NETWORK CODING AND WIRELESS ENVIRONMENT

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Introduction

The concept of Network Theory was introduced into the Theory of Information Science in the publication by Ahlswede et al. in 2000. According to the paper presented, "Network Coding refers to the coding done at a node present in the network". In today's world, Network Coding is a networking scheme through which a node is allowed to generate output data by mixing of the data received at its end. By mixing of data, here we mean computing certain functions over received data. So transmitting evidence about message can be more useful than conveying message themselves. Network Coding is used to optimize the flow of digital signals through routers in a network. The main advantages of this approach are improvement in throughput, robustness and reliability.

In today's world of Internet and Wireless communication, we deliver the information through routing. Here routing refers to a transmission method by which a device in the intermediate network temporarily stores the message or data before sending it to destination or next intermediate network node. Network Coding is a recent generalization of routing and also breaks the conventional routing approach of data forwarding in a network. In Network Coding each network node can perform certain computations whereas in routing the output message can only be the copies of the received messages. This means Network Coding allows information's to get mixed at a node.
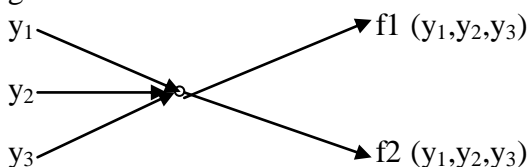

Figure 1: Network nodes can compute functions of received messages.

Let's consider a simple network coding example as presented in the following image:
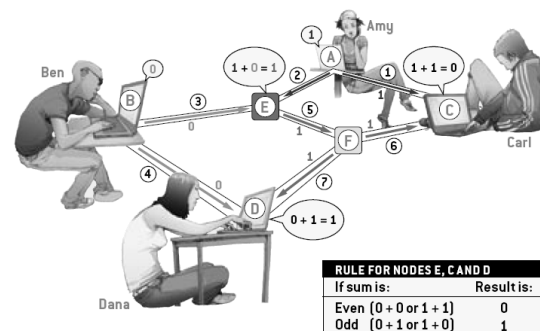

Figure 2: Network Coding Example.

The figure 2 shows a network consisting of six-nodes, four end hosts, one router and one network coder. Let's assume that the rate of message traveling along a node is one-bit per second. First let's consider the situation of a standard network where E is a normal router and see what happens. Both paths from A to D and from B to C requires link 5 to deliver their message. As a results we have a bottleneck - router E receives a total of two bits per second. In addition router E cannot transmit it since the capacity of the link 5 is defined as one bit per second, so the router E can send only one packet at time. This means the router must put the second bit to a queue. This may end up in nightmare as more and more bits are piling up over time, waiting for their turn.

Now let's focus on situation where we have a network coder instead of a router as the node E. The node A sends a packet to nodes E and C. At the same time the node B sends a packet to E and D. The coder at node E sends combined packet to the node F can be seen in the above figure. As we can see there is no delay at the node E. So the node E does not send the message but sends evidence about it. The evidence is later forwarded to the nodes D and C by the node F. The nodes D and C can

decode the messages using the rule.

While talking of Network Coding, the first things we relate it to are wireless communication networks. This is interesting to know that wireless networks have been designed using the wired networks as the blueprints. By mapping one wireless channel to another on top of which standard protocols are deployed. There are certain characteristics of wireless network like broadcasting, dynamic nature which makes it different from the latter. Some of these characteristics can be used as valuable asset by using the network coding technique. Firstly, the broadcast nature of wireless networks which offers an opportunity to solve the unreliability issues of the medium. For example, when a node broadcasts a packet, there is a strong possibility that at least one nearby node receives it, which can then functions as the next-hop and send the packet forward. This approach is in direct opposition to the present design of wireless networks: usually there is a single designated next-hop. In case of failure, a previous hop needs to retransmit the packet. Secondly, data replication can improve throughput in wireless networks. In those networks there is also strong tendency toward duplication of data:
• Because a packets is transmitted over multiple hops, so the data transmitted in the packet are available to many nodes,
• When a hop sends a packet, because of broadcast nature of medium, it is delivered to all nodes within the sender's radio range.

2. Opportunities and challenges

The potential benefits provided by network coding in wireless environment are as follows.

2.1 Throughput

Network coding increases the wireless throughput because coding allows the coders to compress the transmitted packages or packets based on information that is known at various nodes. By matching what each neighbor wants and what each neighbor has, the coder delivers the multiple packets to different destination in a single transmission.
Network coding can be used in content distribution. Today people often listen to music in public places. Let's consider another

example where we all want to listen our favorite song using common hot-spots. Efficient bandwidth usage would be crucial in this scenario. In order to get the song a customer wants it must also present which song it already has. So let say, 1 and 2 are the two customers and S_1 and S_3 be the songs which the users A and B have on their system. Now imagine a wants to listen the S_3 and B wants to listen the song S_1. Instead of sending the separate data streams to both the clients, the service point can broadcast XORed version of the stream which is S_2 ($S_2 = S_1$ xor S_2).
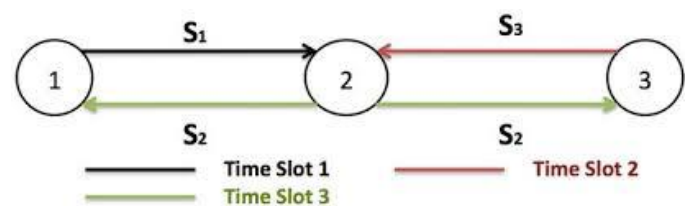

Figure 4: An example of increasing network throughput.

As a result both the customers can easily decode their songs as well as the access point can send half of the data required in the scenario. Thus, network coding doubles the throughput.

Let's take another example, an example shown by Ahlswede et al. showing network coding can increase the possible network throughput, and in the multicast case can achieve the maximum data rate theoretically possible. In figure 4, each link in the graph can carry one bit per second. Using network coding, we can multicast information from the source node s to the two receiver's t1 and t2 at rate 2.0 bit/second, which cannot be achieved using traditional routing.
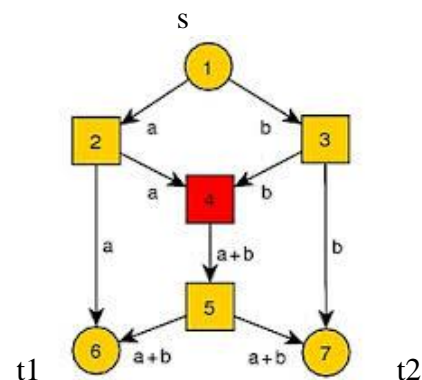

Figure 4: Network Coding increases the throughput of a network.

2.2 Reliability

In today's network by reliability we usually mean the retransmission of the packets in case of packet loss. This works quite well in wired networks, but seems to be inefficient in wireless ones. Network coding gives new approach to reliability. By mixing the information at each node, there are no special packets left in the network. To illustrate it, let's consider example from a traditional approach. In conventional way, without coding a source needs to know which packets the destination has missed in order to retransmit them. In an unreliable environment it may consume some extra bandwidth. If we want to use network coding, we usually do not care about individual packets. A source needs to inform us only if it receives enough packets to encode the transmitted file. There is also one additional benefit, because of improved reliability we also improve throughput of the network (less data needs to be retransmitted).

In the figure 5 example A, the source has perfect link to the router, whilst the destination link to router has 50% probability of successful delivery. In the *802.11* unicast network this requires $2n+2 \log_2 n$ (where n is packets in transmission) after some modification which increased protocol complexity as well as bigger acks from the receiver2. In contrast authors suggest network coding based approach which requires $2n + 2$ transmissions.

In the figure 5 example B, there are 5 nearby nodes which could forward the packet to the destination. Unfortunately, the source is in a dead spot with 80% loss rate to every nearby wireless node. Because of that, each packet has to be transmitted 6 times in the 802.11 networks.

Much better results can be achieved using following schema. The source broadcasts the packets to all its neighbors. A neighbor forwards the perceived packet to the destination. By applying this approach we manage to increase probability of delivery to 67.2% and average packet transition in 2.5x. But this creates a problem when multiple nodes hear the same packet and try to forward it to the destination. This cause additional traffic. The issue can be solved by applying network coding. A rely can transmit linear combination of a new packet and packets received so far. This information is then transmitted to the destination. When the destination can decode the transmitted file it broadcast the acknowledgment which causes that all relies stop their transmit ion.

In the figure 5 example C, multicast case is shown. If the coder R has to retransmit packets p1 and p2 it can retransmit XORed version of the packets. As the result both destinations can recovers their losses, and provide efficient reliability.
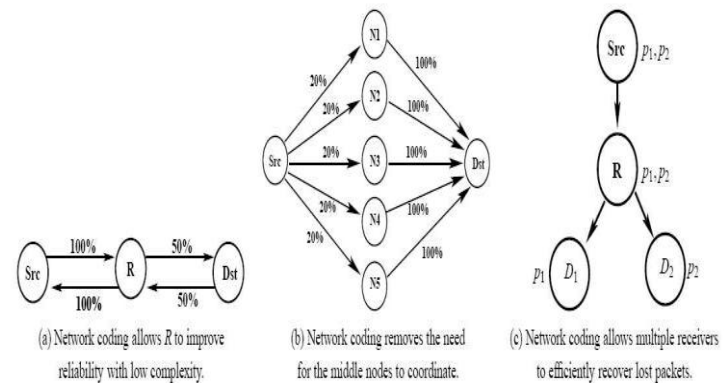

Figure 5: Examples of reliability scenario.

2.3 Monitoring

Network coding can be exploited to better monitor the link loss rate in wireless networks. Let's consider example shown in figure 6. In the example nodes A, B, C, and D are sensors while nodes E and F are sinks connected through a high-bandwidth link. When we use network coding nodes E and F may receive $x1$, $x2$, $x1 + x2$ or nothing depending on the transmission on each link. By sending several rounds of probes from A and B authors can observe link loss on all five links simultaneously. In the paper authors compare this mechanism to traditional tomography (study of network's internal characteristics using information from end to end point) with only multicast or unicast probes and per-link monitoring. Authors observe reduction of probes in both scenarios, which leads to
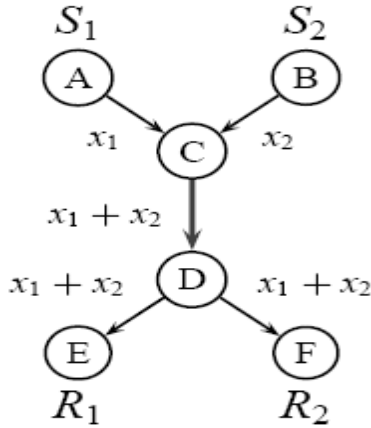
bandwidth and energy savings.

Figure 6: Monitoring Example.

2.4 Mobility

Network coding can improve mobility inside a wireless network. Because of dynamics of wireless networks, routing updates are costly. Let's consider an example shown in figure 7. Let's assume that all nodes want to receive the packets transmitted by D. The node is a mobile node and does not know the environment within its transmission range. Without network coding the node D needs to first detect its neighbors. This leads to some packets exchange. In addition the node A needs to figure out where previous transmissions with the node D ended. Without it a new transmission cannot happen. With network coding however, the node D can keep transmitting new random linear combinations. As long as any of the mixed packets has information unknown to the node A, the coded packet will be new and useful. Furthermore, the coded packet can bring new information to many of the node D's neighbors at once because any neighbor who has missed any of the previous packets will find the packet useful. As the result, the node D need not know who is in its radio range or which packets they have heard. So we can get rid of the need of tracking the quickly changing topology in a wireless network.
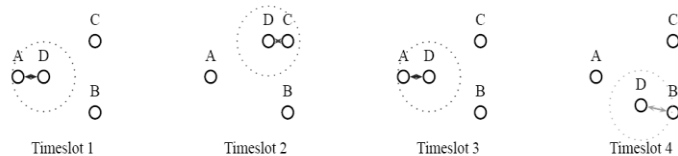

Figure 7: Mobility example: Broadcast information without knowing which nodes are within its range.

2.5 Challenges

In order to fully utilize the broadcast nature of the wireless link entire network stack needs to be redesigned. The change is especially needed in all the mechanism imported from the wired world: MAC, routing and transport protocols. They are optimized to work over point-to-point links, assume a single predetermined path and a layered architecture. The cost of redesigning our network stack is non-negligible. But the wireless throughput is intrinsically limited, which warrants efforts to investigate the potential of new high-throughput architectures. Furthermore, the wireless environment is easily controllable to new deployments than the wired networks, generally such deploys rely only on software updates.

3. **Practical Implementation**

As mentioned earlier, the work on network coding started with a pioneering paper by Ahlswede et al. [2] that established the value of coding in the routers and provided theoretical base on the capacity of such networks. The combination of [16, 15, 11] proves that, for multicast traffic, linear codes achieve the maximum capacity bounds, and coding and decoding can be done in polynomial time. Additionally, Ho et al. show that the above is true even when the routers choose random coefficients. The work on network coding has been extended on many areas: content distribution, secrecy, and distributed storage as well as unicast. It seems that the most beneficial of network coding usage are wireless networks. This work can be divided into three classes. The first is theoretical; it extends some of the known information theory bounds from wired to wireless networks. The second is simulation-based; it designs and evaluates network coding protocols using simulations. The third is implementation-based; it uses implementation and test bed experiments to demonstrate achievable throughput gains for sensors and mesh networks [14, 13, 4].

4. COPE

COPE, a new architecture for wireless mesh networks. In addition to forward packets, routers mix data from different sources so that the information content of each transmission can be increased. As above it's shown that mixing of information using proper technique increases the network throughput.

In this approach "X" topology is used, sources S_1 and S_2 are sending packet to the destinations D_1 and D_2. In the middle there is a router R. Because of the broadcast nature of wireless medium node D_1 hears S_2 packets and D_2 hears S_1 packets. In the middle router R perform *XOR* operation and broadcast modified version. For more general topologies *COPE* leads to even more bandwidth saving because it can code more than a pair of packets.

For more general topologies, COPE leads to larger bandwidth savings than are apparent from the above example. It can XOR more than a pair of packets and produce a multifold increase in the throughput. To summarize, COPE is a MAC extension that has two components:

- Opportunistic Listening: COPE exploits the shared nature of the wireless medium which, for free, broadcasts each packet in a small neighborhood around its path. Each node stores the packets it overhears for a limited period. It also tells its neighbors which packets it has heard by adding comments to the packets it sends. This creates an environment conducive to coding because nodes in each area have a large and partially overlapping reservoir of packets that can be used for decoding.
- Opportunistic Coding: when a node transmits a packet, it uses its knowledge of what its neighbors have heard to deliver multiple packets in a single transmission. The node XORs multiple Packets when each intended next hop has enough information to decode the encoded packet. More precisely, every node uses the following coding rule: To transmit n packets, $p_1, \ldots, p_n$, to n next hops, $r_1, \ldots, r_n$, a node can XOR the n packets together only if each next hop r_i has all $n-1$ packets except the

packet it wants. Theoretically, COPE reduces the number of transmissions by a factor of two, and thus should double the throughput. Katti et al. has shown, however, that in practice the throughput gain is much larger. Experimental throughput gain exceeds the theoretical gain because COPE alleviates hot-spots in the network. Specifically, in an ad hoc network, most paths cross at the center. As a result, nodes in the center of the network experience congestion, build queues, and drop packets. These dropped packets have consumed bandwidth to reach the center of the network. Dropping them in the center wastes network resources and significantly reduces the overall throughput. In contrast, with coding, congested nodes in the center of the network have the opportunity to send multiple packets in a single transmission, allowing them to drain their queues faster and avoid dropping packets.

5. Conclusion

As researchers claim network coding can be base for tomorrow's networks. Moreover, the reality after the mechanism deployment will be totally different. The packets will not only "share the roads" with other transmissions but also enhance them. Users will cooperate with mutual advantage. As a result of collaboration network throughput will increase for both sides. Additionally, especially in wireless environment, energy efficiency can be improved. Moreover, delays in downloading data and lost cell phone call will be less common. On the Internet, routers fail often or are taken down for maintenance and data packets are dropped all the time. In addition because of limited size of queues on routers packets are dropped because routers cannot handle all the data. This has wrong influence on user experience of the Internet. Reliability will increase with network coding, because it does not require every single piece of evidence to get through.

Network coding will also modify way of working for some of today's applications. For example when someone is trying to download a file in peer-to-peer system, it searches for a

collaborating user on whose machine the file resides. But in the network coding case the file would no longer be stored as a whole or in recognizable pieces. A request sent into a network from a user's computer or phone would cause either that individual's computer or a local server to scavenge through the network for pieces of evidence related to a file of interest. The gathered evidence, consisting of algebraically mixed pieces of information relating to the desired file, would help recover that file. As the result the server or an individual's computer would solve a collection of algebraic equations. And, all the while, most people would remain unaware of these operations -just as most of us are ignorant of the complicated error-correction operations in our cell phones.

By changing how networks function, network coding may influence society in ways we cannot yet imagine. Transitioning from our router-based system to a network-coded one will actually be one of the more minor hurdles. That conversion can be handled by a gradual change rather than a sudden overhaul. Some routers could just be reprogrammed, and others not built to perform coding operations would be replaced little by little.

A bigger challenge will be coping with issues beyond replacing routers with coders. For instance, mixing information is a good strategy when the receiving node will gather enough evidence to recover what it desires from the mixture. This condition is always met in multicast networks but may not be the case in general. Moreover, in some circumstances, such as when multiple multicasts are transmitted, mixing information can make it difficult or impossible for users to extract the proper output. How, then, can nodes decide which information can and cannot be mixed when multiple connections share the same network? In what ways must network coding in wireless networks differ from its use in wired ones? What are the security advantages and implications of network coding? How will people be charged for communications services when one person's data are necessarily mixed with those of other users? I believe that future research will allow to answer this question and network coding will be widely used in our lives.

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