Traffic Engineering for Software-Defined Radio Access Networks

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Central Traffic Engineering in RAN

- Traffic engineering (TE) in a network entails
  - Finding path(s)
  - Splitting flow among path(s)
- TE is modeled as a multi commodity flow (MCF) problem
  - Optimize some objective and/or satisfy flow demands subject to network link capacity constraints.
- We introduce a framework for central TE as the main enabler for software-defined radio access network (SD-RAN).
  - The routing and traffic splitting decisions are made by a central controller which has knowledge of network parameters.
Related Work

- Traditionally, the TE problem in RAN is split into two separate problems:
  - Cell selection in the access network, where a user is associated to a single access node, and
  - TE in the backhaul network, where the aggregated traffic of users associated to an access node is routed to the access node.

- Performance of cell selection can be enhanced by considering backhaul limitations [Galeana-Zapién, 7].

- Multi-path TE provides higher network capacity through efficient use of multiple paths between sources and destinations [Danna, 8,9].
Our Contribution

- Multi-path TE framework for SD-RAN with general backhaul topology.
- Incorporating link buffer status usage by TE.
System Model

- The backhaul links have fixed capacities.
- The capacity of a wireless access links is not fixed and depends on
  - the amount of bandwidth assigned to it by the corresponding access node, and
  - the spectral efficiency (SE) of the link
- The capacity of a wireless link with assigned bandwidth $r$ and SE of $s$ is given by $r \times s$.
- The SE of a wireless access link
  - depends on radio transmission configuration at the access node and the interference on the link.
  - is measured in bits/s/Hz.
- We assume fixed radio transmission configuration. In particular, we assume that transmit power at an access node does not change as a result of change in its transmission rate.
SD-RAN TE Problem Formulation

- **Notation:**
  - K users with traffic demands: \(d_1, d_2, \ldots, d_K\)
  - Number of paths for user \(k\): \(l_k\), \(k = 1, \ldots, K\).
  - Path \(j\) of user \(k\): \(p^k_j\), \(j = 1, \ldots, l_k\)
  - Traffic allocation for user \(k\) on path \(j\): \(x^k_j\)
  - \(c_a\) : capacity of wired link \(a\); \(r_n\) : resource at wireless access node \(n\)

- **Demand constraints**
  \[
  \sum_{j=1}^{l_k} x^k_j = d_k, \quad k = 1, \ldots, K \quad (1)
  \]

- **Wired link constraints**
  \[
  \sum_{\text{path } p^k_j \text{ passing link } a} x^k_j \leq c_a, \quad \forall \text{ wired link } a \quad (2)
  \]

- **Wireless access node constraints**
  \[
  \sum_{\text{path } p^k_j \text{ passing node } n} \frac{x^k_j}{s^k a(k,j)} \leq r_n, \quad \forall \text{ wireless access node } n \quad (3)
  \]
SD-RAN TE Problem Formulation (2)

- Weighted Max Min (WMM)

\[
\begin{align*}
\max_{\lambda, x^j} & \quad \lambda \\
\text{s.t.} & \quad \sum_{j=1}^{l_k} x^j \leq \lambda d_k, \quad k = 1, \ldots, K, \\
\end{align*}
\]

If \( \lambda^* < 1 \), the TE problem is infeasible. The WMM TE solution provide every flow with a fixed fraction (\( \lambda^* \)) of their demand.

If the problem is feasible, i.e., \( \lambda^* \geq 1 \), we divide resulting flow allocations by \( \lambda^* \) to obtain final flow allocations to satisfy the original flow demands.

If feasible, the WMM TE solution provides \((\lambda^*-1)x100\%\) over provisioning for flows.
SD-RAN TE Problem Formulation (3)

- Min Radio Resource Usage (MRRU)

\[
\min_{x_j} \sum_{n} \sum_{\text{path } p_j^{k} \text{ passing node } n} x_j \quad s.t. \\
(1), (2), and (3).
\]

- For lightly loaded networks (wired links and wireless node constraints inactive), flow demands are satisfied using only one path per flow in MRRU TE solution.
- As the network load increases, the MRRU TE approach uses more paths per flow as necessary to satisfy flow demands.
TE Using Link Buffer Status

- Buffer may build up occasionally at some links due to wireless channel transients, unpredicted change in flow demands, imperfect traffic splitting at routers, etc.

- Buffer accumulation results in packet delay and overall QoE degradation.

- Using buffer status of links at central TE controller provides robustness against inaccuracies in TE inputs.

- How to utilize buffer status at TE?
  - Treat data stored at buffers as additional sources → TE problem too complex.
  - Our solution: Capacity/bandwidth reservation.
TE Using Link Buffer Status (2)

- Capacity/Bandwidth reservation

- Wired link capacities ($c$)
- Wireless link SEs ($s$)
- Wireless access node resources ($r$)
- Traffic Engineering
- Source-destination pairs
- Flow demands
- Network topology
- Traffic splitting at nodes
TE Using Link Buffer Status (3)

- **Capacity reservation for backhaul links**
  - $t_e$: a predefined time for a backhaul link buffer to get empty
  - $b_a$: the number of bits queued in the buffer of backhaul link $a$
  - Reserved capacity at link $a$:
    \[ c_a^{\text{reserved}} = \frac{b_a}{t_e}, \quad \forall \text{wired link } a \]
  - Available link capacity in TE formulation:
    \[ c_a' = c_a - c_a^{\text{reserved}} \]

- **Bandwidth reservation at wireless access nodes**
  - Reserved resource (bandwidth) at access node $n$:
    \[ r_n^{\text{reserved}} = \frac{1}{t_e} \sum_{a \text{ connected to node } n} \frac{b_a}{s_a}, \quad \forall \text{wireless node } n \]
  - Available resource for access node $n$ in TE formulation:
    \[ r_n' = r_n - r_n^{\text{reserved}} \]
Sample RAN Topology

- 57 wireless access nodes (on X-Y plane)
- Users dropped randomly on the X-Y plane (not shown in the picture)
- Backhaul as shown
- Dynamic flow (session) arrival and departure
- Constant bit rate (CBR) flows
- QoE at least 0.99
Performance Gains

- **Supported rate (demand) for 570 users**

<table>
<thead>
<tr>
<th>Number of paths ($L$)</th>
<th>1 (Baseline)</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supported user rate</td>
<td>1.0 Mbps</td>
<td>1.6 Mbps</td>
<td>1.9 Mbps</td>
<td>2.1 Mbps</td>
</tr>
<tr>
<td>Gain w.r.t. baseline</td>
<td>0%</td>
<td>60%</td>
<td>90%</td>
<td>110%</td>
</tr>
</tbody>
</table>

- **Number of supported users with fixed rates**

<table>
<thead>
<tr>
<th>Number of paths ($L$)</th>
<th>1 (Baseline)</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of supported users</td>
<td>570</td>
<td>1125</td>
<td>1375</td>
<td>1425</td>
</tr>
<tr>
<td>Gain w.r.t. baseline</td>
<td>0%</td>
<td>97%</td>
<td>140%</td>
<td>150%</td>
</tr>
</tbody>
</table>
Effect of TE Objective Function

- CDF of radio resource usage

![CDF of radio resource usage graph](image-url)
TE Using Link Buffer Status Feedback

- CDF of mean packet delay
- QoE vs. rate
Conclusion

- Central multi-path traffic engineering for SD-RAN.
  - Higher network capacity and better user QoE through efficient use of multiple paths between sources and destinations
  - Better control over resource usage across the network for network operator

- Link buffer status usage at TE
  - Robustness against wireless channel transients, flow demand fluctuations, and inaccuracy of wireless network abstraction

- Other TE solutions for SD-RAN
Thank you

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