Link-State Clustering and Synchronization for Wireless Ad-hoc/Sensor Networks

Chao Gao & Riku Jäntti
Department of Computer Science
University of Vaasa
Vaasa, Finland, FIN-65101
Email: gc@puv.fi, riku@uwasa.fi
Outline

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- Link-State Clustering Algorithm
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Introduction & Motivation

- Most ad hoc routing protocols (such as DSDV, DSR, AODV) are designed for flat (i.e., peer-to-peer) networks. These protocols suffer from scalability problem.
- Clustering a large scale network is desirable in term of energy efficiency, collision control, and routing performance (hierarchical routing).
- We suggest a clustering algorithm both heterogeneous and homogeneous ad-hoc/sensor networks. The clustering algorithm is based on the radio link state (received signal quality) between the cluster heads and slaves therefore we denote it as Link State Clustering Algorithm (LSCA).
Link-State Clustering Algorithm

- **System model**
  - Homogeneous network (i.e., all the nodes are identical)
  - All the nodes have Link Quality Indicator (LQI) and are able to use two transmission power levels:
    - the lower one $P_l$ is for intra-cluster communications
    - and the higher one $P_h$ is for inter-cluster communications.
  - Each node has a unique MAC address which is used as **Cluster Identity** (CID) when the node is acting as CLH.
  - A CLH forms a **Slave Table** (ST) in its local buffer. A record in ST contains following information:
    - Slave’s ID
    - Node budget (NB) for CLH re-election.
    - A **timer** which expires if the CLH cannot hear from this slave for a period.
Cluster forming (Random Contention):

- When powered up, a node sets itself unclustered and listens to the channel for $T_w$ sec.
- If no Beacon (BEAC) is heard, the node becomes a CLH and broadcasts beacon every $T_b$ sec. ($T_b < T_w$ to ensure priority) Otherwise the node becomes a salve of the corresponding CLH and record LQI as $\eta$.
Cluster updating (link-state):

- If a slave receives a BEAC from another CLH, it compares the LQI with the previous one. If $\eta_{\text{new}} > \eta_{\text{old}} + \Delta$, it updates its CLH by sending two packets: a BREP to inform the new CLH, and a Slave Cancel (SCAN) to inform the old CLH to remove it. $\Delta$ is a margin for channel fluctuations. Since we have a broadcast medium, BREP and SCAN can be multiplexed together.

![Diagram showing the process of cluster updating](image)

If new LQI of the BEACH$_2$ is large enough, perform cluster updating.
Link-State Clustering Algorithm (cont.)

- **CLH Re-electing:**
  - The energy of CLH drains faster than other nodes. To increase the overall network lifetime, a CLH re-election must be deployed.
  - Here we invoke a **node budget (NB)** to perform the CLH re-election.
    - NB can be battery residual, traffic that the node has taken, or simply a random value.
    - A slave embeds its NB in BREP packets. If a node is set as CLH, it starts a timer $T_h$. When $T_h$ expires, it selects the node that has highest NB as the next CLH and sends it a **Cluster-Head Hand-Over (CHHO)** packet to notify it. The destination node immediately sends a BEAC after the notification.

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Node becomes CLH

$T_h$

Timer expires

BEAC_1

[BREP|NB]

CHHO

BEAC_2

Slave associates with CLH

Slave with largest NB is selected as new CLH
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LSCA State Transition & Example
LSCA for Heterogeneous Networks and Dual Mode

- For heterogeneity, some nodes have much more battery resource than that of other nodes and always act as *Permanent* CLHs (PCLH).
  - The clustering algorithm becomes simpler because there is no need of CLH election and canceling.
  - Two or more CLHs can overlap their BEAC radio disks.
  - A Slave belongs to one and only one CLH.

- LSCA can work in dual mode:
  - A part of nodes can operate as PCLH and the rest of nodes operate in homogeneous mode. When a PCLH receives a BEAC from another CLH or PCLH, it ignores this message; when a CLH receives a beacon from another CLH or PCLH, it performs the CLH-canceling operation. When no beacon is received after $T_w$, a normal node starts the contention to be a CLH. This feature gives great flexibility to the network deployment.
Connectivity of the backbone

- Connectivity of CLHs
  - Penrose (1997) has shown that the longest edge $M_n$ of a minimum spanning tree of $n$ points randomly distributed in unit area satisfies
    \[ \Pr(n\pi M_n^2 - \ln(n) \leq b) = e^{-e^{-b}}, \quad b \geq 0 \]
  - Thus, for $N_c$ CLHs out of $N$ nodes, the range of intra- & inter-cluster communication should be
    \[ R_{flat} = \sqrt{(b + \ln(N))/N\pi} \]
    \[ R_c = \sqrt{(b + \ln(N_c))/N_c\pi} \]
  - For large $b$ (high probability of connectivity)
    \[ \frac{R_c}{R_{flat}} \sim \sqrt{\frac{N}{N_c}} \]
Coverage of the cluster heads

- Koskinen (2003) has shown that the probability of full coverage by \( n \) nodes with radio range \( r \) satisfies

\[
\lim_{n \to \infty} \Pr \left( \frac{\pi r^2 n}{|V|} + \ln \pi r^2 - 2 \ln(-\ln \pi r^2) \leq b \right) = e^{-e^{-b}}
\]

where \( |V| \) is the Lebesgue measure of the network graph \((V;E)\). In a unit square or disk area, \(|V| = 1\).

- In a network using LSCA \( r \) is the radio range of beacon \( R_b \).
Coverage of the cluster heads

- In a homogeneous network using LSCA, if the node density is large enough so that at any position $x$, there exists at least one node to be potential CLH, the CLHs after clustering can be connected if $R_c \geq 2\cos15^\circ R_b \approx 1.932 R_b$.
  - $R_c$: inter-cluster communication range
  - $R_b$: intra-cluster communication range

![Diagram of three CLHs' $R_b$ circles intersecting each other.](image)

- Three CLHs’ $R_b$ circles must intersect each other.

[The diagram shows three circles, each centered at $O_1$, $O_2$, and $O_3$, intersecting each other. The extreme case where $O_1O_2$ is maximum is indicated.

![Diagram of the extreme case](image)
Simulation Settings

- 200 nodes in 600£600m².
- Random way-point moving scheme with nonzero min-speed.
- Simulation time: 300 sec.
- $T_b$: 3sec, $T_w$: 5sec, $T_h$: 30sec, $R_b$: 100m, $R_c$: 200m, $\Delta$: 10m.
- Network statistics are taken every 10sec.
- We inspect the network stability in terms of
  - the number of CLHs $N_c$,
  - the number of slaves $N_s$,
  - the number of unclustered nodes $N_u$,
  - slave connectivity in term of the number of “fake” slaves $N_f$ (number of slaves without connection to any CLH), and
  - cluster head connectivity
Connectivity

- Connectivity:
  - $R_c \geq 2\cos 15^\circ R_b \approx 1.932R_b \approx 200 \text{ m}$
  - $R_c \approx \sqrt{N/N_c} = \sqrt{10} \approx 300 \text{ m}$

(g) CLH connectivity at different $R_c$ with $R_b = 100\text{ m}$.

(h) CLH connectivity when different number of PCLH is given.

- In dual mode, more PCLH increase connectivity.
Network Stability

- (a) shows the $N_c$, $N_s$, $N_u$ in one simulation. $N_c$ keeps stable.
- (b) shows $N_c$ converges as node density increasing.

(a) $N_c$, $N_s$ and $N_u$ at checkpoints in one simulation
(b) Average number of CLH at different beacon ranges (600x600m$^2$)
Unclustered & Fake Slaves

- Mobility increases the instability of network.
- Reducing $T_w$ is preferred over reducing $T_b$.

(d) $N_u$ and $N_f$ at different mobility settings.

(e) $N_f$ at different $T_b$ settings. Mobility is set as $V_{min} = 6$, $V_{max} = 9$. 
Unclustered and Fake Slaves in Dual mode

- More PCLH also increase stability.
- But increase clustering overhead.

(i) Average $N_u$ and $N_f$ when different number of PCLH is given.

(k) Statistics of clustering overheads when different number of PCLH is given.
Synchronization

- A synchronization scheme in a sensor network helps the nodes coordinate the transmission/reception of data, analyze the events correctly, and perform a more efficient sleeping policy for energy saving.

- Synchronization in wireless sensor networks
  - can be done either globally or locally.
  - using either external clock reference (e.g. GPS) or internal (i.e., nodes agree a common clock among themselves).

- In wireless sensor network, internal synchronization is usually performed by passing a time-stamped message to the nodes that need to be synchronized.
Synchronization (cont.)

- Clustered synchronized network operates in three phases
  - C-phase: Cluster head election
  - S-phase: Synchronization
  - O-phase: Network operation
Synchronization (cont.)

- When clustering phase $T_c$ is over, the CLHs wait for synchronization beacon (SB). A **synchronizer** is denoted as S-node. S-node is CLH by default ($T_w=0$).

- A SB is denoted as $S(L, \tau_d)$, $L$ is the synchronization layer ($L=0$ for S-node) and $\tau_d$ is a random counter $2(0, W_s)$. $W_s$ is denoted as **synchronization window (SWIN)** consists of a number of time slots.

- The time slot duration $t_s$ is assumed to be much greater than the propagation time $t_p$. ($t_c >> t_p$)

- The CLHs of 1st synchronization layer that have received SB$(0, \tau_d)$ will align their clock to start next SWIN at the same time as they know $\tau_d$ from the received SB. Each CLH differs the rebroadcast of SB by a random $\tau_d$. 
Synchronization - illustration
Synchronization (cont.)

- The idea of random delay of SB is similar to CSMA/CA, in which a random back-off is deployed to avoid collision.
- The idea that the CLHs having received a SB frame will be aligned to start next layer synchronization is similar to IEEE 802.11 DCF function, in which NAV is used to align the neighbouring nodes for the next channel contention.
- A CLH may fail to be synchronized due to the collision of SB frames. In this case, the CLH will run in non-synchronized mode until it receives a SB in next round.
Synchronization Probability

- Only CLHs are involved. Each CLH is surrounded by maximum 6 CLHs. Synchronization starts from S-node, it is unlikely that all the neighboring CLHs belong to the upper layer.
- Suppose there are $n$ $i$-th layer CLHs neighboring to an unsynchronized CLH. The probability that this node will be synchronized is: at least one $i$-th layer CLH sends SB in a time slot different from other $n-1$ CLHs, denoted as

$$Pr(n, N) = \frac{\sum_{k=1}^{n} (-1)^{k+1} \binom{n}{k} \binom{N-k}{n-k} \binom{N}{n}}{N^n} \quad (N \geq n)$$
Synchronization Probability (cont.)
Synchronization Probability (cont.)

- Simulation result (Sync. Prob. vs. Mobility)

![Graph showing the relationship between mobile speed and synchronization probability](image)

The graph illustrates the simulation result of synchronization probability versus mobile speed. The x-axis represents mobile speed in meters per second (m/s), while the y-axis represents the probability of synchronization. The graph shows a trend where the synchronization probability increases with increasing mobile speed.
Network Operation after synchronization

- A synchronized CLH starts operation (O) phase after \( N \times W_s \) time. \( N=3 \) or \( 4 \) to avoid co-channel interference.

- CB frames sent by a synchronized CLH is now denoted as \( \text{CB}(i, d) \), where \( i \) is the synchronization layer of the CLH and \( d \) is the random delay in term of \( t_s \). The random delay of CB is used to avoid collision on those slave nodes that can hear CB two or more CLHs from the same layer.

- A slave node that has received a \( \text{CB}(i, \ast) \) should keep awaken in next \( W_s \) for the case that \( \text{CB}(i+1, \ast) \) may be heard.

- A synchronized network operates \( M \leq N \leq W_s \) sec. \( M \) is dependent on mobility and clock precision.
Network Operation (cont.)

- The slave node $n$ can receive CB from CLHs at different layers without collision
Issues about IEEE 802.15.4

- LQI is a standard feature in IEEE 802.15.4.
- S-node can be by default the PAN-coordinator.
- A Zigbee superframe consists of 16 slots and duration is 15ms: $t_s = 1$ ms. Radio range $< 200m \rightarrow t_p = 0.67 \mu s$.
- Thus SWIN can be set as 16 slots.
- If $M = 100$, then every period of synchronization is $M \times N \times W_s = 6.4$ (N=4) sec. Nowadays the embedded sensor clock drifting is about $10^{-6}$. In 6.4 sec the accumulated drifting is still much less than 1ms.
Conclusion Remarks

- LSCA forms a wireless ad hoc/sensor network into two layers and the cluster heads construct a virtual backbone for multi-hop communications.
- Simple, fast to converge, fully distributed and dynamic.
- Can be applied to both homogeneous and heterogeneous networks and the combination of these two (dual mode).
- An important observation is that preassigning some permanent cluster heads will significantly increase the clustering stability in terms of connectivity, the number of unclustered nodes and fake slaves.
- The proposed synchronization scheme achieves a high success ratio and offers a precision in one millisecond under current hardware achievement.
Thank you