# CS 559: Algorithmic Aspects of Computer Networks Fall 2007

**Lecture 6 – September 24, 2007**

**Lecture: John Byers BOSTON UNIVERSITY Scribe: Praveen Sharma**

Today, we continued our discussion on the COPE[1] paper, for which we had laid down a foundation in the previous lecture. Then, we moved on to the MORE[2] paper. The main contribution of both the COPE and the MORE paper is to apply network encoding (so far a theoretical concept) in real-world wireless applications.

## *6.1. The COPE Approach*

### *6.1.1. Summary from the Previous Week*

In the previous lecture we described the motivations behind the COPE architecture. We said that the architecture improved network throughput by using network encoding. Using a simple example, we showed (and also described in the paper [1]) how wireless routers used only 3 transmissions instead of 4 transmissions to facilitate packet exchanges between two any nodes when they encoded the packets.

### *6.1.2. Discussion (Today)*

The COPE architecture provides a high network throughput in a wireless mash networks by utilizing network encodings. It incorporates a protocol for network encoding in the network stack by injecting a shim layer (Figure 1) in between the MAC and the IP layers thereby forwarding multiple packets in a single transmission.

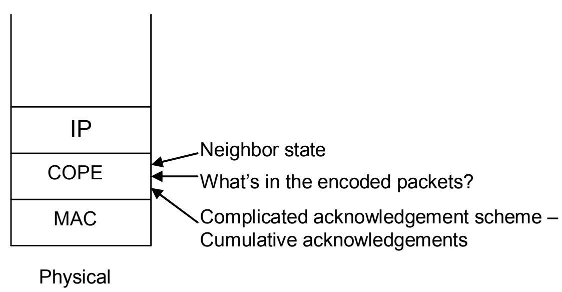


Figure 1: COPE layer shown as a shim between the IP and the MAC layer

COPE achieves this by utilizing the following three techniques:

- Opportunistic Listening
- Opportunistic Coding
- Learning Neighbor State

#### 6.1.2.1. *Opportunistic Listening*

COPE tries to listen to the packets going over the wireless links with a goal to learn about the neighbor states especially since listening is relatively cheap (as compared to transmitting over the wireless links). It optimizes opportunistic listening by just analyzing the headers (in contrast to analyzing whole packets, which is computationally expensive).

#### 6.1.2.2. *Opportunistic Coding*

COPE performs network encoding by performing an XOR or combining packets linearly so that almost all the receivers can decode the message and get the packet that they desire. The decision to select the packets that needs to be encoded is based upon the *next-hop* basis. That is, decision to encode a packet in a given transmission is based upon if the receiving node hasn't received that packet so far, and that the receiving node has all the other packets.

#### 6.1.2.3. *Opportunistically Learning the Neighbor State*

In order to encode a packet based on the next-hop, COPE needs to know what packets a neighboring node needs and the packets that the node has received so far. To address this, the COPE approach utilizes a *Probability Matrix Pij* (estimate of probability that a packet sent by node i arrived at node j). It requires each node to have this probability matrix.

#### 6.1.2.4. *Challenges Encountered in Learning Neighbor State*

The COPE approach encountered several challenges in using the techniques described above. Following is a list of some of these challenges:

- *Challenges encountered in learning neighbor state*
    - Learning neighbor state in a bandwidth constrained environment is challenging. COPE addresses this challenge by piggybacking: a node piggybacks its state information when it transmits a data packet.
    - Learning neighbor state using the existing MAC protocol is difficult. As the MAC protocol uses hop-by-hop acknowledgements, any particular node can receive information about only one node to which it has tried to send packets. COPE addresses this issue by using a randomized approach of packet transmission: that is each node *randomizes the destinations at the MAC layer*. For example, when a give node sends a packet to specific node, it randomly sends packets to other neighboring nodes as well. Another promising approach to address this challenge is the Round-Robin approach. However, since wireless nodes are not static (not all nodes participate in packet transmissions equally), the Round-Robin approach may not be effectively solving the problem described here.
    - Keeping the packet header consistently small is challenging. This is because a header needs to include as much neighbor state as much possible. (I don't know How COPE handles this?)
- *Challenges encountered in encoding packets*
    - It is difficult to encode (e.g., XOR) packets of different sizes which is the situation a given node finds itself (since different packets transmitted by different nodes are of different sizes). COPE addresses this problem by encoding packets of the same sizes. However, to encode packets of the same sizes, COPE requires packets that may not be in sequence. This has the potential of confusing the TCP protocol. COPE handles this by buffering of packets.

## 6.2. The MORE Approach

MORE paper talks about ***Network Encoding*** and ***Opportunistic Routing.***

### 6.2.1. Defining ETX (Expected Number of Transmissions) as a Superior Metric for Measuring the Shorted Path

The paper tries to define metrics for determining a good route. Different researchers defined a good route as the shortest route defined by sing the following metrics:

- Lowest latencies
- Wide bandwidths
- Hand tuning of weights.

The MORE paper asserts that in a wireless networks, a shortest route may not be the best route. Instead a route that minimizes link-loss probabilities is a better metric. The paper measures loss of packets as ***ETX (Expected number of Transmissions).*** A ETX is inverse of *Probability of a successful transmission (based on the link loss probabilities) from node i to node j(Pij)* of a packet from one node to another node.

Let us understand ETX using the example described in Figure 2. The example tries to determine the best route between node A and node C. Node A can either directly send a packet to node C using $P_{AC}$=0.2 or it can send a packet to node B using $P_{AB}$=0.95 . Node B can then send packet to node C using $P_{BC}$=0.97. Previously, it was believed that sending packet from node A to node C was the shortest (best) route. Contradictory to this opinion the MORE approach shows that sending packet from node A to node C via node B is a better route because the latter will require fewer network transmissions. Here is the detailed explanation for this claim.

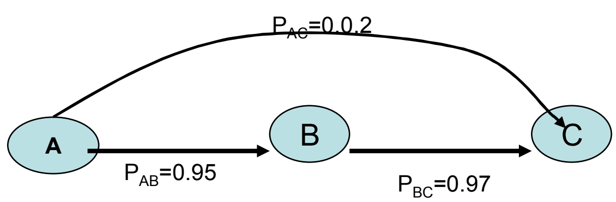


Figure 2: depicting Probabilities of successful transmission between different nodes.

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$ETX_{AC} = 1/P_{AC}$

$= 1/0.2 = 5$

(Probability of success is 0.2 and therefore, it will take 5 trails to transmit the packet).

$ETX_{ABC} = 1/P_{AB} + 1/P_{BC}$

$= 1/0.98 + 1/0.97$

=approx 1.02 + qpprox 1.03 = 2.05

So we see that path from node A to node C via node B requires fewer transmission than a direct path from node A to C.

The formula described above with a specific example can be generalized as:

$$\mathbf{E_{YX}\ path\ q = \sum_{e \in q} 1/P_e}$$

where, $1/P_e$ is edge weights or lengths for edge e in the path, and $P_e$ is loss probability along an edge.

The MORE approach shares $1/P_e$ with all nodes and aims to minimize ETX (as a metric for the shorted path).

### 6.2.2. Main Techniques of the MORE Approach

The main techniques used by the MORE approach are as following:

#### 6.2.2.1. Opportunistic Routing

The *main idea* is that for a given transmission, that is bound to be overheard by multiple nodes, allow the node closest to the destination (by ETX) to assume responsibility for forwarding the packet. For example, as shown in figure 3, when a node (node A) transmits a packet destined for node C, different nodes ($B_1$, $B_2$, …, $B_4$,, that have different ETX distance from node C with node B4 being the closest) will over hear the packet. Opportunistic routing desires node $B_4$ (the node with the smallest ETX) to take ownership (by arbitrating among its neighbors: $B_1$, $B_2$, and $B_3$) of transmitting the packet to node C.

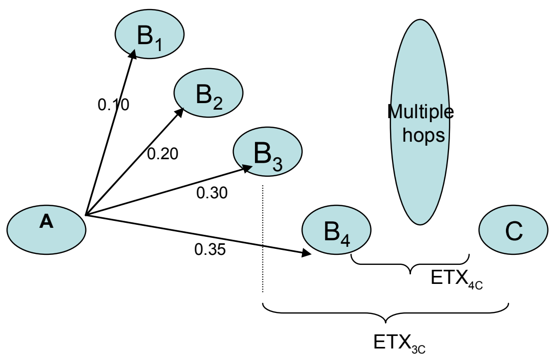


Figure 3: demonstrates opportunistic routing. The numbers on the edges show a probability that $B_i$ will be the node to assume ownership of forwarding the packet.

The MORE paper leverages on network encoding and not worry about if more than a single node (like node $B_1$, $B_2$, $B_3$, and $B_4$) has received the packet.

#### 6.2.2.2. Network (En)Coding

The *main idea* of the encoding*:* Assume likelihood that we are the node that minimizes ETX for this packet, if this likelihood is "decent", place a packet into a pool of other packets for network encoding.

For example, as also shown in figure 3, there is a probability associated with each receiver ($B_1$, $B_2$, $B_3$, and $B_4$ ) that it will further forward the packet by assuming ownership, That is, B1 will assume ownership 10% of times, node B2 will assume ownership 20% of times, node B3 will assume ownership 30% of times and node B4 will assume ownership 35% of times. Consequently node C will get a good mix of packets and will be able to decode the packets that it needs, if encoding is done right.

## 6.3. Key Difference(s) Between the Approaches Defined In COPE and MORE

1. Even though there are many differences between the approaches defined in the COPE and MORE papers, here is one key difference: while COPE supports inter-flow encoding and requires decoding at hop-by-hop basis, MORE supports intra flow encoding and requires end-to-end decoding (Illustrated in Figure 6).

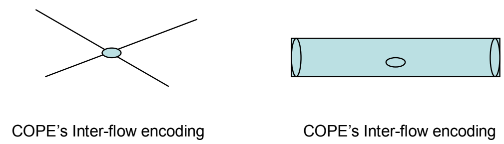


**Figure 4 depicts key difference in network encoding pattern between the COPE and MORE protocols**

## 6.4. Reference

[1] Sachin Katti, Hariharan Rahul, Wenjun Hu, Dina Katabi, Muriel Medard, and Jon Crowcroft, "XORs In The Air: Practical Wireless Network Coding,", ACM SIGCOMM, 2006.

[2] Szymon Chachulski, Michael Jennings, Sachin Katti, and Dina Katabi, "Trading Structure for Randomness in Wireless Opportunistic Routing", ACM SIGCOMM, 2007.