Network Coding-Aware Queue Management for Unicast Flows over Coded Wireless Networks

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Wireless Mesh Networks

- Throughput increases by mixing packets
One-hop network coding

Output queue

Output queue

Virtual queue

Virtual queue
Motivation

- **Problem:**
  - TCP over COPE does not fully exploit the NC potential

- **Intuition:**
  - Not enough coding opportunities due to TCP burstiness
  - Coded flows do not compete for resources
Motivation

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- **Possible Solution:**
  - Artificially delay packets at intermediate nodes
    
  
  - Throughput increases with small delay, but decreases with large delay
  
  - Optimal delay depends on the network topology and the background traffic, and may change over time
  
  - Not practical
Motivation

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- **Proposed Solution:**
  - Network Coding-Aware Queue Management (NCAQM)
  - No changes to TCP and MAC
  - Formulate network utility maximization (NUM) problem
  - TCP+NCAQM doubles the network coding benefit of TCP+COPE
Previous Work

Intra-session Network Coding

- Minimum cost multicast for wired and wireless:
  - D. S. Lun, N. Ratnakar, M. Medard, R. Koetter, D. R. Karger, T. Ho, E. Ahmed, and F. Zhao, “Minimum-cost multicast over coded packet networks,” ToIT’06.

- Minimum cost unicast with for wireless:
Previous Work

Inter-session Network Coding

- **Optimal Scheduling and Routing:**

- **Energy efficient network coding:**

- **End2end pairwise network coding:**
**Motivation**

**Proposed Solution:**
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**Our work in perspective:**
- Multiple unicast flows over wireless with given network coding scheme and pre-determined routing paths
- Connection between optimization and protocol design
- Intuition for practical implementation
Outline

- Introduction
- Network Utility Maximization (NUM)
- Network Coding-Aware Queue Management (NCAQM)
- Performance Evaluation
- Extensions & Summary
Network utility maximization

Formulation

\[
\text{maximize } \sum_{s \in S} U_s(x_s)
\]

\[
s.t. \sum_{k \in K_h} \max_{s \in S_k} \{H^{s,k}_h \alpha^{s,k}_h x_s\} \leq R_h \tau_h, \ \forall h \in A
\]

\[
\sum_{h(J) \in A} \sum_{k \in K_h} \alpha^{s,k}_h = 1, \ \forall s \in S, i \in P_s
\]

\[
\sum_{h \in C_q} \tau_h \leq \gamma, \ \forall C_q \subseteq A
\]
Network utility maximization

Solution I:

\[
\max_{s \in S_k} \{H^{s,k}_h \alpha^{s,k}_h x_s \} \quad \equiv \quad \max_m \sum_{s \in S_k} H^{s,k}_h \alpha^{s,k}_h x_s m^{s,k}_h \\
\text{s.t.} \quad \sum_{s \in S_k} m^{s,k}_h = 1
\]

\[
\max_{x, \alpha, \tau} \sum_{s \in S} U_s (x_s) \\
\text{s.t.} \quad \sum_{k \in K_h} \sum_{s \in S_k} H^{s,k}_h \alpha^{s,k}_h x_s (m^{s,k}_h)^* \leq R_h \tau_h, \quad \forall h \in A \\
\sum_{h \in C_q} \sum_{k \in K_h} \alpha^{s,k}_h = 1, \quad \forall s \in S, i \in P_s \\
\sum_{h \in C_q} \tau_h \leq \gamma, \quad \forall C_q \subseteq A
\]
Network utility maximization

Solution II:

\[ x_s = (U_s')^{-1} \left( \sum_{h \in A} \sum_{k \in K} \sum_{s \in S} q_h H_h^{s,k} \alpha_h^{s,k} (m_h^{s,k})^* \right) \]

\[ q_h(t + 1) = \left\{ q_h(t) + c_t \left[ \sum_{k \in K} \sum_{s \in S} H_h^{s,k} \alpha_h^{s,k} (m_h^{s,k})^* x_s - R_h \tau_h \right] \right\}^+ \]

\[ \min_{\alpha} \sum_{h(J) \in A} \sum_{k \in K} \sum_{s \in S} q_h H_h^{s,k} (m_h^{s,k})^* \alpha_h^{s,k} \]

\[ \text{s.t. } \sum_{h(J) \in A} \sum_{k \in K} \sum_{s \in S} \alpha_h^{s,k} = 1, \forall i \in P_s \]

\[ \max_{\tau} \sum_{h \in A} q_h R_h \tau_h \]

\[ \sum_{h \in C_q} \tau_h \leq \gamma, \forall C_q \subseteq A \]
Network Coding-Aware Queue Management (NCAQM)

Protocol modifications, mimicking the optimal solution

<table>
<thead>
<tr>
<th>Implementation Summary</th>
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</thead>
</table>
| Queue management (NCAQM) | • Network coding  
• Packet dropping |
| TCP                     | No change (TCP-SACK) |
| MAC                     | No change (802.11)   |

Minimal and intuitive
NCAQQM
Maintaining queues and packet transmission

\[ q_h(t+1) = \left\{ q_h(t) + c_t \left[ \sum_{k \in K_k} \max_{s \in S_k} \{ H_{h,k}^{s,k} \alpha_{h,k}^{s,k} x_s \} - R_h \tau_h \right] \right\}^+ \]

Modification I

- \(Q_i\) is the output queue at node \(i\)
- Store network coded packets (when an opportunity arises) instead of uncoded packets
- Keep track of hypearc queues
- Estimate traffic splitting parameters
- Packet scheduling is according to FIFO queue
NCAQM
Rate control and packet dropping

Optimal Rate Control

$$x_s = \left( \sum_{h(i) \in P_s} q_{h(i)}^s \right)^{-1}$$

Sum of network coded queue sizes across all nodes on the path

Modification II

- Upon congestion, compare $Q_i^s$ for all flows $s$. Drop an uncoded packet from the largest flow.

- How to calculate $Q_i^s$?
  - Determine hyperarc queues that flow $s$ is dominating (has the largest number of packets)
  - Sum the number of packets of flow $s$ over these hyperarc queues
NCAQM
Implementation Summary

- **Problem:**
  - TCP over COPE does not fully exploit the NC potential

- **Intuition:**
  - Flows coded together do not compete for resources
  - Not enough coding opportunities due to TCP burstiness

- **Modifications**
  - Store network coded packets (when an opportunity arises) instead of uncoded packets.
  - Compare $Q_\delta$ for all $s$. Drop an uncoded packet from the “largest” flow.
Outline

- Introduction
- Network Utility Maximization (NUM)
- Network Coding-Aware Queue Management (NCAQM)
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- Extensions & Summary
Performance evaluation

Scenarios

[Glomosim + NC]
Performance evaluation
Throughput improvement compared to noNC

<table>
<thead>
<tr>
<th></th>
<th>TCP+COPE (%)</th>
<th>TCP+NCAQM (%)</th>
<th>Optimal (%)</th>
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<tbody>
<tr>
<td>A &amp; B</td>
<td>12</td>
<td>27</td>
<td>33</td>
</tr>
<tr>
<td>Cross</td>
<td>16</td>
<td>31</td>
<td>60</td>
</tr>
<tr>
<td>X</td>
<td>10</td>
<td>22</td>
<td>33</td>
</tr>
<tr>
<td>Grid</td>
<td>8</td>
<td>19</td>
<td>-</td>
</tr>
</tbody>
</table>

TCP+NCAQM doubles the improvement of TCP+COPE
Performance evaluation
Throughput improvement vs buffer size
Extensions
Multi-hop network coding

- Network utility maximization problem is extended for multi-hop network coding
- Distributed solutions are derived
  - Only traffic splitting part changes
  - In practice, traffic splitting parameter is estimated
  - NCAQM is directly applied to multi-hop network coding
Summary

- Proposed queue management schemes to improve the performance of TCP over coded wireless networks
  - Formulated network utility maximization problem and proposed a distributed solution
  - Designed NCAQM scheme, mimicking the structure of the optimal solution. No changes TCP and MAC.
  - Simulations show that TCP+NCAQM doubles the improvement of TCP+COPE as compared to noNC.
Thank you!

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