Weighted Contention and Interference routing Metric (WCIM)

Report 2: Simulations

Introduction

Simulations setup
### Simulation setup:
- **Fixed parameters in evaluations**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propagation model</td>
<td>Two-ray propagation model</td>
</tr>
<tr>
<td>Fading</td>
<td>Rayleigh fading with factor 5</td>
</tr>
<tr>
<td>Transmission Power</td>
<td>30mW</td>
</tr>
<tr>
<td>IEEE Standard</td>
<td>IEEE 802.11a</td>
</tr>
<tr>
<td>Broadcast, preamble and ACKs</td>
<td>Transmission rate</td>
</tr>
<tr>
<td>Minimum sensitivity at 6Mbps</td>
<td>-82dBm in reception (IEEE 802.11 standard)</td>
</tr>
<tr>
<td>Maximum carrier sensing range</td>
<td>197 meters</td>
</tr>
<tr>
<td>Minimum sensitivity at 12 Mbps</td>
<td>-79dBm in reception (IEEE 802.11 standard)</td>
</tr>
<tr>
<td>Max. communication range at 12Mbps</td>
<td>167 meters</td>
</tr>
<tr>
<td>Noise level</td>
<td>-95dBm in reception</td>
</tr>
<tr>
<td>Max. interference range</td>
<td>418 meters</td>
</tr>
<tr>
<td>RTS/CTS mode</td>
<td>Off</td>
</tr>
<tr>
<td>Link rates</td>
<td>Randomly fixed at 8Mbps or 12Mbps</td>
</tr>
<tr>
<td>MAC queue size</td>
<td>14 packets</td>
</tr>
<tr>
<td>MAC retry limit</td>
<td>4 retransmissions</td>
</tr>
<tr>
<td>IP routing</td>
<td>Flow based routes (Source, destination &amp; TuB)</td>
</tr>
<tr>
<td>Type of flows</td>
<td>UDP, Constant-Bit-Rate, unidirectional</td>
</tr>
</tbody>
</table>

### Evaluation procedure:
- **Four independent RNGs are used**
  - PHY, MAC, routing and application layer
- The “Application layer” seed controls the sources, the destinations (if not fixed) and the link bit rates of the nodes
  - Thus, we denote as a network a group of simulations with this seed being fixed
- **Evaluation methodology:**

![Diagram showing simulation scenarios and networks with varying seeds for physical, MAC, and routing layers.](image)
Comparison of routing metrics

<table>
<thead>
<tr>
<th>Routing metric</th>
<th>#Hops</th>
<th>Bit error rate</th>
<th>Link bit rate</th>
<th>Load-awareness</th>
<th>Inter-flow interference</th>
<th>Flow diff.</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hop Count</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>Experimental</td>
</tr>
<tr>
<td>ETX</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>Experimental</td>
</tr>
<tr>
<td>ETT</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>Experimental</td>
</tr>
<tr>
<td>ALM</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>Experimental</td>
</tr>
<tr>
<td>MTM</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>Experimental</td>
</tr>
<tr>
<td>MIC</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>N_i</td>
<td>no</td>
<td>Simulation</td>
</tr>
<tr>
<td>ETT</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>(i,j)</td>
<td>no</td>
<td>Simulation</td>
</tr>
<tr>
<td>LBAR</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>Number of active routes</td>
<td>N_f</td>
<td>no</td>
<td>Simulation</td>
</tr>
<tr>
<td>IAR</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>Busy time percentage</td>
<td>Measured</td>
<td>no</td>
<td>Simulation</td>
</tr>
<tr>
<td>ILA</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>Bytes transmitted</td>
<td>N_i</td>
<td>no</td>
<td>Simulation</td>
</tr>
<tr>
<td>IAWARE</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>Interference Ratio: SNR/SNR</td>
<td>Sensed: Sender- or Receiver-side</td>
<td>no</td>
<td>Experimental</td>
</tr>
<tr>
<td>WCIM</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>Channel occupancy</td>
<td>Weighted contention and interference model</td>
<td>yes</td>
<td>Experimental and evaluation</td>
</tr>
</tbody>
</table>

AODV vs FB-AODV

Analysis
AODV vs FB-AODV

Analysis

• Destination-based vs flow-based routing
  • AODV = Routes per destination
    – Same destination + same intermediate node (or source) = same route
  • FB-AODV = Routes per flow
    – Same destination + same source + same ToS = same route

• Analysis:
  – Average of 10 networks
    ▪ 10 simulations per network
  – Four flows between Node 1 and Node 64
    ▪ 500Kbps, 1472 bytes, a new flow each 50 seconds
    ▪ AODV:
      – Same route for all the flows
      – Congestion
    ▪ FB-AODV:
      – Different ToS = chance of different routes
      – Load-balancing

• AODV \equiv Routes per destination

  \begin{itemize}
  \item The first two flows are supported by the route
  \item The third and fourth flows cause congestion and route breaks
    \begin{itemize}
    \item Degradation of the goodput and delay per flow
    \item ETT and ILA give better results than HOPS
    \item They use faster links (12Mbps)
    \end{itemize}
  \end{itemize}
AODV vs FB-AODV

Analysis

• FB-AODV ≡ Routes per flow

– Multipath routing:
  • The first three flows are routed with good performance
    – The third one causes some congestion
  • The fourth flow causes congestion and some route breaks
    – Unavoidable congestion at the receiver!

• Flow-based routing improvement:
  • Goodput:
    – Average increase of 45% (HOPS), 42% (ETT) and 45% (ILA)
  • Delay:
    – Average decrease of 28% (HOPS), 35% (ETT) and 39% (ILA)
  • The number of link breaks and route errors because of congestion becomes also reduced (around 50% less)

• Conclusions:
  • Flow-based routing possibilities load-balancing
    – WCIM and ILA metrics are load-aware
      • Each new flow considers the interference of the previous ones
    – ETT and HOPS are load-unaware, i.e. by definition flow-based routing is not useful (the best route does not change with load conditions). However...
      • ETT is aware of link-quality degradation: some HELLOs are lost because of congestion
      • HOPS becomes multipath by chance: some RREQs are lost because of congestion
Routing metrics as efficient route selectors

Analysis

- Analysis of goodput, Packet Loss Rate (PLR) and end-to-end delay
  - Comparison between different routing metrics
    - HOPS, ETT, ILa and WCIM
  - Four scenarios
    - Scenario I: 6 flows, random sources and destinations
    - Scenario II: 6 flows, random sources and a fixed destination (Gateway 64)
    - Scenario III: 6 flows, random sources and a fixed destination (Gateway 28)
    - Scenario IV: 15 flows, random sources and destinations
  - Average results of 100 simulations
    - 10 different networks per scenario
      * 10 simulations per network
    - Analysis of the time interval when all the traffics are active
Routing metrics as efficient route selectors

Scenario I: 6 flows, random destinations

- **Scenario I:**
  - 6 random flows
    - (1472 bytes, 75 Kbps) x 2
    - (972 bytes, 50 Kbps) x 2
    - (172 bytes, 10 Kbps) x 2
  - Every 10 seconds a new flow is started
    - Flow duration of 200 seconds
    - Time interval with all the 6 flows being routed: 250s – 400s
  - **Ten configurations**
    - C1: Total Throughput = 270 Kbps
    - C2: Total Throughput = 2x 270 Kbps
    - ........
    - C10: Total Throughput = 10x 270 Kbps

Example of routing strategies:

- **Simulation #47, configuration 5:**

Routing metrics as efficient route selectors

Scenario I: 6 flows, random destinations
Routing metrics as efficient route selectors
Scenario I: 6 flows, random destinations

- Scenario I:
  - Example of routing strategies:
    - Simulation #47, configuration 5:

<table>
<thead>
<tr>
<th>Metric</th>
<th>#hops</th>
<th>#links at 6Mbps</th>
<th>#links at 12Mbps</th>
<th>Goodput (kbps)</th>
<th>PLR (%)</th>
<th>Delay (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOPS</td>
<td>37</td>
<td>17</td>
<td>20</td>
<td>1206</td>
<td>10.346</td>
<td>57.075</td>
</tr>
<tr>
<td>ETT</td>
<td>37</td>
<td>12</td>
<td>25</td>
<td>1226</td>
<td>9.654</td>
<td>52.020</td>
</tr>
<tr>
<td>ILA</td>
<td>45</td>
<td>15</td>
<td>30</td>
<td>1248</td>
<td>10.195</td>
<td>61.875</td>
</tr>
<tr>
<td>WCIM</td>
<td>37</td>
<td>13</td>
<td>24</td>
<td>1328</td>
<td>3.981</td>
<td>48.707</td>
</tr>
</tbody>
</table>

- **HOPS metric:**
  - Slower routes and congestion/interference with traffic increase
- **ETT metric:**
  - Fast routes, but can lead to congestion/interference with traffic increase
- **ILA metric:**
  - Longer routes because of interference overestimation and does not obtain better PLRs
- **WCIM metric:**
  - Fast routes and congestion/interference avoidance if necessary

Routing metrics as efficient route selectors
Scenario I: 6 flows, random destinations

- Performance evaluation:
  - Route performance

![Graphs](image-url)

- Goodput
- Packet Loss Rate
- End-to-end delay

<table>
<thead>
<tr>
<th>Offered load (kbps)</th>
<th>Goodput</th>
<th>Packet Loss Rate</th>
<th>End-to-end delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>0%</td>
<td>0 ms</td>
</tr>
<tr>
<td>25</td>
<td>95</td>
<td>0.5%</td>
<td>5 ms</td>
</tr>
<tr>
<td>50</td>
<td>90</td>
<td>1%</td>
<td>10 ms</td>
</tr>
<tr>
<td>75</td>
<td>85</td>
<td>1.5%</td>
<td>15 ms</td>
</tr>
<tr>
<td>100</td>
<td>80</td>
<td>2%</td>
<td>20 ms</td>
</tr>
<tr>
<td>125</td>
<td>75</td>
<td>2.5%</td>
<td>25 ms</td>
</tr>
<tr>
<td>150</td>
<td>70</td>
<td>3%</td>
<td>30 ms</td>
</tr>
<tr>
<td>175</td>
<td>65</td>
<td>3.5%</td>
<td>35 ms</td>
</tr>
<tr>
<td>200</td>
<td>60</td>
<td>4%</td>
<td>40 ms</td>
</tr>
<tr>
<td>225</td>
<td>55</td>
<td>4.5%</td>
<td>45 ms</td>
</tr>
<tr>
<td>250</td>
<td>50</td>
<td>5%</td>
<td>50 ms</td>
</tr>
<tr>
<td>275</td>
<td>45</td>
<td>5.5%</td>
<td>55 ms</td>
</tr>
<tr>
<td>300</td>
<td>40</td>
<td>6%</td>
<td>60 ms</td>
</tr>
</tbody>
</table>

![Graphs](image-url)

- HOPS
- ETT
- ILA
- WCIM
Routing metrics as efficient route selectors
Scenario I: 6 flows, random destinations

- Performance evaluation:
  - Per hop performance

```
Scenario II: 6 flows, gateway 64

- 6 random flows
  - (1472 bytes, 75 Kbps) x 2
  - (972 bytes, 50 Kbps) x 2
  - (172 bytes, 10 Kbps) x 2

- Every 10 seconds a new flow is started
  - Flow duration of 200 seconds
  - Time interval with all the 6 flows being routed: 250s – 400s

- Eight configurations
  - C1: Total Throughput = 270 Kbps
  - ........
  - C8: Total Throughput = 8x 270 Kbps

- Scenario characteristics
  - Longer routes than in the previous scenario
  - Unavoidable interference/congestion at the receiver
```
Routing metrics as efficient route selectors
Scenario II: 6 flows, gateway 64

- Performance evaluation:
  - Route performance

![](chart1.png)

Routing metrics as efficient route selectors
Scenario II: 6 flows, gateway 64

- Performance evaluation:
  - Per hop performance

![](chart2.png)
Routing metrics as efficient route selectors

Scenario III: 6 flows, gateway 28

- Scenario III:
  - 6 flows with fixed destination (gateway 28)
    - (1472 bytes, 75 Kbps) x 2
    - (972 bytes, 50 Kbps) x 2
    - (172 bytes, 10 Kbps) x 2
  - Every 10 seconds a new flow is started
    - Flow duration of 200 seconds
    - Time interval with all the 6 flows being routed: 250s – 400s
- Six configurations
  - C1: Total Throughput = 270 Kbps
  - .......
  - C10: Total Throughput = 6x 270 Kbps
- Scenario characteristics
  - Short routes
  - Unavoidable interference/congestion at the receiver

Performance evaluation:

Route performance

- Goodput
  - [% of offered load]
- Packet Loss Rate
  - [% of offered load]
- End-to-end delay
  - [ms]

- Offered load (kbps)
  - 270 540 810 1080 1350 1620
  - HOPS
  - ETT
  - ILA
  - WCIM
Routing metrics as efficient route selectors

Scenario III: 6 flows, gateway 28

- Performance evaluation:
  - Per hop performance

- Scenario III:
  - 15 random flows
    - (1472 bytes, 75 Kbps) x 5
    - (972 bytes, 50 Kbps) x 5
    - (172 bytes, 10 Kbps) x 5
  - Every 5 seconds a new flow is started
    - Flow duration of 300 seconds
      - Time interval with all the 15 flows being routed: 270s – 500s
  - Five configurations
    - C1: Total Throughput = 675 Kbps
    - ..........
    - C5: Total Throughput = 5x 675 Kbps
  - Scenario characteristics
    - Higher number of flows (load/congestion/interference)
Routing metrics as efficient route selectors
Scenario IV: 15 flows, random destinations

Performance evaluation:
• Route performance

- a) Goodput
- b) Packet Loss Rate
- c) End-to-end delay

- a) Average length of routes
- b) Packet Loss Rate per hop
- c) Delay (ms)

Number of hops

Offered load (kbps)

HOPS ETT ILA WCIM

Delay (ms)

Offered load (kbps)

HOPS ETT ILA WCIM

Number of hops

Offered load (kbps)

HOPS ETT ILA WCIM
Routing metrics as efficient route selectors

Analysis

• Conclusions:
  • HOPS metric
    – Does not differentiate between links at 6Mbps or at 12Mbps
    – Does not consider load or interference
    – Shorter routes, but slower (less available bandwidth) and interfered links
      ▪ Very high PLRs and delays (even with low load)
      ▪ Significant performance degradation with the increase of load
      ▪ Obtains the worst results in almost all the simulations
  • ETT metric:
    – Tries to select links at 12Mbps
    – Does not consider load or interference (but ETX metric does it explicitly!)
  • ILA metric
    – Gives priority to low interfered links
    – Longer and low interfered links
      ▪ With low interference, ILA leads to low PLRs but higher delays because of longer routes
      ▪ With high interference, improvement is only slightly better than ETT
        – Selected links are less interfered, but the number of hops (transmissions) is very high
        – Longer routes become less effective especially in scenarios where load-balancing or interference avoidance routing is difficult to apply (GW27)
  • WCIM metric
    – Maximizes available bandwidth and minimizes delay
    – Shorter and low interfered links
      – Gives good results in a variety of scenarios and network conditions
        ▪ With low interference or unavoidable interference, its routing strategy is similar to ETT (faster links)
          – WCIM obtains better performance because of being load-aware
        ▪ With high interference, its routing strategy is similar to ILA (interference avoidance)
          – WCIM obtains better performance because of a better design
Routing metrics as performance estimators

Analysis

- Performance estimation is a key factor in order to design an efficient routing metric
  - All routing metrics are designed in order to characterize some phenomena that affects traffic performance
    - For instance: less number of hops $\equiv$ less delay, more bandwidth
  - In additive routing metrics:
    - Lower routing metric value $\equiv$ Better performance

- The objective is to obtain a routing metric which variations correspond to similar performance variations
  - For instance:

<table>
<thead>
<tr>
<th>Route</th>
<th>Delay</th>
<th>HOPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 hop at 6Mbps</td>
<td>$\times 3$</td>
<td>$x_1$</td>
</tr>
<tr>
<td>1 hop at 12Mbps</td>
<td>$x_2/3$</td>
<td>$A/2$</td>
</tr>
<tr>
<td>2 hops at 18Mbps</td>
<td>$2A/3$</td>
<td>$2A/3$</td>
</tr>
</tbody>
</table>
Routing metrics as performance estimators

• Analysis of metric values in relation to flow performance
  • Three types of flows are defined:
    • F4: 1472 bytes, 500 Kbps
    • F5: 972 bytes, 200 Kbps
    • F6: 172 bytes, 50 Kbps
  – 5 networks, 10 simulations per network
  – Flow duration of 200s
  – Random sources and destinations
• Analysis procedure:
  – Initial load and interference conditions:
    • zero, one or two flows are active in the network (5 load conditions per analyzed flow)
      – For instance, load conditions for flow 4: 0 flows, f5, f6 and f5, f6 and f5
  – Routing of a new flow:
    • The analyzed one
      – We obtain the routing metric of the followed route
      – We obtain the average end-to-end delay of the followed route
      – We plot both parameters

F4 (1472 bytes, 500 Kbps):
Routing metrics as performance estimators

- F4 (1472 bytes, 500 Kbps):
  - Results are averaged each 1 millisecond
    - ~ transmission delay of 1 hop at 12 Mbps
    - Figures show if the variations of delays and routing metrics are well coupled

<table>
<thead>
<tr>
<th>HOPS: Routing metrics and end-to-end delay pairs (average)</th>
<th>ETT: Routing metrics and end-to-end delay pairs (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>![HOPS graph]</td>
<td>![ETT graph]</td>
</tr>
</tbody>
</table>

Routing metrics as performance estimators

- F5 (972 bytes, 200 Kbps):

<table>
<thead>
<tr>
<th>HOPS: Routing metric and end-to-end delay pairs</th>
<th>ETT: Routing metric and end-to-end delay pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="HOPS graph" /></td>
<td><img src="image2" alt="ETT graph" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ILA: Routing metrics and end-to-end delay pairs (average)</th>
<th>WCIM: Routing metrics and end-to-end delay pairs (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>![ILA graph]</td>
<td>![WCIM graph]</td>
</tr>
</tbody>
</table>

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Routing metrics as performance estimators

**Analysis**

- **F5 (972 bytes, 200 Kbps):**
  - Results are averaged each 0.75 milliseconds: Variation
    - \(\approx 1\) transmission delay of 1 hop at 12 Mbps
    - Figures show if the variations of delays and routing metrics are well coupled

**Tables**

<table>
<thead>
<tr>
<th>HOPS</th>
<th>Routing metrics and end-to-end delay pairs (average)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Delay</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Graphs**

- HOPS: Routing metric and end-to-end delay pairs
- ETT: Routing metric and end-to-end delay pairs
- ILA: Routing metric and end-to-end delay pairs
- WCIM: Routing metric and end-to-end delay pairs

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Routing metrics as performance estimators

**Analysis**

- **F6 (172 bytes, 50 Kbps):**

**Tables**

<table>
<thead>
<tr>
<th>Delay (ms)</th>
<th>End-to-end delay</th>
<th>HOPS metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>0.63</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td>1.26</td>
<td>1.26</td>
<td>1.26</td>
</tr>
<tr>
<td>1.89</td>
<td>1.89</td>
<td>1.89</td>
</tr>
<tr>
<td>2.52</td>
<td>2.52</td>
<td>2.52</td>
</tr>
<tr>
<td>3.15</td>
<td>3.15</td>
<td>3.15</td>
</tr>
<tr>
<td>3.78</td>
<td>3.78</td>
<td>3.78</td>
</tr>
</tbody>
</table>

**Graphs**

- HOPS: Routing metric and end-to-end delay pairs
- ETT: Routing metric and end-to-end delay pairs
- ILA: Routing metric and end-to-end delay pairs
- WCIM: Routing metric and end-to-end delay pairs
Routing metrics as performance estimators

Analysis

- F6 (172 bytes, 50 Kbps):
  - Results are averaged each 0.25 milliseconds: Variation
    - ~ transmission delay of 1 hop at 12 Mbps
    - Figures show if the variations of delays and routing metrics are well coupled

Routing metrics as performance estimators

Analysis

- Delay/Metric parameter
  - Division of the delay measurements and the metric values
    - Average of 250 values (simulations) per type of flow
Routing metrics as performance estimators

Analysis

• Delay/Metric parameter

| Standard deviation of delay/metric ratio (expressed as a percentage of the average) |
|-------------------------------------------------|-----------------|-----------------|-----------------|
| Routing metric | f4 (large packets) | f5 (medium packets) | f6 (short packets) |
| HOPS            | 18%              | 20%              | 28%              |
| ETT             | 7%               | 8%               | 19%              |
| ILA             | 54%              | 61%              | 76%              |
| WCIM            | 5%               | 5%               | 5%               |

– In the case of long packets (F4 and F5), the main delay source is the nominal transmission time of the links (except cases with heavy congestion or interference)
  - ETT and WCIM obtain better results because of being aware of the link rate
  - WCIM results are slightly better since it considers link efficiency and load/interference

– In the case of short packets (F6), interference and congestion affect delay in a major proportion since the nominal transmission delays are smaller
  - In addition, link efficiency becomes also more significant
    - Physical and MAC overheads (Preamble, DIFS, SIFS, etc.)
  - WCIM results are better since it considers link efficiency and load/interference

Routing metrics as performance estimators

Analysis

• Conclusions:

• Performance estimation
  - Number of hops is insufficient (HOPS)
  - Link quality awareness is fundamental in multi-rate networks (ETT)
  - Interference awareness is useful (ILA and WCIM)
  - Traffic differentiation becomes also useful (WCIM)
    - Link efficiency, delay estimation according to packet size...
  - Routing metric design is fundamental
    - ILA case: Severe interference overestimation leads to poor results

• WCIM obtains in all the cases the minimal standard deviation
  - Its variation according to the network conditions results similar to the variation of the delay measurements

• In addition, since WCIM definition is in terms of delay (and considers the packet size), the average of the delay/metric parameter is very close to 1
  - WCIM metric could be considered an acceptable estimator of the delay of a route (in microseconds) with final network conditions (there aren’t any subsequent flows)