QoS and Fault Tolerance Considerations in Wireless Mesh Networks

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Agenda

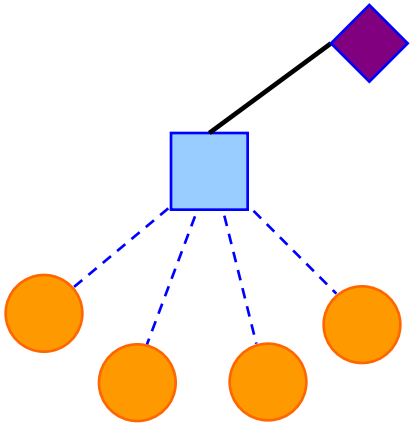
- Introduction to Wireless Mesh Networks
- Problem Definition – Gateway Placement
- Background and Related Work
- Gateway Placement Algorithm
- Simulation Results
- Fault Tolerance Issue
- Fault Routing in Regular Mesh
- Conclusion

Intro - Wireless Network Architectures

Point to Point

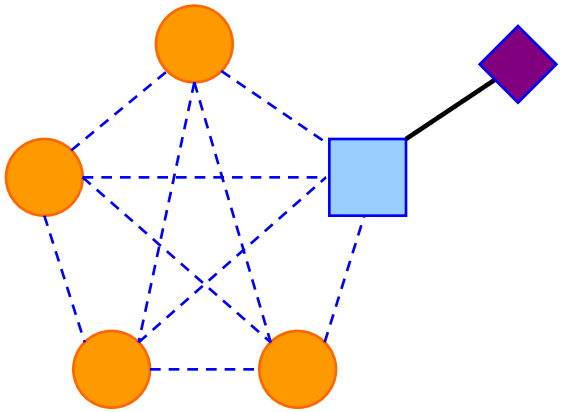
Dedicated links

Point to Multipoint



Currently Most Common

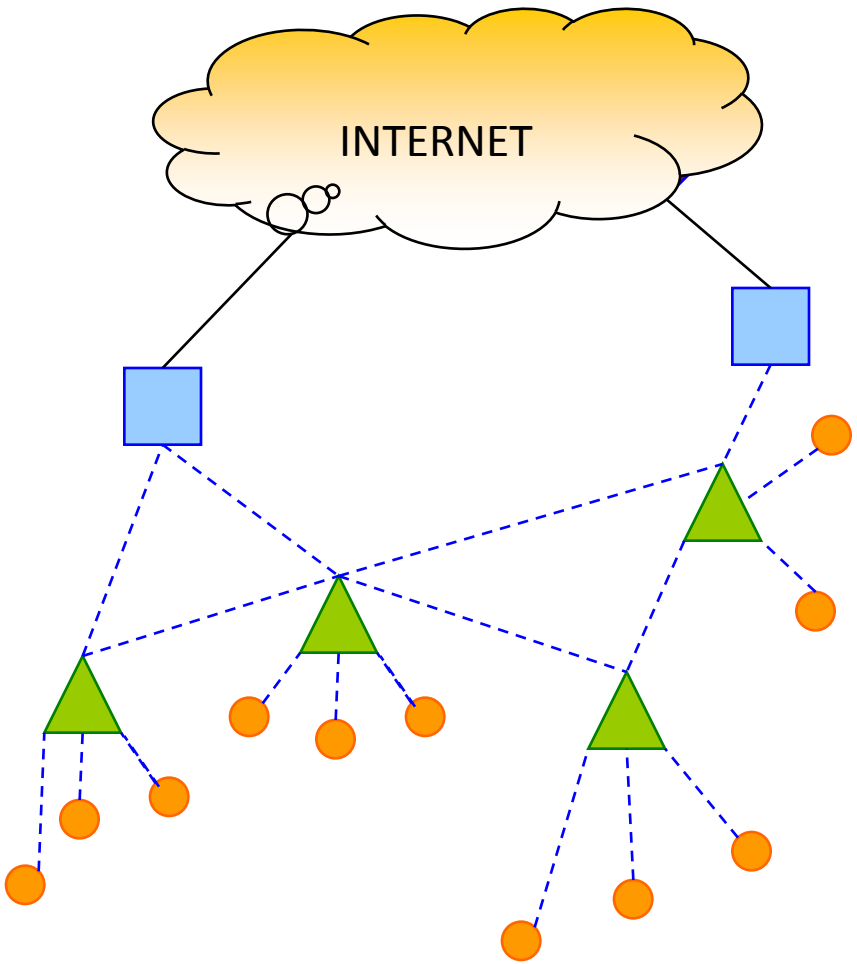
Multipoint to Multipoint



Our Focus

Topology	Reliability	Adaptability	Scalability	Routing Complexity
P to P	High	Low	None	None
P to M	Low	Low	Moderate	Moderate
M to M	High	High	High	High

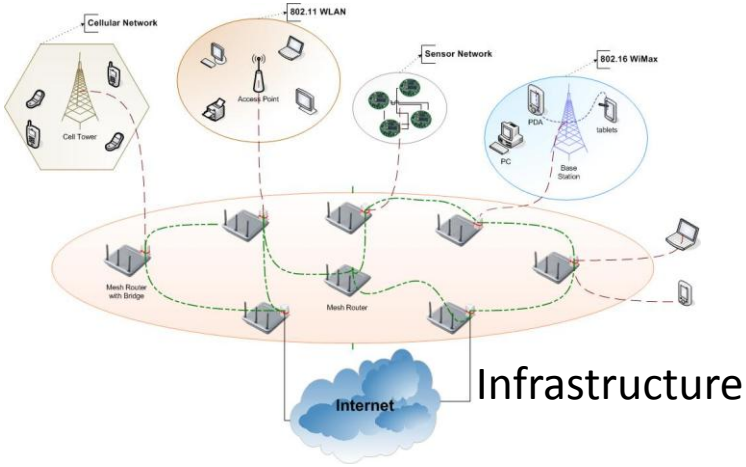
Wireless Mesh Networks (WMN)



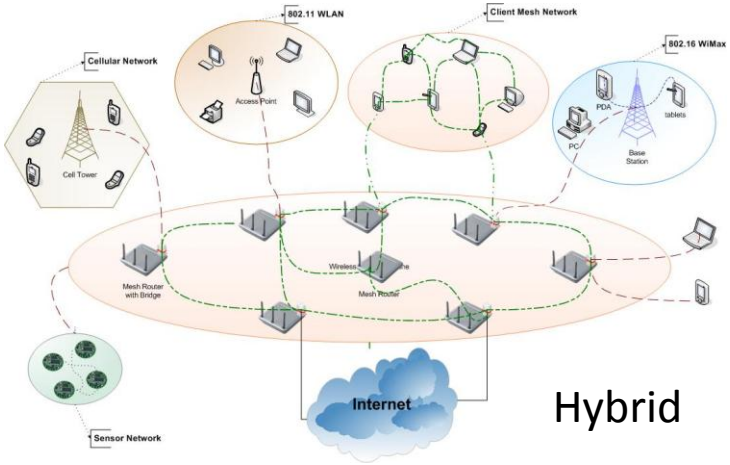
- Structured, energy rich wireless multi-hop networks:
  - Wireless Client
    - Mobile, no routing, limited power
  - Wireless Router
    - Low mobility, routing and power rich
  - Wireless Gateway
    - Router with access to wired network.

Types of Wireless Mesh Networks

- Infrastructure Mesh
  - All routing goes through a base station/gateway
- Client Mesh
  - No base station (ad-hoc)
- Hybrid Mesh
  - Combination of client mesh and infrastructure mesh.



Infrastructure



Hybrid

Challenges in WMN

- **PHY Issues**
  - Co-channel interference, Selective fading
  - Network size, network density, traffic/node effect link quality
- **MAC Issues**
  - Distributed Control
  - Hidden and Exposed node
- **Routing Issues**
  - Depending on MAC functionality
  - Exploiting alternate routes for fault tolerance and load balancing
- **Deployment Issues**
  - How to cover a given area with the minimum number of nodes?
  - Given a topology, what is the best way place gateways?

FOCUS ON: Deployment and Fault Tolerance

Goal of Research

"Improve capacity and QoS of WMN"

- **Gateway Placement**
  - Improve capacity and overall throughput
  - Reduce deployment costs
  - Improve QoS provisioning
  - Improve fault tolerance
  - Reduce traffic congestion due to traffic skew

- **Fault Tolerant Layer 2 Routing**
  - Ability to do alternate routing in case of link/node failure.
  - Develop alternate routing algorithms (deterministic and Probabilistic)

Gateway Placement Problem

- Given:
  - A connected network topology of wireless routers
- Find
  - Location and association of wired gateways with wireless routers
- Minimize
  - Number of wired Gateways that can service the demand
  - Average network delay
- Maximize
  - Wired Gateway Utilization
- Constraints
  - Maintains Connectivity
  - Meet QoS of Each Wireless node
  - Provide Fault Tolerance

Related Work

- [Bejerao,04] – Greed select cluster. Traverse the cluster spanning tree and break at QoS violations.
- [Chandra,05] – Greed select the gateway that satisfies most demand.
- [Aoun, 06] – Greed select cluster, but recursively look ahead to see if selection will lead to problem.

Notations and Definitions

- *G(V,E)* – Network graph
- *C* - A cluster of G(V,E) is an acyclic sub-graph of G
- Ψ - A clustering of G(V,E) is a set of clusters such that:

Property 1: $\bigcap_{i=1}^{k} C_i = \emptyset$,
Property 2: $V(\Psi) = V(G)$.
Property 3: $E(\Psi) = \bigcup_{i=1}^{k} E(C_i) \subseteq E(G)$.

- Conjunction Matrix (represents Ψ) :

$$K[i,j] = \begin{cases} 1 & \text{if } v_j \in C_i \quad (a) \\ 0 & \text{otherwise} \quad (b) \end{cases}$$

- Hop Distance (H_q)

$$h(c_i, v) \leq H_q, \quad \forall\, v \in C_i \text{ and } v \neq c_i$$

- Cluster Size (S_q)

$$|C_i| \leq S_q \quad \forall C_i \in \Psi$$

- Relay Load (L_q)

$$L(v) = \sum_{v' \in T_v} \ell(v') \leq L_q \quad v' \neq v$$

where T_v is a sub-tree of the spanning tree T_i and rooted at v

ILP Formulation

$$\min\{k \mid \bigcup_{i=1}^{k} C_i = G\}$$

Subject to:

$$\bigcup_{i=1}^{k} C_i = G \qquad (a)$$

$$\bigcap_{i=1}^{k} C_i = \varnothing \qquad (b)$$

$$|C_i| \leq S_q \qquad 1 \leq i \leq k \qquad (c)$$

$$\text{radius}(C_i) \leq H_q \qquad 1 \leq i \leq k \qquad (d)$$

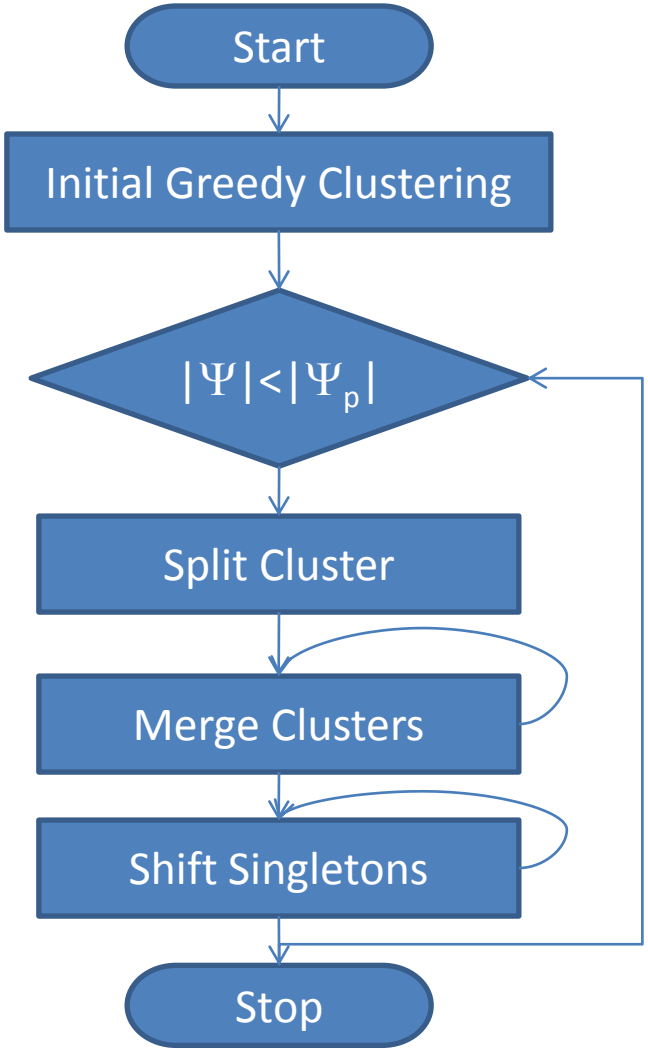
$$\text{relay}(c) < L_q, \qquad c \in C_i, \quad 1 \leq i \leq k \qquad (e)$$

Proposed Algorithm

Algorithm 1: Gateway Placement

input : A, S_q, L_q, H_q; [QoS constraints]
output : $\Psi = \{C_1, C_2, \cdots, C_k\}$; [set of clusters]

$D \leftarrow \sum_{j=1}^{n} A[i,j], 1 \leq i \leq n$; [initial clustering] ;
while $V(\Psi) \neq V(G)$ **do**
  $c_i \leftarrow \max\{D[i], 1 \leq i \leq n, v_i \notin \Psi\}$; [select a node with highest degree, not $V(\Psi)$];
  $C_i \leftarrow c_i \cup v_j 1 \leq j \leq n$, where
  $A[c_i, v_j] = 1, v_j \notin \Psi, |\Psi| < S_q$;
  $\Psi = \Psi \cup C_i$ [Make cluster part of solution];
end
$\Psi_p \leftarrow \Psi$; $flag \leftarrow false$;
while $|\Psi| < |\Psi_p|$ **do**
  if $flag$ **then**
    $\Psi_p \leftarrow \Psi$;
    $C_i \leftarrow$ FindSplitCandidate(Ψ);
    $\Psi \leftarrow$ Split(C_i) ;
  end
  while *Changed*(Ψ) **do**
    $[C_i, C_j] \leftarrow$ FindMergeCandidates(Ψ);
    $\Psi \leftarrow$ Merge(C_i, C_j) ;
  end
  while *Changed*(Ψ) **do**
    $[C_i] \leftarrow$ FindShiftCandidate(Ψ);
    $\Psi \leftarrow$ Shift(C_i)
  end
  $flag \leftarrow true$
end



Algorithm – Initialization

Hq=3,*Sq*=8, *Lq*=15

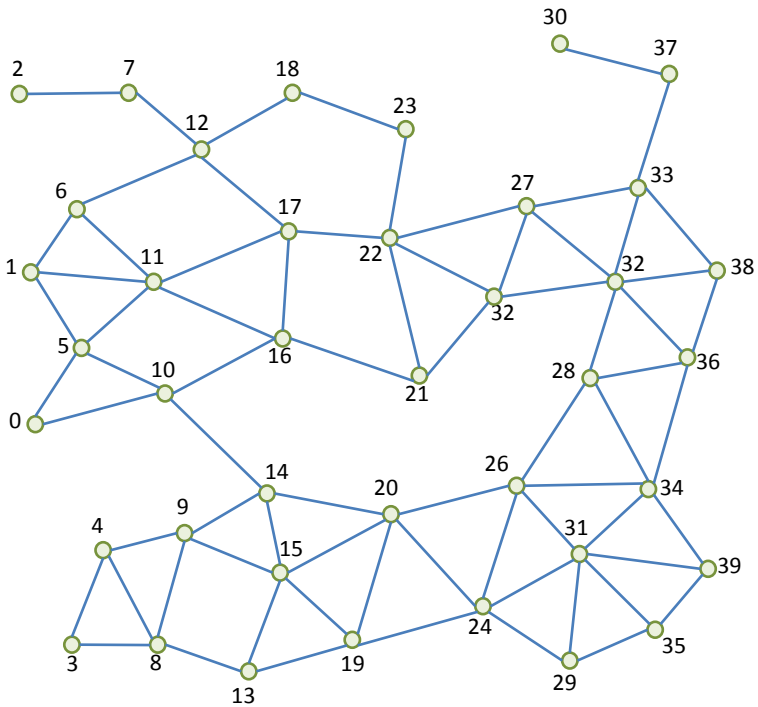


Fig A:Original G(V,E)

Initial Clustering

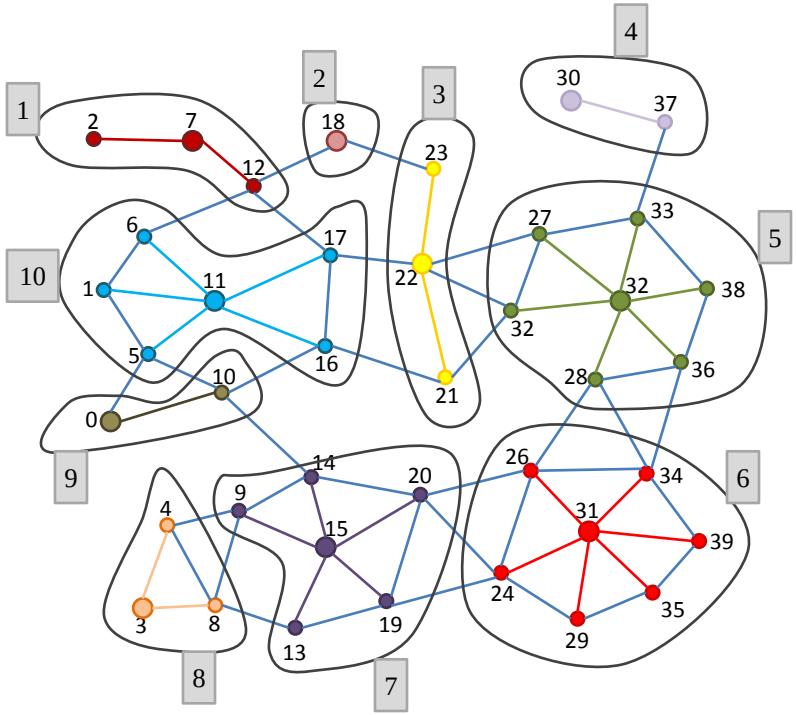
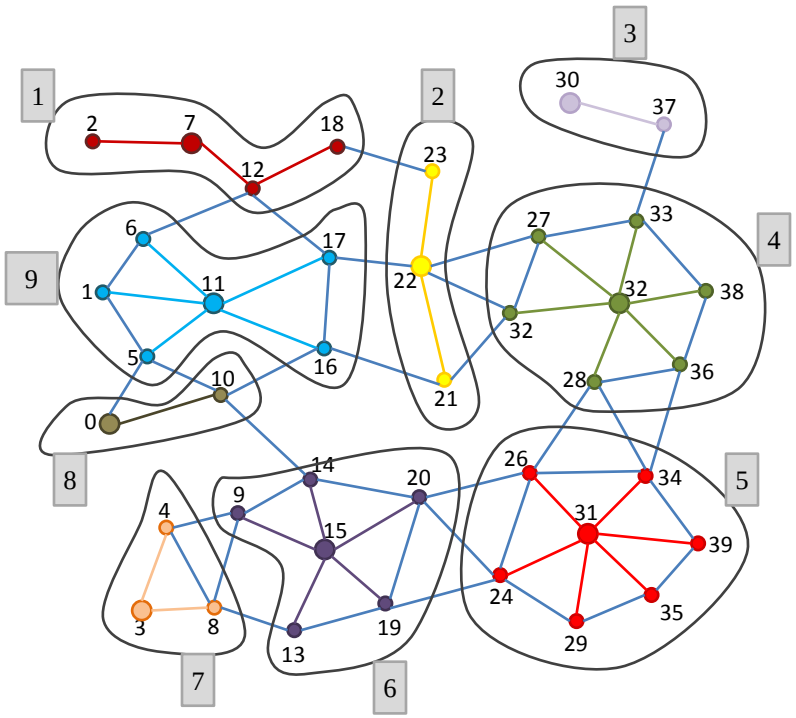


Fig B: Initial Greedy Clustering

Algorithm – Merging

Hq=3,*Sq*=8, *Lq*=15



Merging Continued

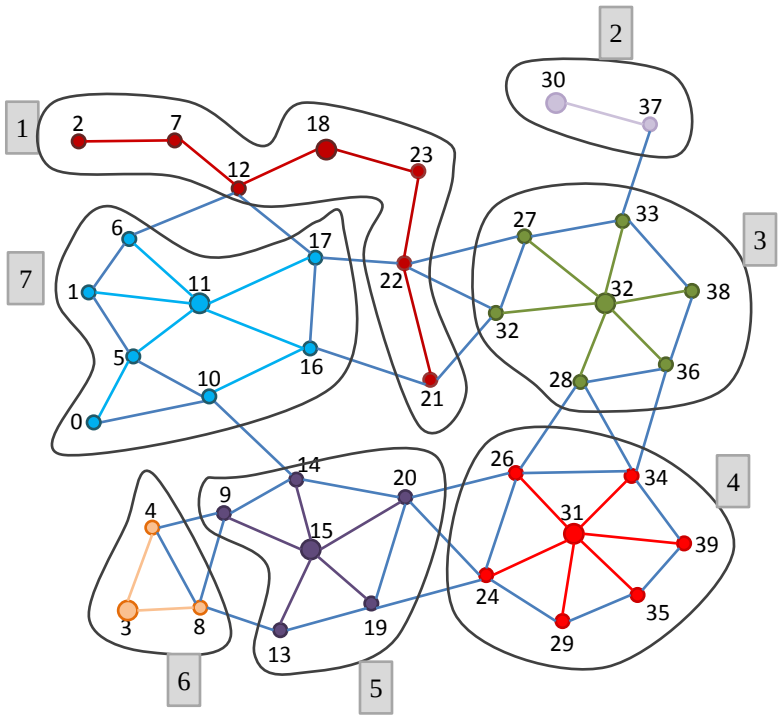


Fig C:Merging Step 1

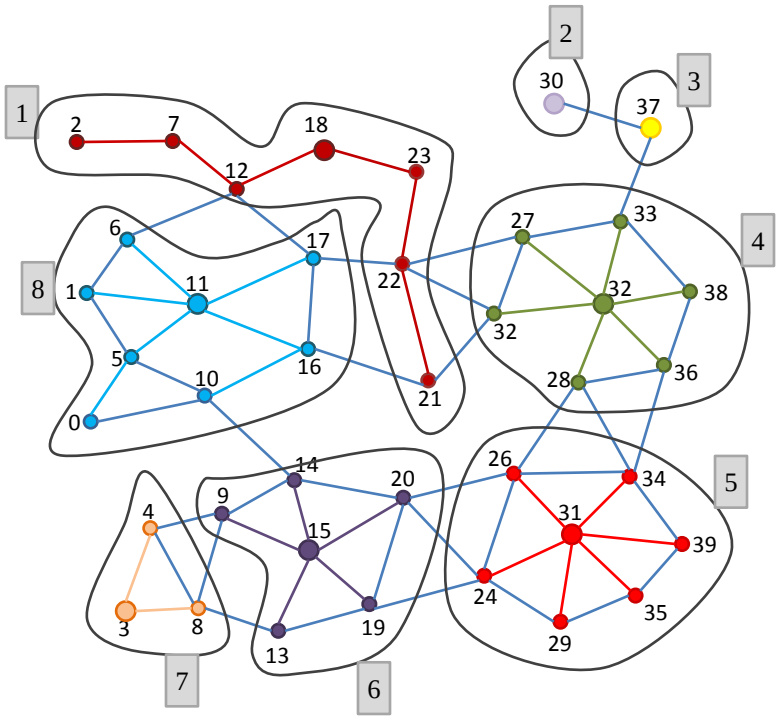
C1 merges into C2 (Fig B)

Figure D: Merging Step 2

C1 merges with C2 (Fig C)

Algorithm – Split and Merge

Hq=3,*Sq*=8, *Lq*=15



Splitting to Merging

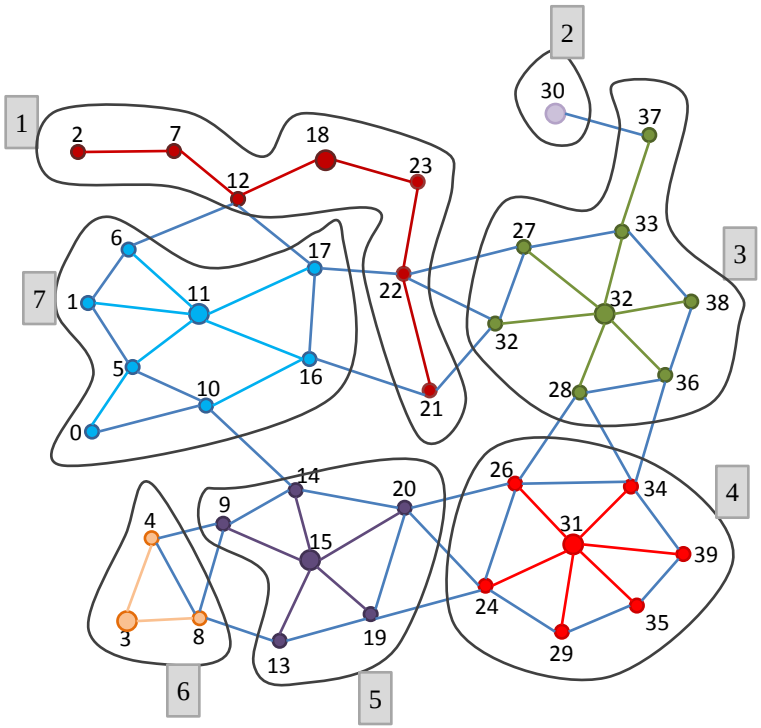


Fig E:Spliting

Split C2(Fig D) into C2 and C3 (Fig E)

Figure F: Merging Step 1

C3 (Fig E) merges with C3 (Fig F)

Algorithm – Final Solution

Hq=3,*Sq*=8, *Lq*=15

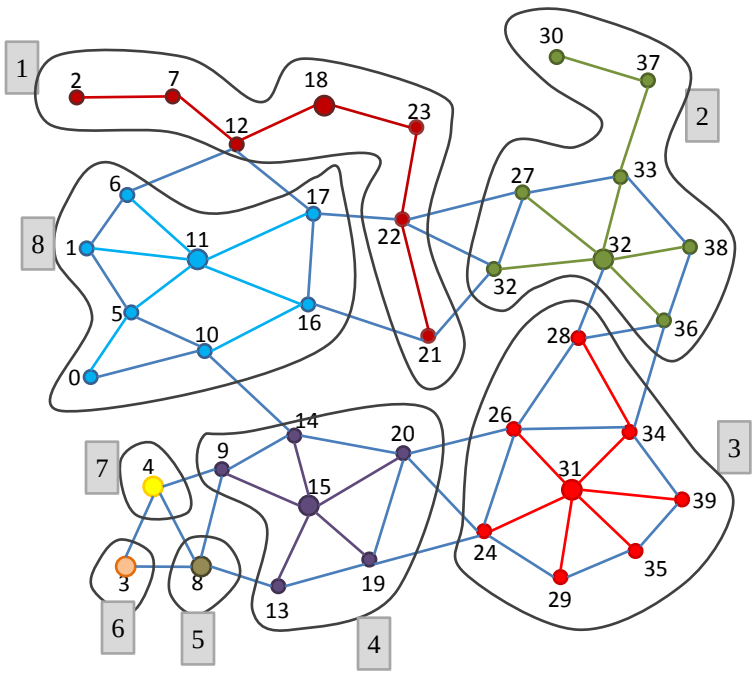


Fig F:Spliting, Merging, Shifting

Multiple iterations

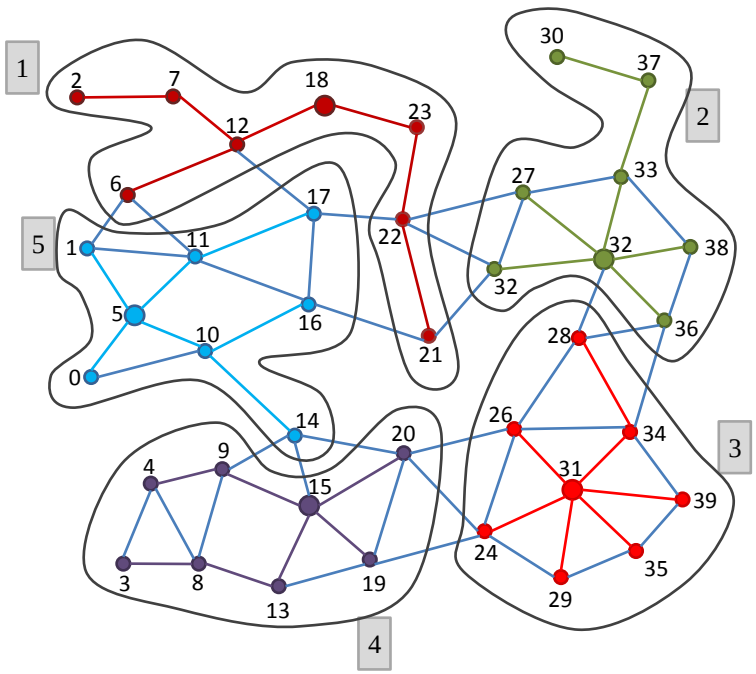
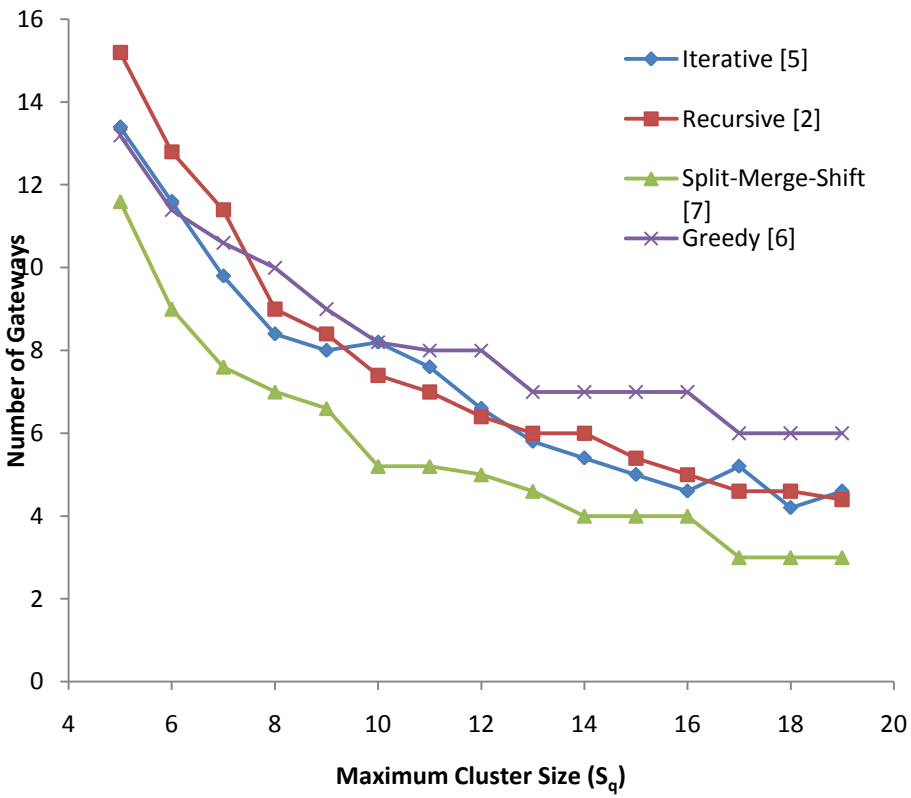


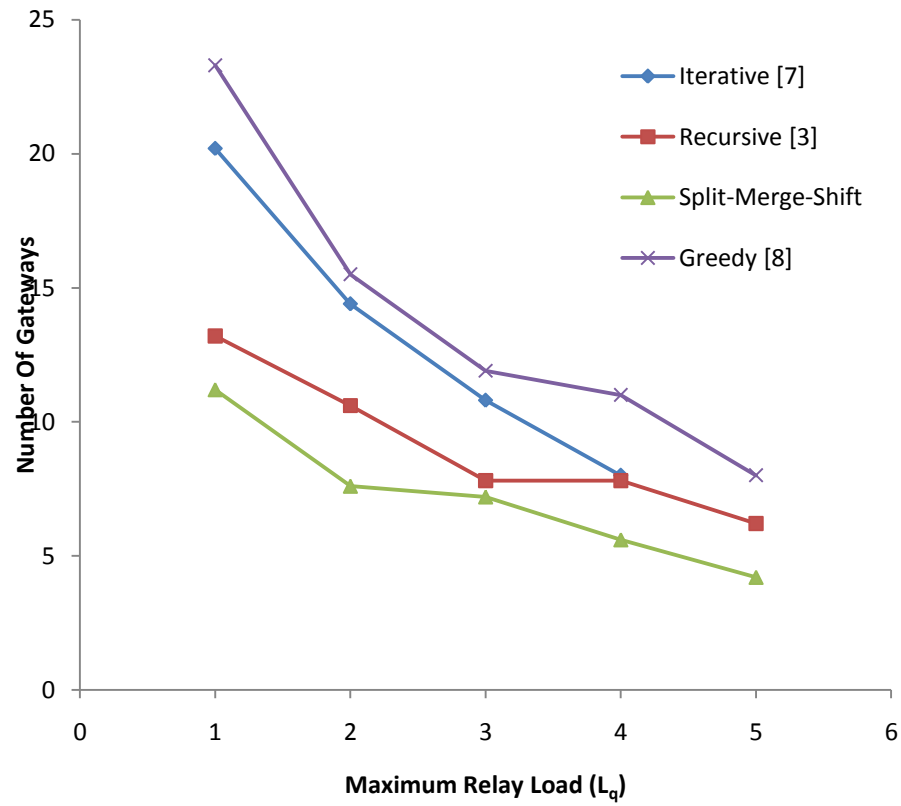
Figure G: Final Solution

Performance Evaluation

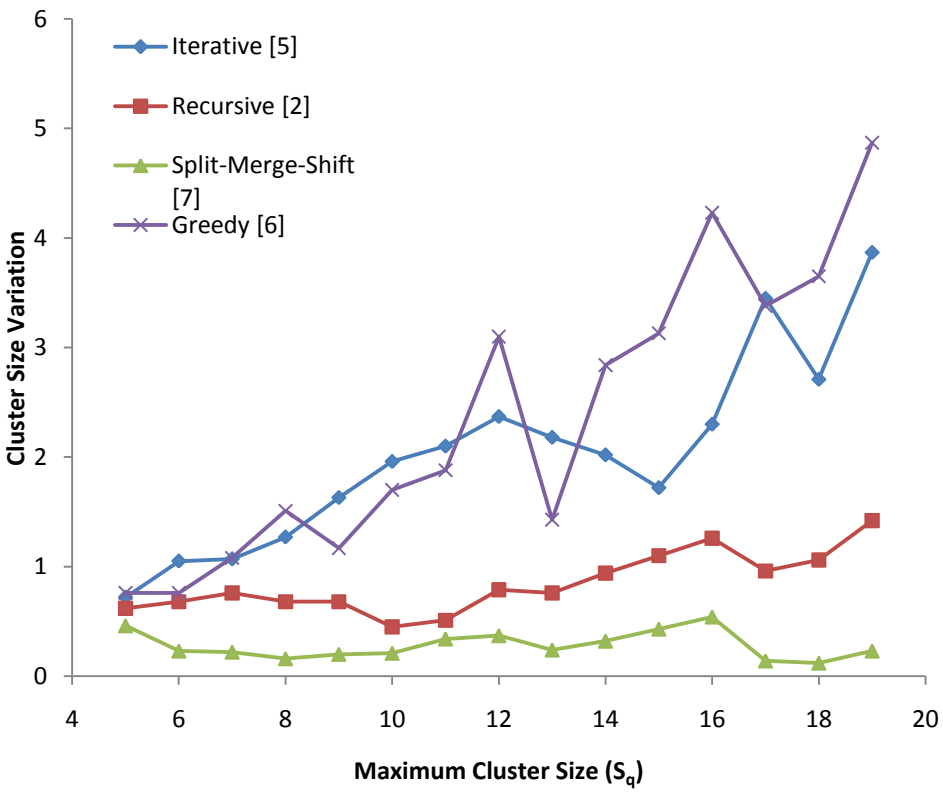
Effect of *Sq* on Gateway Count



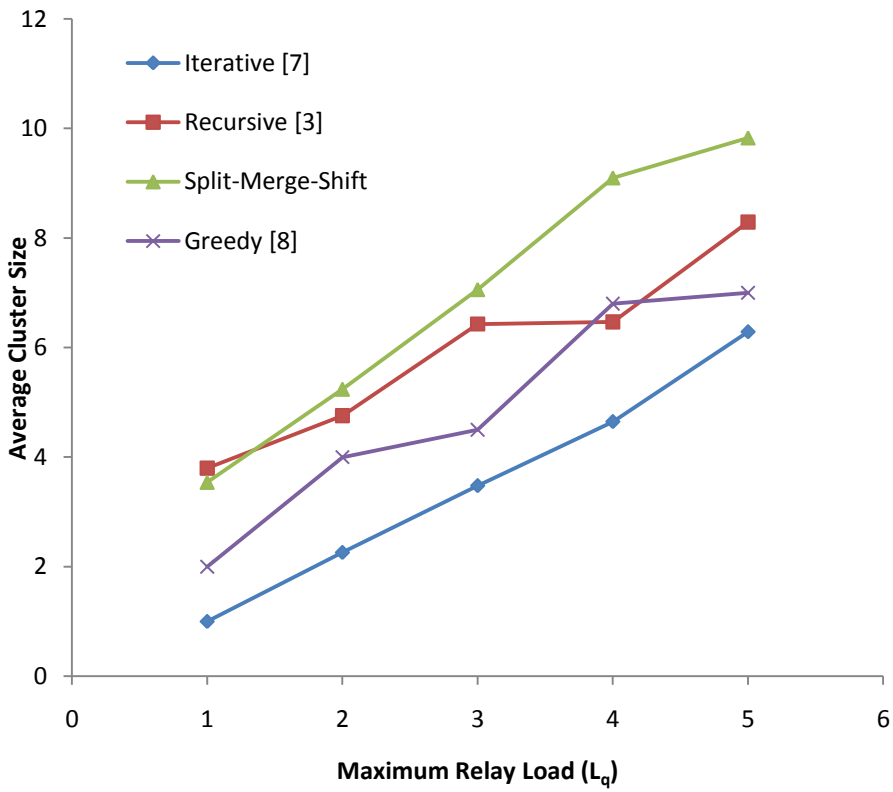
Effect of *Lq* on Gateway Count



Effect of *Sq* on Cluster Size Variation



Effect of *Lq* on Ave. Cluster Size

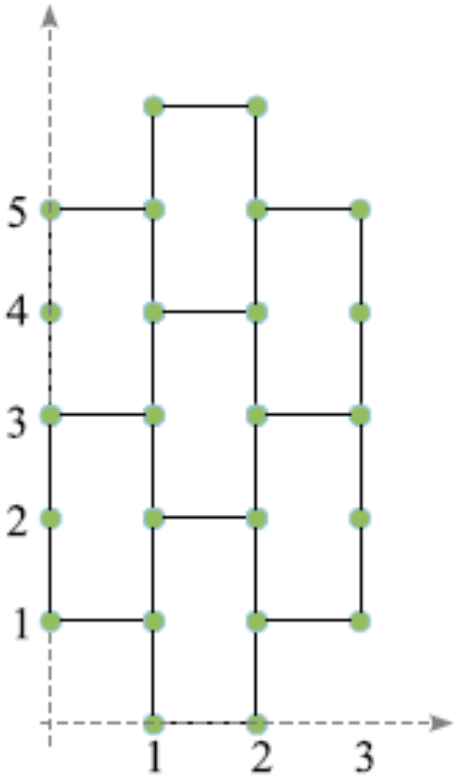


Fault Tolerance In Regular Mesh

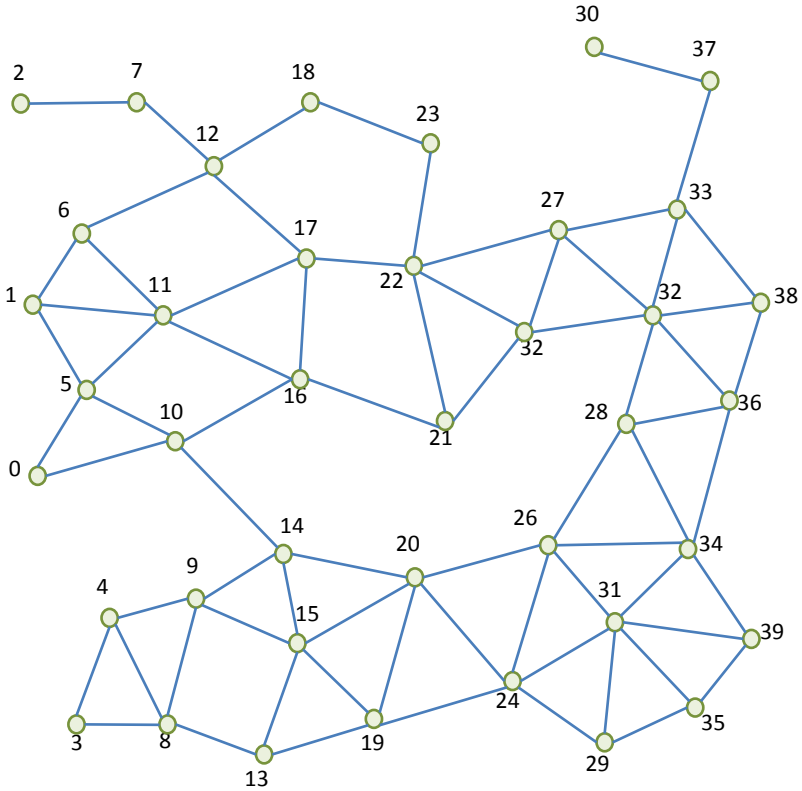
FAULT TOLERANCE ISSUE

Topological Classification of WMN

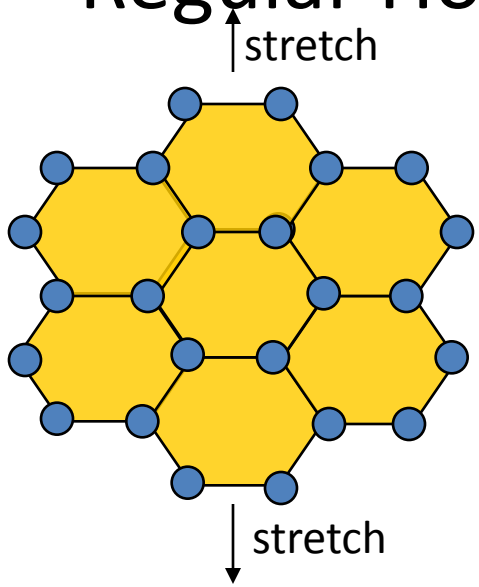
Regular Mesh Network



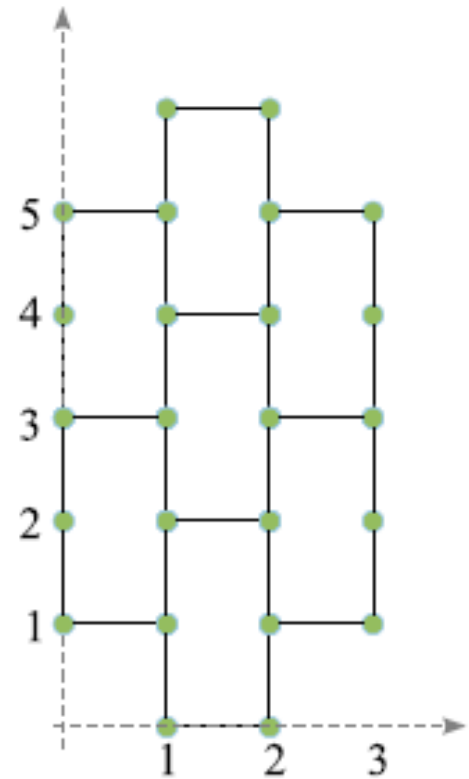
Irregular Mesh Network



Regular Honeycomb Brick Representation



Isomorphic pruned 2D square mesh



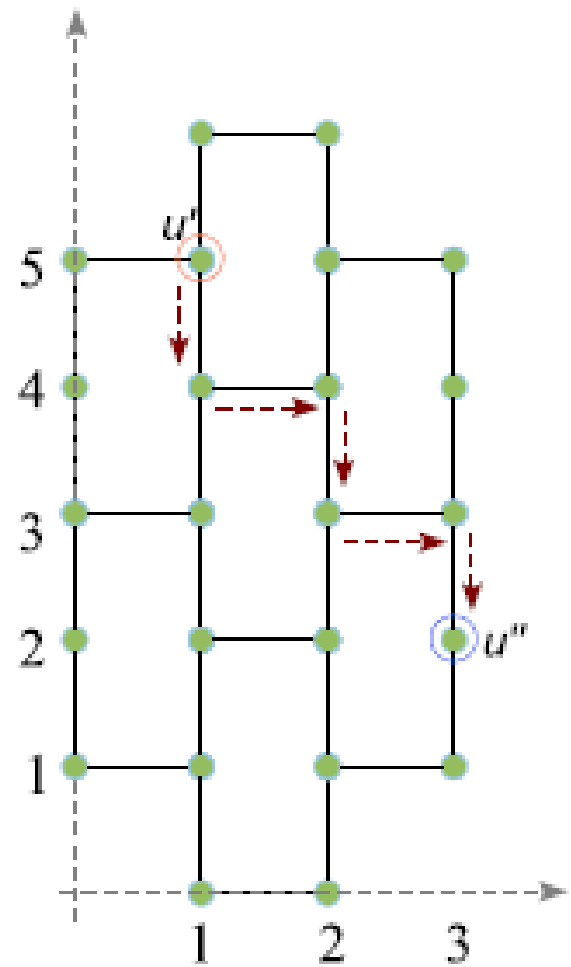
- Two dimensional representation of honeycomb
- Each node can be represented by a co-ordinate (x,y)
- They have 25% smaller degree than regular grid meshes.

$$E : \begin{cases} (x,y) \leftrightarrow (x \;\; y \pm 1) & (x,y) \in V \\ (x,y) \leftrightarrow (x+1 \;\; y) & \text{If } (x+y) \text{ is odd} \\ (x,y) \leftrightarrow (x-1 \;\; y) & \text{If } (x+y) \text{ is even} \end{cases}$$

Shortest Path Routing Algorithm

Algorithm 1 Route(S, D))

```
Initialize : U ← S, Δ ← D − U
while (Δx ∧ Δy) ≠ 0 do
        U ← Move(U), Δ ← D − U
end
proc Move(U)                          // δx, δy from Eq. 2
   if δx < 0 then p = δx(e(Ux) ⊕ e(Uy))
                 else p = δx(e(Ux) ⊕ e(Uy))
   fi
   q = δy(1− | p |)
   Boundary(p, q)
   Ux = Ux + p
   Uy = Uy + q
end
proc Boundary(p, q)                   // boundary conditions
   cases:
   p = 1 ∧ Ux = xmax :    q = p, p = 0
   p = −1 ∧ Ux = xmin :   q = p, p = 0
   q = 1 ∧ Uy = ymax :    q = −1
   q = −1 ∧ Uy = ymin :   q = 1
   end
end
```



Fault Tolerance In Brick Networks

- Link faults common in wireless networks
- How do we handle a fault in a mesh network?
  - Localized Temporal Routing
- Temporal Routing Based on
  - Final direction of packet
  - Position of fault
  - Number of faults

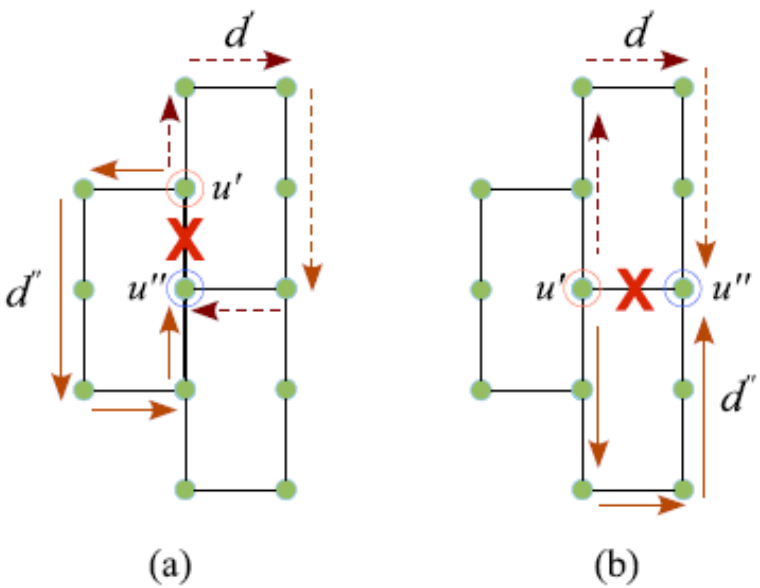


Figure 4. Detours, d' and d'', around faults.

Fault Tolerant Routing Algorithm

Algorithm 2 RouteUnderFault$(S, D))$

```
Initialize : U ← S, Δ ← D − U
while (Δx ∧ Δy) ≠ 0 do
    Get Δ from Algorithm 1
    Check for faulty link to next hop
    if fault detected go to recovery
      Apply detour d′ from Eqn 7
      if d′ fails
        Track back to initial fault node
        Apply detour d″ from Eqn 8
        if d″ fails
          Drop Packet
        end
      end
    end
    Resume normal routing
end
```

- **Fault detection:** Physical layer or the Medium Access Layer detects the fault.
- **Fault avoidance:** Once a fault has been detected, the algorithm goes into recovery mode. Exploited topological properties to define alternate path.

Conclusion

- Limitations
  - Fault tolerance is a trade-off between delay and deliverability.
  - Model needs ground up deployment
  - Suitable only in structured deployments
- Future work
  - Extent to irregular mesh
  - Effect of fault provisioning on gateway placement