# INTEGRATION OF NETWORK CODING TECHNIQUES IN FUTURE INTERNET ARCHITECTURES

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**Abstract: The paper introduces several new methods and experimental results on the integration of Network Coding techniques into the architectures proposed for the future Internet. Also, there are shortly presented some of the main research initiatives proposing the design of future Internet architectures and the concepts developed. Particularly, the paper analyzes how Network Coding can be integrated into service centric and role based architectures and proposes a solution for integration of XOR based coding into the Generic Path framework. It is shown that the coded transmissions are not always beneficial and therefore adaptive activation of Network Coding is required according to the communication context and network parameters.**

***Keywords:*** *Future Internet, Generic Path framework, integration, network architecture, Network Coding.*

## I. INTRODUCTION

The original Internet was designed 40 years ago with the goal of having a simple, packet-switched communication infrastructure. The network provided basic communication services most of the complexity of networking protocols being implemented on the end systems. This environment has significantly evolved in time from a communication network connecting universities and government agencies to a complex architecture, which is not adequate to meet the user requirements all the time. For example, from the security point of view, the trust-all operating environment assumption is not true since the commercialization of the Internet, so security is going to be a major concern for the future Internet (FI). The Internet is data centric, the content distribution mechanisms being an important part of it, and it is evolving from centralized server based distribution mechanisms to more distributed approaches. The Internet of the future will require robust and scalable methods to prepare for the growth of content delivered.

Permanent connectivity and fixed end-systems were supposed in the initial design of the Internet. In heterogeneous networking environment, which is the case of today's Internet, continuous end-to-end connectivity cannot be supposed. Energy efficient protocol designs and implementations, and federation of heterogeneous networking environments are required.

The Internet has grown, both in size and in complexity, from a few hundreds of nodes to a distributed system consisting of millions of nodes. The communication protocols employed today were not designed for such a context, so more scalable and distributed solutions, both for communications and network management purposes, are necessary. With the growth of the number of network-able devices participating in the Internet basic services (routing, mobility, QoS, multicasting, security) became hard to be realized in a scalable and consistent way.

Since introduction of Network Coding (NC) techniques in 2000, many studies were dedicated to the theoretical analysis and to the integration of these techniques into communication networks. It was demonstrated that NC techniques can eliminate the need for tight synchronization between servers in Content Delivery Networks (CDN) and can reduce de server's storage space, what makes NC a competitive solution in emerging CDNs [1]. Also, NC techniques can reduce up to 60% the required transmission capacity [2] having strong influence over network congestions. It has been demonstrated that using NC for multicast transmissions the maximum capacity of the network can be achieved [3]. Besides offering a solution for congestion control, NC techniques can decrease the delays and improve the error resilience in the networks. These techniques are also suitable for dealing with some of the security issues [4]. These advantages of NC techniques make them ideal candidates for providing solutions to many of the current Internet problems, integration of NC techniques in future Internet architectures being an important and up to date research topic.

This paper is organized as follows: Section II presents a short overview of the future Internet architecture initiatives and research projects. Section III proposes the integration of Network Coding techniques into two selected future Internet architectures. Section IV describes a case study concerning the integration of XOR based NC used in wireless networks into the Generic Path (GP) framework [5] and Section V concludes the paper.

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## II. OVERVIEW OF FUTURE INTERNET ARCHITECTURES INITIATIVES

The networking research community has introduced newer protocols and architectural designs for the Internet, but the basic principles were not changed. The Internet has to be redesigned to meet the present requirements and to easily integrate the future ones. Many research projects are showing significant effort to develop the next generation Internet.

In the USA the NSF (National Science Foundation) is financing the GENI (Global Environment for Network Innovations) initiative which is developing infrastructures to test new networking ideas proposed by the FIND (Future Internet Design) initiative. The GENI project has as goal the construction of experimental environments on actual networks using innovative technologies. The FIND project is focusing on network architecture design research, the experiments being performed on the GENI testbeds [6].

There are many initiatives in FIND, each of them dealing with a specific objective of network technologies. One of them is the Relationship-Oriented Networking project, which is trying to provide better security, usability and trust in the network, based on trust relationships among the people, entities and institutions on the Internet. Another initiative is the one of Content Centric Networking, which proposes a shift from the host centric design of the current Internet to a content centric view of the Future Internet.

Service centric architectures were also proposed in the FIND initiative, like the Information Transfer and Data Service architecture (ITDS) or the NetServ project. The next generation internetworking architectures include proposals like eFIT (enabling Future Internet innovation through Transit wire) which proposes a new routing architecture based on the separation of the transit and user networks [6].

Prior to GENI and FIND there was the DARPA-supported program NewArch [7], started in 2000, which analyzed basic functions such as addressing, layered structure of protocols, etc. The NewArch program included projects developing new addressing methods (FARA) [7], layerless architecture design (RBA) [7] and others.

In Europe the FIRE (Future Internet Research and Experimentation) initiative [8] is supporting several next generation networking projects under the $7^{th}$ Framework Program. FIRE tries to connect the academic-driven research and the industry-driven experimentation by building a network infrastructure for a next generation network testbed. The multiple research projects include initiatives like 4WARD [9], TRILOGY [10], SOA4ALL [11], etc. The 4WARD project aims to increase the competitiveness of the European networking industry by creating a family of dependable and interoperable networks providing direct and ubiquitous access to information [9]. The aim of the TRILOGY project is to develop new solutions for the control architecture of the Internet and remove the known technical deficiencies while avoiding prejudging commercial and social outcomes [10]. SOA4ALL aims at realizing a world where billions of parties are exposing and consuming services via advanced Web technology. The main objective is to provide a framework that integrates complementary and evolutionary technical advances into a coherent and domain-independent service delivery platform [11].

In Japan the AKARI initiative [12], sponsored by the Japan National Institute of Information and Communications Technology (NICT), is developing new Internet architectures provisioning QoS guarantees, adaptive services and interconnection of heterogeneous devices and networks. Other Future Internet related research initiatives are in progress in China, Australia and other parts of the world.

## III. INTEGRATION OF NC TECHNIQUES IN FUTURE INTERNET ARCHITECTURES

Even if the advantages and the potentials of NC are well understood, the design of network architectures allowing a low complexity and scalable integration of NC techniques received much less attention from the research community than other techniques and technologies intended for the future Internet. Due to the complexity of the processing required by NC operations and the distributed nature of these operations, many research initiatives are focusing on more “conservative” solutions. In the following the integration of NC techniques in FI architectures, identified by the authors as ones the most suitable for such operations, is analyzed. Integration of the NC techniques into the GP architecture [5], proposed by the FP7-4WARD project is analyzed in more details in Section IV.

### *3.1 Integration of NC into the Service Centric Architecture*

The concept of Service Centric Architecture (SCA) was proposed by T. Wolf in [13], and new abstractions for information transfer and data services were introduced. This architecture concept is based on the explicit separation of communication and processing, which allows the expansion of network capabilities. The process of handling data and storage of information is considered a service. This provides increased flexibility in the network, a service being able to receive, store, process and transmit the data. Data services can implement different mechanisms, like encoding, buffering, processing, etc., based on the semantic information about the data stream.

This approach offers several advantages, like clearer programming model, advanced congestion control, more efficient usage of the network’s links, easier traffic control, but several challenges have to be solved, like the localization of intermediary processing points, queue management at the intermediary nodes, security issues, etc.

The architecture proposed in [13], uses router-based functionalities to implement the data services, but this requires significant processing capabilities on the routers.

Allowing the network nodes to process the data is the key requirement to integrate NC techniques into any network architecture, the basic idea of NC being that of data processing at the intermediary nodes in the network. This makes the SCA a very good candidate architecture allowing the integration of NC techniques.

I. Baldine proposed a similar architecture in the FIND project, called Service Integration Control and Optimization (SILO) [14], based on cross-layer techniques. This architecture is composed of a collection of services which are activated on demand and are specific for a given application. The fundamental blocks of the SILO architecture are the services, which realize different functions on the received data. These functions allow a higher granularity and flexibility than the current protocols.

The architecture defines mechanisms through which the services can interact in order to satisfy complex communication processes. The services are selected dynamically for a given task, and their order of execution is depending on a constraint set given by the application requirements. The architecture defines only the services and the interfaces, not the methods implementing them. A set of methods implementing a group of services represents a SILO, which is a vertical stack of methods.

Our proposal is to see NC and the related operations as a data service or, alternatively, to consider NC as a single service interworking with a set of specific services, such as synchronization, rate matching, etc. The NC and the related services are composed by a set of methods, as it follows:

1. NC service (Service s1) composed of the methods:
- m1,1: Coding/decoding coefficient generation method;
- m1,2: Coding method;
- m1,3: Decoding method.

2. Flow synchronization service (Service s2) composed of the following methods:
- m2,1: Header analysis & processing method;
- m2,2: Timestamp generation & extraction method;
- m2,3: Flow ID generation and processing method.

3. Rate matching service (Service s3) composed of:
- m3,1: Rate statistics generation & analysis method;
- m3,2: Packet padding method;
- m3,3: Packet segmentation method.

4. NC specific encapsulation service (Service s4) composed of the following methods:
- m4,1: Packet encapsulation method;
- m4,2: Header generation method.

5. NC specific routing (Service s5) composed of:
- m5,1: Routing algorithm (multicast, unicast) selection method;
- m5,2: Routing table update & forwarding method.

6. NC specific signaling service (Service s6) composed of the following methods:
- m6,1: Signaling message generation & processing;
- m6,2: Signaling related routing;
- m6,3: Signaling data flow control.

All the NC related services are activated on demand based on signaling messages which indicate that the destinations can decode the coded packets and that congestion occurred on some link in the network. The NC related services will have to interact in order to deliver the data to the destinations and to ensure correct decoding.

As an example, in Figure 1 it is presented the proposed integration of the NC operations realized in a Butterfly topology into the SILO architecture. The services are activated by the control agent, which also supervises the construction of SILOs. The control agent must have a global view on the network, in order to identify which services have to be instantiated in which nodes, and it also has to interact strongly with the network management system.

*3.2 Integration of NC into the Role Based Architecture*

The Role Based Architecture (RBA) is a layerless architecture proposed by R. Braden in [15]. It ensures a high level of flexibility and advanced control capabilities in the network.

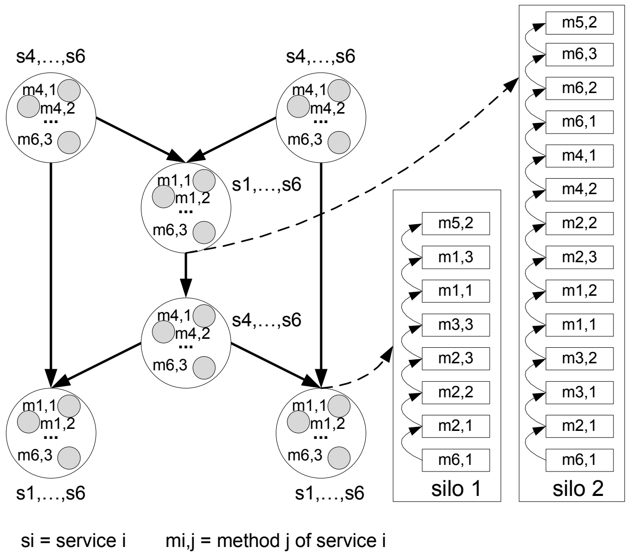


*Figure 1. NC operations realized in a Butterfly topology integrated into the SILO architecture.*

The communication processes are organized based on functional entities, called roles. These are modular protocol units, which realize different functions dedicated to data processing and data transmission. The roles are not organized in a hierarchical manner, they can interact and they can be composed of different sub-roles. The inputs/ outputs of a role are represented by the data received/sent from/to the applications and by the control metadata.

The structure of the metadata is a very important component of the RBA architecture. The header of the packets contains variable length metadata, which can be inserted, accessed, modified or removed at any given moment by any node on the communication path. These variable length blocks represent the Role Specific Header (RSH), which implements the communication and the interactions between different roles.

In Figure 2 the integration of the NC operations performed in a Butterfly topology into the RBA is proposed. There are defined two roles: a multicast role and a NC role. Each role is composed of several sub-roles, as follows:

1. The NC role is composed of the sub-roles:
- r1,1: Packet ID sub-role;
- r1,2: Signaling sub-role;
- r1,3: NC coding sub-role;
- r1,4: NC decoding sub-role.

2. The multicast role is composed of a single sub-role performing the routing table updates and address field management of the multicasted packets.

In Figure 2 the structure of the packets in different nodes of the Butterfly topology is also presented.

The multicast role is instantiated in nodes R1, R2 and R6, and it defines RSH3, which contains the addresses of the source and destination nodes. The initial RSH3 header inserted by nodes R1 and R2 is modified during the transmission by node R5 performing the coding, and by the intermediary node R6, performing also multicast routing.

The sub-roles composing the NC role, instantiated in every node of the topology, define a set of RSHs, as follows: the "Packet ID sub-role" defines RSH1, which contains a sequence number necessary for identification of the packets applied to the decoder. In this way the synchronization between the flows applied to the decoder is achieved. The "Signaling sub-role" defines RSH2, which contains the signaling flags used for NC activation/deactivation at node R5, if all the necessary conditions are satisfied. The "Coding sub-role" defines RSH4 and RSH5, which contain the coded and uncoded data at the output of the coder. The "Decoding sub-role" defines RSH6 which contains the decoded data at the output of the decoder.

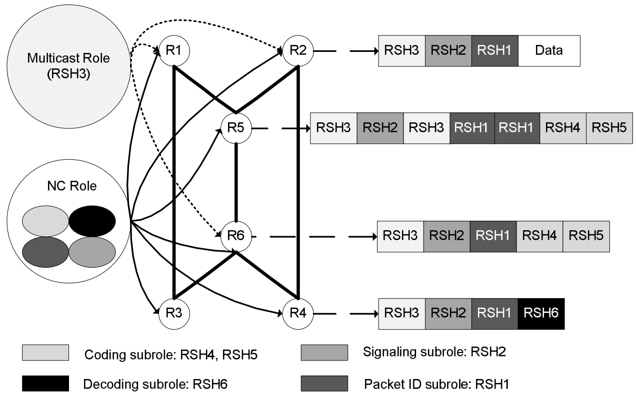


*Figure 2. NC operations realized in a Butterfly topology integrated in the RBA architecture.*

## IV. INTEGRATION OF NC TECHNIQUES IN THE GENERIC PATH FRAMEWORK. A CASE STUDY

### *4.1 NC in wireless networks*

Consider the following scenario: user *A* and user *B* want to exchange data packets in a wireless environment as presented in Figure 3. They have two possibilities: use the direct links between them, if these links exist or send the packets through the relay node (*R*), if such a node exists.

If there is no direct radio link between nodes *A* and *B*, the packets can be sent from node *A* to node *B*, and vice versa, only through the relay node *R*. If node *A* sends packet *a* to node *B*, and node *B* sends packet *b* to node *A*, there are necessary 4 transmission time intervals to deliver these packets to their destinations, supposing that a TDMA access method is employed. If the relay node uses NC, it will XOR the received packets, *a* and *b*, and will send the coded packet $c = a \oplus b$ to the destination nodes *A* and *B*. Node *A* will decode packet *b* using the coded packet *c* and its own data packet *a*, and node *B* will decode packet *a*, using the coded packet *c* and its own data packet *b*. As we can see if NC is used, there are necessary only 3 transmission time intervals to deliver both packets to their destinations [16].

### *4.2 The GP framework*

This architecture framework was developed within the FP7-4WARD project, and its main components are the following [5]:

a. Entity: produces, processes and consumes the information;

b. Generic Path (GP): is a mean for transferring the data between the End Points (EP). A GP may have processing capabilities. This property is very important for integration of NC techniques which require in-network processing;

c. Mediation Point (MP): is a special entity interconnecting several GPs. It allows a flexible GP composition in order to create more complex GPs from GPs providing basic communication functionalities;

d. Cooperation and Coding Framework (CCFW): accumulates all the necessary functionalities for cooperation and coding techniques;

e. In-Network Management (INM): allows cross-layering and has an important role in link, flow and topology related information acquisition. It creates the framework necessary for identification of the NC capable topologies;

f. Compartment: is a set of GPs of the same type, which can be accessed through MPs. It may correspond to the whole network or to a sub-network/administrative domain;

g. Hook/port: allows the communication between entities located in compartments situated at different level;

Remark: the GP architecture is not a layered architecture, but some layering has to be permitted between compartments integrating GPs with different functionalities.

### *4.3 Integration of NC into the GP framework*

In Figure 3 is presented the way the previously described architecture concepts are used to implement the cooperative communication between nodes *A* and *B*. For comparison the figure also gives the implementation of the direct (non-cooperative) transmission between nodes *A* and *B*. Each node (both the source and the relay nodes) instantiates two entities, namely: the Mediation Point (MP) entity and the In-Network Management (INM) entity.

The Mediation Point entity instantiates the EPs allowing accessing the GPs used for data and signaling information transfer. It also acts as an intelligent switch, transferring the data between the various GPs ending in the instantiated EPs. The MP entity is instantiating also a CCFW module, which defines the methods necessary for implementing the NC coding and decoding. When NC is necessary the appropriate methods will be instantiated, with the help of CCFW, in the EPs of the GPs sending or receiving coded data.

The INM entity implements the resource management operations necessary for performing the coding and decoding operations and for deciding on the NC activation/deactivation. It relies heavily on cross-layer operations in order to acquire the link and network state information, and possibly to change the link and network parameters. More details can be found in [17].

Figure 3 shows all the GPs which can be instantiated in order to implement the direct and cooperative transmissions with or without NC. These GPs are not instantiated in the same time, but according to the actual operation mode: direct transmission, transmission through the relay node without NC, transmission through the relay node with NC. The signaling information is transmitted on separate dedicated GPs, which are not presented in Figure 3.

When there is a direct link between nodes *A* and *B*, the data packets will be sent on this link, and the relay *R* will not be involved in the transmission process. In this case the MP of node *A* instantiates a unicast GP ending in node *B* and node *B* instantiates another unicast GP ending in node *A*.

In the second operation mode, when no direct link is available between nodes *A* and *B* and no NC operations are performed, two unicast GPs are created between node *A* and the relay node *R* and other two unicast GPs are created between node *B* and node *R*. In this situation the relay is doing a simple forwarding and the MP of the relay node is transferring the data between the mentioned GPs.

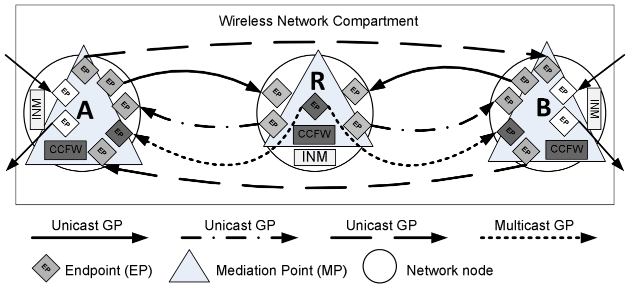


*Figure 3. NC in a wireless scenario. Integration in the Generic Path architecture framework.*

The GPs instantiated in the third operation mode, when no direct link is available between nodes *A* and *B* and NC operations are performed, are presented in Figure 4. Node *A* and *B* create unicast GPs connecting them to the relay node *R*. The source EPs ($EP_{uA}$ and $EP_{uB}$ in Figure 4) of these GPs store the transmitted packets in a local buffer. These packets are necessary for decoding of the coded packets received from the relay *R*. The MP entity of the relay instantiates a multicast GP to nodes *A* and *B*, which carries the coded data. The coding operations are realized in the source EP ($EP_{mR}$ in Figure 4) of this GP. The decoding of the received packets takes place in the destination EPs of the multicast GP ($EP_{mA}$ and $EP_{mB}$ in Figure 4). These EPs receive also the transmitted packets stored in the source EPs of the unicast GPs connecting the source nodes to node *R*.

The NC coding is realized at packet level by simply XOR-ing the bits of the packets. Padding operations are performed before coding in order to equalize the length of the packets. The CCFW module holds all the necessary functions for NC coding and decoding.

Remark: the coding/decoding operations do not necessarily have to take place in the EPs, they can be implemented also in other points of the architecture ("inside the GP"), but the former solution is the simplest one. More details related to this subject could be found in [5].

*4.4 Implementation of XOR-based NC in a wireless scenario*

In order to check the interaction between the GP architecture elements implementing the NC operations in the described scenario and to evaluate the appropriateness of this architecture for such an application, a testbed was implemented according to scenario described in Figure 4. The radio interfaces employed were IEEE 802.11 b/g.

The MP and the INM entities are implemented at the application layer (or compartment) and the instantiated EPs communicate directly with the MAC layer (or MAC compartment) through hooks/ports implemented using the *pcap* (*libcap*) packet capture library. In order to ensure that no information is lost, as consequence of packets dropped (erased) by the wireless environment, a simple stop and wait algorithm was implemented and integrated into the NC based cooperative transmission. The structure of the packets was defined in such a way that it allows the necessary operations for NC. In this application two types of packets are defined: data packets and ACK packets. The length of the data packets is 1500 bytes, out of which 50 bytes represent the packet header and 1450 bytes the payload. The acknowledgement (ACK) packets have no payload, so their length is 50 bytes. The structure of the header is: 12 bytes for MAC header and 38 bytes for custom header.

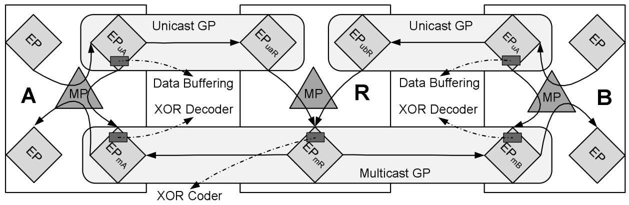


*Figure 4. Generic Paths instantiated for implementing the NC-based transmission when XOR encoding is used.*

The custom header defined for this application allows the control of the NC operations (i.e. detection of the moments when coding is employed or not) and synchronization of the flows involved in the coding and decoding operations.

The coding operation implemented at the relay node allows the encoding of data flows having different rates. The coding is performed only if the local buffer of the NC coded GP EP has packets from both source flows. In the opposite case (i.e. the buffer has only packets from one flow) the relay simply forwards the received packets (see Figure 5).

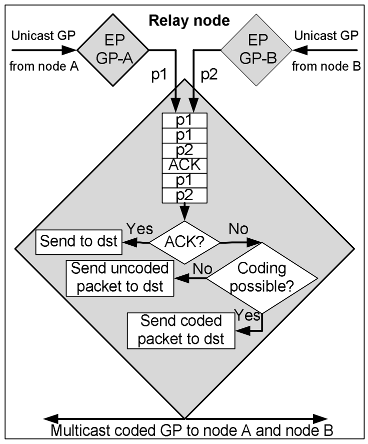


*Figure 5. Operations performed by the coded GP EP.*

*4.5 Test results*

Field tests were carried out using three laptops representing nodes *A*, *B* and *R*. Nodes *A* and *B* were placed in two different buildings while the relay node *R* was placed between the buildings. There were set up three main testing scenarios corresponding to: direct transmission; relay assisted transmission without NC; relay assisted transmission with XOR based NC. These operation modes were obtained by changing the positions of the nodes in such a way to ensure the desired link qualities, i.e. direct and relay links qualities. On each machine was running the specific application implemented in C++ under the Linux operating system. For each of the above test scenarios it was considered both the situation when only one node is transmitting data and when both nodes are transmitting. 400 packets were sent in each test by both source nodes and the transfer rate was set to 2Mbps. The measured transmission times for the tests performed are presented in Table 1.

*Table 1. Transmission time in different test scenarios.*

| | Direct link | With NC | Without NC |
|---|---|---|---|
| Both stations | 4s | 29s | 120s |
| One station | 2.5s | 25s | 18s |

These transmission times are valid only for these scenarios, but the ratio between the measured transmission times is expected to remain the same for other similar test scenarios. The lowest transmission time is obtained for the direct transmission (if possible), because there is no delay caused by the processing at the relay node and fewer collisions happen in the wireless transmission medium, due to the CSMA/CA access technique.

In the case of relay assisted transmission when both stations are sending data, the transmission time is lower when the XOR based NC is activated. The XOR coding reduces from 4 to 3 the required channel uses and the number of collisions in the wireless medium as well. The results in this case show a significant difference between the transmission times obtained with and without coding, in the second case the transmission time being larger with 75%.

When only one station is sending data, the transmission time is lower when the relay does not employ coding operations. This is because the packets are received by the relay only from one station and coding operations are not necessary, being eliminated the coding related delays.

The obtained results show clearly that NC techniques have to be used only in some situations, i.e. when direct link is not available and duplex transmissions are performed.

The employment of the MP and EP concepts allowed an easy and flexible implementation of the coded and uncoded transmissions as well as a flexible switching between these transmissions (i.e. between the GPs implementing these transmissions). This switching is performed by the MP entity which instantiates and activates the required EPs and implements the data transfer between them. The switching between the coded and uncoded GPs is performed based on the information provided by the INM entity. In our implementation this entity is detecting the flows sent by the sources, in order to identify the situations when both stations transmit or when only one station transmits data, and implements a simple "ping" application. By using the received "ping" packets the INM entity could detect if the direct link between the source nodes can be used for transmission or it is necessary to employ relaying. The simplified diagram of the signaling operations controlling the activation/deactivation of NC is presented in Figure 6.

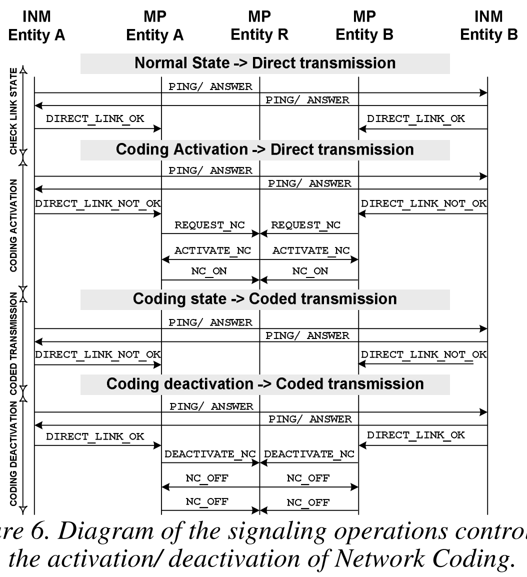


*Figure 6. Diagram of the signaling operations controlling the activation/ deactivation of Network Coding.*

## V. CONCLUSIONS

The paper presents a short overview of the most important future Internet architecture research initiatives. From these FI architectures the Service Centric, the Role Based and the Generic Path architectures are selected and analyzed from the point of view of NC integration. For the first two architectures the paper proposes a theoretical analysis concerning the integration of NC, while for the GP architecture the paper proposes the analysis of a particular use case, namely the integration of XOR based NC in a wireless transmission. There are defined the GPs performing the NC based cooperative transmission as well as the functionalities of the GP architecture elements for the situation considered. A real testbed was implemented in order to check the effectiveness of the mentioned architecture elements in scenarios employing NC.

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## REFERENCES

[1] K. Nguyen, T. Nguyen and S. Cheung, "Video streaming with network coding", *Journal of Signal Processing Systems*, vol. 59, no. 3, pp. 319-333, June 2010.

[2] N. Thomos and P. Frossard, "Network coding: from theory to media streaming", *Journal of Communications*, vol. 4, no. 9, pp. 628-639, 2009.

[3] R. Koetter and M. Medard, "An algebraic approach to network coding", IEEE/ACM Trans. on Networking, vol. 11, no. 5, pp. 782-795, Oct. 2003.

[4] A.L. Toledo et al., "First Report on Application Layer Aspects of Network Coding", *Deliverable 3.2, FP7-N-CRAVE "Network Coding for Robust Architectures in Volatile Environments"*, http://www.n-crave.eu/, 2010.

[5] F. Guillemin et al., "Architecture of a Generic Path", *Deliverable 5.1, FP7-4WARD "Architecture and Design for the Future Internet"*, http://www.4ward-project.eu/, 2008.

[6] S. Paul, J. Pan, R. Jain, "Architectures for the Future Networks and the Next Generation Internet: A Survey", *Computer Communications, UK,* vol. 34, no. 1, pp. 2-42, 2011.

[7] NewArch project: http://www.isi.edu/newarch/

[8] FIRE project: http://cordis.europa.eu/fp7/ict/fire/

[9] 4WARD project: http://www.4ward-project.eu/

[10] TRILOGY project: http://trilogy-project.org/

[11] SOA4ALL project: http://www.soa4all.eu/

[12] AKARI project: http://akari-project.nict.go.jp/

[13] T. Wolf, "Service-Centric End-to-End Abstractions in Next-Generation Networks", *Proc. of 15th International Conference on Computer Communications and Networks,* pp. 79-86, 2006.

[14] R. Dutta, G.N. Rouskas, I. Baldine, A. Bragg, D. Stevenson, "The SILO Architecture for Services Integration, control, and Optimization for the Future Internet", *Proc. of IEEE International Conference on Communications (ICC2007),* pp. 1899-1904, 2007.

[15] R. Braden, T. Faber, M. Handley, "From Protocol Stack to Protocol Heap: Role-Based Architecture", *SIGCOMM Computer Communication Review,* vol. 33, no. 1, pp. 17-22, 2003.

[16] S. Katti, H. Rahul, Hu Wenjun, D. Katabi, et al., "XORs in the Air: Practical Wireless Network Coding", *IEEE/ACM Trans. on Networking,* vol. 16, no. 3, pp.497-510, 2008.

[17] G. Nunzi et al., "In-Network Management Concept", *Deliverable 4.2, FP7-4WARD "Architecture and Design for the Future Internet"*, http://www.4ward-project.eu/, 2009.