# Multipath Network Coding in Wireless Mesh Networks

Velmurugan Ayyadurai, Klaus Moessner, and Rahim Tafazolli

Centre for Communication Systems Research (CCSR), University of Surrey, Guildford, UK

{v.ayyadurai,k.moessner,r.tafazolli}@surrey.ac.uk

**Abstract.** A practical wireless network solution for providing community broadband Internet access services are considered to be wireless mesh networks with delay-throughput tradeoff. This important aspect of network design lies in the capability to simultaneously support multiple independent mesh connections at the intermediate mobile stations. The intermediate mobile stations act as routers by combining network packets with forwarding, a scenario usually known as multiple coding unicasts. The problem of efficient network design for such applications based on multipath network coding with delay control on packet servicing is considered. The simulated solution involves a joint consideration of wireless media access control (MAC) and network-layer multipath selection. Rather than considering general wireless mesh networks, here the focus is on a relatively small-scale mesh network with multiple sources and multiple sinks suitable for multihop wireless backhaul applications within WiMAX standard.

**Keywords:** mesh networks, multipath, multihop, network coding.

## 1 Introduction

Today's world depends a lot on wireless to provide faster connectivity and more broadly than anyone may have expected. Future wireless systems are expected for very high demands in terms of data rate, latency, reliability and robustness. A wireless communication system relies on wireless links between wired infrastructure devices and end user devices for voice and data transmission.

The mesh network approach is to employ mobile stations as intermediate routers to establish multihop communication paths between mobile stations and their corresponding base stations. Utilizing this, an opportunistic routing will take advantage of the spatial diversity and broadcast nature of wireless networks to combat the time-varying links by involving multiple neighboring nodes as forwarding candidates for each packet relay. This breakthrough has created a vast interest in developing protocols for wireless mesh networks (WMNs).

Currently, WMNs are very diverse and different in several aspects. One aspect of WMN uses mobile station as intermediate access points on fixed locations by network operators or simply be other idle mobile stations that are not transmitting their own data. Although, depending on how radio resources are allocated for routing paths of

J. Del Ser et al. (Eds.): MOBILIGHT 2011, LNICST 81, pp. 267–274, 2012.

active connections, different protocols at the medium access control and routing layers can be designed. Radio resources for mobile stations at different hops may be allocated in time division duplex (TDD) or frequency-division duplex (FDD) mode. Frequency bands other than the cellular frequency bands can also be used for relaying. The intermediate mobile stations will serve toward various objectives, such as enhancing data rate coverage and enabling range extension in WMNs.

With this motivation, there has been a recent interest in both academia and industry in the concept of multipath network coding in the networking perspective with scheduling and resource allocation algorithms to improve throughput with a cross-layer perspective. Network coding is first proposed in [1] for noiseless wireline communication networks to achieve the multicast capacity of the underlying network graph. The essential idea of network coding is to allow coding capability at network nodes acting as routers in exchange for capacity gain, i.e., an alternative tradeoff between computation and communication.

## 2 Network Coding Scenario and Related Works

Wireless network properties require a strategy for medium access control (MAC) in order to coordinate reliable packet transmissions between source-sink pairs. The problem of throughput increase and delay decrease strongly depends on the cross-layer interactions between MAC and the network layers. Hence, they need to be jointly designed for efficient wireless network operation. For stable operation of the queues, the possible underflow of relay packets opens up new questions regarding the optimal queue management and the optimal use of network coding on the instantaneous queue contents.

The focus of our discussions is based on relay-based WMNs, which essentially generalizes the examples shown below in various ways depending on the network model. The intermediate mobile station receives multiple transmissions that contain the same data and relaying amounts to mere multi-hopping only when the receiver obtains one copy of the data. For unicast communication in [2], the back pressure algorithms achieve the maximum stable throughput region at the expense of poor delay performance. On the other hand, the capacity analysis of wireless networks has been limited to saturated queues with infinite delay in [3].

In Fig.1a, suppose the source S wants to multicast two bits $X_1$ and $X_2$ to two sinks $Y_1$ and $Y_2$ simultaneously. Each of the paths in the network is assumed to have a unit capacity of 1 bit per time slot (bps). With traditional routing, each mobile station between S and the two sinks simply forwards a copy of what it receives. It is then impossible to achieve the theoretical multicast capacity of 2 bps for both sinks; sink in the middle can only transmit either $X_1$ or $X_2$ at a time. However, with network coding, as shown in Fig.1b, the intermediate mobile station can perform coding, in this case a bitwise exclusive-or operation, upon the two information bits and generate $X_1$+$X_2$ to multicast towards its outgoing paths. Sink $Y_1$ receives $X_1$ and $X_1$+$X_2$, and recovers $X_2$ as $X_2 = X_1 + (X_1 + X_2)$. Similarly, sink $Y_2$ receives $X_2$ and $X_1 + X_2$ and can recover $X_1$. Both sinks are therefore able to receive at 2 bps, achieving the multicast capacity.

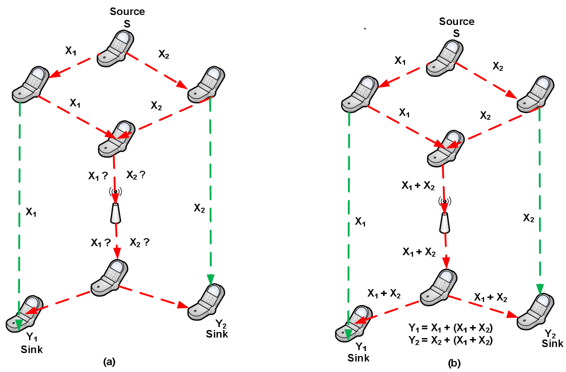


**Fig. 1.** The butterfly network example of network coding. (a) With traditional routing, the link in the middle can only transmit either $X_1$ or $X_2$ at a time. (b) With network coding, the relay node can mix the bits together and transmit $X_1 + X_2$ to achieve the multicast capacity of 2 bps.

With this simple mathematical and potential for practical network coding, the communications and networking communities have devoted a significant research efforts to utilize in a number of wireless applications, ranging from opportunistic routing in mesh networks. In the above example, the network coding operation is bitwise exclusive-or, which can be viewed as linear coding over the finite field i.e. Galois Field GF (2).

Following the seminal work of [1], Li et al. in [4], showed that a linear coding mechanism suffices to achieve the multicast capacity. Ho et al. in [5], further proposed a distributed random linear network coding approach, in which nodes independently and randomly generate linear coefficients from a finite field to apply over input symbols without a priori knowledge of the network topology. They proved that receivers are able to decode with high probability provided that the field size is sufficiently large. These works lay down a solid foundation for the practical use of network coding in a diverse set of applications. After the initial theoretical studies in wireline networks, the applicability and advantage of network coding in wireless networks were soon identified and investigated extensively in [6]. The performance gains have been verified through experimental results in [7].

There is a lot of work for opportunistic routing in wireless mesh networks, with or without network coding. COPE [7], MORE [8] and $MC^2$ [9] investigate network coding with opportunistic routing in wireless networks with broadcast transmissions, focusing exclusively on the throughput improvements. In this work we use redundant paths to send uncoded packets in order to recover the information using packets from another path, thus decreasing the delay in transmission with a gain in throughput. The goal of this paper is to investigate the performance that can be achieved by exploiting path diversity through multipath forwarding and redundancy through network coding.

## 3 Opportunistic Mesh Networks - Multipath Network Coding

In the Mesh mode, several mobile stations can constitute a small multipoint to multipoint wireless connection, without specific uplink and downlink sub-frames. It may enable direct communication between mobile stations that can also be used as relays to forward other's data. Two kinds of routing and scheduling are used to coordinate transmissions: centralized and distributed. Here, for the easy operation and high reliability, we focus on the centralized approach. The centralized approach organizes all the nodes of the WiMAX network in a tree structure rooted at a particular node, namely the base station. The ways in which the tree is built and the choice of the links used have a deep impact on the capacity that a WiMAX backbone may offer.

Using multipath routing in mesh networks provide multiple alternative paths through a network, which can yield a variety of benefits such as fault tolerance, increased bandwidth, or improved security. The multiple paths computed might be overlapped, edge-disjointed or node-disjointed with each other. In Fig.2 shows the multipath mesh network transmission, adopting the multihop technology based on packet combining and delay management.

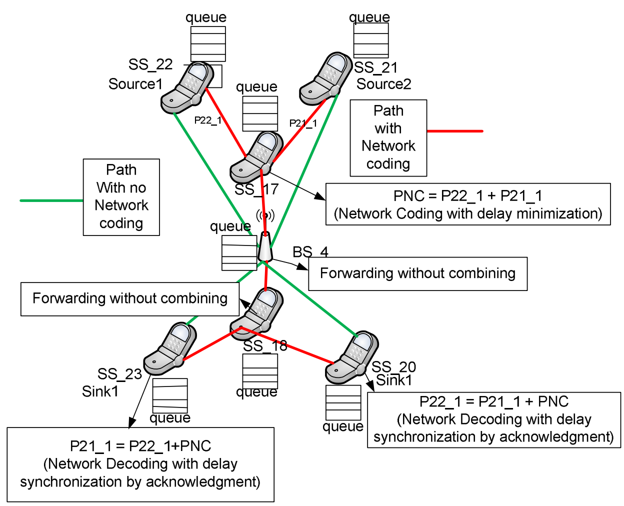


**Fig. 2.** Multipath mesh routing with network coding and buffer management

### 3.1 Multipath Routing Tree

In centralized routing, the base station determines the path for all the mobile station in a centralized manner like PMP mode, and traffics from or to the base station can be relayed by other mobile stations through a multihop route which is different from PMP mode. Using multipath routing mechanism, are able to increase spatial reuse rate and next-hop selection. The model assumed is a multiple source unicast mesh network with directional links using smart antennas. Multipath routing makes maximum utilization of network resources by giving the source nodes a choice of next hops for the same destination and to lower delay. The choice of multipath entails that, to synchronise across various paths, buffers need to be established at the network nodes so that the packets can be stored and sequenced appropriately. The nodes inside the network (except the source and sink) act as routers, do not decode the information but simply forward coded packets that have been previously received from the source or the previous node as shown in Fig.2.

The scheduling first established with fixed multipath routing tree and assign traffics to routes according to multipath routing tree. Let base station be level = 0. The node one hop from base station will be level (n) = 1(relay). The source nodes can only choose the nodes that are level (n) = i-1 as their next hop ($n_p$). Node n must be in transmission range of node $n_p$ and is connected to node $n_p$. The source nodes transmit copies of packets belonging to a single flow on all the paths. The base station can effectively works on the principle that higher performance can be achieved by utilizing more than one feasible path.

### 3.2 Network Coding with Delay Management

It has been shown from Fig.2, the intermediate nodes in a network, when performing network coding are able to combine a number of packets received into one or more new outgoing packets. Network coding permits instead of binary field operations, moving to larger field sizes, being able to perform more complex operations when combining incoming packets in intermediate nodes, becoming one of the most successful network coding algorithms as it permits achieving network capacity when multicasting, with relatively low complexity. In network coding each data unit is processed using finite fields $F_q$ with ‘q’ a prime number or, considering a Galois Field (GF), $q = 2^m$ for some integer m, where $F_2$m refers to $[0, 2^{m-1}]$.

The intermediate network nodes used to encode the data packets by combining the two packets from sources SS_22 and SS_21 into (PNC = P22_1 + P21_1) with a FIFO queue management system as shown in Fig.2. The FIFO queue management system used to calculate the processing delay based on the service capacity and arrival rate time of the bursty packet sources. The intermediate network nodes need to calculate the data synchronisation time by getting an acknowledgment from sinks. The network coding delay uses the equation (1) and throughput uses the equation (2). Each path is given with equal service capacity (μ) and the arrival rate λ varies depending on the bursty packet sources.

$$D_{NC} = \frac{2}{(\mu - \lambda_1)(\mu - \lambda_2)} \quad (1)$$

$$Thr = \frac{1}{D_{NC}} \quad (2)$$

## 4 Simulation and Analysis

The simulation scenario is constructed using OPNET 14.5 simulator on the existing SMART Net project using smart antennas. The scenario for data flow in one direction has sources (SS_22, SS_21) and sinks (SS_23, SS_20) with two paths as shown in Fig.3. The packets of two sources have to reach two sinks simultaneously. The first path is through the intermediate network node using packet combining with forwarding. The second path is through the base station (BS_4) with intermediate network node (SS_18) for forwarding to get the path delay for data synchronisation. The traffic from the sources should be of same type for combining the packets of same size. The traffic assumed for source nodes SS_22 and SS_21 is voice packet and traffic for source nodes SS_23 and SS_20 is data. The average delay is measured with the average time that a data packets from source node to destination node. The average throughput is measured with the bit of data packet received.

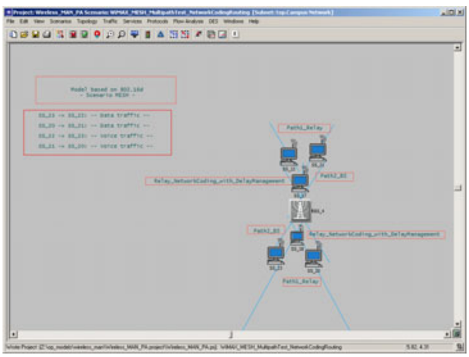

**Fig. 3.** Multipath Network Coding Scenario in OPNET

The figures Fig.4a and Fig.4b show the output of data traffic in SS_23 for average delay and average throughput. The first path is through SS_23->SS_18->BS-4->SS_17->SS_22 using packet combining and forwarding on the intermediate node SS_18 with delay in buffering. The second path is through SS-23->BS-4-> SS_17->SS-22 with packet forwarding without delay in buffering. The figures Fig.5a and Fig.5b show the output of data traffic in SS_20 for average delay and average throughput. The first path is through SS_20->SS_18->BS-4->SS_17->SS_21 using packet combining and forwarding on the intermediate node SS_18 with delay in buffering. The second path is through SS-20->BS-4-> SS_17->SS-21 with packet forwarding without delay in buffering. The analysis shows with multipath network coding and delay synchronization, there is very high throughput improvement, but only a slight reduction in delay. This gives the required possibility to use multipath network coding feature in mesh networks for high throughput applications.

The figures Fig.6a and Fig.6b show the output of voice traffic in SS_22 for average delay and average throughput. The first path is through SS_22->SS_17->BS-4->SS_18->SS_23 with packet combining and forwarding on the intermediate node SS_17 with delay in buffering. The second path is through SS-22->BS-4->

SS_18->SS-23 with packet forwarding without delay in buffering. The figures Fig.7a and Fig.7b show the output of voice traffic in SS_21 for average delay and average throughput. The first path is through SS_21->SS_17->BS-4->SS_18->SS_20 with packet combining and forwarding on the intermediate node SS_17 with delay in buffering. The second path is through SS-21->BS-4-> SS_18->SS-20 with packet forwarding without delay in buffering. The analysis shows with multipath network coding and delay synchronisation, there is very large reduction in delay, but only a slight improvement with throughput. This gives the required possibility to use multipath network coding feature in mesh networks for delay-sensitive applications.

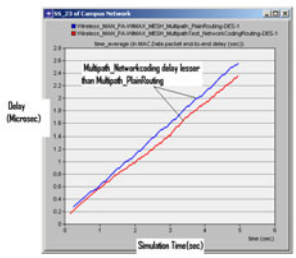


**Fig. 4a.** SS_23 delay for data traffic

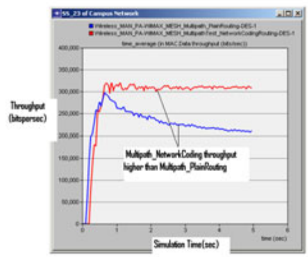


**Fig. 4b.** SS_23 throughput for data traffic

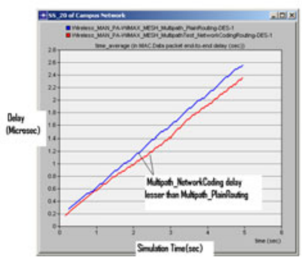


**Fig. 5a.** SS_20 delay for data traffic

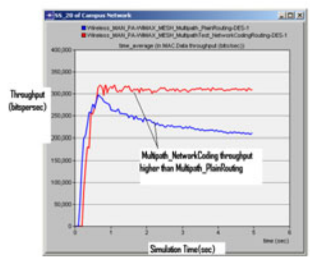


**Fig. 5b.** SS_20 throughput for data traffic

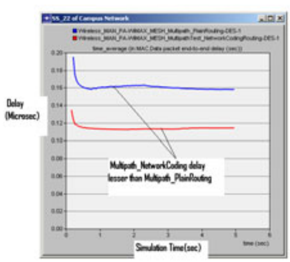


**Fig. 6a.** SS_22 delay for data traffic

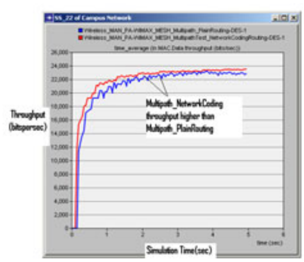


**Fig. 6b.** SS_23 throughput for data traffic

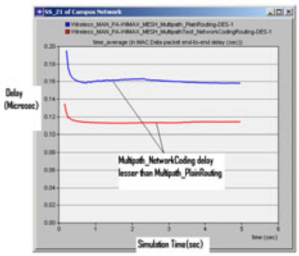


**Fig. 7a.**SS_21 delay for data traffic

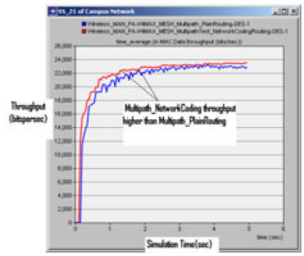


**Fig. 7b.** SS_21 throughput for data traffic

# 5 Conclusion

A scenario for multipath routing using network coding for traffics of voice and data are simulated in WiMAX mesh networks. The analysis shows an improvement in average delay and average throughput with a tradeoff. The simulation provides the suitability for delay-sensitive applications. The future wireless networking expectations for very high demands in terms of data rate and latency can be improved with the existing resources but changing the way of forwarding and computational requirements.

# References

1. Ahlswede, R., Cai, N., Li, S.-Y.R., Yeung, R.W.: Network Information flow. IEEE Trans. Inf. Theory 46(4), 1204–1216 (2000)
2. Tassiulas, L., Ephremides, A.: Stability properties of constrained queuing systems and scheduling for maximum throughput in multihop radio networks. IEEE Trans. Autom. Control 37(12), 1936–1949 (1992)
3. Gupta, P., Kumar, P.R.: The capacity of wireless networks. IEEE. Trans. Inf. Theory 46(4), 1204–1216 (2000)
4. Li, S.-Y.R., Yeung, R.W., Cai, N.: Linear network coding. IEEE Trans. Inform. Theory 49(2), 371–381 (2003)
5. Ho, T., Medard, M., Koetter, R., Karger, D.R., Effros, M., Shi, J., Leong, B.: A random linear network coding approach to multicast. IEEE Trans. Inf. Theory 52(10), 4413–4430 (2006)
6. Wu, Y., Chou, P.A., Kung, S.-Y.: Information exchange in wireless networks with network coding and physical-layer broadcast. In: Proc. 39th Annual Conference on Information Science and Systems, CISS (2005)
7. Katti, S., Katabi, D., Hu, W., Rahul, H., Medard, M.: The importance of being opportunistic: practical network coding for wireless environments. In: Proc. 43rd Annual Allerton Conf. Communication, Control, and Computing (September 2005)
8. Chachulski, S., Jennings, M., Katti, S., Katabi, D.: Trading structure for randomness in wireless opportunistic routing. In: ACM SIGCOMM (2007)
9. Gkantsidis, C., Hu, W., Peter, K., Radunovic, B., Gheorghiu, S., Rodriguez, P.: Multipath code casting for wireless networks. In: ACM SIGCOMM (2005)