SPEED: A Stateless Protocol for Real-Time Communication in Sensor Networks

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Introduction to Real-Time Systems
Outline

- Main idea
- Introduction
- State of art in routing protocols
- Design Goals
- SPEED Protocol
- Experimentation and Evaluation
- Conclusion
Main idea

- **SPEED**: Real-time communication routing protocol for sensor networks

- 3 types of real-time communication services
  - Real-time unicast
  - Real-time area-multicast
  - Real-time area-anycast

- Stateless, localized algorithm with minimal control overhead

- Maintain desired delivery speed across network to achieve end-to-end soft real-time communication.
  - Feedback control
  - Non-deterministic geographic forwarding
Introduction

- Large-scale sensor networks need efficient, robust routing protocols.

- Main function of sensor networks: data delivery.

- 3 types of communications patterns:
  - **Unicast**: one part of network detects activity to report to remote base station.
  - **Area-multicast**: Base station issues command or query to an area in the network.
  - **Area-anycast**: any node in an area responds.

- Communication in sensor networks should meet real-time constraints. Examples of networks with these constraints are surveillance systems.

- SPEED supports soft real-time communication by using feedback control and stateless algorithms.
State of art in routing protocols

- Sensor networks are a sub-category of ad-hoc networks.
- Location is more important than a specific node’s ID. (Tracking applications)
- Sensor networks usually use location-aware routing.
- Like other location-based routing protocols, SPEED utilizes geographic location to make localized routing decisions.
- Unlike other routing protocols, SPEED’s main goals are congestion avoidance and soft real-time communication service.
- No routing algorithm has been specifically designed to provide soft real-time guarantees for sensor networks.
Design Goals

- **Stateless architecture**: only maintains immediate neighbor information. Memory requirements are minimal.

- **Soft Real-Time**: uniform delivery speed provided across network.

- **Minimum MAC Layer Support**: No real-time or QoS aware MAC support. Feedback control scheme provides this support.

- **Quality of Service Routing and Congestion Management**: Backpressure re-routing to re-route packets around large-delay links.

- **Traffic Load Balancing**: Non-deterministic forwarding to balance each flow among multiple concurrent routes.
Design Goals

- **Localized Behavior:** all distributed operations are localized to achieve high scalability.

- **Void Avoidance:** guaranteed discovery of greedy routes between source and destination.

- **Design requirement:** end-to-end delay is proportional to distance between source and destination.

- SPEED guarantees a desired delivery speed across network. Delivery speed refers to approaching rate along a straight line from source toward destination.
SPEED Protocol

- SPEED maintains desired delivery speed across sensor networks by both diverting traffic at networking layer and locally regulating packets sent to the MAC layer.

- SPEED has 7 major components as shown below.

![Diagram of SPEED Protocol](image)

Figure 1. SPEED Protocol
SPEED Protocol

- **SNGF**: routing module responsible for choosing next hop candidate.

- **NFL/Backpressure rerouting**: reduce or divert traffic when congestion occurs.

- **Delay estimation**: mechanism where node determines whether congestion has occurred.

- **Beacon exchange**: provides geographic location of neighbors.

- **Last Mile Process**: supports the three communication semantics.
SPEED Protocol
Application API and Packet Format

- 4 application-level API calls
  - `AreaMulticastSend (position, radius, packet)`
  - `AreaAnyCastSend (position, radius, packet)`
  - `UnicastSend (Global_ID, packet)`
  - `SpeedReceive()`: permits nodes to accept packets targeted to them.

- Except for `SpeedReceive()`, the above calls send packets with speed above desired value.

- Data packet format
  - `PacketType`: AreaMulticast, AreaAnyCast or Unicast
  - `Global_ID`: identify destination node for unicast communication
  - `Destination Area`: describes space with center point and radius
  - `TTL`: hop limit used for last mile processing
  - `Payload`
SPEED Protocol
Neighbor Beacon Exchange

- Every node periodically broadcasts beacon packet to its neighbors.

- Periodic beaconing used for exchanging location information between neighbors.

- 2 types of on-demand beacons, which identify traffic changes in the network:
  - Delay estimation beacon
  - Backpressure beacon

- Each node keeps neighbor table to store beacon information.

- Neighbor table entry structure
  - Neighbor ID
  - Position
  - SendToDelay (delay estimation to neighbor node)
  - Expire Time
SPEED Protocol
Delay Estimation

- Delay is measured at sender. Sender timestamps packet entering output queue and calculates round trip single hop delay for packet when receiving ACK.

- At receiver side, duration for processing ACK is put into ACK packet.

- Single-trip time = (round trip delay) – (receiver processing time).

- Current delay estimation is computed by combining newly measured delay with previous delays using exponential weighted moving average.

- Delay estimation is a better metric than average queue size for representing congestion level in wireless network. (Congestion occurs even with small queue sizes)
SPEED Protocol
Stateless Non-deterministic Geographic Forwarding (SNGF)

- **Definitions**
  - **Neighbor set of node i:** set of nodes inside radio range of node i.
  - **Forwarding candidate set of node i:** set of nodes that belong to NS$_i$ and are closer to the destination.
  - **Relay speed:** $\text{Speed}_i^j(\text{dest}) = \frac{L - L_{\text{next}}}{\text{HopDelay}_i^j}$

- Nodes store the Neighbor Set (NS), but don’t keep a routing table. Memory requirements are proportional to number of neighbors.

![Diagram](Image)

**Figure 2. NS and FS definitions**
SPEED Protocol
Stateless Non-deterministic Geographic Forwarding (SNGF)

- **SNGF protocol rules**

  - Packets forwarded only to nodes that belong to $FS_i(\text{dest})$. If no nodes inside $FS_i(\text{dest})$, packets are dropped and backpressure beacon sent to upstream nodes.

  - Nodes inside $FS_i(\text{dest})$ divided into 2 groups:
    - Nodes have relay speeds larger than desired speed $S_{\text{setpoint}}$.
    - Nodes that cannot sustain such desired speed. ($S_{\text{setpoint}}$ depends on communication capability of nodes and desired traffic workload. It represents uniform speed to be maintained across network)

  - Forwarding candidate chosen from first group. Neighbor node with highest relay speed has a higher probability of being chosen.

  - If no nodes belong to first group, a relay ratio is calculated based on NFL.
SPEED Protocol
Stateless Non-deterministic Geographic Forwarding (SNGF)

- SNGF Properties

  - Soft real-time end-to-end delivery achieved: $\text{Delay Bound} = \frac{L_{e2e}}{S_{setpoint}}$.
  
  - Balance traffic and reduce congestion by dispersing packets into large relay area.
  
  - MAC layer adaptation and congestion reduction by locally dropping (or optionally buffering) packets.
SPEED Protocol
Neighborhood Feedback Loop (NFL)

- Maintain a single hop relay speed above $S_{\text{setpoint}}$.

- Definition of miss
  - Packet delivered to neighbor node has relay speed less than $S_{\text{setpoint}}$.
  - Packet loss due to collision

- NFL forces the miss ratios of neighbors to converge to a set point, namely zero.

Figure 3. Neighborhood Feedback Loop (NFL)
SPEED Protocol
Neighborhood Feedback Loop (NFL)

- **Relay Ratio controller**
  - It takes miss ratios of neighbors as inputs and proportionately calculates relay ratio.
  - \( u = 1 - K \frac{\sum_{i} e_i}{N} \) if \( \forall e_i > 0 \)
  - \( u = 1 \) if \( \exists e_i = 0 \)

  \( e_i \): miss ratio of neighbor \( i \) inside FS set
  \( N \): size of FS set, \( K \): proportional gain
  \( u \): output (relay ratio) to SNGF

- Controller activated only when all nodes inside forwarding set cannot maintain \( S_{\text{setpoint}} \), and drop is necessary to maintain single hop delay.
- Re-routing has higher priority than dropping.

- NFL maintains relay speed by reducing sending rate to downstream nodes.

- NFL does not solve hotspot problem. (Upstream nodes unaware of congestion) Back-pressure re-routing needed.
SPEED Protocol
Back-Pressure Rerouting

- Naturally generated from collaboration of NFL routines and SNGF.
- Network layer adaptation to reduce congestion.
- Network layer adaptation has higher priority than MAC layer adaptation.
- Packets are not dropped via feedback loop unless absolutely necessary.
- On-demand backpressure beacon needed in case 2. (ID, Dest, AvgSendToDelay)

Figure 4. Backpressure rerouting case one

Figure 5. Backpressure rerouting case two
SPEED Protocol
Void Avoidance

- Greedy geographic based algorithms may fail to find a path even though one does exist.
- Node 2 sends out backpressure beacon with fields: (ID, Destination, $\infty$).
- Node 1 sets the SendToDelay for node 2 to $\infty$.

- This scheme is guaranteed to find a greedy path if one exists.
- Backtracking is not allowed to violate the desired speed setpoint.

Figure 6. Void avoidance scheme
SPEED Protocol
Last Mile Process

- This function used only when packet enters the destination area.

- 3 services provided by last mile process:
  - **Area-anycast**: nodes inside area deliver packet to transport layer without relaying it onward.
  - **Area-multicast**: nodes, which first receive packet coming from outside of destination area, set a TTL. This allows packet to survive inside diameter of the area.
  - **Area-unicast**: same as the multicast process, except node with specified global_ID delivers the packet to the transport layer.
Experimentation and Evaluation

- SPEED simulated on GloMoSim.
- Simulation plan
  - end-to-end delay under different congestion levels
  - miss ratio
  - control overhead
  - communication energy consumption
  - Packet delivery ratio under different node densities.

<table>
<thead>
<tr>
<th>Routing</th>
<th>AODV, DSR, GF, SPEED, SPEED-S, SPEED-T</th>
</tr>
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<tbody>
<tr>
<td>MAC Layer</td>
<td>802.11 (Simplified DCF)</td>
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<tr>
<td>Radio Layer</td>
<td>RADIO-ACCNOISE</td>
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<tr>
<td>Propagation model</td>
<td>TWO-RAY</td>
</tr>
<tr>
<td>Bandwidth</td>
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<td>Payload size</td>
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<tr>
<td>TERRAIN</td>
<td>(200m, 200m)</td>
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<tr>
<td>Node number</td>
<td>100</td>
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<tr>
<td>Node placement</td>
<td>Uniform</td>
</tr>
<tr>
<td>Radio Range</td>
<td>40m</td>
</tr>
</tbody>
</table>

Table 1. Simulation settings
Experimentation and Evaluation

- Description of protocols
  - **GF**: forwards a packet to node that makes most progress toward destination.
  - **SPEED-S**: replaces SNGF with a MAX-SPEED routing algorithm.
  - **SPEED-T**: replaces SNGF with a MIN-DELAY routing algorithm.
  - Both SPEED-S and SPEED-T have no backpressure rerouting mechanisms.
  - **DSR/AODV**: on-demand routing, that uses route discovery mechanism.

- Sensor Network Traffic Pattern
  - Base station pattern
  - Peer-to-peer pattern

- End-to-end delay in base station pattern is major part of delay for the sensing-actuation loop.
Experimentation and Evaluation

Congestion Avoidance

- DSR, AODV and GF are insensitive to long delays as long as no link failures occur.
- SPEED-T and SPEED-S don’t provide traffic adaptation.
- SPEED locally reduces traffic, and diverts traffic into a large area through backpressure mechanism.

Figure 7. E2E Delay Under Different Congestion

Figure 8. E2E Delay Under Different Congestion
Experimentation and Evaluation
End-to-End Deadline Miss Ratio

- $S_{setpoint} = 1$km/s, which leads to end-to-end deadline of 200ms.
- Flooding algorithms (AODV, DSR) drastically increase congestion.
- GF routing decision considered only on distance.
- SPEED-T considers only single hop delay.
- SPEED-S provides no adaptation to congestion.
- Purely localized algorithms outperform flooding when congestion increases.

Figure 9. MissRatio Under Different Congestion
Figure 10. MissRatio Under Different Congestion
Experimentation and Evaluation
Control Packet Comparison

- GF, SPEED-S and SPEED-T use periodic beacons, which are constant under different congestion levels.
- SPEED uses on-demand and periodic beacons.
- AODV not considered since it generates very high number of control packets.

Figure 11. Control packet overhead comparison
Geographic based routing tends to reduce number of hops in the route.
SPEED, SPEED-S and GF have nearly same power consumption under low congestion.
Under heavy congestion, SPEED uses on-demand beacons unlike the other geographic base routing algorithms.

Figure 12. Energy Consumption for transmission
Experimentation and Evaluation
Void Avoidance

- DSR is a flooding-based route discovery algorithm.
- SPEED uses backtracking under low density conditions.
- Other geographic based routing algorithms don’t use backtracking.

Figure 13. Deliver ratio under different density
Conclusion

- Sensor networks have real-time requirements and nodes which are constrained in computing power, bandwidth and memory.

- Advantages of SPEED:
  - It reduces the number of packets that miss their end-to-end deadlines.
  - It reacts to transient congestion in most stable manner.
  - It efficiently handles voids with minimal control overhead.

- SPEED has improved performance over other standard routing protocols.

- SPEED ultimately meets the requirements of sensor networks in real-time situations.