Network coding in wireless environment

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Abstract

An approach called network coding is a new research area that could dramatically enhance the reliability and efficiency of practical networking systems. Network coding can enable intermediate nodes to send out packets that are combinations of previously received information. So transmitting evidence about messages can be more useful than conveying messages themselves. There are two main advantages of this approach: improvements in throughput and robustness. This paper is literature survey on network coding in wireless environment. The paper explains what network coding does and how it does it. It also presents practical implementations of wireless network coding in order to show how this approach can be used in realistic scenarios.

KEYWORDS: Network coding, wireless networks.

1 Introduction

Traditional network architectures are based on the *end-to-end arguments* [18]. It is set of principles that describe how the Internet has been build. However this rules does not suite well in wireless environments. Today's wireless networks have been designed using the wired network as the blueprint. As a result, point-to-point links are mapped to wireless channels, on top of which standard protocols are deployed. For example the routing mechanism. It mainly uses shortest path protocols. Classical algorithms dealing with this problem are based on the *store and forward* paradigm. As a result, reliability relies on retransmissions, which is not good solution for unreliable and dynamic environments in wireless world.

As stated in [6], the wireless medium is fundamentally different. For a start, wired networks are more reliable and predictable than wireless ones. In addition wireless links have high bit error rate, and are more dynamic: their characteristics can change in short periods of time. There is also another additional difference: wired links are unicast links, while majority of wireless links are broadcast links. Thus, transmissions over a wired network do not interfere with each other, which is quite common for the wireless networks. There are also issues related with mobility and portability in wireless networks (not present in wired counterparts). In general, network design based on a wired realm do not utilize the characteristic of wireless environments effectively.

The characteristics of wireless medium, presented in previous paragraph, give some directions in designing wireless networks. Some of them can even be used as valuable assets. Firstly the broadcast nature of wireless medium offers an opportunity to solve unreliability issue. For example, when a node broadcasts a packet, there is a strong possibility that at least one nearby node receives it, which can then function 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.

There is an new approach that can utilize the mentioned characteristics of the wireless medium. It is network coding.

The concept of network coding was introduced into the theory of information science in the publication by Ahlswede at al. in 2000 [2]. By applying this methodology we can increase the transmission capacity of a network. In wired *store and forward* networks, packets are forwarded hop-by-hop along the routers from a source to a destination. In order to meet the *end-to-end* requirements intermediate node should not analyze the packet and forwards it as fast as it can. Computer networks are essentially a maze of merging and intersecting paths. On each of this paths bits, grouped into packets, are routed to their final destinations. Each of those packets contains a label, which describe this final destination. Thus the described situation is similar to traffic. So a path can be expressed as a road while packets are groups of cars or buses on a road. Furthermore at each intersection of roads there is a router which analyzes the packet's header and forwards it to a proper road. But bits are not cars. When two vehicles converge at the same intersection, they must take turns traversing the bottleneck. By contrast when two packets arrive at a holdup, more options are available. Network coding techniques allow an intermediate node (a coder) to combine data from different input roads before sending the combined data on its output roads. In order to perform merging a liner combination of input data is usually used. Furthermore recent research [14] has shown that this approach can increase network capacity.There is also one additional goal. In spite of investments in network infrastructure network bandwidth is still an issue. As a result some *Internet Service Providers* have started to block applications that cause huge traffic loads in their networks [1] [1]. Network coding utilizes cheap computational power needed for performing coding operations increase network efficiency.

This paper presents basic concepts of network coding in the context of wireless networks. Section 2 presents simple example of network coding usage in broadcast environment. Section 3 discusses opportunities and challenges in wireless networks coding. Section 4 reviews current practical implementations of network coding for wireless medium.

2 Example communication

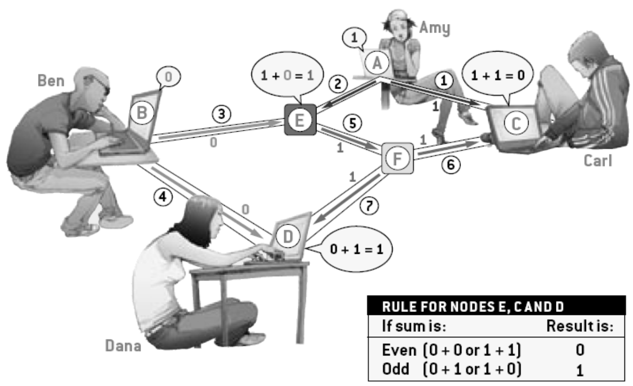


Figure 1: Network coding example [5].

The figure 1 presents a simple network coding example. On the image we have a simple six-node network, we have four end hosts, one router and one network coder. Lets assume that messages travel along links at one bit per second rate. First lets imagine what happens in a standard network (let host *E* be a normal router). Both paths from *A* to *D* and from *B* to *C* requires link 5. As a results we have a bottleneck - router *E* receives a total of two bits per second. In addition router cannot transmit it because capacity of the link 5 is one, so the router *E* can send only one packet at time. So the router must put the bit to a queue. This may end up in nightmare as more more bits are pilling up over time, waiting their turn.

Now lets focus on situation where we have 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* (see the rule in the box 1). As we can see there is no delay at the node *E*. So the node *E* does not send the message but an 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.

3 Opportunities and challenges

I present examples that will illustrate potential benefits of using network coding in wireless environments [6].

3.1 Throughput

The throughput of today's wireless networks is far form optimal. Network coding increases wireless throughput because coding allows the coders to compress the transmitted packets based on information that are known at various nodes. By matching what each neighbor has with what another neighbor wants, a coder can deliver multiple packets to different sources in a single transmission. This type of transformation is named *inter-flow network coding* because the coding is done over packets that differ in their nexthop, and thus from different flows. This approach is used e.g in *COPE* [14].

Network coding can be used in content distribution [6]. Today people often listen to music in public places. I can imagine situation in which many people wants to listen to their favorite music using common hot-spots. Efficient bandwidth usage is crucial in this type of scenarios. Lets consider situation in which two clients are users of this service. Each of them has some songs on their devices and want to listen to a song it does not have. In order to get the song a customer wants it also must present which songs it already has. So *A*,*B* are customers of the service, S_A and S_B songs which users *A and B* have on their devices. Now imagine that the user *A* wants to listen the song S_B, and the user *B* wants to listen the song S_A. Instead of sending the separate data streams to both of the users, the service point can broadcast *XOR'ed* version of the stream. As the result both of the users can easily decode their songs as well as the access point can send half of the data required in the scenario. In this example network coding doubles the throughput.

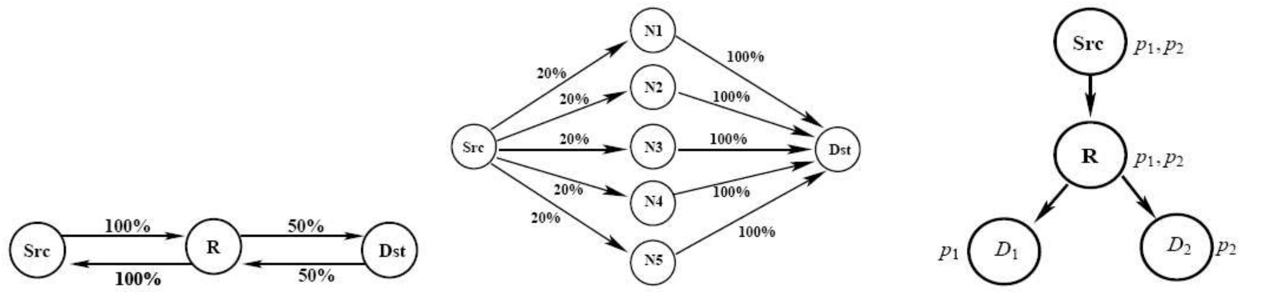
3.2 Reliability

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. As the result of mixing information, there are no special packets. To illustrate it, lets consider example from a traditional approach. Without coding a source needs to know which packets the destination 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).

The authors in [6] give more examples where network coding provides reliability benefits. In the figure 2 example A, the source has perfect link to the router, whilst the destination link to router has 50% probablity of successful delivery. In the *802.11* unicast network this requires $2n+2\log_2 n$ after some modification which increased protocol complexity as well as bigger acks from the receiver[2]. In cotrast authors suggest network coding based approach which requires $2n + 2$ transmissions. In the figure 2 example B, there are 5 nearby nodes which could forwad the packet to the destination. Unfortunately, the source is in a dead spot with 80%

[1] This kind of actions have been currently questioning by the Federal Communication Commission

[2] where *n* is packets in transmission



(a) Network coding allows *R* to improve reliability with low complexity.

(b) Network coding removes the need for the middle nodes to coordinate.

(c) Network coding allows multiple receivers to efficiently recover lost packets.

Figure 2: Example reliability scenarios [6].

loss rate to every nearby wireless node. Becasue of that, each packet have 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 neighbours. A neighbour forward the preceived packet to the destination. By applying this approach authors manage to increase probability of delivery to 67.2% and average packet transmittion 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 combianation of a new packet and packets received so far. This information is then transmited to the destination. When the destination can decode the transmitted file it broadcast the ackgnowledgmetn which casuses that all relies stop their transmition. In the figure 2 example C, authors show the multicast case. If the coder R has to retraansmit packets p_1 and p_2 it can retransmitt *XORed* version of the packets. As the result both destinations can recovers their losses, and provide efficient reliability.

3.3 Mobility

Network coding can improve mobility inside a wireless network [6]. Because of dynamics of wireless networks, routing updates are costly. Lets consider an example shown in 3. Lets 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.

3.4 Monitoring

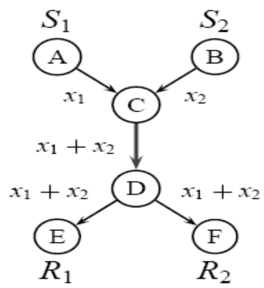


Figure 4: Monitoring example[6].

Network coding can be exploited to better monitor the link loss rate in wireless networks [6]. Lets consider example shown in 4. 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 x_1, x_2, $x_1 + x_2$ 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 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.

3.5 Challenges

In order to fully utilize the broadcast nature of the wireless link entire network stack needs to be redesigned [6, 14]. The change is especially needed in all the mechanism imported from the wired world : MAC, routing and transport protocols.

4 Practical implementations

As mentioned in 1 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] prove that, for multicast traffic, linear codes

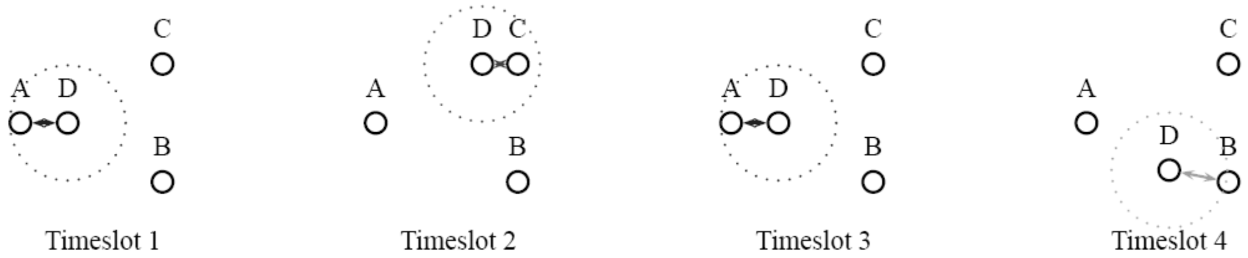


Figure 3: Mobility example.

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 [9]. The work on network coding has been extended on many areas: content distribution [8], secrecy [3], and distributed storage [12] 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 [10]. The second is simulation-based; it designs and evaluates network coding protocols using simulations [17]. The third is implementation-based; it uses implementation and testbed experiments to demonstrate achievable throughput gains for sensors and mesh networks [14, 13, 4]. This paper focuses on *COPE* implementation.

4.1 COPE network

COPE [14] exploits the shared nature of the wireless medium. In the algorithm each packet is broadcasted in a small neighborhood around its transmission path. This creates an environment good and suitable for network coding because of the increased rate of duplicated data. This data can be later used for decoding purpouses.

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.

In general *COPE* is a *MAC* extension which has two components:

- *Opportunistic Listening*. Packets which are broadcasted in a small neighborhood are stored for limited time periods. In addition neighbors are informed which packets has been heard by annotating the packets it sends. This creates an environment suitable for network coding because it contains lots of overlapping data that can be used for decoding.

- *Opportunistic Coding*. When node transmits the packets it uses the information of its neighbors state, in order to deliver multiple packets in a single transmission. If the source wants to transmit n packets, $p_1, ..., p_n$, to n nexthops, $r_1, ..., r_n$, a node can *XOR* the *n* packets together only if each nexthop r_i has all *n - 1* packets, except the packet it wants.

As authors claim, in theory this approach can double the throughput. However, according to the experimental results it showed *3-4x* improvement. The results are better because *COPE* uses hot-spots architecture in its wireless network. Because the hot-spots are in the center of the network and they are highly loaded, they experience huge congestion. As the result they build queues and drop the packets. Dropping the packets significantly consumes the bandwidth. 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 [5] 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 [7].

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 maintenanace 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.

References

[1] Comcast, bittorrent pass the digital peace pipe. InternetNews.

[2] R. Ahlswede, N. Cai, S.-Y. Li, and R. Yeung. Network information flow. *Information Theory, IEEE Transactions on*, 46(4):1204–1216, Jul 2000.

[3] N. Cai and R. Yeung. Secure network coding. *Information Theory, 2002. Proceedings. 2002 IEEE International Symposium on*, pages 323–, 2002.

[4] S. Chachulski, M. Jennings, S. Katti, and D. Katabi. Trading structure for randomness in wireless opportunistic routing. *SIGCOMM Comput. Commun. Rev.*, 37(4):169–180, 2007.

[5] M. Effros, R. Koetter, and M. Medard. Breaking network logjams,. *Scientific American*, 6:78–85, 2007.

[6] C. Fragouli, D. Katabi, S. Katti, A. Markopoulou, M. Medard, and H. Rahul. Wireless network coding: Opportunities and challanges. *Proceedings of Military Communications Conference*, 2007.

[7] C. Fragouli, J. Widmer, and J.-Y. Le Boudec. A network coding approach to energy efficient broadcasting: From theory to practice. *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*, pages 1–11, April 2006.

[8] C. Gkantsidis and P. Rodriguez. Network coding for large scale content distribution. *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*, 4:2235–2245 vol. 4, 13-17 March 2005.

[9] T. Ho, M. Medard, R. Koetter, D. Karger, M. Effros, J. Shi, and B. Leong. A random linear network coding approach to multicast. *Information Theory, IEEE Transactions on*, 52(10):4413–4430, Oct. 2006.

[10] S. Jaggi, M. Langberg, S. Katti, T. Ho, D. Katabi, and M. Medard. Resilient network coding in the presence of byzantine adversaries. *INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE*, pages 616–624, May 2007.

[11] S. Jaggi, P. Sanders, P. Chou, M. Effros, S. Egner, K. Jain, and L. Tolhuizen. Polynomial time algorithms for multicast network code construction. *Information Theory, IEEE Transactions on*, 51(6):1973–1982, June 2005.

[12] A. Jiang. Network coding for joint storage and transmission with minimum cost. *Information Theory, 2006 IEEE International Symposium on*, pages 1359–1363, July 2006.

[13] A. Kamra, V. Misra, J. Feldman, and D. Rubenstein. Growth codes: maximizing sensor network data persistence. In *SIGCOMM '06: Proceedings of the 2006 conference on Applications, technologies, architectures, and protocols for computer communications*, pages 255–266, New York, NY, USA, 2006. ACM.

[14] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Médard, and J. Crowcroft. Xors in the air: practical wireless network coding. In *SIGCOMM '06: Proceedings of the 2006 conference on Applications, technologies, architectures, and protocols for computer communications*, pages 243–254, New York, NY, USA, 2006. ACM.

[15] R. Koetter and M. Medard. An algebraic approach to network coding. *Networking, IEEE/ACM Transactions on*, 11(5):782–795, Oct. 2003.

[16] S.-Y. Li, R. Yeung, and N. Cai. Linear network coding. *Information Theory, IEEE Transactions on*, 49(2):371–381, Feb 2003.

[17] J.-S. Park, M. Gerla, D. S. Lun, Y. Yi, and M. Medard. Codecast: a network-coding-based ad hoc multicast protocol. *Wireless Communications, IEEE [see also IEEE Personal Communications]*, 13(5):76–81, October 2006.

[18] J. H. Saltzer, D. P. Reed, and D. D. Clark. End-to-end arguments in system design. *ACM Trans. Comput. Syst.*, 2(4):277–288, 1984.