Using Cross-layer Heuristic and Network Coding to Improve Throughput in Multicast Wireless Mesh Networks

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Abstract— Wireless mesh networks (WMNs) receive much research interests because of their reliability, scalability and low cost. Obtaining high-throughput for multicast applications (e.g. video streaming broadcast) in WMN is challenging due to the interference and the change of channel quality. Cross-layer design and network coding are approaches which have been recently received considerable attention for high-throughput problem in wireless networks. In this paper, we propose an approach namely CLNC (Cross-Layer Network Coding) which is a combination of the above approaches to improve throughput in multicast wireless mesh networks. Our simulation results show that when the number of receivers is high CLNC’s throughput is higher at least 30% than that of known methods such as AODV, DSDV and DSR and higher than that of MAODV. Moreover, PDR (Packet Delivery Ration) of CLNC is higher than that of MAODV and DSDV.

I. INTRODUCTION

Wireless mesh networks are multihop networks of wireless router platforms. The clients are mobile but wireless routers are typically stationary. Mesh networks offer the cost-effective and flexible wireless solution. Mesh networks meet the needs of real applications especially for broadband service providers and video streaming broadcast. Three key advantages of WMNs include robustness, higher bandwidth, and spatial reuse.

Networking protocols are normally developed in layers; each layer is responsible for a different aspect of the communications. The benefits of layered design are simplicity for standardizing and flexibility for deploying new protocols. However, the layered design does not obtain high performance in wireless networks due to characteristic of wireless medium. Cross-layer is a potential approach for wireless applications. It exploits the interactions between layers to improve the performance of the network. A number of cross-layer approaches are proposed. Cross-layer proposals comprise jointly optimal routing and scheduling, jointly congestion control and scheduling, jointly optimal routing, scheduling and power control, jointly congestion and contention control. Ahlswede et al. are the first authors who introduced network coding in 2000 [1]. Traditionally, coding was used at the source nodes and the relay nodes’ tasks are forwarding without modifying packets to receivers. However, in network coding, the relay nodes do not only store and forward the packets but also process data. They mix incoming packets into a packet. Ahlswede shows that network coding can obtain higher throughput than traditional routing techniques. In some aspects, routing can be viewed as a special case of network coding. Network coding improves performance in real applications such as peer-to-peer networks, content distribution networks, live broadcast…

In this paper, we propose a cross-layer approach that joins power control and routing with random linear network coding to improve throughput in multicast wireless mesh networks. We solve multicast problem thanks to two algorithms. An optimal power algorithm is used to choose the best power level of node and network coding technique is used to transmit packets on the network. Our approach is suitable for wireless mesh networks which have the quick change condition and the number of nodes is large. We analyse our proposal by simulation with NS-2 simulator and compare with other routing approaches such as MAODV, AODV, DSDV and DSR.

The rest of the paper is organized as follows. Section II introduces the multicast problem in wireless mesh networks and gives an overview of network coding and cross layer. In section III, we discuss the related works. Next, we describe our proposal in section IV and V. The simulation results are in section VI. Finally, we conclude this paper in section VII.

II. MULTICAST PROBLEM IN WIRELESS MESH NETWORKS

A network is modelled by a directed graph \( G = (V, E) \), where \( E \) is the set of edges, \( V \) is the set of nodes and we assume that \( G \) is an acyclic graph. In \( G \), there is a source node \( S \) and there are some sinks \( R_1, R_2, ..., R_s \).

Multicast problem’s goal is to find a route from the source to each of the sinks simultaneously to achieve optimal throughput. Finding multicast trees is the traditional approach to solve this problem. It is formulated as Steiner Tree Packing problem that is shown to be a \( NP \)-hard problem by Jain et al in [9]. Ahlswede shows that the traditional approach
does not obtain the optimal network throughput [1]. He represents the novel network coding technique that can obtain the optimal throughout. Ahlswede also shows that it is possible to finding a solution in polynomial time with network coding.

Fig. 1 A source $s$ and two sinks $y, z$

Fig. 1 is an example of the benefit of network coding [1]. Assume that each network has a directed unit capacity link. Obtaining multicast rate at 2 bits per time is possible without networking in Fig. 1 a). But in Fig. 1 b) there is a bottleneck in link from $w$ to $x$, network coding has to be used to obtain the same rate in this case. However, Ahlswede et al. [1] do not show how to build a network coding solution. They only show that the solution is existent. Li et al. [2] show that if there is a network coding solution, a linear network coding solution is existent.

We use random linear network coding technique [4] for our approach. In our approach, each relay node broadcasts coded packet to all of its neighbours. This makes strong inference in the network. Transmission power level and transmission rate of node are different, so the interference with its neighbours is different. To minimum the interference in network, physic layer should know the information of network layer to adapt its power level. To improve the throughput of the network, we combine two techniques that are cross-layer and network coding in our proposal.

III. RELATED WORK


Yuan et al. [12] propose a cross-layer optimization approach of jointing flow routing and power control in a multicast. The main technique used in this paper is the method of dual decomposition for convex optimization problems. Luigi et al. [13] propose a cross-layer heuristic approach that joints power control and routing in wireless mesh networks. They do not perform power optimization and route discovery at once, but they structure the algorithm in two sub-algorithms that are local power optimization algorithm and the route discovery algorithm for unicast transmission.

IV. NETWORK CODING IN PRACTICE

In section II we assume that symbols flow synchronously throughout network and edges have unit capacity. This model requires the central knowledge about network topology and coding functions. However, in real networks, information flows asynchronously and packets have random delays and loss, edges have various capacity. It is difficult to obtain centralized knowledge. To using the network coding in real network, we use three main techniques: (1) random linear network coding, (2) appending global network coding coefficient into encoded packets, and (3) buffer model [3].

A. Random Linear Network Coding

Assume source $S$ wants to multicast content $x$ to all sinks. The content $x$ is segmented into $n$ packets $x = [x_1, x_2, ..., x_n]$, each has fixed number of bytes $k$, means that each packet can be seen as an element of a finite field $GF(2^n)$. Each relay node receives $m$ coded packets from input links $[x_1, x_2, ..., x_m]$. With each output link, it independently and randomly chooses a set of $m$ coding coefficients in the Galois field $GF(2^n) [c_1, c_2, ..., c_m] (m \leq n)$. Then it computes $y = \sum_{i=1}^{m} c_i x_i$ and send $y$ to output link, $y$ is a coded packet which has number of bytes $k$.

B. Global Network Coding Coefficient

The set of coefficients $[c_1, c_2, ..., c_m]$ is seen as a local coding vector. The global coding coefficient vector is computed by multiplying local coding vector with $m \times n$ matrix of coding coefficient embedded in the incoming packets. The node embeds global coding coefficient in the coded packet $y$ and broadcasts to all of its neighbours. When the destination node receives $n$ coded packets and the rank of $n \times n$ matrix $G$ of coefficient of these packets is $n$, it starts encoding process (each row of $G$ is coefficients embedded in the incoming packet). It inverses $G$ matrix and multiply $G^{-1}$ with $y^T$, the results are the original packets ($G^{-1} y^T = x$). Wu [6] shows that if field size is $2^8$ and the number of edges in network less than $2^8$ then $G$ matrix is invertible with the probability being more than $1 - 2^8 = 0.996$.

C. Buffer Model

Each node has a buffer to store packets. When receiving a packet from an incoming link, it checks the innovation of the packet. Innovative packet is the packet needed for decoding. Katti et al. [7], Deb et al. [8] and Wu et al. [9] show that if field size is $2^8$ and the number of edges in network less than $2^8$ then $G$ matrix is invertible with the probability being more than $1 - 2^8 = 0.996$. Each node has a chance to transmit to an outgoing link, it
combines all packets in a buffer by random linear network coding technique and broadcast the coded packet to all their neighbours. Innovation technique can be seen as a routing technique for network.

V. COMBINATION OF NETWORK CODING AND CROSS-LAYER DESIGN

In this paper, we propose the CLNC approach which is a combination of heuristic cross layer and network coding for the single source multicast problem in wireless mesh networks. Our proposal is jointly optimal routing and power control. We use an optimization power algorithm to control the power level of a node for each transmission. We consider the first three layers of protocol stacks (physical layer, mac layer and network layer) for cross-layer design.

A. Transmission Rate, PER, Interference

Wireless cards support different transmission rate levels. For example, 802.11b standard’s transmission rates are 11Mbps, 5.5Mbps, 2Mbps and 1Mbps; transmission rates of 802.11a standard are 48, 36, 24, 18, 12, 9, 6 (Mbps). Transmitting with high data rate has a disadvantage that the transmission power has to be high to correctly decode the signal. In fact, increasing the transmission power means that increasing transmission range. The higher the transmission range is, the more interference the system has.

Previous research work shows that PER (Packet Error Rate) strongly affects throughput. We do not use the function \(\text{PER} = 1 - (1 - \text{BER})^N\) (where \(N\) is the number of bits) to compute PER because it assumes that bit errors are independent and distributed uniformly. In real life, the bit errors are not completely independent but may occur in bursts. Moreover, the error distribution is also not exactly uniform. We compute PER based on the SNR sampling which is extremely sensitive with link status. A model called interference trend index estimator is used to predict the interference of a packet transmission as follows:

\[
I(P) = \frac{N(P)}{N(P_{\max} + \beta)} \sqrt{\frac{P^2 + P_{\max}^2}{2P_{\max}^2}}
\]

where \(N(P)\) is the number of neighbour nodes when the transmission power is \(P\), \(N(P_{\max})\) is the number of neighbour nodes when the transmission power is maximum and the transmission rate is minimum. Here \(\beta\) is a dimensionless factor that greater or equal to 1.

B. Discovery Neighbours

This is the set of power level is available on network card:

\[
\pi = \{P_{\min} = P_0, P_1, ..., P_{|\pi|-1} = P_{\max}\}
\]

The set of data rate is:

\[
\Phi = \{R_{\min} = R_0, R_1, ..., R_{|\Phi|-1} = R_{\max}\}
\]

We use a discovery protocol in network layer for finding the neighbours of a node. This protocol sends a HELLO packet at all transmission power and transmission rate and collect responds from its neighbours. The set of a node’s neighbours is stored in matrix \(M\).

C. Optimal Power Algorithm

Fig. 2 describes relation between interference, PER and transmitting power.

![Fig. 2 Relation between interference, PER and transmitting power.](image)

Algorithm 1 Optimal Power Algorithm

1: Set \(N = N_i\)
2: \(\forall j \in N\) Set \([d^* = 2, P_{opt} = P_{\max}, R_j = R_{\max}, d_{avg}, d]\)
3: For \(r = R_{\max}\) to \(R_{\min}\)
4: For \(p = P_{\max}\) to \(P_{\min}\)
5: \(d = 0\)
6: For \(j \in M_{r,p}\)
7: \(d = d + d^*(I_j(p), \text{PER}_j(p))\)
8: End For
9: \(d_{avg} = d / |M_{r,p}|\)
10: If \((d_{avg} < d^*_j) \&\& (\text{PER}_j(p) < \text{PER}_{\max})\)
11: Set \([d^* = d_{avg}]\)
12: Set \([P_{opt} = p]\)
13: Set \([R = r]\)
14: End If
15: End For
16: \(N = (N \setminus M_{r,p})\)
17: End For

As can be seen from the Fig. 2, to obtain the best trade-off between interference and PER, we need find the best transmission power point. This point must be closest with ideal optimum tradeoffs point. It is difficult to find this point by math calculating. We use heuristic function to obtain this point:

\[
P_{opt} = \arg \min_{p \in \pi, R(p) = \max{r \in \Phi_j}} d(I(p), \text{PER}(p)) \quad \text{PER}(p) < \text{PER}_{\max}
\]
where $P^{\text{opt}}_j$ is the optimal power on $j$ link, $j$ is the link between node and its neighbours, $\Phi_j$ is the set of transmission rate on $j$. $\text{PER}_{\text{max}}$ is the maximum of $\text{PER}$ on that link. Distance $d^*$ is defined by:

$$d^*(I(p), \text{PER}(p)) = I + \text{PER}_{\text{avg}}(p)$$

where $\text{PER}_{\text{avg}}$ is the average $\text{PER}$ of all links between a node and its neighbours with transmission power level $p$.

The following is the algorithm finding the optimal power of a node for a certain transmitting:

### D. Our Proposal for Cross-Layer Architecture

![Fig. 3 CLNC architecture](attachment:image)

Fig. 3 describes our proposal architecture. We implement the Cross-layer Network Coding module which can intercommunicate with three layers of protocol stack that are network layer, MAC layer, physical layer. When the node has an opportunity to transmit data, the system uses the optimal power algorithm to choose the optimal power level. It considers information at MAC layer including transmission rate, interference (using the trend index estimation), packet error rate (PER) to adapt the power level at physical layer. After that, the network coding technique is used to routing the packets at network layer.

In details, our system works as follows. When the relay node receives a packet, it checks whether the packet is the innovative one. If the packet is innovative then the node stores the packet in its buffer, otherwise it drops the packet. When the node has a chance to transmit, it chooses the best power level by using optimal power algorithm. Then it randomly chooses local coding coefficients in $\mathbb{GF}(2^8)$ and mixes all the packets in its buffer to make the coded packet. It computes global coding coefficient and embed this coefficient into the coded packet and broadcast to all its neighbours. The source node works in the same manner as the relay node but the source node does not mix all the original packets; it randomly chooses some packets. When the destination node receives enough coded packet from its incoming links, it starts decoding process. It uses the coding coefficient which embedded in coded packet to recover original packets.

Our proposal works effectively for networks which have the quickly change of network conditions and require the sources for computing, so it is suitable for wireless mesh networks.

### VI. SIMULATION RESULTS

#### A. Simulation Setup

We use NS-2 simulator to simulate our approach. The area of all simulation is of $1000 \times 1000$ meters. The number of nodes is 15. We vary the number of senders (1 and 2) and the number of receivers from 2 to 15. In NS-2, there is not the Ricean propagation model for mobility. We have downloaded and implemented this model from CMU Monarch group and use this model for all simulations. We performed all measurements using UDP traffic sent at a constant bit rate (CBR), and packet size at MAC layer of 1500 bytes. The transmission rates of the nodes are 11 Mbps, 5.5 Mbps, 2Mbps and 1Mbps. We disable the RTS/CTS handshake of the MAC layer because it makes the throughput capacity decrease significantly.

MAODV (Multicast Ad hoc On-Demand Distance Vector) is a multicast method which is well suited for wireless networks. It is not available in NS-2, so we use implementation of MAODV by Zhu et al. [14] for evaluation.

#### B. Results Analysis

Our proposal is called CLNC (Cross-Layer Network Coding). The routing approaches such as AODV, DSDV and DSR are popular routing techniques. We compare our approach with the other routing approaches including MAODV, AODV, DSDV and DSR. Fig. 4 and Fig. 5 show that the throughput of CLNC is far better than that of the other approaches including AODV, DSDV, DSR and better than that of MAODV.

![Fig. 4 The throughput capacity (the number of senders is 1)](attachment:image)

As data shown from Fig. 4, when the number of receivers is 10, 15 the throughput of CLNC is higher around 60% and 30% respectively than that of AODV, DSDV, and DSR. Throughput of MAODV is quite high because MAODV is the actual multicast routing technique and the popular routing method for wireless network. As the number of receivers is 15, the throughput of CLNC is higher nearly 2% than that of MAODV. As seen from Fig. 5 the throughput of CLNC is many times higher than that of AODV, DSDV, and DSR in the case the number of receivers is 2 and 5. As regards the number of receivers is 10, CLNC’s throughput more twice as high as throughput of AODV, DSDV, DSR. When the number of receiver is 15, throughput of CLNC is higher than that of AODV, DSDV, DSR.
about 50% than that of MAODV. In brief, Fig. 4 and Fig. 5 indicate that as for throughput, using CLNC is more effective than using MAODV when the number of receivers is high.

![Graph showing throughput capacity](image)

**Fig. 5 The throughput capacity (the number of senders is 2)**

PDR is Packet Delivery Ratio. This parameter is computed as total received packets / (total send packets × the number of receivers). From the data shown in TABLE I, when the number of receivers is small (such as 2, 3), the PDRs of MAODV and DSDV are higher CLNC. However, PDR of CLNC is better than that of others when the number of receivers is higher (such as 5, 10, and 15). As regards the num of senders is 2, the pattern is repeated (from data shown in TABLE II). Shortly, the tables present that PDR of CLNC is better than that of others when the number of receivers is large.

TABLE I

<table>
<thead>
<tr>
<th></th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLNC</td>
<td>0.9766</td>
<td>0.9616</td>
<td>0.9639</td>
<td>0.9301</td>
<td>0.9102</td>
</tr>
<tr>
<td>MAODV</td>
<td>0.9772</td>
<td>0.9724</td>
<td>0.9469</td>
<td>0.9196</td>
<td>0.8845</td>
</tr>
<tr>
<td>DSDV</td>
<td>0.9824</td>
<td>0.9425</td>
<td>0.9152</td>
<td>0.9014</td>
<td>0.8796</td>
</tr>
</tbody>
</table>

TABLE II

<table>
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<tr>
<th></th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>15</th>
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<tbody>
<tr>
<td>CLNC</td>
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<td>0.92341</td>
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<tr>
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<td>0.96751</td>
<td>0.93015</td>
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<td>0.97387</td>
<td>0.95278</td>
<td>0.90478</td>
<td>0.88267</td>
<td>0.87569</td>
</tr>
</tbody>
</table>

In this paper, we propose an approach which is a combination of cross-layer and network coding technique. We compare our proposal with other routing method for wireless networks including MOADV, DSR, DSDV, and AODV. The results show that our proposal can improve throughput of the single source multicast wireless mesh networks. Our proposal is suitable for wireless mesh networks which have the quick change condition and the number of nodes is large.

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**VII. CONCLUSION**