A Self-stabilizing Publish/Subscribe Middleware for WSN

Gerry Siegemund, Khaled Maâmra, and Volker Turau

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Domain Overview

WSN
- unreliable radio
- low computation power
- error prone

Domain
- inherently fault tolerance
- self-stabilizing algorithm
- eventually correct

Publish/Subscribe
- topic based
- content based
- data dissemination
Self-stabilization

A system is self-stabilizing if and only if:

1. Starting from any state, it is guaranteed that the system will eventually reach a correct state (convergence).
2. Given that the system is in a correct state, it is guaranteed to stay in a correct state, provided that no fault occurs (closure).

- any: a faulty state (e.g., due to message loss), or wrongly initialized ⇒ not specified
- correct: well defined: for pub/sub routing tables correct & all published message reach all subscribers

Considered model in WSN:
Distributed, unfair scheduler with message passing
Usage in WSN

- Publisher (P)
  - Acquire sensor data
  - Aggregate values
    - Publication (Pub-Msg)
    - Advertisement (Adv-Msg)
- Subscriber (S)
  - Actuator
  - Sink
    - Subscription (Sub-Msg)
- Channels (C)
  - Control channel
  - Collection channel
Broker Overlay as Routing Structure

- Broker nodes (Fig.)
- Broker overlay acyclic (alternatively spanning tree)
- Subscribers only attach to “leaf”-brokers
  - P advertises generation of data
  - S subscribes to content
  - Rooting tables are built to “connect” P & S at the broker nodes (filter)

Self-stabilizing Attempt

- Periodic resending of advertisement and subscription (*leasing*)
- On given broker overlay (Mühl/Jaeger)
  - Overlay needs to be constructed (self-stabilizing)
- Disadvantage:
  - Dedicated routing nodes
  - Adding notes that are only connected to leaf nodes?
  - Higher density, more useful communication links unused
Self-stabilizing Publish/Subscribe

Self-stabilizing Attempt II

- Sub-Msg “flooded” (send to every node) through the tree
- Routing (Pub-Msg) on a tree
- Routing table states if S in sub-tree/parent
- Regular exchange of neighboring routing tables (self-stabilizing error correction)
  - Scaling: parts of neighboring table are exchanged (bloom filter)
  - No renewal of routing tables
  - Self-stabilizing property uncertain

Zhenhui Shen. Techniques for building a scalable and reliable distributed content-based publish/subscribe system. 2007[14]
Network Stack

- SS Publish/Subscribe
- SS Virtual Ring
- SS Spanning Tree
- Neighborhood Management
- MAC

To physical
Network Stack

Medium Access Control - Layer

- Broadcast (Back-off)
- Unicast (Back-off, ACK, Retry, . . .)

1. SS Publish/Subscribe
2. SS Virtual Ring
3. SS Spanning Tree
4. Neighborhood Management
5. MAC
6. to physical
Network Stack

Neighborhood Management - Layer

- Stable neighborhood relation
- Restricted set of neighbors, i.e., Topology control
- Dynamic, addition/removal of nodes possible

Gerry Siegemund et al. Brief
Network Stack

Self-stabilizing Spanning Tree - Layer

- Well known concept
- Distance to dedicated root node is shared with neighbors
- Closest node to root is excepted as parent
- Each node shares parent id
  ⇒ Parents can deduce children
Network Stack

Self-stabilizing Virtual Ring - Layer

- Ordered structure of node positions
- Each node has one prede-/suc-cessor
- Routing over all positions is straightforward
Network Stack

Self-stabilizing Publish/Subscribe - Layer

- Multiple channels
- Routing over virtual ring

Diagram:
- SS Publish/Subscribe
- SS Virtual Ring
- SS Spanning Tree
- Neighborhood Management
- MAC
  - to physical
Ring Routing Structure

- Ordered structure of node positions
- Each node has one prede-/suc-cessor
- Routing is straight forward
- Not every topology is a ring
  → therefore virtual ring will be used
A Virtual Ring

- Each physical node may have multiple positions on the virtual ring.
- Physical structure might not contain a straightforward ring.
- Example: only positions depicted (original node IDs transparent to upper layer(s)).
A Virtual Ring with Short-Cuts

**Short-Cut**

Actual connection between nodes (in underlying topology) which is not already part of the virtual ring.

```
1
pos=1

2
pos=2

3
pos=3

4
pos=4,6

5
pos=5

6

1

2

3

4

5

6
```
How to Build a Virtual Ring

- A tree is used as e.g. Bosilca proposed
- Sequential (depth first) search could be used
- For the ring itself Pos would not be explicitly necessary

George Bosilca et al. Constructing Resilient Communication Infrastructure for Runtime Environments. 2009
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Building the Ring from a Tree

- Tree is built
- Each leaf node sends an *up-cast* message (ucm) with number of children \( c = 1 \)
Building the Ring from a Tree

- Parent waits until all children sent dcm.
- Aggregates number of sub-tree children and sends dcm with \( c = \sum c_s + 1 \) up to their parent.
Building the Ring from a Tree

- Parent waits until all children sent dcm
- Aggregates number of sub-tree children and sends dcm with $c = \sum c_s + 1$ up to their parent

\[
c := 4 + \text{wait} + \text{wait}
\]
\[
c := 2 + \text{wait}
\]
\[
c := \text{wait} + 1
\]
\[
c := 3
\]
Building the Ring from a Tree

- Root collects data of all children
Building the Ring from a Tree

- Calculate root Pos
  \[ \text{Pos}_{\text{first}} := 0 \]
  \[ \text{Pos}_{\text{next}} := \text{Pos}_{\text{prev}} + 2 \times \text{Children}_{\text{sub-tree}} \]

- Root sends dcm with corresponding position to appropriate child

- Each child computes its Pos
Building the Ring from a Tree

- Children compute Pos & send dcm
Building the Ring from a Tree

- Position aware tree is done, i.e., the virtual ring
- Number of positions on the ring: \(2(n - 1)\) (same as Bosilca)
Routing on a Virtual Ring with Short-cuts

- Each node shares its positions with its neighbors
Routing on a Virtual Ring with Short-cuts

- Example with (at first) one subscriber S at position 26
- Subscribes to 1 channel
Sub-Message travel around the ring → received by every node
\[\text{SUBMSG <all Positions of } S\]  
Each node calculates and stores, for all its own positions, the next position on the way to the next subscriber \( S \)
- self-stabilization ensured through leasing (periodic refreshing of subscriptions / unsubscribe ⇔ timeout)
Routing on a Virtual Ring with Short-cuts

- Sub-Msg travel around the ring → received by every node
  \text{\texttt{SUBMSG <all \textit{Positions} of S>}}

- Each node calculates and stores, for all its \textit{own positions}, the next position on the way to the next subscriber \textit{S}

- self-stabilization ensured through leasing (periodic refreshing of subscriptions / unsubscribe ⇔ timeout)
Routing on a Virtual Ring with Short-cuts

- **Sub-Msg travel around the ring** → received by every node
  
  SUBMSG <all Positions of S>

- Each node calculates and stores, for all its own positions, the next position on the way to the next subscriber S

- self-stabilization ensured through leasing (periodic refreshing of subscriptions / unsubscribe ⇔ timeout)
Routing on a Virtual Ring with Short-cuts

- Sub_Msg travel around the ring → received by every node
- \text{SUBMSG} <all Positions of S>
- Each node calculates and stores, for all its own positions, the next position on the way to the next subscriber S
- self-stabilization ensured through leasing (periodic refreshing of subscriptions / unsubscribe ⇔ timeout)
Routing on a Virtual Ring with Short-cuts

→ Pub-Msg are routed from P along the forwarding positions

- Best case routing: from P to the next S to next S, ..., without using intermediate nodes
Routing on a Virtual Ring with Short-cuts

Pub-Msg are routed from P along the forwarding positions

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Routing on a Virtual Ring with Short-cuts

→ Pub-Msg are routed from $P$ along the forwarding positions
  - Best case routing: from $P$ to the next $S$ to next $S$, $\ldots$, without using intermediate nodes
Routing on a Virtual Ring with Short-cuts

Updating routing tables:

- Only the closest S in front of a node (counter clockwise) influences the fPos

- Routing table at position 1 (and 7) need to be changed to avoid excluding S at position 15 from routing path
Routing on a Virtual Ring with Short-cuts

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Updating routing tables:
- Only the closest $S$ in front of a node (counter clockwise) influences the $fPos$
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Shorter Path vs Shortest Path

→ much shorter path
- but not shortest path (light blue)
Complete System Assessment
Comparison vs Flooding

- grid network, multiple densities (up to 20 nodes in range), OMNeT++ with MiXiM (collisions, fading)
Comparison vs Flooding

Message overhead

- Routing structure overhead:
  - Neighborhood management
  - Spanning tree
  - Virtual ring

- More subscribers $\Rightarrow$ increased routing efforts $\Rightarrow$ less gain for our approach

- Broadcast $\Rightarrow$ number of messages constant (not considering message loss)

Timings for rebuilding of routing structure need to be proportional to publication interval (e.g., rebuilding routing structure more regularly then sending publications increases overhead)
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Gerry Siegemund
Research Associate

Phone  +49 / (0)40 428 78 3448
e-Mail  gerry.siegemund@tu-harburg.de

http://www.ti5.tu-harburg.de/staff/siegemund

Institute of Telematics
TUHH
Hamburg University of Technology