated management platform on top of physical network; Most signaling is between neighboring cells in the access.	Central Cognitive Plane/ ICMP messages
Sutton at el.	Whole protocol stack	At node (mostly) and network levels	Cross-layer signaling inside node with minor inter-node signaling.	Central Cognitive Plane/ ICMP messages
CogNet	Intra-layer modules	At the node level distributed between layers	Communication between cognitive nodes and CogNet controller using high-level (HTTP) protocols.	Central Cognitive Plane/ ICMP (HTTP) messages
Thomas at el.	Lower protocol layers and network sensors	At the network level (distributed)	Network and intra-node signaling is minimized with high degree of autonomy of all cognitive network elements.	Direct Interlayer Communication/ ICMP messages
CPN	Packets	Inside Packets	Heavy in-band signaling. Along with user data the packets carry routing and flow control parameters and instructions for routers.	Interlayer signaling pipe/ Packet headers
SPIN	Standalone cognitive plane	At the network level (distributed)	Out-of-band dedicated channel signaling	ICMP messages

GogNet (Cognitive Complete Knowledge Network), an ongoing research project funded by NSF [18], is one of the most advanced cognitive networks projects with a focus on practical implementation.

Architecture: CogNet architecture, designed to maintain layered abstraction of TCP/IP protocol stack, extends each layer with so-called Intra-layer Cognition Modules, which are software agents performing intra-layer monitoring, control, and coordination functions.

A unique property of the proposed architecture is the cognitive functions implemented in the intra-layer are the distribution of cognitive elements between different protocol layers. Such design simplifies the cognitive processes running in the network and it reduces signaling overhead.

Signaling: cognitive information gathered by cognitive nodes implemented on top of VoyageOS (a version of Debian Linux) is stored in a local file which is periodically updated by the CogNet controller and by the Repository system located between the local network segment and by the WAN network. This signaling scheme is considered to be implemented using application-level protocols such as HTTP.

Thomas at el. proposed a cognitive network model in [7].

Architecture: It is composed of three horizontal planes. The top level is responsible for specification and translation of user/application requirements into goals understandable by the cognitive process.

The lowest layer of the model consists of modifiable network elements and sensors. The communication between modifiable elements and the cognitive plane is performed using the SAN APIs. Such an architectural solution brings modularity and flexibility into the design of modifiable elements.

Signaling: Signaling messages transmitted between network nodes are obtained by the nodes after processing and aggregating values they monitor. At node level, a high degree of autonomy is associated with each plane. This minimizes intra-node signaling and results in more robust design.

Cognitive Packet Networks (CPN) approach [20] adopts the concept of cognitive packet networks, which basically moves routing and flow control capabilities from network nodes into packets.

Architecture: This approach is fundamentally different. The packets, called cognitive packets, "route themselves" and learn to avoid congestion and avoid being destroyed. Each cognitive packet contains a cognitive map and a piece of code that is executed every time the packet arrives at the network node (router).

Signaling: in order to support CPN functionality, a high degree of network support is required. Practically, all the routers should be capable of cooperating with packets, look inside them, and implement the pieces of code they carry. As a result, most of the signaling information is carried by the packets – constituting an in-band signaling approach.

Software Programmable Intelligent Network (SPIN) presented [18] merges concepts of IP, PSTN, cellular, and ad hoc networks for overcoming the fundamental limitations of IP networks.

Architecture: The SPIN architecture consists of three planes interconnected by layer-2 transport infrastructure: the forwarding plane responsible for switching and monitoring, the control/management plane controlling the forwarding plane devices targeting flow optimization based on the received measurements, and the cognitive plane providing intelligence for and administration of the entire system.

Signaling: the logical separation of forwarding, control/management, and cognitive functionalities into standalone planes creates an attractive design choice - bringing flexibility and simplicity into network management and control, with the cost of additional overhead of out-of-band signaling.

B. Comparison

Table II summarizes comparison between main characteristics of different cognitive network.

Reconfigurable elements specify the scope of reconfiguration. Solutions such as m@ANGEL, furnish reconfigurability at the lower protocol stack layers close to hardware. As a consequence, incremental deployment in existing networks is possible, while other proposals such as

E2R, SPIN and that in [19] require modifications of the entire protocol stack, thus limiting their incremental deployment.

Cognitive process implementation ranges from centralized to distributed implementations. Centralized implementations are able to provide better control and optimization properties, while distributed ones lead to reduced operational complexity and more failures. Most of the proposals combine centralized and distributed implementation of the cognitive process, in an attempt to achieve an optimal trade off by implementing the cognitive engine in the access part of the network.

Signaling requirements implemented by different approaches varies depending on the level of distribution of cognitive process in the network. Approaches such as CogNet, implemented cognitive functionalities inside the node, reduce network signaling to the minimum. Other approaches, which tend to limit the scope of cognitive engine implementation to the access part of the network, such as E2R, m@ANGEL, and that in [19], require a moderate level of signaling information transfer over the network.

Appropriate signaling methods column presents signaling methods most appropriate for each cognitive network solution for node- and network-level signaling. Most of the solutions adapt Central Cognitive Plane signaling which allows the design of node centric signaling and cognitive optimization algorithms. At the network-level most of the available cognitive network approaches implement out-of-band methods of signaling using dedicated protocol like ICMP messages.

CPN is the only approach adapting in-band signaling at the node and well as network levels. Signaling information being encapsulated into packet headers propagates along the data transmission path.

IV. Conclusions

Signaling is a key issue for the deployment of cognitive networks. As information exchange is essential to the analysis and reasoning on the network status. However, signaling needs to be optimized since the choice of a specific signaling architecture can represent a performance bottleneck for the whole system. Furthermore, secure signaling is required in cognitive networks in order to avoid protocol attacks attempted by non-friendly network nodes, which furnish incorrect cross-layer information in order to trigger specific behavior.

Acknowledgements

The authors would like to acknowledge the funding support from VTT Technical Research Centre of Finland in the framework of the Intelligent Telecommunication Systems with Enhanced Cognitive Processing (ITSE) project as well as the research fellowship provided by the European Research Consortium for Informatics and Mathematics (ERCIM).

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