Introduction and Applications of Network Coding

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Abstract: *This article quantified the benefits of Network Coding (NC) concept as applied in a wireless network. To the best of our knowledge, there has been no comprehensive discussion about NC and its application in the literature. Therefore, the tutorials related to the basic concepts of NC are presented. Under appropriate categories, much attention has been given to various proposed wireless-RN: Digital NC and NC. We have been illustrated the NC applications in overlay network, mobile, LTE and CONERTO system.*

Keywords: *Network coding, network coding aware, cooperative network*

Introduction

Companies are formulating Information Technology infrastructure to reduce the gap between strategy and execution. Implementation comes to success, the increasing need to incorporate insight, efficiency and flexibility are critical. Insight will achieve enhanced performance and increase the ability of the company systems to evaluate programs or software and recognize initiatives. Efficiency again, will engineer optimized resources to achieve business goals and objectives while at the same time minimize costs. Flexibility, in the same line, encourages timely response within and outside your business to ever-evolving company policies, government legislation, convention, and other regulated areas that come in contact with the company operations. In our globalized world where most people work from home it is important that each one knows the immense benefits associated with IT investment, and the biggest advantage is less costs incurred.

The future of wireless networks is necessary to meet rising demands with high spectral efficiency as well as mobility and low energy consumption. The reasonable question here related to network resources (i.e., bandwidth and energy), what is the superior performance that the wireless network can be maintained as well as how it can be achieved efficiently in wireless network design?

With the current growth in wireless network, there are demands for new techniques and schemes to overcome the emerging challenges. Recently, network coding (NC) has appeared as a new technique to improve the network capacity. Hence, the throughput of network can be increased. The main definition of NC *is to allow the intermediate node to combine the incoming information.* In contrast to conventional network, the intermediate node has restricted function. At the first time, the NC introduced in wired network, and now it applied in a wireless network. NC is a fundamental strategy for wireless networks to enhance the broadcast nature of wireless transmission.

Cooperative communications (i.e. Relay Network (RN)) is a specific area of wireless communication that has been extensively explored within the last decade. The idea of RN builds upon a network architecture where nodes assist each other to realize spatial goals of diversity. Traditionally, the messages directly transmit between any 2-end users. Due to a number of factors such as the transmission range, natural obstacles, or poor quality of a direct transmission link etc., the data packet transmission cannot be completed very well (i.e. the destination node doesn't receive enough data packets). Therefore, there is a need to deploy a node between the two nodes to bridge the connection. The traditional functionality of the relay nodes is to repeat and forward the information to the subsequent nodes. However, in general the networks have many nodes, and there are several available middle nodes that are responsible for relaying the data packets. The basic idea of relay channel has been introduced and elaborated in [1] and [2], where authors considered the main network topology consisting of 3-nodes: source (**S**), relay (**R**), and destination (**D**). There are several challenges in terms of transmission over wireless networks, such as system performance, interference, noise, fading, bandwidth, and power constraints.

To overcome these issues, NC appears to cooperate. The NC method achieves the max-min-cut throughput as well as supporting the integrated accurate flow of data packets while transmitting from source(s) to receiver(s), *Wu et al.* in [3] and *Katti et al*. in [4] have described the straightforward implementation of NC in a topology consisting of a three node wireless network. The NC has shown to be successfully implemented for unicast, multicast [5], and broadcast [3], [6] transmissions over a given network topology. Interested readers should refer to [7] where details related to the fundamentals as well as advanced concepts of NC are available.

The rest of this article is structured as follows. Section II describes the NC system model. The details related to the classification of NC are presented in section III. The section IV provides an overview of NC application. The conclusion of this study is presented in section V.

Wireless NC Concept

Firstly, we present a concise description of min-cut max-flow theorem, a multicast network problem statement. In a network, a cut is a set of edges whose removal disconnects source from destination. A min-cut is a cut with the smallest (minimal) value among all cuts. The sum of the capacities of the edges on the cut is equal to the value of the cut. According to the multicast network problem statement, maximum flow from source to destinations in any network is equal to the size of min-cut [8] ,[9]. The state of the main theorem of NC: "***Consider an acyclic directed graph G = (V,E) where V is the set of vertices connected by a set of unit capacity edges E, h unit rate sources located on the same vertex of the graph and N receivers***". If the min-cut value to each receiver is h, then there exists a multicast transmission scheme over a large enough finite field F_q , in which intermediate network nodes linearly combine their incoming information symbols over F_q and are responsible to deliver the information from the sources simultaneously to each receiver at a rate equal to h." [10].

NC System Model

Even though wireless networks suffer from low throughput, the implications of Wireless NC fundamentally improves the throughput of multi-hop wireless networks by exploiting the broadcast nature of a wireless channel. To show the obvious use of NC within wireless networks, we can model a wireless network communication system by considering a graph $G = (V,E)$ where V is the set of vertices connected by a set of directed edges E.

These vertices and edges symbolize nodes and channels of a wireless communication system as shown in Figure 1; where nodes that transmit data packets into the network are source nodes (S_1 and S_2), and the nodes that receive messages are called receiver nodes (R_1 and R_2) for a particular multicast session. Each source wants to transmit packet b_1 and b_2 to receiver nodes R_1 and R_2. Due to the limitation of transmission range, packets have to pass through intermediate nodes that act as relay nodes between source and receiver. Nodes A and B are in the transmission range of source nodes S_1 and S_2, respectively.

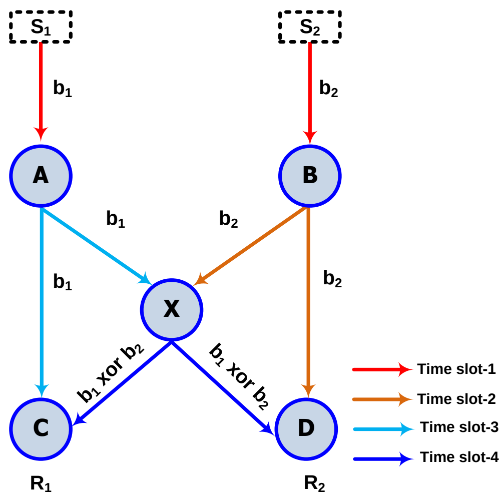

Figure 1 Butterfly system model

The Illustrations of wireless NC in multiple unicast sessions are show in Figure 2 below. We can observe that, using of NC reduce the number of time slots to three.

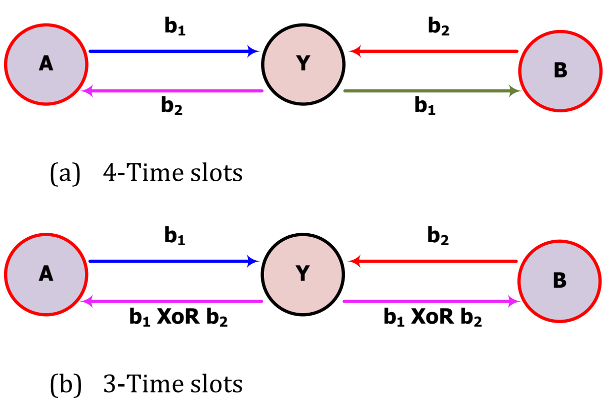

Figure 2 (a) without / (b) with NC in multiple unicast sessions

Classification of Network Coding

Depending on the NC application, the NC can be classified into two categories, i.e. Digital-NC and Analog-NC as depicted in Figure 6.

Digital-NC:

Refers to the straightforward NC in which the source node or the intermediate nodes are responsible for combining packets at the network layer [4], [11] and [12]. In wireless ad hoc networks, for both unicast and multicast sessions, routing can be classified in different ways as shown in Figure 3. On the basis of regular or on-demand methods to obtain route information, self organize routing protocols have been classified as proactive (i.e. table- driven), reactive (i.e. on-demand, and hybrid routing protocols, Position-based, and geographical, routing protocols require the availability of location information of nodes upon which forwarding decisions are based. This section concerned with the main definitions of opportunistic routing and details of emerging NC-aware routing protocols.

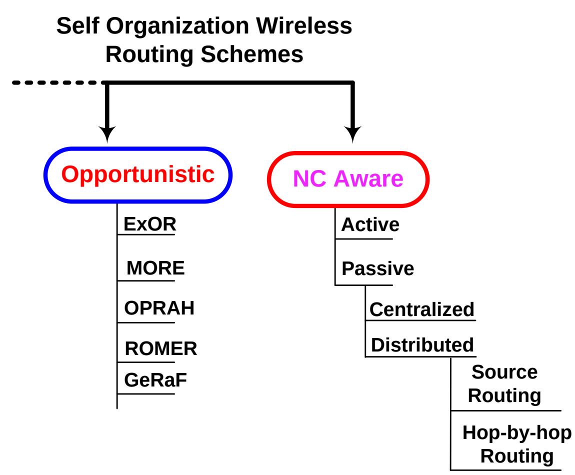

Figure 3 Taxonomy of routing protocols for self organization wireless networks

i. Opportunistic Routing

In conventional routing, a fixed (not dynamic nature) selected next-hop is responsible for forwarding data packets. In opportunistic routing, multiple neighbors can overhear a transmitting node. In the end user, any selected set of a sender's neighbour continue to forward the packet further towards the destination while meeting certain conditions. Opportunistic routing fundamentally consists of two main components: Forwarder set selection and hop-by-hop forwarder set selection. The Forwarder set selection method depends on the duplicate packet forwarding. Hop-by-hop method refers to each packet holding node is responsible for independently determining its own forwarder set towards the intended destination.

Example of COPE Coding: COPE coding inserts a coding layer between the IP and MAC layers. Node-1 has 4-packets (P_1, P_2, P_3 and P_4) in its queue, whose next-hops are listed in (ii) which its neighbors have overheard some of these packets. When the MAC permits Node-2 to transmit, Node-2 takes packet p1 from the head of the queue. Each neighbor of Node-2 has stored some packets as depicted in (a). Node-2 can make a number of coding decisions (as shown in (iii)), but should select the last one because it maximizes the number of packets delivered in a single transmission. The coding options are depicts in Figure 4 where the rule to achieved decode the XOR-ed: "To transmit n packets, P_1, P_2, . . . , P_n, to n next-hops, r_1,r_2 . . . , r_n, a node can XOR the n packets together only if each next-hop r_i has all $n - 1$ packets p_j for $j \neq i$".

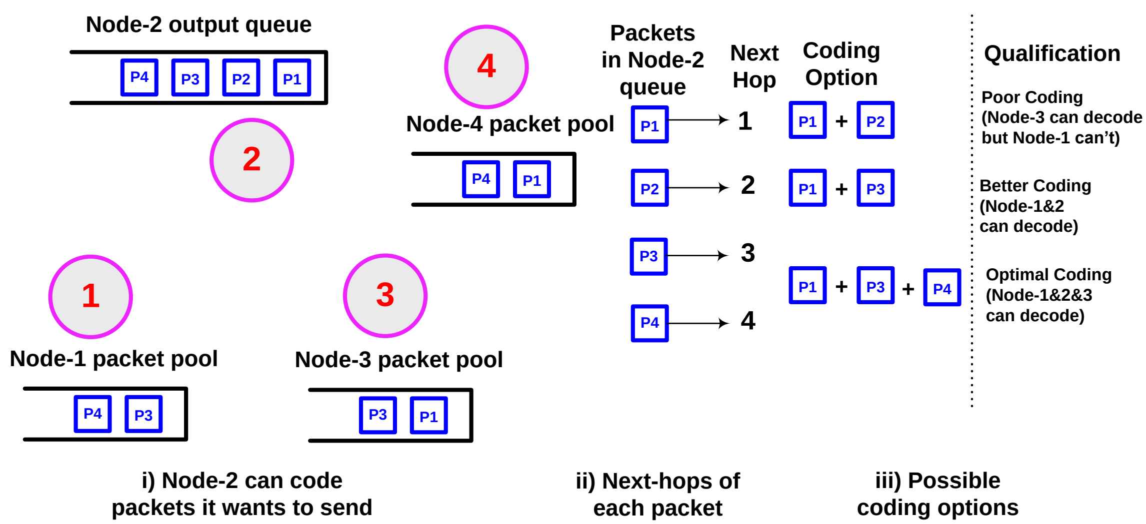

Figure 4 Example of COPE Coding

The opportunistic routing protocols follow under the self organization wireless network: Geo-distance-based Geographic Random Forwarding (GeRaF) [13], ETX-based Medium access control-independent Opportunistic Routing and Encoding (MORE) [14], ETOX-based MORE [15], credit-value-based resilient and opportunistic routing solution for mesh networks (ROMER) [16], etc.

ii. NC-Aware Routing

NC-aware routing protocols can be classified into different classes with respect to different criteria. Generally there are two major types of NC-aware routing protocols; Active and Passive NC-aware routing protocols. In Active NC-aware routing, each node actively optimizes the routing of packets along the paths (to exploit potential opportunities) with the best coding options to reduce the number of transmissions. On the contrary, in passive NC-aware routing, each node passively waits for NC opportunities based on local topology information through response information's.

The NC-aware routing paradigm considers NC opportunities at coding points to assist route selection for packet delivery in wireless networks. The primary troubles with NC-aware routing in wireless networks are related to detection the routes with the highest coding opportunities and determining the precise coding ability at each node in the wireless network. The intention of these two detections is to reduce the number of transmissions required to distribute data from various sources to respective destinations within a certain network topology. The first practical NC architecture is the COPE approach [17]. COPE was the first NC approach that practically supported unicast communications by performing coding of packets before forwarding to destination. It adds a coding layer between IP and MAC layers to detect coding opportunities and utilize them to forward multiple packets in a single transmission. Three techniques; opportunistic listening, opportunistic coding, and learning neighbour state are mix in fundamentally COPE. The fundamental operation of COPE describe in the following figures. When apply COPE's in node C to encode the packet transmit from *node-A* and *node-B* coding conditions, is not capable to encode flow f_1 and f_2 because opportunistic overhearing is several hops away from C, as shown in Figure 5 (c).

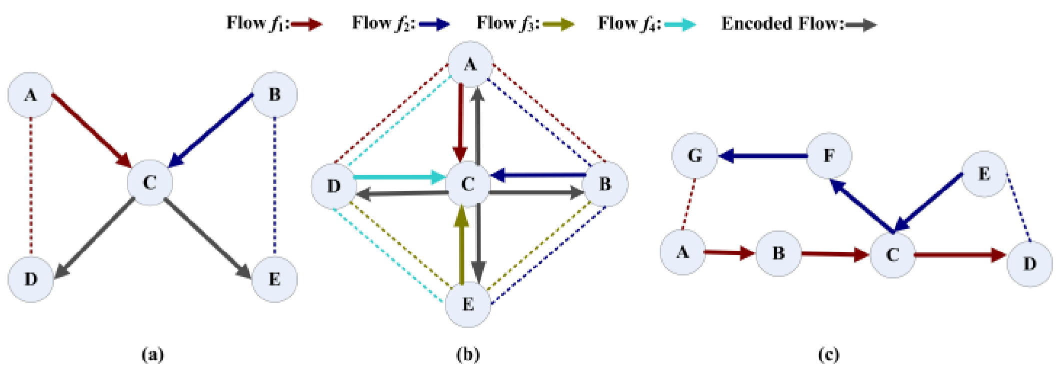

Figure 5 (a) Opportunistic overhearing coding scenario (b) Hybrid (overhearing + non-overhearing) coding scenario (c) Coding scenario beyond two-hops

Analog-NC:

Analog NC is also referred to as physical-layer NC (PNC) is the combining of symbols at the physical layer (PHY) [18], [19], [20] and [21]. If the relay forward the continuous value via posterior probability to other node (destination) [22], [23], [16] then this schemes called continuous-NC or soft-NC.

As a result, there exists a link between NC and RN as both schemes represent *cooperative behavior*. The NC-based relay nodes are different from traditional network relay nodes. Traditional network relay nodes simply replicate and forward received information. On the contrary, in case of NC applied on the intermediate node (in terms of arithmetic functions) that leads to improved performance of the system model. The performance metrics supported by the system model based protocols are capacity, symbol error rate, outage probability, power allocation, and throughput.

Even as the degree of RN is widely, we list in this section some of the important choices. Figure 6 depicts a classification of a wireless RN with some choices/parameters.

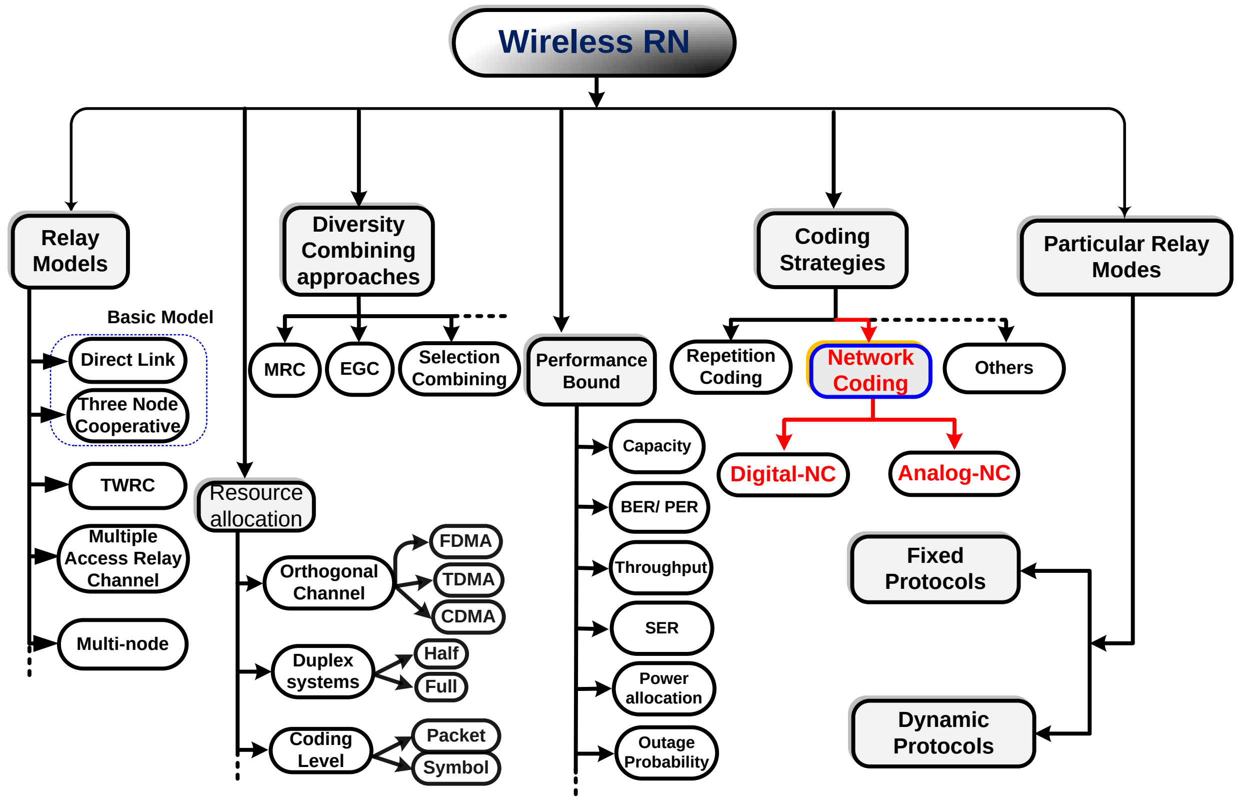

Figure 6 Classification of Wireless RN

Example of PNC over TWRC

Consider the three-node linear network in Figure 7. S_1 and S_2 are nodes that want to exchange information but they are out of each other's transmission range. *R* is the relay node between them. We assume the three nodes are using BPSK modulation. The output of each node is given by $b_i = 2*x_i - 1 \in \{\pm 1\}$. The relay node obtains the desired XOR information $Y_R = (x_1 \oplus x_2) \in \{\pm 2, 0\}$. In addition, the XOR operation in the *straightforward* digital NC can be realized through PNC mapping in Figure 7. More detail is available Table 1.

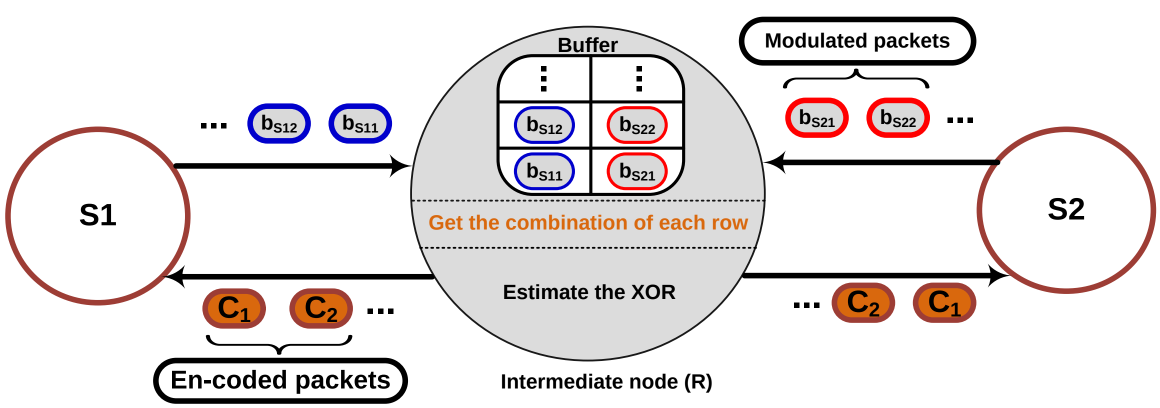

Figure 7 An example of describing NC in PNC

Table 1 PNC mapping and De-modulation

Generate and Modulation the information at S_1& S_2				Demodulation at the relay node R and retrieval the information.		Retrieve source information	
Data bit (m_i) generated at sources		Signal output after modulation ($2m_i$-1)		Relay input (Amplitude of a baseband signal) $(x_1 + x_2)$	Relay output (Modulation mapping) $((x_1 + x_2)/2) - 1) \bmod M$ $M : Level$ OR: $x_R = (S_1 Å S_2)$	$S_{\text{i-retrieve}} = (x_R Å S_l)$, $i = 2,1$ *and* $l = 1,2$	
S_1	S_2	x_1	x_2	y_R	x_R	S_1	S_2
0	0	-1	-1	-2	0	0	**0**
0	1	-1	1	**0**	**1**	1	0
1	0	1	-1	0	1	0	1
1	1	1	1	**2**	**0**	1	1

NC Applications

The NC was presented in the past decade as a phenomenon in the research community. NC has spreader to Multi discipline of science start from physical layer to upper layer. Its include channel coding, wireless communications, computer networks, switching theory, cryptography, data storage, and computer science. Furthermore, in mathematics, NC has act together with matroid theory, graph theory, optimization theory, and game theory. As well as in physics, quantum NC was considered, and in biology, linear NC has been used for modeling intracellular communication.

Overlay Networks

The questions that researchers are asked, how can NC be applied to P2P Content distribution? Why is NC cooperative in P2P Content distribution? How can Network Coding be applied to P2P multimedia streaming? Why is NC helpful in multimedia streaming?

In case of P2P content distribution, the ***block scheduling issue*** deciphers utilizing NC in an amazingly simple and effective way. The results have been shown that the lower latency of file downloads and better robustness to peer departures.

In P2P multimedia streaming, streaming protocols is required to redesign to obtain occupied pros of NC. In particular, a new streaming system design with NC was provided. The using of NC is able to fully utilize available bandwidth resources, thereby improving the overall system performance.

Mobile Devices

This section provides the picture viewer application of NC on mobile phones. The main thought is that users share content over short range technologies such as WiFi. The authors [24] have been shown that the energy consumption increases with the generation size.

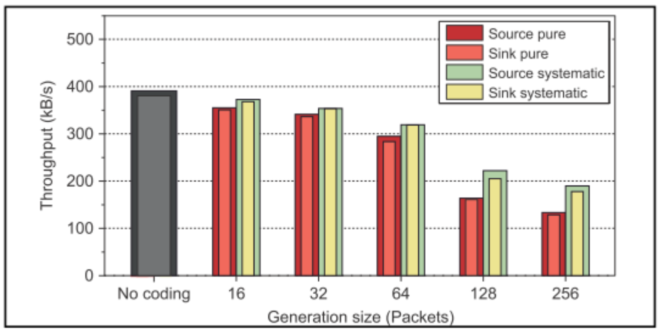

Figure 8 Throughput vs. generation with/without NC [24].

Network Coding for LTE

This fragment provides the accessible of NC in LTE networks. NC appears to overcome challenges such as streaming, download services in future mobile communication systems, the bandwidth and energy. The article was presented through the simulation tool; the NC can save up to 80% of redundant information of the cellular link, as long as there are at least two cooperative mobile devices. Furthermore, in case of four devices in the cooperation cluster NC saves more than half of the traffic in the short-range.

The linear combinations of packets transmit from sender refer to layer-1 in figure. The accumulation and multiplication are performed over GF having the same size to the original packets. In the company of Random Linear NC, the coding coefficients are preferred at random. Refer to middle layer and due to the channel situation in wireless network, the packets may lose. The decoder received the encoded message from the sender, which will be capable to recover the original data packets after receiving at least g linearly independent packets.

Furthermore, the receiver nodes able to produce and send new encoded packets, even before decoding the entire generation. They figure fresh linear combinations of the packets that they have previously received. This operation is known as recoding, and it is a unique feature of NC. Conventional coding schemes need the original message to be completely decoded before it can be encoded again.

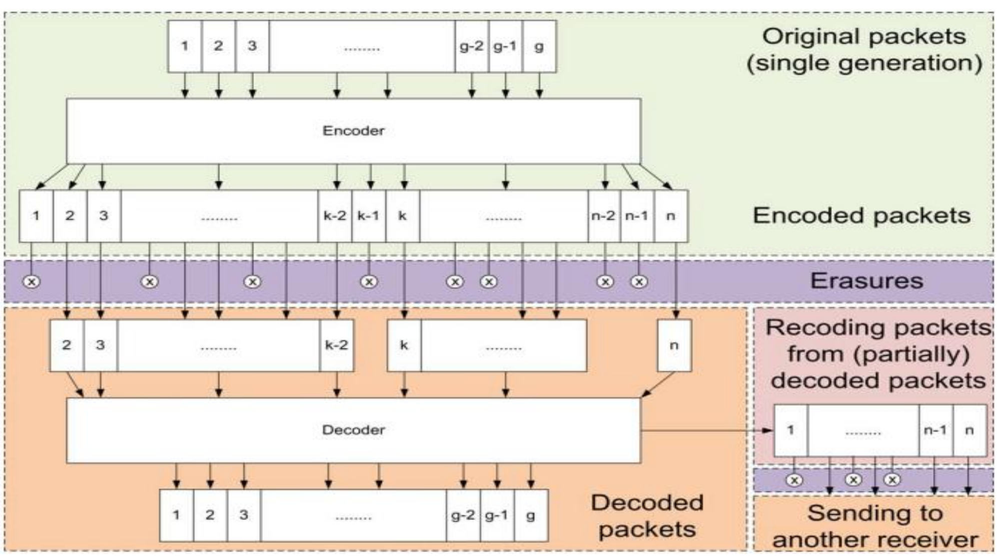

Figure 9 NC scenario [25]

CONCERTO system based on NC

The CONCERTO system was developed by team of BAE Systems and it's a solution of MANET system. It stands for Control over NC for Enhanced Radio Transport Optimization. It was shown to support two to three times more video throughput than a state-of-the-art set of protocols, as well as up to 7 times distance-utility product.

The emergence of projects article in chronological order article that belong to communications and networking categories is shown in Figure 10 in chronological order.

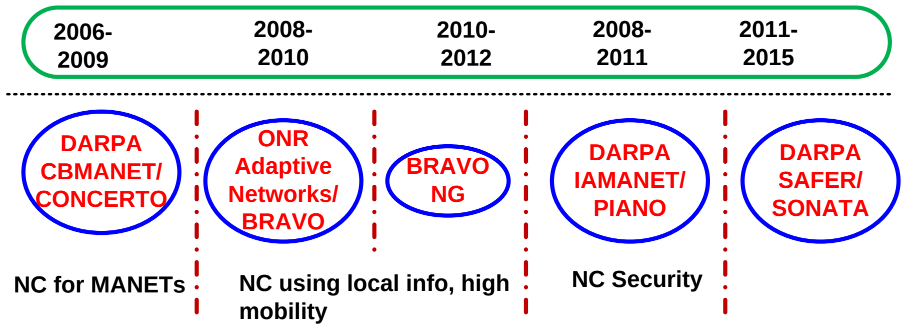

Figure 10 Emergence projects article in chronological order.

To supports the whole range of network types i.e., unicast, multicast, and broadcast, CONCERTO system is become visible to joint routing and transport protocol that capable the exchange the packets between the nodes.

Two basic models of CONCERTO system:

- Replaces the conventional forwarding of data packets with transmission of information via network coded data.

- Data propagation over sub-graphs.

The components of the CONCERTO system are describes in Figure 11.

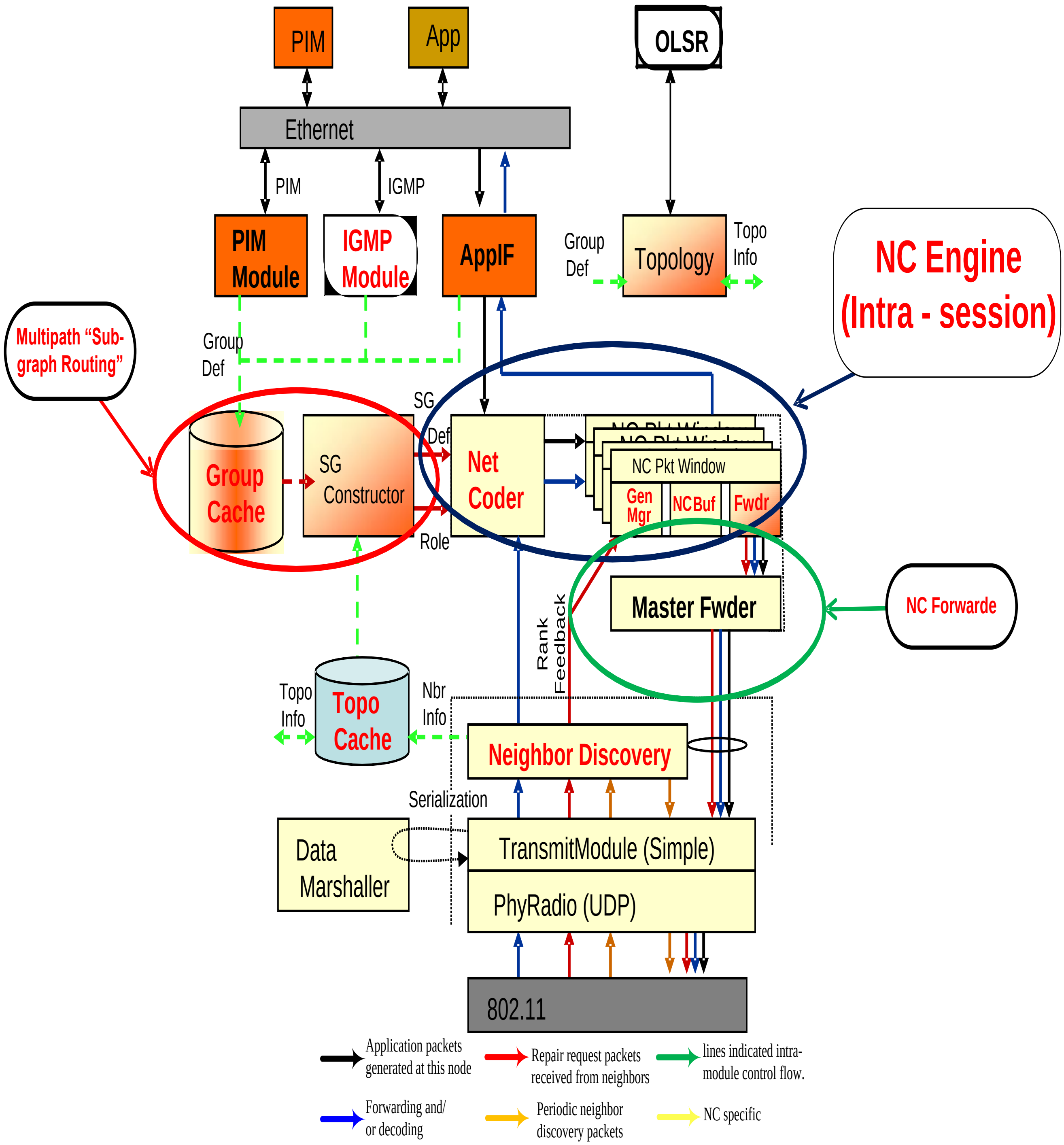

Figure 11 CONCERTO Architecture [26]

- Application interface (***AppIF***): receives packets from applications running on PCs that are connected to CONCERTO via an Ethernet, classifies them into traffic types and passes them to the NC module.

- NC module (***Net Coder***): groups application packets into generations, performs *random linear coding* over packets in a generation, provides coded packets to the forwarding engine upon request, and decodes packets at destination nodes.

- Subgraph Constructor (***SG Constructor***): uses information about network topology, multicast groups, and source and destination nodes to select the nodes that will forward network coded packets for each application session as well as to determine forward traffic amount for each of these nodes.

- Forwarding engine (**Master Fwder, Fwdr**): uses novel transport protocols for make a decision which packets need to be encoded, forwarded, decoded, discarded, retransmitted, and timed-out.
- Neighbor Discovery, Topology Discovery (***Topology, Topo Cache***): determines node connectivity and estimates link quality; uses the efficient Optimized Link State Routing (*OLSR*) protocol to disseminate connectivity information throughout the network to support the sub-graph construction and to distribute multicast group membership.
- Group Manager (Internet Group Management Protocol (***IGMP***) ***Module, Group Cache***): keeps track of which destinations are in each multicast group and provides this information to the sub-graph constructor.

Conclusion

Our vision of a future NC system includes a combination of existing and novel technologies. We have quantified the benefits of NC concept as applied in wireless network. Finally, we illustrate the NC application in overlay network, mobile, LTE and CONERTO system. Furthermore, in future work we can see the application of NC in multicast communication in the presence of passive eavesdroppers and active jammers, data compression, scaling laws and disruption tolerant networks.

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