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

Tian He, John Stankovic, Chenyang Lu, Tarek Abdelzaher

Prepared by:

Samuel Bushra

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.

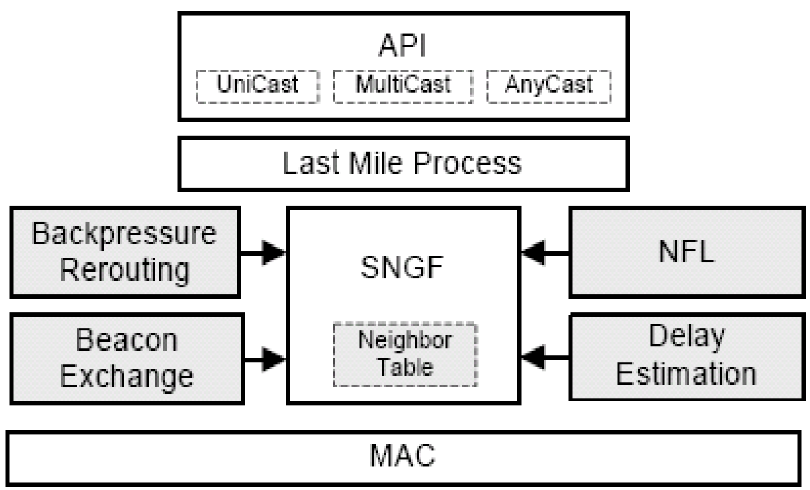

Figure 1. SPEED Protocol

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
  - <u>PacketType:</u> AreaMulticast, AreaAnyCast or Unicast
  - <u>Global_ID:</u> identify destination node for unicast communication
  - <u>Destination Area:</u> describes space with center point and radius
  - <u>TTL:</u> hop limit used for last mile processing
  - <u>Payload</u>

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 network:
  - Delay estimation beacon
  - Backpressure beacon
- Each node keeps neighbor table to store beacon information.
- Neighbor table entry structure
  - NeighborID
  - Position
  - SendToDelay (delay estimation to neighbor node)
  - ExpireTime

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: $Speed_i^j(dest) = \dfrac{L - L\_next}{HopDelay_i^j}$
- Nodes store the Neighbor Set (NS), but don't keep a routing table. Memory requirements are proportional to number of neighbors.

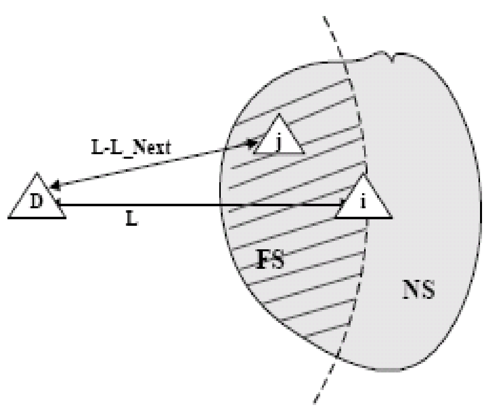

Figure 2. NS and FS definitions

SPEED Protocol
Stateless Non-deterministic Geographic Forwarding (SNGF)

- <u>SNGF protocol rules</u>

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

- Nodes inside FS_i(dest) divided into 2 groups:
  - Nodes have relay speeds larger than desired speed $S_{setpoint}$.
  - Nodes that cannot sustain such desired speed. ($S_{setpoint}$ 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: *Delay Bound* = $L_{e2e} / S_{setpoint}$.
- 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 $S_{setpoint}$.
- Definition of miss
  - Packet delivered to neighbor node has relay speed less than $S_{setpoint}$.
  - Packet loss due to collision
- NFL forces the miss ratios of neighbors to converge to a set point, namely zero.

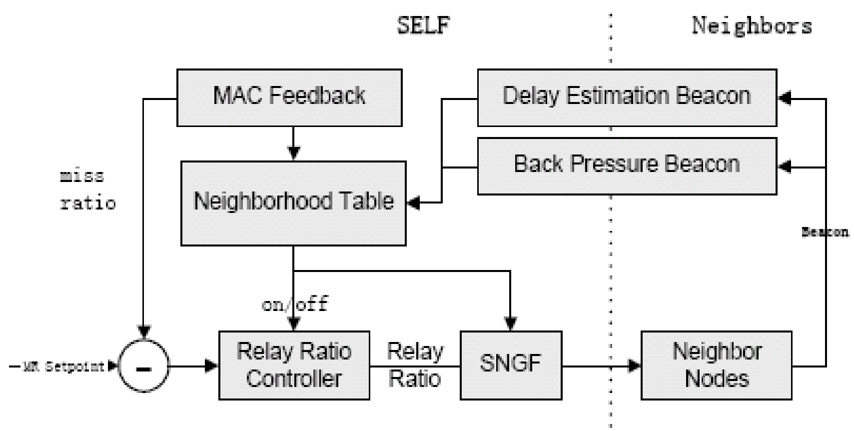

Figure 3. Neighborhood Feedback Loop (NFL)

SPEED Protocol

Neighborhood Feedback Loop (NFL)

- Relay Ratio controller
  - It takes miss ratios of neighbors as inputs and proportionately calculates relay ratio.
  - $$u = 1 - K\frac{\sum e_i}{N} \text{ if } \forall\, e_i > 0$$
    $$u = 1 \text{ if } \exists\, e_i = 0$$
    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 $S_{setpoint}$, 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)

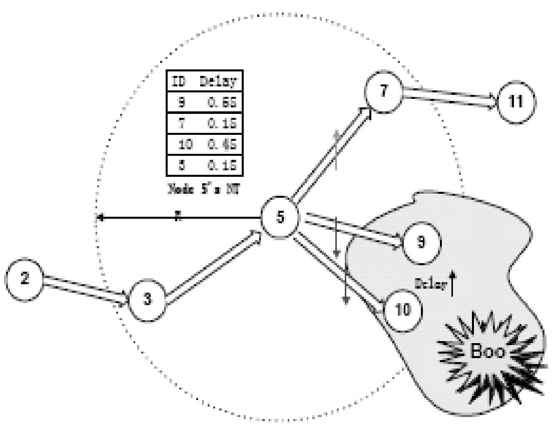

Figure 4. Backpressure rerouting case one

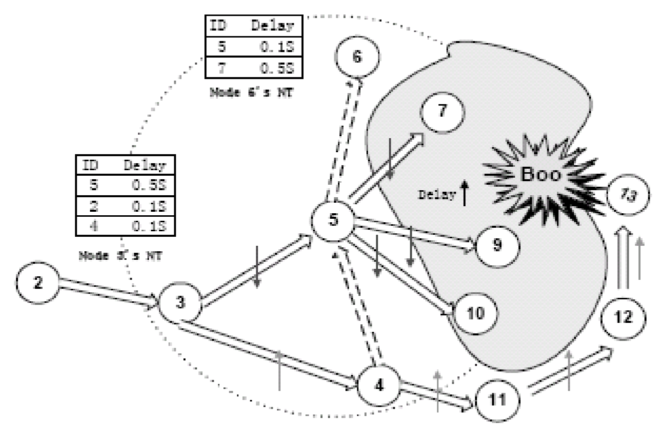

Figure 5. Backpressure rerouting case two

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, ∞).
- Node 1 sets the SendToDelay for node 2 to ∞.

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

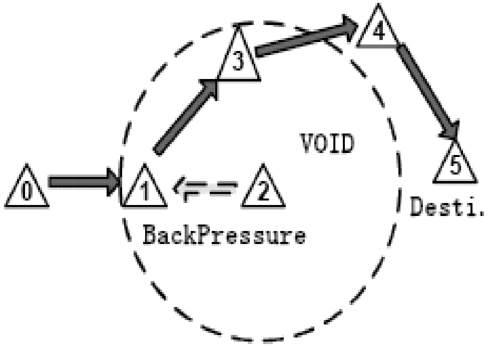

Figure 6. Void avoidance scheme

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.

Routing	AODV, DSR, GF, SPEED, SPEED-S, SPEED-T
MAC Layer	802.11 (Simplified DCF)
Radio Layer	RADIO-ACCNOISE
Propagation model	TWO-RAY
Bandwidth	200Kb/s
Payload size	32 Byte
TERRAIN	(200m, 200m)
Node number	100
Node placement	Uniform
Radio Range	40m

Table 1. Simulation settings

Experimentation and Evaluation

- Description of protocols
  - <u>GF:</u> forwards a packet to node that makes most progress toward destination.
  - <u>SPEED-S:</u> replaces SNGF with a MAX-SPEED routing algorithm.
  - <u>SPEED-T:</u> replaces SNGF with a MIN-DELAY routing algorithm.
  - Both SPEED-S and SPEED-T have no backpressure rerouting mechanisms.
  - <u>DSR/AODV:</u> 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.

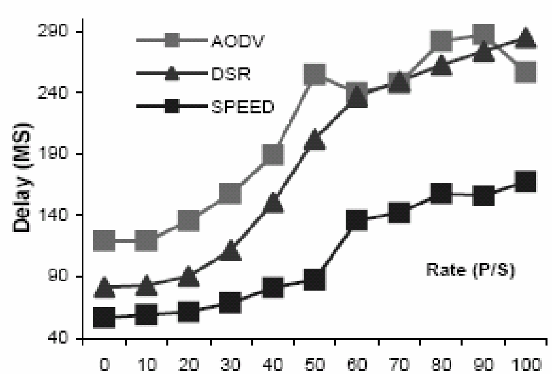

Figure 7. E2E Delay Under Different Congestion

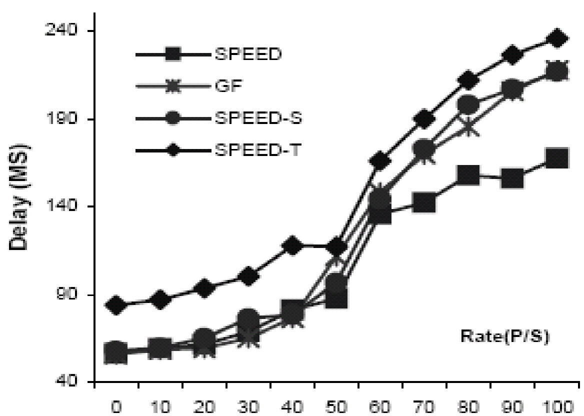

Figure 8. E2E Delay Under Different Congestion

Experimentation and Evaluation

End-to-End Deadline Miss Ratio

- $S_{setpoint}$ = 1km/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.

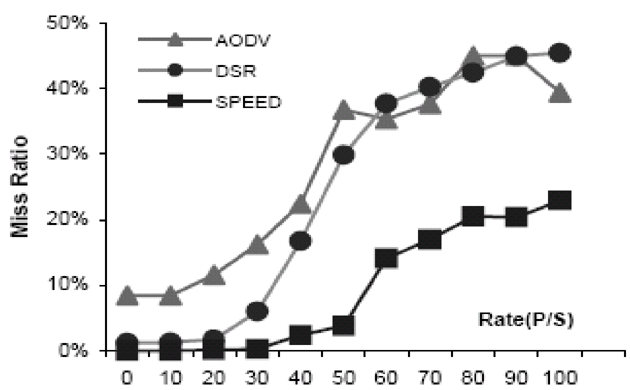

Figure 9. MissRatio Under Different Congestion

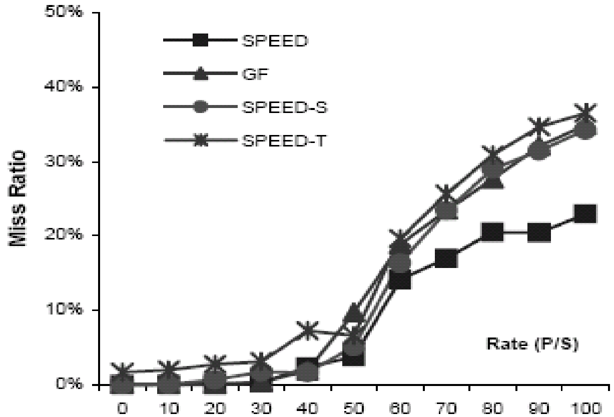

Figure 10. MissRatio Under Different Congestion

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.

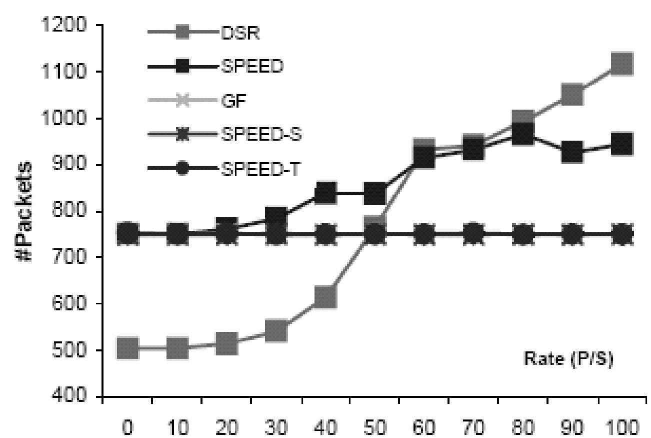

Figure 11. Control packet overhead comparison

Experimentation and Evaluation
Energy Consumption

- 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.

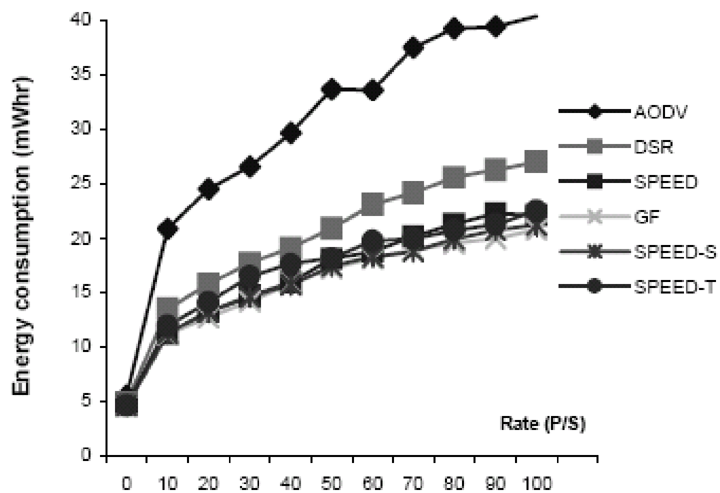

Figure 12. Energy Consumption for transmission

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.

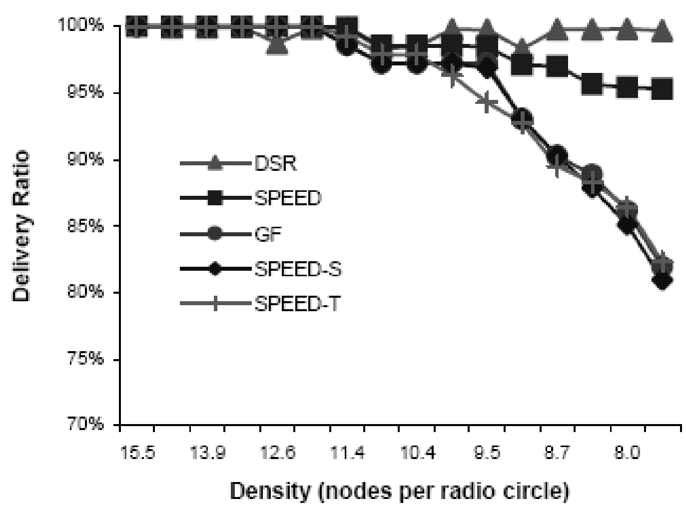

Figure 13. Deliver ratio under different density

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.