An Intelligent WDN for Future Ubiquitous Society

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Goal

Improve performance of Wireless Distributed Networks (WDS) by giving Intelligence to nodes so that they can achieve "Cognitive" Local Path Optimization.

Outline

- Background
- Related Works and Problems
- Cross-Layer Cognitive Approach
- How to Control Local Path in Fading Environment
- Analysis and Simulation Results
- Conclusion
Wireless Distributed Communications will play important roles in the future communications such as:

- Small power ubiquitous and sensor networks for realizing IoT (Internet of Things)
- Means for Cellular System Offloading to accommodate huge data traffic from Smart Phones
- Indoor coverage method by ad hoc Pico/Femto-cells
- Easy-to-deploy Temporally Networks, after current network infrastructure suffered serious damage due to disasters

However, many Wireless Distributed Communications require Multi-Hop Connection because of their limited power resources.
Reliability of Communication is a serious issue.
- Only one hop link error blocks whole transmission.

If a low quality link is initiated as a hop, multi-hop transmission will not succeed.

Route determination is always critical.

Under fading environment, probability of link error changes after a route is determined.

Route management should track fading.
Only one hop link error blocks whole transmission. If a low quality link is initiated as a hop, multi-hop transmission will not succeed. Route determination is always critical.

Under fading environment, probability of link error changes after a route is determined. Route Management should track fading.

If we add margin of each link by shortening link distance, it consumes much resource and increases multi-hop delay.

High Reliability and small Delay/Resource conflict, if we follow any predetermined routes.
Intelligence in WDN

- Intelligence is an essential feature of advanced systems.
- The most important ability of WDN enabled by intelligence is "Adaptability".
- If distributed nodes can cooperate each other while adapting dynamically to fading channel, performance of WDN will be greatly improved.

Therefore this speech discusses, how multi-hop communication quality in WDN can be maintained by the intelligence of distributed nodes that always watch surrounding node's behavior and take adaptive action to change signal paths dynamically.
On-Demand Routing Protocol such as AODV determines multi-hop route by exchanging Route Request (RREQ) and Route Reply (RREP) messages.

Sender node S chooses the minimum hop counts route (S-A-B-D).
Thus, Hop links have longer distances and little tolerance for fading.
Simulated Multi Hop Routes with AODV

[Simulation Condition] IEEE802.11b, Rayleigh fading, No ARQ

- **2-hop route examples**
  - Inter-Node distance: 100m
  - Generation Prob.: 4%
  - Delivery Success: 2%
  - Delay: 2 hops

- **3-hop route examples**
  - Generation Prob.: 77%
  - Delivery Success: 23%
  - Delay: 3 hops

2 and 3 hop routes include long-distance links. Multi-hop delay is small, packet delivery ratio is poor.
Simulated Multi Hop Routes with AODV

- 4-hop route examples
  
  ![4-hop route diagram](image)
  
<table>
<thead>
<tr>
<th>Route Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation Prob.</td>
</tr>
<tr>
<td>Delivery Success</td>
</tr>
<tr>
<td>Delay</td>
</tr>
</tbody>
</table>

- 5-hop route examples
  
  ![5-hop route diagram](image)
  
<table>
<thead>
<tr>
<th>Route Details</th>
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<tbody>
<tr>
<td>Generation Prob.</td>
</tr>
<tr>
<td>Delivery Success</td>
</tr>
<tr>
<td>Delay</td>
</tr>
</tbody>
</table>

4 and 5 hop routes consist of shorter links. Packet delivery ratio is better, multi-hop delay is large.
<table>
<thead>
<tr>
<th>Hop Count</th>
<th>Number of generation</th>
<th>Node #s on the route</th>
<th>Hop distance (x100m)</th>
<th>Route distance (x100m)</th>
<th>Delivery Ratio</th>
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<td>1 2 4 7 10</td>
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<td>1 1 2 1 1</td>
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<td>0.35994905</td>
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</table>
Majority is the 3 hops. However, 19% are 4 or 5 hops, 4% are 2 hops.
Routes with large hop count have better packet delivery ratio, although the ratio is still not good. To the contrary, multi-hop delay increases.

Suggest great influence of routing.
MANET Routing Protocols cannot track link quality fluctuation due to fading.

MAC-ARQ is not effective to cover link error in slow fading conditions, i.e. nodes are fixed or not moving fast.

If we set longer ARQ retransmission duration, it can cover link error caused by slower fading. However, it will reduce link throughput and increase delay.

End-to End ARQ (TCP-ARQ) consumes much network resources. Therefore it is not efficient for covering single hop error.
A lot of methods in different approaches have been studied to improve reliability of multi-hop wireless communication.

**NW Layer**  
**Multipath Routing**
- Route redundancy improves reliability
- Consumes much network resources such as power and spectrum.
- Cannot adapt to fast fading.
- Thus, not cost-effective in wireless environments.

**PHY Layer**  
**Cooperative Diversity**
- Reliability improvement is large with reasonable spectrum efficiency.
- Receiver signal processing is heavy for small power source devices.
- Relay node determination is not coordinated with multi hop routing.

These approaches are within the framework of the OSI layer.
Current multi-hop techniques are based on the OSI layer model.

OSI layer model defines the roles of each layer, which makes engineers easy to develop whole system by work sharing.

However, it does not mean the system performance can be maximized by the layer model.

On the contrary, “walls” between layers often limit the potential of the system.

Then, what shall we do?

We should get over the walls by acquiring multi-layer knowledge and create new composite-style techniques.

Forwarder List: \{B>C>A\}

higher priority

Higher Priority is given to the node that has higher potential to reach destination

EX-OR gains route diversity effect without network resource increase. Effectiveness was proved in roof-top mesh network experiments.

However, it is difficult to apply this method to networks with rapid channel changing, because it needs to calculate profit function for each link from averaged link quality.
Reliability of a multi hop route can be improved by selecting an “available path” in local area when transmitting a packet.

A route is not a “line”, but an "area".

Distributed Path Control by Environment-Adaptive (Cognitive) Behavior of individual nodes. It is possible by creating a new cross-layer multi-hop protocol.

Then, How shall we do?
Cross-Layer Approach Lead by MAC

Only MAC Layer can interwork with both PHY and NW Layers.

- Route Determination,
- End-to-End Transmission Quality Measurement

Route Information

- Fast Route Management is possible

- Link Quality/Error

- Individual Link Quality Measurement (RSSI, CRC)
- Link Quality Adaptations (AMC)

However, the role of current MAC layer is limited to manage single link, not covers multi-hop links.

Enhancement of MAC protocol to multi hop links is necessary.
Basic Concept of Proposal

Cross-layer Cognitive Path Control method lead by MAC

NW Layer determines a basic route

- On-demand Routing Protocols such as AODV can be used.
- Repair route after a node has moved out from the route.

Enhanced MAC Layer selects an “available local path” after transmitting a packet

- “Available local paths” are:
  - the default path, bypassed path, and shortcut path

- Nodes on the default route and in its vicinity prepare for Bypass and Shortcut, by referring route information they have.
Dynamic Bypass and Shortcut

Due to **Fading, and Interference**

Sometimes

- **Fading**
- **Interference**

Sometimes Does not Reach

- Temporary Bypass

Sometimes Over Reach

- Temporary Shortcut

Bypass

Basic Routes were determined at the time of **Route Search**. However, Link Quality changes due to fading. Thus the Basic Route is not always the best one.

Shortcut

Multi hop Route should be dynamically changed according to the status of each Link.
Integration of Bypass and Shortcut

- Bypass: Path Diversity Effect
- Shortcut: Reduction of Hop Count and Radio Resources, Path Diversity Effect

Integration of two Methods will gain Greater Effects

Integrated Dynamic Path Selection Control

Greater Path Diversity Effect
Reduction of Hop Count and Radio Resources
Integrated Dynamic Multi-Hopping (IDMH)

Issue; Conflict happens among Candidate Paths.

Ex; Transmitted Signal from node A is captured by node C (shortcut), B (Basic route), E (Bypass). They try to forward it to the next hop nodes.

Integrated Dynamic Path Selection Control should

✓ be localized,
✓ avoid any conflict among candidate paths, and
✓ choose the best path.
Priority of Paths and Cognitive Control Actions

1. Shortcut (A→C)
2. Default Path (A→B→C)
3. Bypass (A→E→B→C, A→B→E→C)

1. Priority is given to the paths with smaller hop count.

Table 1 Cognitive Action after Transmission from A

<table>
<thead>
<tr>
<th>Packet reception status</th>
<th>Next action</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-C</td>
<td>A-B</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Case I</td>
<td>Success</td>
</tr>
<tr>
<td>Case II</td>
<td>Fail</td>
</tr>
<tr>
<td>Case III</td>
<td>Fail</td>
</tr>
</tbody>
</table>
Case I, Nodes B, C, E can receive data packet from node A.

**STP: Stop Forwarding Message (Including Ack)**

**ICM: Intermediary Candidate Message**

**IRM: Intermediary Request Message**

In order to give priority, IFS (Inter Frame Spacing) of CSMA/CA for three control messages are differentiated as:

IFS(STP) < IFS(Ack) < IFS(ICM)
Bypass; RREP from B is monitored by node E. Then a Monitoring List Entry (A→B) is created.

Shortcut; Adding Previous Hop Address (C) to RREP information, Routing Table Entry of A, and MAC Header sending by A.
Transmission Probability of Paths for IDMH

- **One Hop Path (Shortcut)**
  \[ P_{1h} = P_{pathI} = P_{AC} = P_1 \]

- **Two Hop Path (Basic Route)**
  \[ P_{2h} = (1 - P_{1h}) \cdot P_{pathII} = (1 - P_{1h}) \cdot P_0^2 \]

- **Three Hop Paths (one Bypass)**
  \[ P_{3h} = (1 - P_{1h}) \cdot (1 - P_{2h}) \cdot P_{pathIII} \\
  = 2 \cdot (1 - P_{1h}) \cdot (1 - P_{2h}) \cdot P_0^4 \cdot P_0 \]

- **Four Hop Path (Two Bypass)**
  \[ P_{4h} = (1 - P_{1h}) \cdot (1 - P_{2h})^2 \cdot P_{pathIV} \\
  = (1 - P_{1h}) \cdot (1 - P_{2h})^2 \cdot (P_0^4)^2 \]
Average Hop Count for Successful Transmissions

- Packet Transmission Success Probability; \( P_I \)
- \( p \)-Hop Path \((p=1, 2, 3, 4)\) Selection Probability; \( K_p \)
- Average Hop Count for Successful Transmissions; \( E_h \)

\[
E_h = \frac{\sum_{p=1}^{4} K_p \cdot p}{P_I}
\]

\[
K_1 = P_{\text{path I}} = P_{AC} \quad K_2 = (1 - P_{\text{path I}})P_{\text{path II}} = (1 - P_{AC})P_{AB} \cdot P_{BC}
\]

\[
K_3 = (1 - K_1 - K_2)(P_{\text{path IIIa}} + P_{\text{path IIIb}} - P_{\text{path IIIa}} \cdot P_{\text{path IIIb}})
\]

\[
K_4 = (1 - K_1 - K_2 - K_3)P_{AE} \cdot P_{BE}^2 \cdot P_{CE}
\]
RF Channel Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Frequency</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Bit rate</td>
<td>11 Mbps</td>
</tr>
<tr>
<td>Tx Power</td>
<td>15 dBm</td>
</tr>
<tr>
<td>Rx Sensitivity</td>
<td>-81 dBm</td>
</tr>
<tr>
<td>Path Loss Model</td>
<td>ITU-R p.1411</td>
</tr>
<tr>
<td>Antenna Heights</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Fading</td>
<td>Flat Rayleigh</td>
</tr>
</tbody>
</table>

Location of Nodes

Nodes are located on a regular triangle lattice with the distance of $R_0$ to the adjacent nodes.

$R_1 = \sqrt{3}R_0$
The IDMH has the best packet success probability, because it can choose one of three candidate paths.

Reduce packet error from 20% to 3%
from 30% to 9%
The IDMH MAC provides **automatic migration** among Shortcut, Normal 2-Hop, and Bypassed paths.
The IDMH can reduce the multi-hop delay when node distance is less than 250 m.
Conclusions

- The Integrated Dynamic Multi-Hopping (IDMH) scheme employing cross-layer and Cognitive approach has been proposed
  - to provide better packet transmission probability gained from three-path diversity effect
  - to reduce multi-hop delay and save radio resources by giving priority to shorter hop paths

- The gained improvements promise increase of throughput in multi-hop networks.
  It will be confirmed by the ongoing work.


Thank you for listening!