Utility-based Routing

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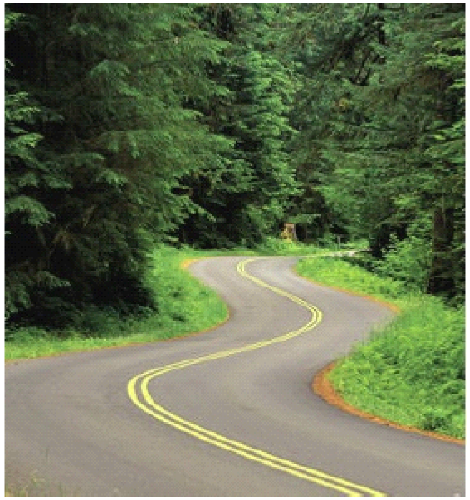
Roadmap

- Introduction
- Why Another Routing Scheme
- Utility-Based Routing
- Implementations
- Extensions
- Some Final Thoughts



1. Introduction

- Z. Mao (Serve the People)
  - Knowledge begins with practice.
  - Theoretical knowledge acquired through practice, must then return to practice.

- G. H. Hardy (A Mathematician's Apology)
  - The real mathematics of the real mathematicians is almost wholly useless.
  - It is not possible to justify the life of any genuine mathematician on the ground of the utility of his work.

Implications

- Politicians (when they become politically weak)
  - Start new revolutions

    (and young people become followers)

- Mathematicians (when they become old)
  - Start writing books

    (and young people prove theorems)

- Professors (when they become seniors)
  - Give presentations

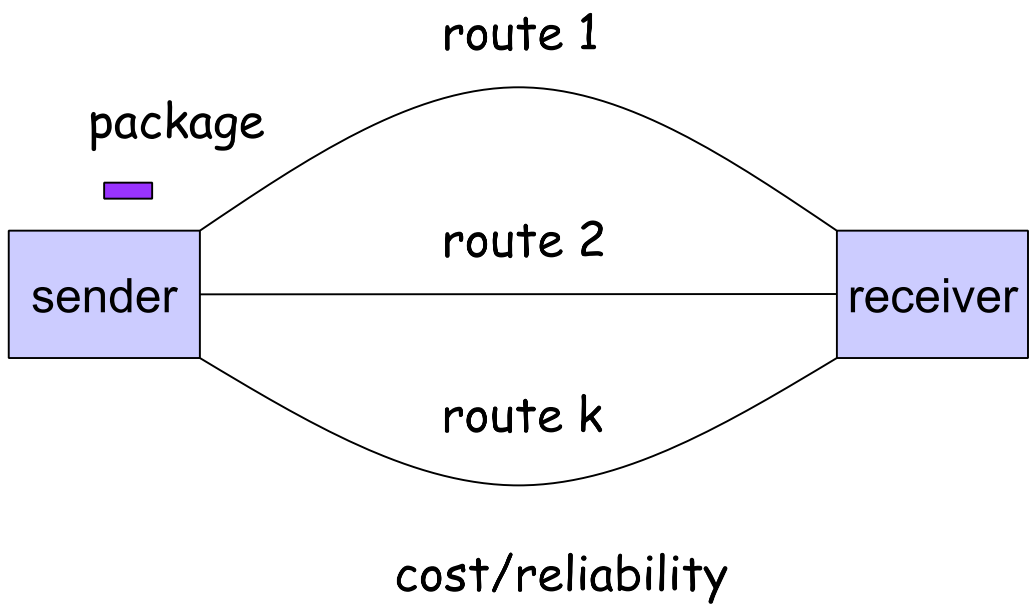
    (and students write papers)

2. Why Another Routing Scheme

- Why routing again?
  - Because it is interesting (a non-serious answer)
- A new routing algorithm: composite utility
  - Benefit (of packet delivery)
  - Cost (of forwarding)
  - Reliability (of links)
  - Timeliness (of reaching a destination)

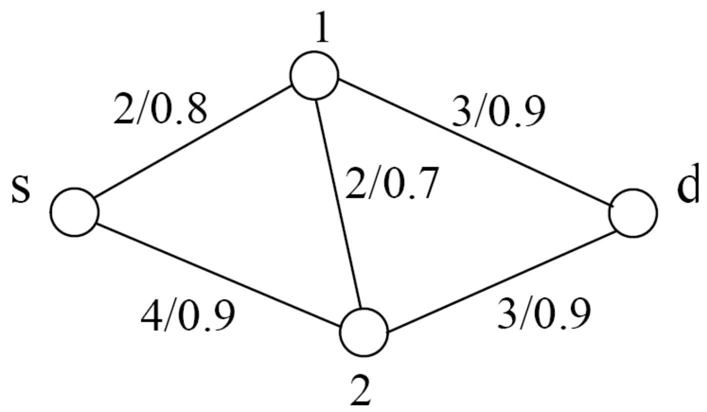
A Postage Example

- Best route: importance of the package
  - Valuable package: Fedex (more reliable, costs more)
  - Regular package: Regular mail (less reliable, costs less)



A Sample Network

- Traditional metrics: cost/reliability
  - The minimum cost path: s → 1 → d
    - Cost 2 + 3 = 5
    - Reliability 0.8 × 0.9 = 0.72
  - The most reliable path: s → 2 → d
    - Cost 4 + 3 = 7
    - Reliability 0.9 × 0.9 = 0.81

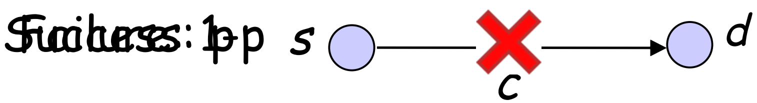


3. Utility-Based Routing (Lu&Wu'06)

- Each packet is assigned a benefit value, v
- s transmits a packet with benefit v to d
  - Transmission cost/reliability: c/p
  - Utility: v – c if success, 0 – c otherwise
  - Expected utility:

$$u = p(v-c) + (1-p)(0-c) = pv - c$$

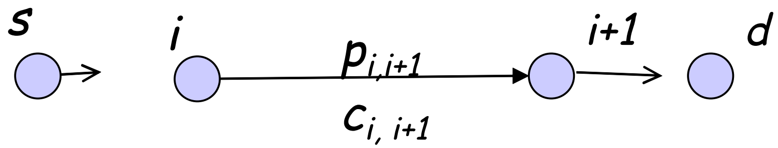
  - The best route maximizes u



A General Expression

- General form of *u* for path

R: s (= 0), …, i, i+1, …, d (= n)

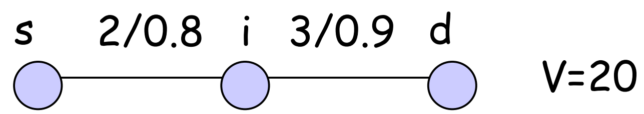


$$u = \left(\prod_{i=0}^{n-1} p_{i,i+1}\right)v - \sum_{i=0}^{n-1}\left(c_{i,i+1}\prod_{j=0}^{i-1} p_{j,j+1}\right) = P_R v - C_R$$

where P_R: route stability, and C_R: route cost

How to calculate *u* ?

- Direct calculation
  - 0.8 *0.9*20 - 2 - 3*0.8=10



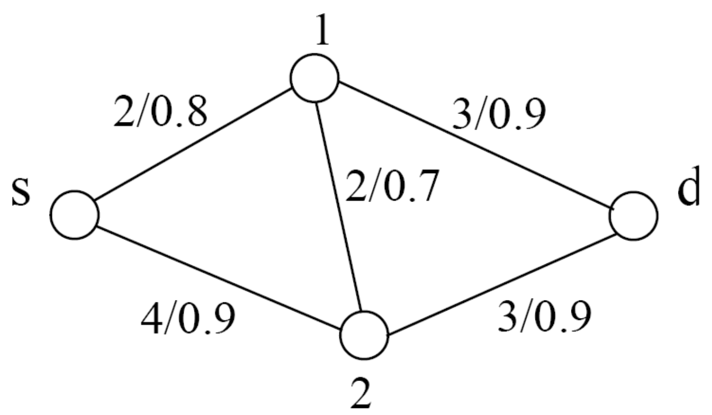
- Backward calculation

  $u_i = p_{i,i+1} u_{i+1} - c_{i,i+1}$ (virtual s/d)

  - 0.9*20 - 3 = 15 (at i)

    0.8*15 - 2 = 10 (at s)

Benefit-Dependent Best Paths



R_1: s→1→d

R_2: s→2→d

R_3: s→1→2→d

R_4: s→2→1→d

R_i	P_i	C_i
R_1	0.72	4.4
R_2	0.81	6.7
R_3	0.5	5.3
R_4	0.57	7.7

v=20

R_i	U_i
R_1	10
R_2	9.5
R_3	4.7
R_4	3.7

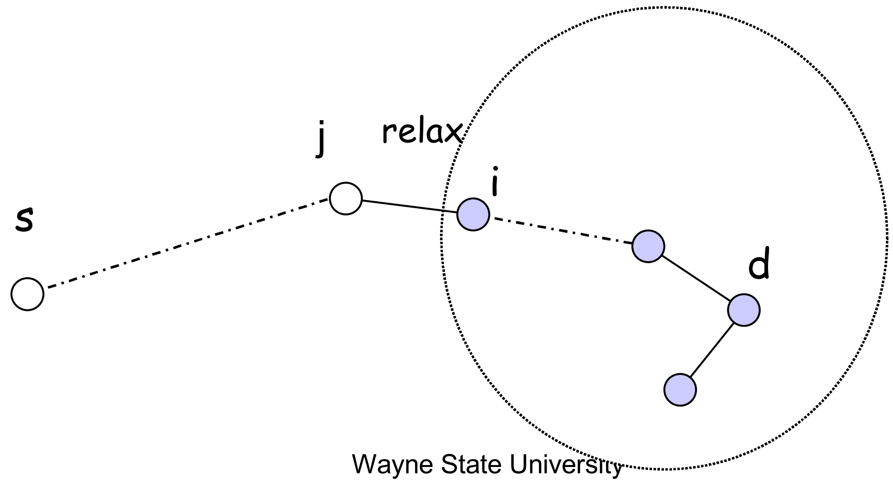
v=30

R_i	U_i
R_1	17.2
R_2	17.6
R_3	9.7
R_4	9.4

Different benefit values may have different best paths!

4. Implementations

- Centralized greedy approach
  - Applies the Dijkstra's shortest path from d
  - Each node i maintains the maximum u_i (init. to 0)
  - i relaxes j: $u_j = p_{j,i} u_i - c_{j,i}$ until reaching s
- Wireless and mobile: reactive approach
  - Route discovery (from s) followed by route reply (from d)
  - Time out: each node set an appropriate order of relaxations



5. Extensions

- All optimal routes
  - Different benefit values
- Wireless networks
  - Opportunistic routing
- Incentive compatible routing
  - Handling selfish nodes
- Real-time responses
  - Duty cycles in WSNs
  - Probabilistic contacts in DTNs

(Others: data gathering and network coding)

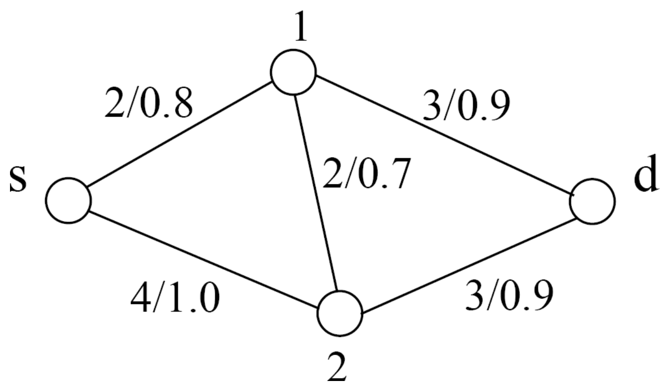
All Optimal Routes

- Requirement
  - Find all optimal routes for different benefits
- Challenges
  - Enumerating all benefits is infeasible
    - For a given range of benefits
  - Checking all paths is too expensive
    - Exponential to the number of nodes
- One important property
  - The benefits range can be partitioned into sub-ranges, each of which has one distinct optimal path

Intersection Point

R1: s -> 1 -> d
R2: s -> 2 -> d

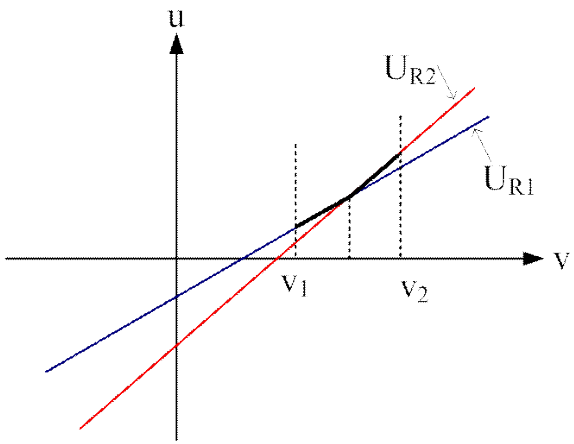
$U_{R1} = 0.72v - 4.4$
$U_{R2} = 0.9v - 7$

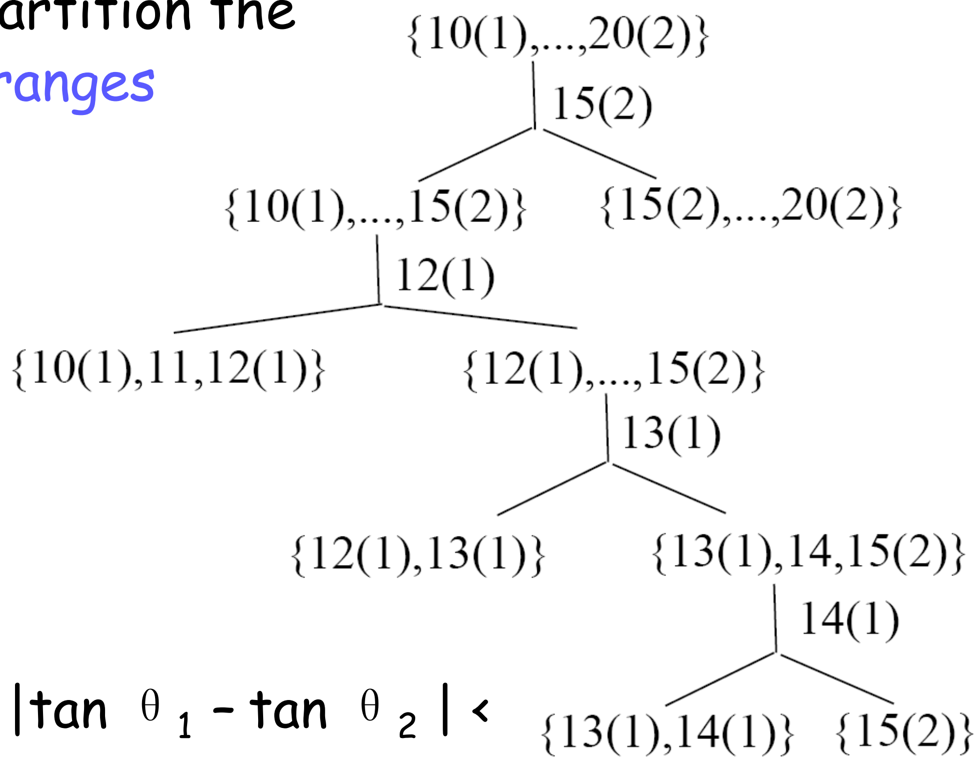


Complexity: $O(R^2)$
(R: number of paths)

Binary Partition

Iterative and parallel partition the benefit range into sub-ranges





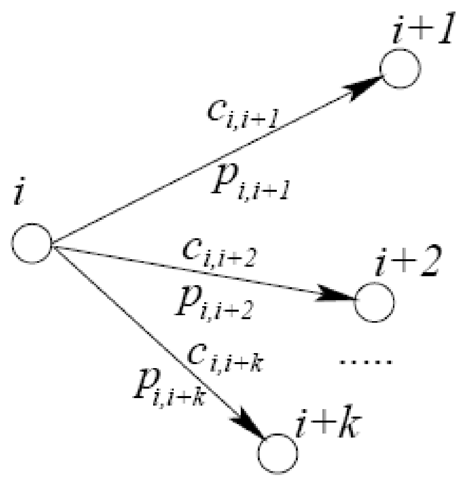
Stoppage condition: $r \times |\tan\theta_1 - \tan\theta_2| < \Delta$

(r: sub-range, θ_1 and θ_2 : angle of R_1 and R_2)

Wireless Networks (Wu, Lu, & Li'08)

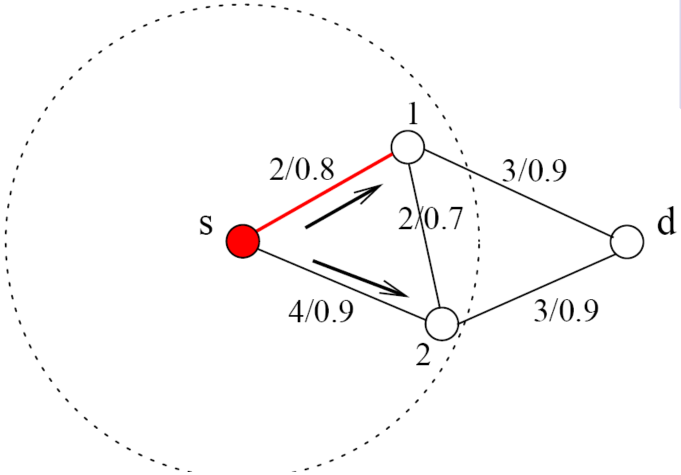
- Opportunistic routing (OR) with adjustable transmission range
- Relay set: more than one node can relay
- Priority: ETX or "cost" to destination

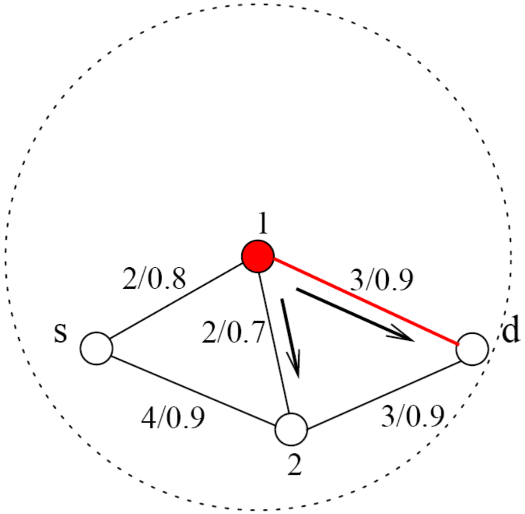
$$opu_i = \sum_{j=i+1}^{i+k} (opu_j \cdot p_{i,j} \cdot \prod_{l=i+1}^{j-1} (1 - p_{i,l})) - c$$



OR Example

- Best expected utility
  - u_s = 10 for v = 20
- Priority
  - s < 2 < 1 < d
- Best expected opportunistic utility
  - opus = 14.6 for v = 20
- Optimal solution
  - NP-hard: the difficulty lies in the global priority





Incentive Compatible Routing

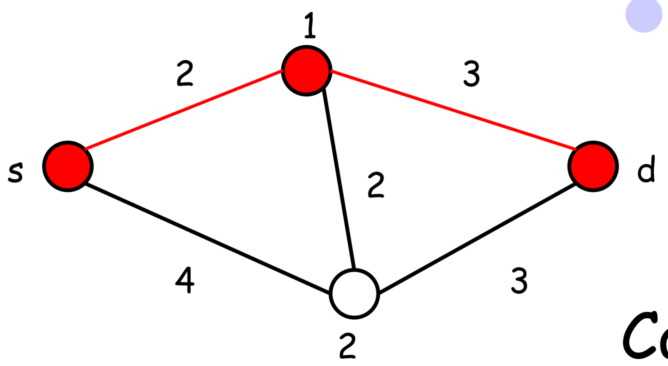
- Nodes are selfish and give false cost information
  - Without reward, they will not help relay packets
  - Maximize utility = payment – cost
- Mechanism design
  - Tie self-interest to societal interest
- VCG scheme: enforcing the reporting of correct costs
  - Nodes on optimal path: utility remains the same when lying
  - Nodes not on optimal path: utility reduces when lying

Second Price Path Auction: VCG

- Why doesn't the first price work?
  - Societal objective is inconsistent with individual nodes' objectives
- The solution: second price
  - Loser's payment is 0
  - Winner i's payment:

(lowest cost without i - lowest cost with i) + cost of node i

A VCG Example



Case 1: nodes on an optimal path lie

- If (s, 1) is changed to 3
  - S still gets 7 – 6 + 3 = 4
    (same as 7 – 5 + 2 = 4)

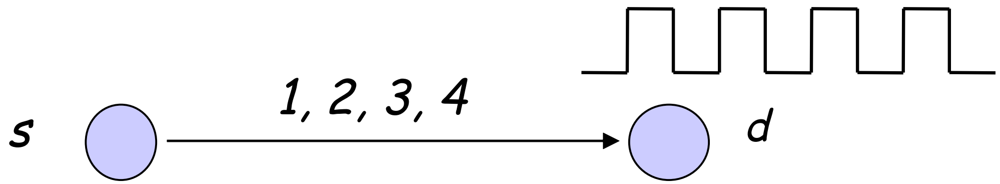
Case 2: nodes on a non-optimal path lie

- If (2, d) is changed to 1
  - 2 gets 5 – 5 + 1 = 1 < 3
    (utility is negative)

Who is paying the price difference: society
Even an ideal society charges tax

Real-Time Responses
(Xiao, Wu, & Wang'12)

- Energy saving: on/off mode in WSNs
  - Duty cycle = 4: up every 4 units
- Asynchronous send
  - With a delay 1, 2, 3, or 4



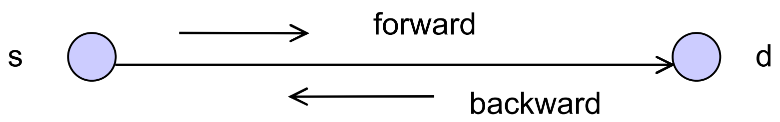
- Extending utility function: delay-sensitive

Duty Cycles in WSNs

- Utility for a delivery path R: s (=0), 1, 2, …, n-1, d (=n)
  - Direct computation

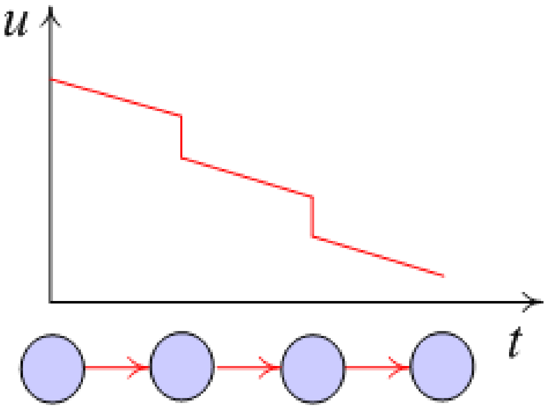
$$u = \prod_{i=0}^{n-1} p_{i,i+1}\left(v - \delta \sum_{i=0}^{n-1} t_{i,i+1}\right) - \sum_{i=0}^{n-1}(c_{i,i+1}\prod_{j=0}^{i-1} p_{j,j+1})$$

  - Iterative computation
    - forward $v_{i+1} = v_i - \delta\ t_{i,i+1}$
    - backward $u_i = p_{i,i+1}u_{i+1} - c_{i,i+1}\ (u_n = v_n \text{ init}, u\ = u_0\ )$

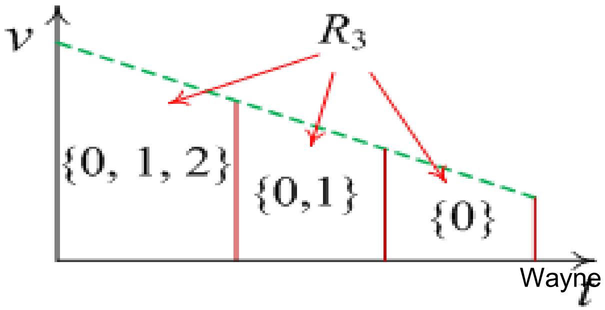


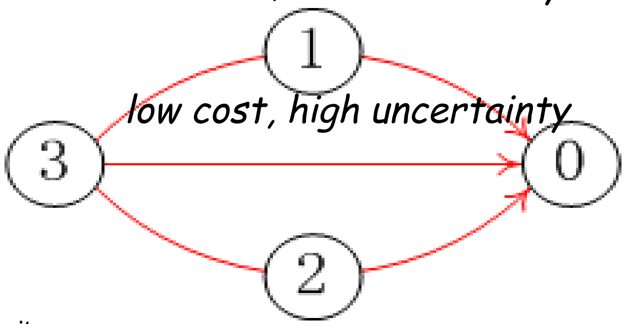
Probabilistic Contacts in DTNs

- DTNs
  - Probabilistic contacts (uncertainty)
  - Minimizing the expected decreased utility



- Opportunistic forwarding
  - Relay is extended from a single node to a time-varying forwarding set (FS)
  - A message copy is forwarded from i to the first contact j at time t if j is in FS(i, t)





6. Some Final Thoughts

- Is research on routing over?
  - Probably yes: MANETs and sensor nets
  - No: Other networks (e.g. DTNs and social networks)

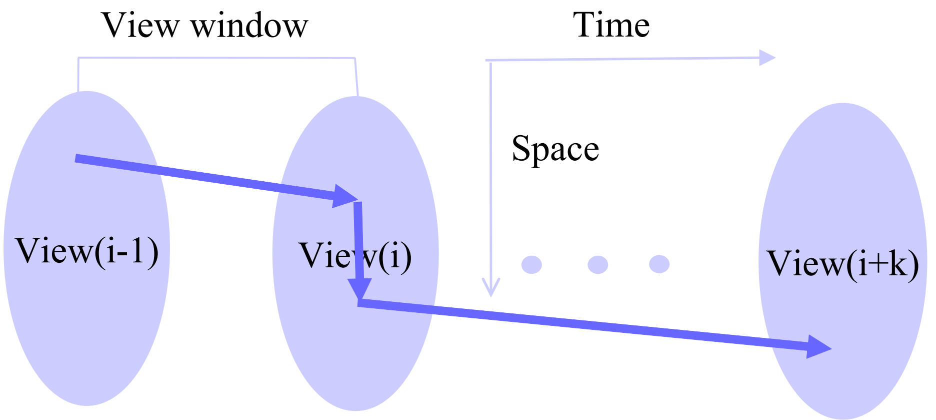
- Mobility in Wireless Networks: Friend or Foe ?
  - Mobility as a Foe: tolerating and masking
  - Mobility as a Friend: mobility-assisted routing

Some Challenges

- Future world being more wireless and mobile
- Complexity and diversity
- New challenges for routing protocol design
  - From top: more demand from the end user (e.g., mobility support)
  - From bottom: emerging technologies (e.g., new abstraction for wireless links)

Graphs for Dynamic Networks

- E.g. Mobility affects network model/protocol
- Time-space view vs. space view



- View consistency in static graphs
  - Wu & Dai (IEEE Network'05): function of multiple views
- Connectivity & routing in evolving graphs
  - Liu & Wu (MobiHoc'07, '08, '09)
  - Wu (Graph and Computing'10)

Collaborators

- Former students
  - Prof. Mingming Lu (CSU)
  - Prof. Feng Li (IUPUI)
- Visiting scholar
  - Prof. Mingjun Xiao (USTC)

Questions