System and layer independent network coding architecture design

COST Action IC 1104 on Random Network Coding and Designs over GF(q)

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IRTF #93 – Prague – NWCRG meeting

Layout

Context: COST Action IC 1104

PART 1: Proposed architecture design methodology

- Rationale of the proposal
- Network coding as a network function to service-oriented systems
- Proposed architectural design framework

PART 2: Preliminary validation over LTE-A and SATCOM

- LTE-A
- DVB-S2X.

Next steps

Layout

Context: COST Action IC 1104

PART 1: Proposed architecture design methodology

- Rationale of the proposal
  - Interdisciplinary evolving concept and abstraction to cope with it.
- Network coding as a network function to service-oriented systems
  - Different design goals (reliability, delay, quality of experience, etc)
- Proposed architectural design framework

PART 2: Preliminary validation over LTE-A and SATCOM

- LTE-A
- DVB-S2X.

Next steps

COST Actions

- COST Actions started in 1971, they bring together researchers working on related funded research, building the **European Research Area**.
- **250 million euro in the period 2007-2013** (Seventh Framework Programme).
- **COST Actions dissemination of scientific results**
  - COST 207 provided channel models for which standardization of GSM/EDGE was based.
  - COST 231 provided channel models recommended by the European Telecommunication Standard Institute (ETSI) for use in Personal Communication Network/Personal Communication System (PCN/PCS).
  - COST 255 and 280 provided satellite channel models later used for DVB standards for transmission over satellite.
  - COST 259 channel models and simulations of access technique for UMTS supporting ETSI for final decision.
- **This presentation: dissemination activity of COST Action IC 1104.**

COST Action IC 1104

- **Chairmen**: Marcus Greferath (Aalto Universiy, Finland) and Mario Osvin Pavčević (University of Zagreb, Croatia).
- 27 countries, 2012-2016.
- **WG 1:** Bounds on the size of network codes
  - 45 participants, mostly mathematicians and theoretical computer scientists.
- **WG 2:** Development of encoding and decoding schemes, practical aspects of network coding
  - 39 participants, app. 50% engineers and 50% math/computer scientists.
- **WG 3:** Cryptographic aspects of network codes
  - 23 participants, only mathematicians and computer scientists.
- **WG 4:** Constructions of network codes and Grassmannian codes
  - 53 participants, mostly mathematicians.
- **WG 5:** Foundational Aspects, Algebraic Methods in Random Network Coding, Distributed Storage
  - 48 participants, mostly mathematicians.
- **This presentation: dissemination activity of COST Action WG 2 work.**

WG2. Practical Aspects of Network Coding

- **Engineers from 11 countries:**
  - Denmark – Aalborg University
  - Greece – University of Peloponnese
  - Macedonia – IBU Skopje
  - Portugal – ISCTE, University of Lisbon
  - Serbia – University of NoviSad
  - Slovakia – Pan-European University
  - Slovenia – Jozef Stefan Institute
  - Spain – Autonomous University of Barcelona
  - Turkey – Istanbul Technical University, Özyğin University
  - UK – Lancaster University, University of Strathclyde
  - *Australia – University of Southern Queensland*

This contribution

- Nourished with work from national, European Union and European Space Agency funded projects.
  - Focus on architectural design NOT on coding: **network codes developed within the COST Action are kept out of this contribution.**
  - **Only two systems considered: wireless cellular and SATCOM.**
- COST members: Ioannis Chatzigeorgiou, Andrea Tassi (University of Lancaster, UK) and Dejan Vukobratovic (University of Novi Sad, Serbia).

[1]A. Tassi, I. Chatzigeorgiou and D. Vukobratović, "Resource allocation frameworks for network-coded layered multimedia multicast services", IEEE Journal on Selected Areas in Communications, Special Issue on Fundamental Approaches to Network Coding in Wireless Communication Systems. Feb. 2015.

[2]Andrea Tassi, Chadi Khirallah, Dejan Vukobratovic, Francesco Chiti, John Thompson, Romano Fantacci: "Resource Allocation Strategies for Network-Coded Video Broadcasting Services over LTE/LTE-A," IEEE Transactions on Vehicular Technology. May 2015.

[3]Andrea Tassi, Ioannis Chatzigeorgiou, Dejan Vukobratovic: "On Optimization of Network-coded Scalable Multimedia Service Multicasting," Wireless SNOW Workshop. March 2015.

[4]A. Tassi, I. Chatzigeorgiou, D. Vukobratovic, "Optimized Network-coded Scalable Video Multicasting over eMBMS Networks". IEEE ICC. June 2015.

This contribution

- COST members: M. A. Vázquez-Castro (Autonomous University of Barcelona) and Paresh Saxena (AnsuR Technologies, Norway, formerly with Autonomous University of Barcelona).

[5] M. A. Vázquez-Castro, “A Geometric Approach to Dynamic Network Coding”, Information Theory Workshop, Oct. 2015.

[6] R. Alegre-Godoy and M. A. Vázquez-Castro. "Network Coded Multicast over Multi-beam Satellite Systems." Mathematical Problems in Engineering. May 2015.

[7] M. A. Vázquez-Castro and Paresh Saxena, “Network coding over satellite: from theory to design and performance”, **Invited paper**. WiSATs. July 2015.

[8] P. Saxena and M. A. Vázquez-Castro. "Link Layer Systematic Random Network Coding for DVB-S2X/RCS." IEEE Communications Letters. May, 2015.

[9] P. Saxena and M. A. Vázquez-Castro. "DARE: DoF-Aided Random Encoding for Network Coding over Lossy Line Networks." IEEE Communications Letters. June, 2015.

[10] M. A. Pimentel-Niño, Paresh Saxena and M. A. Vázquez-Castro, “QoE Driven Adaptive Video with Overlapping Network Coding for Best Effort Erasure Satellite Links, 31st AIAA International Communications Satellite Systems Conf. May 2015.

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Next steps

Origins: error-free networks

- **Seminal work**
  - By computer scientists.
  - Network coding makes it possible for a source to achieve a multicast rate equal to the minimum of the max-flow to the individual destinations [1].
- **Follow up**
  - Mostly computer scientists adding algebraic formalization, coding theory and control theory:
    - Transfer matrix $A(I - F)^{-1}B^T$ for each receiver is non-singular [2].
    - LP-formulation [3], RNC [4], constructions [5].

[1] R. Ahlswede, et al, "Network information flow", 2000.

[2] R. Koetter and M. Médard, "An algebraic approach to network coding", 2003.

[3] Z. Li, et al, "On Achieving Maximum Multicast Throughput in Undirected Networks", 2006.

[4] T. Ho, et al, "A random linear network coding approach to multicast", 2006.

[5] S. Jaggi, et al, "Polynomial Time Algorithms for Multicast Network Code Construction", 2005.

Network coding for wireless networks

- **Seminal work**
  - Jointly telecom engineers [1][2] and computer scientists [3], different focus.
- **Follow up:**
  - Same concept of mixing at intermediate nodes, combinations of lattice points.
  - Algebra, information theory, coding theory, scarce networking aspects.
    - Coding theory and classic algebraic framework [4].
    - Lattice-based algebraic framework for communication and computation [5][6].

[1] S. Zhang et al., ”Hot topic: physical-layer network coding", *2006*.

[2] P. Popovski et al., “The anti-packets can increase the achievable throughput of a wireless…,” 2006.

[3] K. Lu et al., “On capacity of random wireless networks with physical-layer network coding.”, 2009.

[4] B. Nazer et al., “Reliable physical layer network coding,” 2011.

[5] C. Feng et al., “An algebraic approach to physical layer network coding”, 2011.

[6] B. Nazer et al., “Expanding the compute and forward framework:…,” ArXiv 2015.

Network coding for error correction

- **Coherent**
  - Network error correction as a generalization of classical link-by-link error correction.

[1] N. Cai and R. W. Yeung, "Network coding and error correction," ITW 2002.
[2] R. W. Yeung and N. Cai, "Network error correction, Part I: Basic concepts and upper bounds; Part II: Lower bounds," Comm. in Inform. and Systems, 2006.
[3] R. Matsumoto, "Construction algorithm for network error-correcting codes attaining the Singleton bound," IEICE Trans. Funda., 2007.
[4] Z. Zhang, "Linear network error correction codes in packet networks," IEEE Trans. Inf. Theory, 2008.
[5] S. Yang, R. W. Yeung, and C. K. Ngai "Refined Coding Bounds and Constructions for Coherent Network Error Correction," IEEE Trans. Inf. Theory, 2011.

- **Non-coherent**
  - Network coding and error correction over network coded networks can be tackled as separated problems.

[1] S. Jaggi, M. Langberg, S. Katti, T. Ho, D. Katabi, M. Médard and M. Effros, "Resilient network coding in the presence of Byzantine adversaries," IEEE Trans. Inf. Theory, 2008.
[2] R. Kötter and F. R. Kschischang, "Coding for errors and erasures in random network coding," IEEE Trans. Inf. Theory, 2008.
[3] D. Silva, F. R. Kschischang, and R. Kötter, "A rank-metric approach to error control in random network coding," IEEE Trans. Inf. Theory, 2008.
[4] D. Feng, R. W. Nóbrega, D. Silva, and F. R. Kschischang, "Communication over Finite-Ring Matrix Channels," IEEE Trans. Inf. Theory, 2013.

Rationale of the proposal

NC is an evolving concept. Unified theoretical framework still missing

- NC theorists abstract away network/system/layers (some codes remain theoretical).
- NC (theoretical) computer scientists work with logical and mathematical network models for analytical treatment.
- NC engineers design network/system- specific (possibly physical-specific) solutions and analyze performance abstracting away the network codes.

Simultaneously, evolving concepts of networking/system/service involving higher level of abstractions

- **5G European research activities (**https://5g-ppp.eu/**):**
  - "The development of specialized services is as important as the Internet Access Service."
  - "5G design will ensure high flexibility and be driven by a service approach."
  - "Paradigm shift in network design …. by virtualisation/"softwarisation"… dynamic reconfiguration of the network …"
- **Future networks**: self-organized networks, self-management frameworks, cyber-physical systems, Thing-to-thing, Machine-to-machine, Cloud computing, …

Proposal of NC architectural design

- **Objective**: operative framework for the **design of the (dynamic) structural properties of the network communication flow** (includes reliability properties).
  - Structural properties should optimize known/to be known design goals.
  - Dynamic structural properties are to be signaled/transported by (one/two way) protocols.
  - Need of interdisciplinary design.
- **Features: configurable/reprogrammable architecture:**
  - Network code-independent.
  - System- and layer-independent.
  - (Specialized) service-oriented.
- Seems **to comply with (but not constrained by) 5G ideas and future network concepts**.
- Seems to be in line with other proposals in the IRTF-NWCRG: functional building-block based architecture. Our proposal introduces higher level of abstraction and a framework to allow interdisciplinary interaction.
- TBC whether or not in line with work in other WGs/RGs.

Proposed architectural design domains

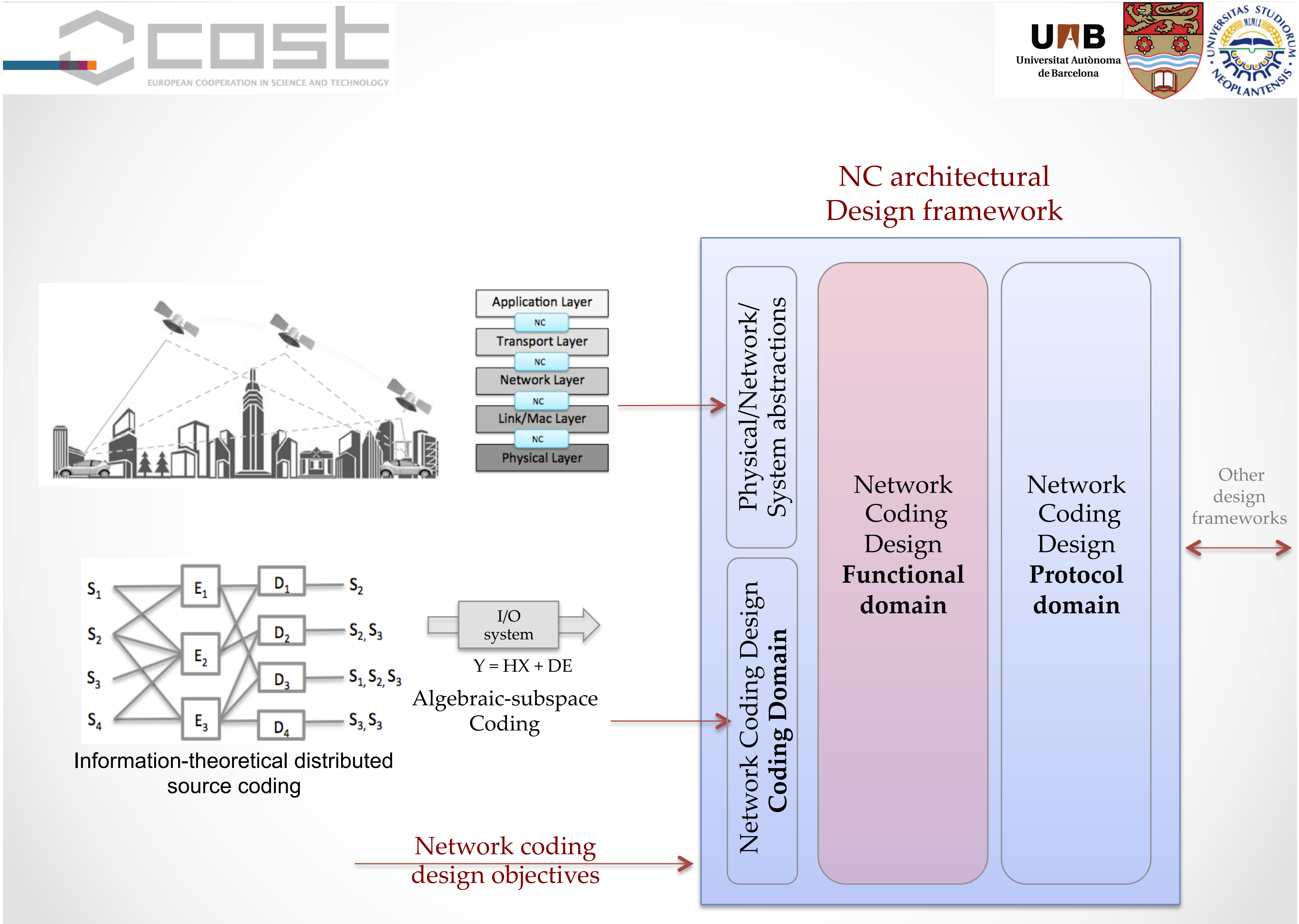
Coding domain – coding theoretical network codes, performance benchmarks, appropriate mathematical-to-logical maps, encoding/decoding algorithms. *(Interaction with theoretical experts)*.

(Per-node) functional domain – allows to shape the structural properties of network coding (practical vs. theoretical) properties to match design requirements. Builds upon abstractions of: *(Interaction with system designers/engineers)*

- **Network**: by choosing a reference layer and logical nodes for network coding and re-encoding (sets time/space resolution of the design).
- **System**: by abstracting the underlying physical or functional system (at the selected layer) e.g. Software Defined Networking and/or function virtualization.

Protocol domain: dynamic structural properties are to be signaled/transported across the network in (one way or interactive) protocols. (*Interactions with app developers, protocol developers, etc*).

The three domains conform the network communication flow.


COST
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
UAB
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UNIVERSITAS STUDIORUM NEOPLANTENSIS
NC architectural Design framework
Application Layer
NC
Transport Layer
NC
Network Layer
NC
Link/Mac Layer
NC
Physical Layer
Physical/Network/ System abstractions
Network Coding Design Coding Domain
Network Coding Design Functional domain
Network Coding Design Protocol domain
Other design frameworks
S1
S2
S3
S4
E1
E2
E3
D1
D2
D3
D4
S2
S2, S3
S1, S2, S3
S3, S3
Information-theoretical distributed source coding
I/O system
Y = HX + DE
Algebraic-subspace Coding
Network coding design objectives

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Methodology for validation

In this presentation, focus only in the functional domain.

Identify common **functionalities that network coding design needs** for system-specific designs.

In particular, designs within COST Action:

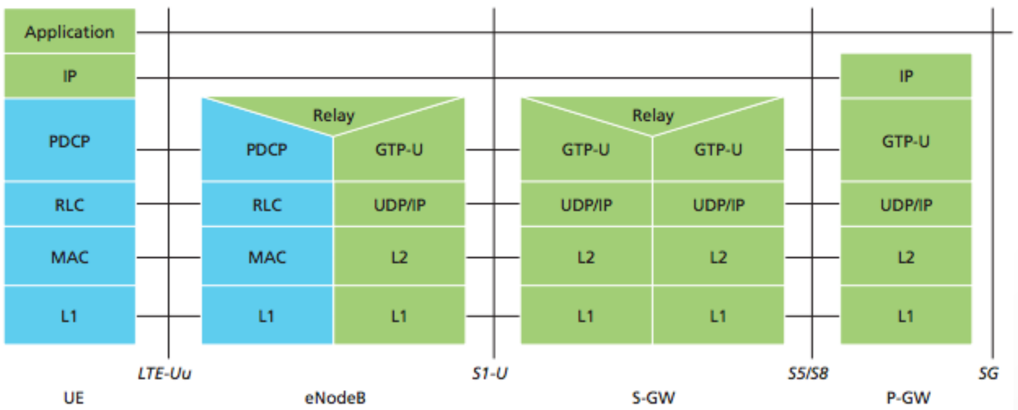
1. Wireless terrestrial access systems
2. Wireless satellite access systems

Preliminary set of functionalities

- Core Functionalities (core architectural functionalities):
  - **NC Logic**: logical interpretation of coding use, coding scheme selection (intra-session/inter-session, coherent/incoherent, file-transfer/streaming, systematic/non-systematic), coding coefficients selection (random/deterministic), etc.
  - **NC Coding**: elementary encoding/re-encoding/decoding operations, encapsulation/de-encapsulation, adding/removing headers, etc.
- Interoperability functionalities
  - **NC Resource Allocation**: optimal allocation of NC parameters.
  - **NC Congestion Control**: controlling congestion, interoperable with other congestion-control algorithms.
- Console Functionalities
  - **NC Storage**: interactions with physical memory.
  - **NC Feedback Manager**: settings for feedback.
  - **NC Signaling**: coordinating signaling parameters.

Long Term Evolution-Advanced (LTE-A)

- 4G mobile broadband wireless access systems, defined by the Radio sector of the International Telecommunication Union (ITU-R) as International Mobile Telecommunication-Advanced (IMT-Advanced) Radio Interface Technologies, is based on IEEE 802.16m, or 3GPP LTE-Advanced.
- Evolved Packet Core uses the concept of "EPS bearers" to route IP traffic from to the User Equipment. A bearer is an IP packet flow with a defined quality of service (QoS) between the gateway and the UE.

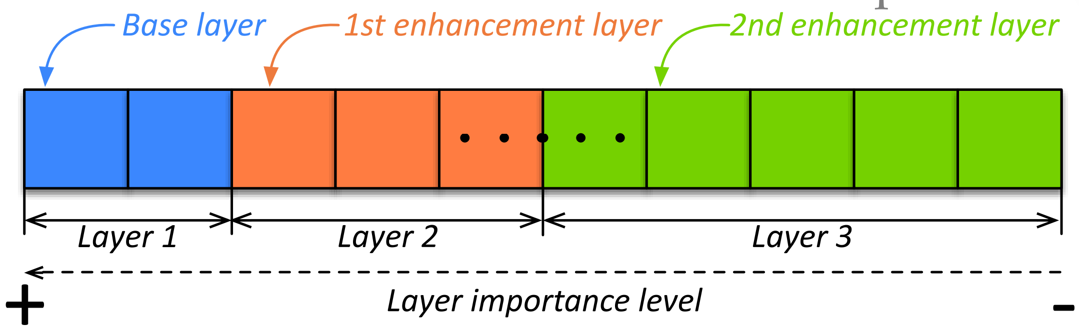


LTE-A User Plane Protocol Stack

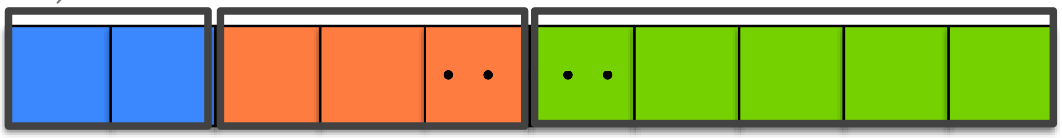
Source: LTE Alcatel-Lucent White paper

Layered Network Coding for LTE-A[1][2]

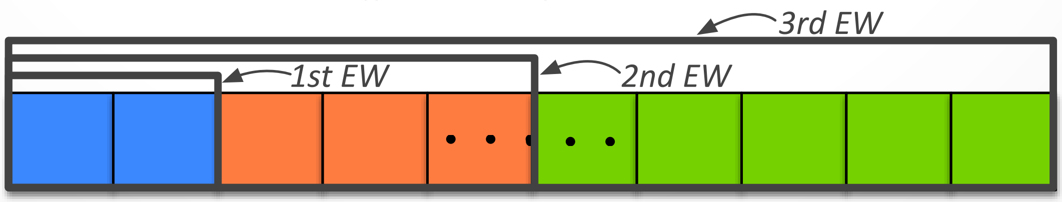
- Any layered coded multimedia service can be represented as



- NC can be performed on each layer independently (Non-Overlapping-NC, **NOW-NC**).



- Expanding Window-NC (**EW-NC**): encoding operations are performed on a NESTED structure of Expanding Windows (EW) [1][2]



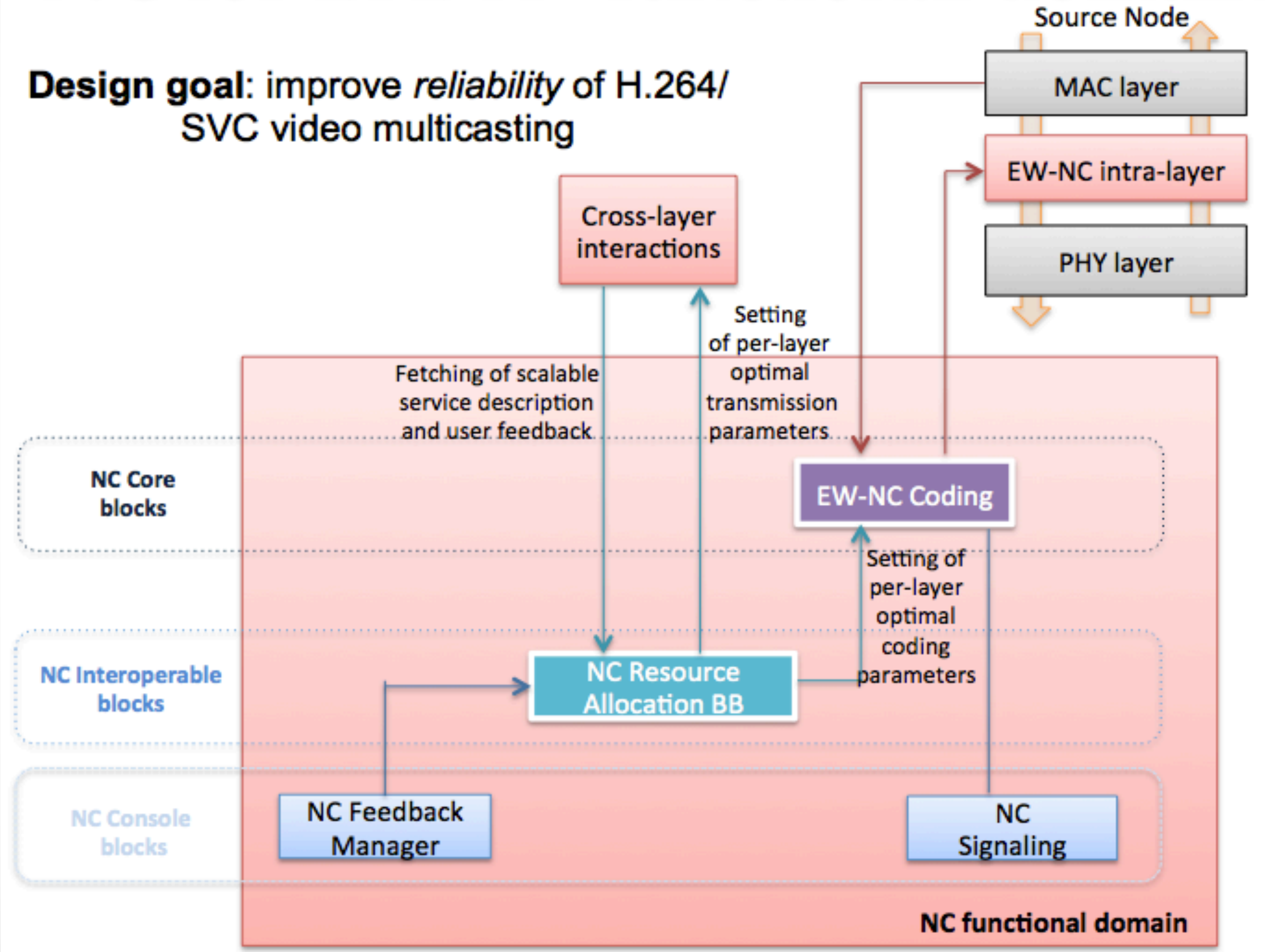
EW-NC functional architecture

- NC layer is between MAC and PHY: the most important layers are better protected than the least important ones. For instance, layer 1 information is spread across all the coded packets associated with any EW.

- Different design goals define the network flow structure to be transmitted to the users [1]-[4], e.g.:
  - Minimize the number of transmitted packets while meeting a minimum set of service level agreements.
  - Quality of Experience (QoE).

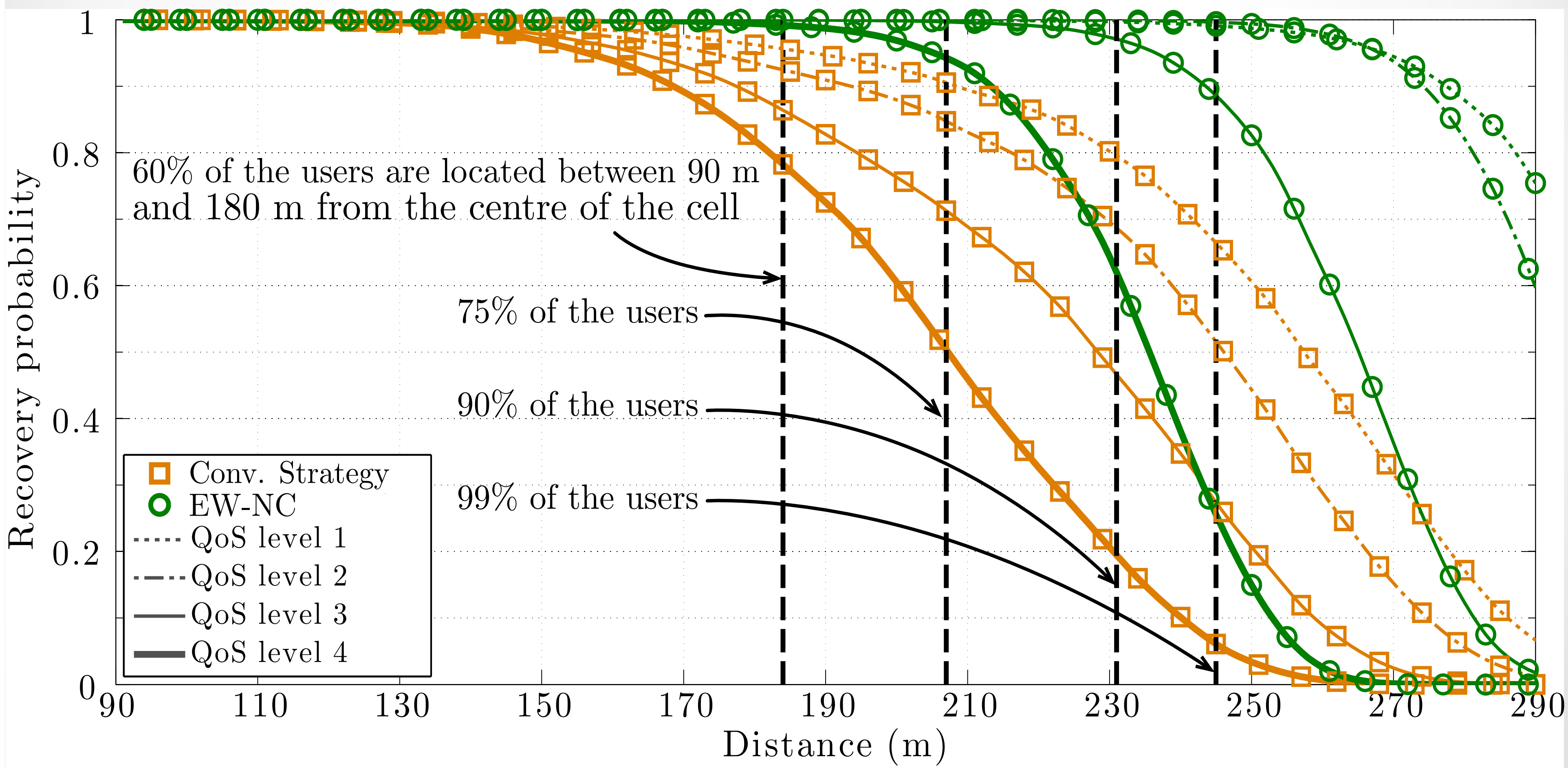
- Abstraction of the underlying system allows to identify functionalities.

EW-NC for LTE-A - functional domain



EW-NC 4 LAYERS – illustration of performance[1]

Users placed along the symmetry axis one cell-sector.



Digital Video Broadcasting (DVB-S2/X/RCS)

- DVB-S2/X is a widely spread air interface standard in the satellite market with application in sports, news contribution, professional video distribution, IP trunking, cellular backhauling, Governmental networks, etc
- Highly adaptive air interface with (fine-granular) adaptive coding and modulation at the physical layer.
- DVB standardization based on common building blocks.
- DVB-S2/RCS incorporates link layer packet-level Forward Error Correction for mobile transmission (railway channel with periodic erasures).
- Here we use the design examples in [6] of a link-layer systematic network coding (LL-SNC) solution is worked out over DVB-S2/x/RCS.

LL-SNC - functional architecture

- LL-SNC layer is between IP and MAC: dimensionality of network codes compatible with standard. Network Coding dynamic properties depend on channel conditions AND congestion (due to underlying adaptive coding and modulation).

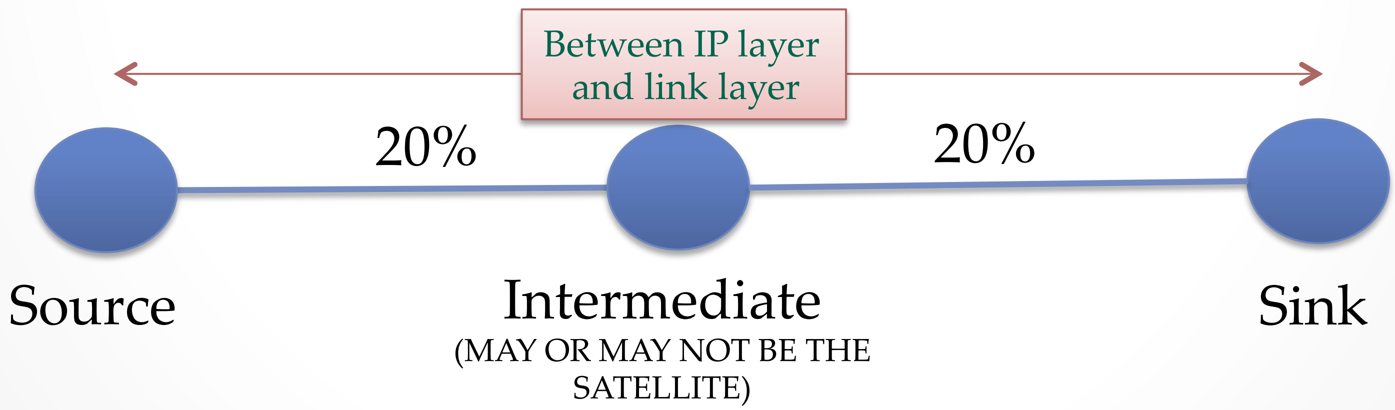
- Preliminary protocol used: Generic Stream Encapsulation (GSE), common to the family of DVB standards.

- Different design goals define the network flow structure to be transmitted to the users [5]-[10], e.g.:
  - Quality of Service (QoS).
  - Quality of Experience (QoE).

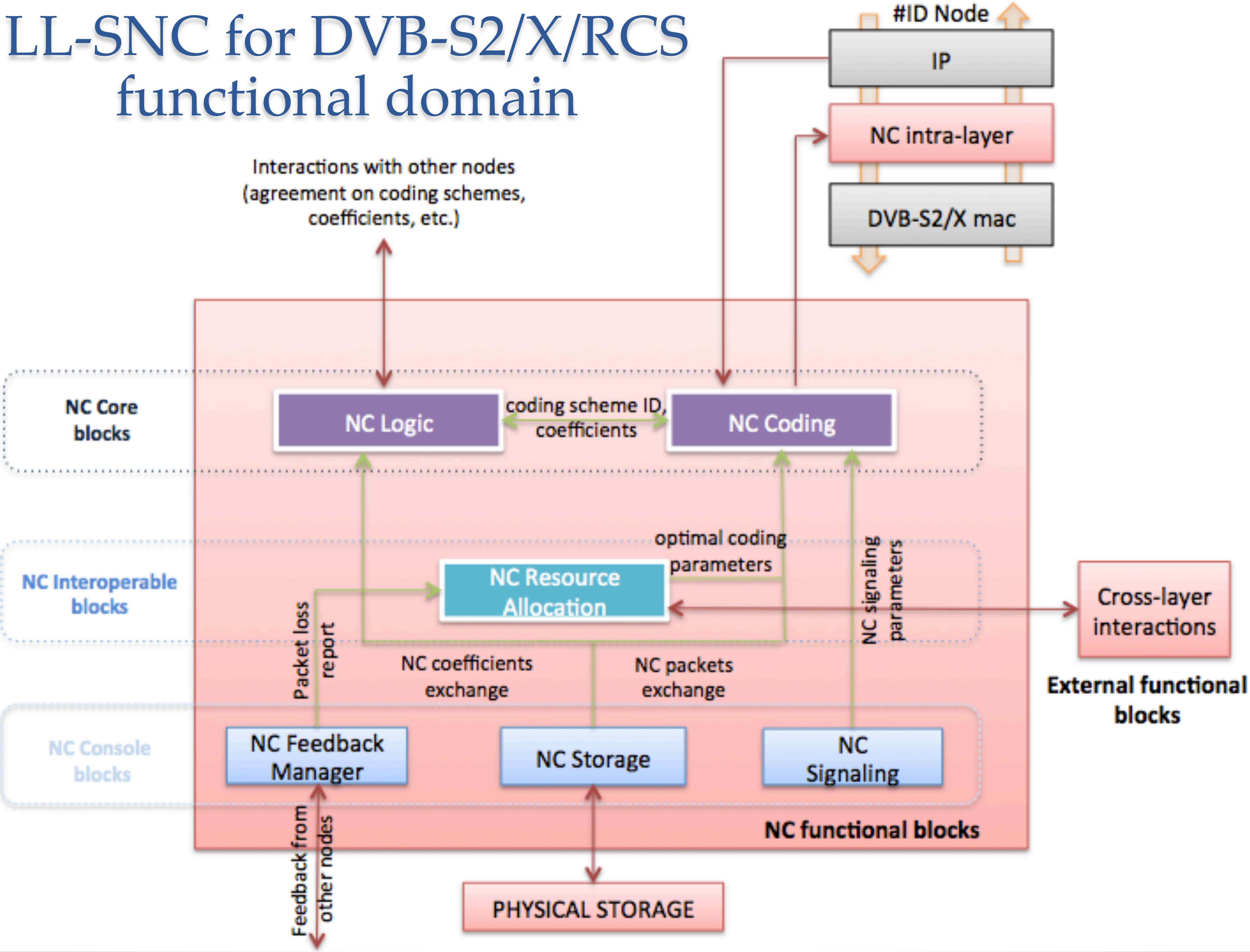
LL-SNC

Abstraction of the underlying system allows to identify functionalities.

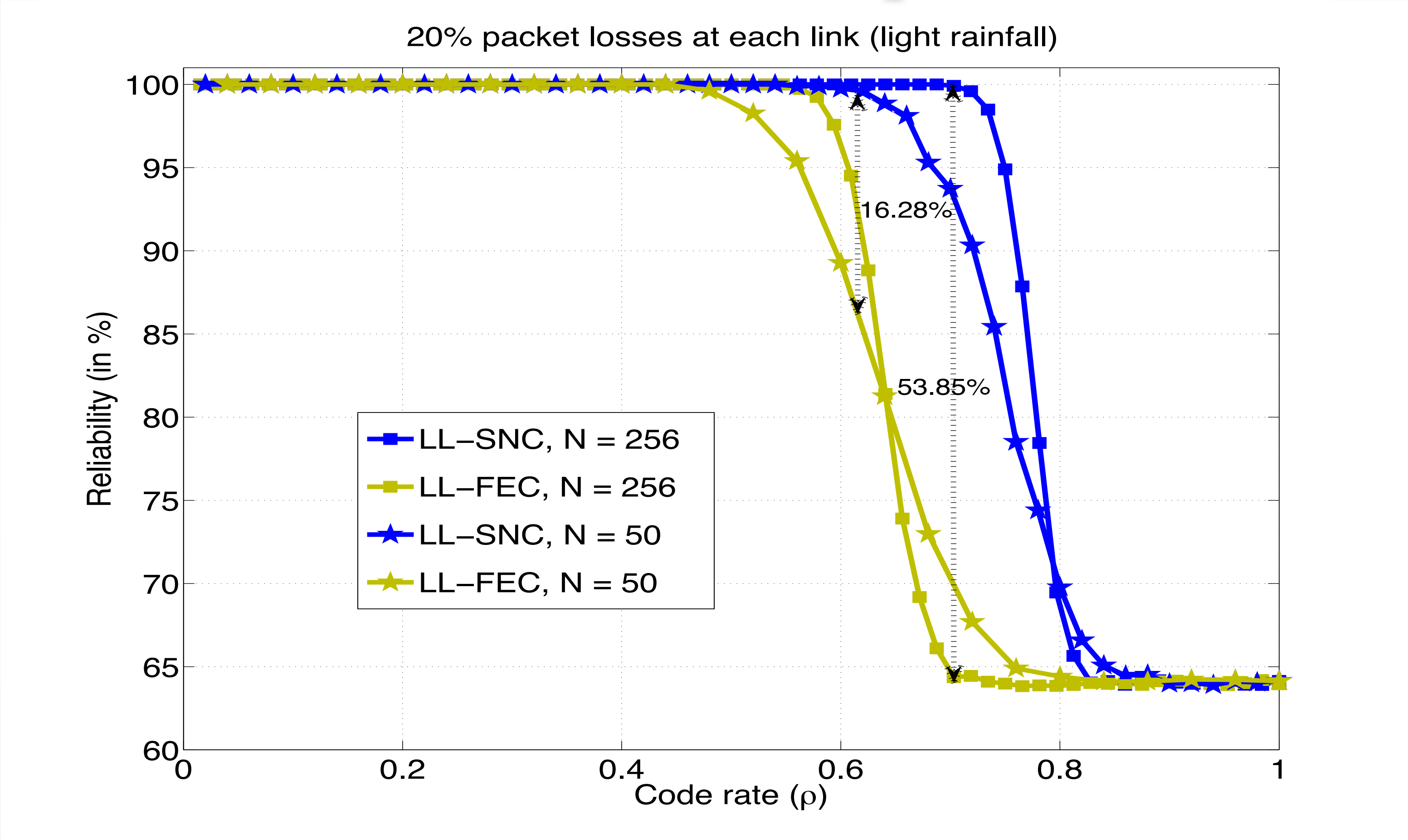
The abstraction decouples conventional SATCOM system design from underlying system functions and physical equipment!: satellite as one more logical node the network flow traverses.



LL-SNC for DVB-S2/X/RCS functional domain



LL-SNC illustration of performance



LL-SNC achieves Max-flow Min-cut providing up to 53.85% higher reliability than existing LL-FEC in DVB-S2 standard

Conclusions – Next steps

- Non-reductionist inter-disciplinary system/layer-independent network coding design framework.
- Preliminary functional domain identified within COST Action IC 1104 specific designs over two different systems. Needs to be validated with more use-cases.
- Proposed framework seems compatible with upcoming (more general) design frameworks e.g. 5G/future networks and work in IRTF/NWCRG.

- **Next steps:**
  - Further elaboration.
  - Coding domain.
  - Protocol domain.
  - Roadmap?.
  - Inter-disciplinary?.

Děkuji!