TEMPLE UNIVERSITY

中国科学技术大学 University of Science and Technology of China

Time-Sensitive Utility-Based Routing in Duty-Cycle Wireless Sensor Networks with Unreliable Links

Mingjun Xiao[a,b], Jie Wu[b], Liusheng Huang[a]

[a] University of Science and Technology of China

[b] Temple Univeristy

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Introduction: utility-based routing

- **Concept** : Utility-based routing
  - **Utility** is a composite metric

  Utility (u) = Reliability (p) * Benefit (b) – Cost (c)

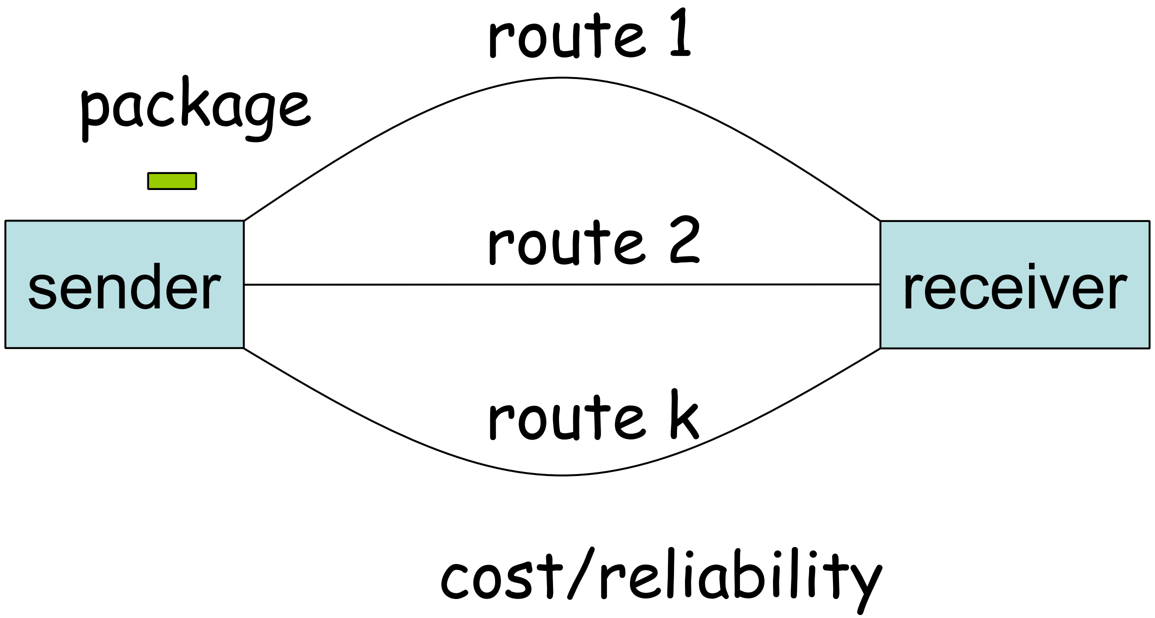
  - **Benefit** is a reward for a routing

    succeed: a positive reward

    fail: 0 reward
  - **Cost** is the total transmission cost for the routing
  - Benefit and cost are uniformed as the same unit
  - **Objective** is to maximize the utility of a routing

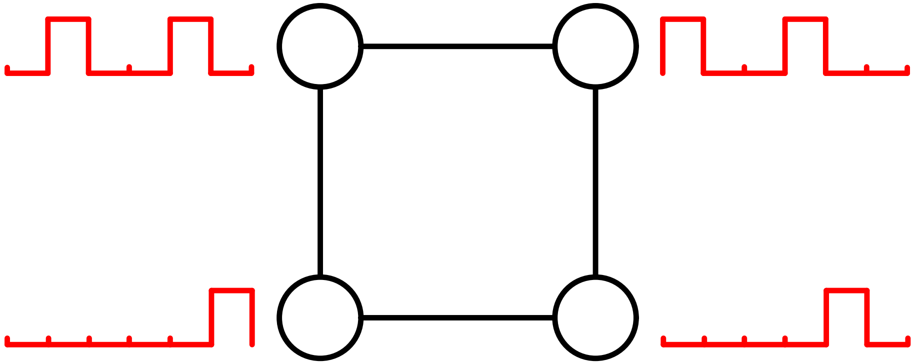
Introduction: utility-based routing

- **Motivation** of Utility-based Routing
  - Valuable package: Fedex (more reliable, costs more)
  - Regular package: Regular mail (less reliable, costs less)



Introduction: duty-cycle WSN

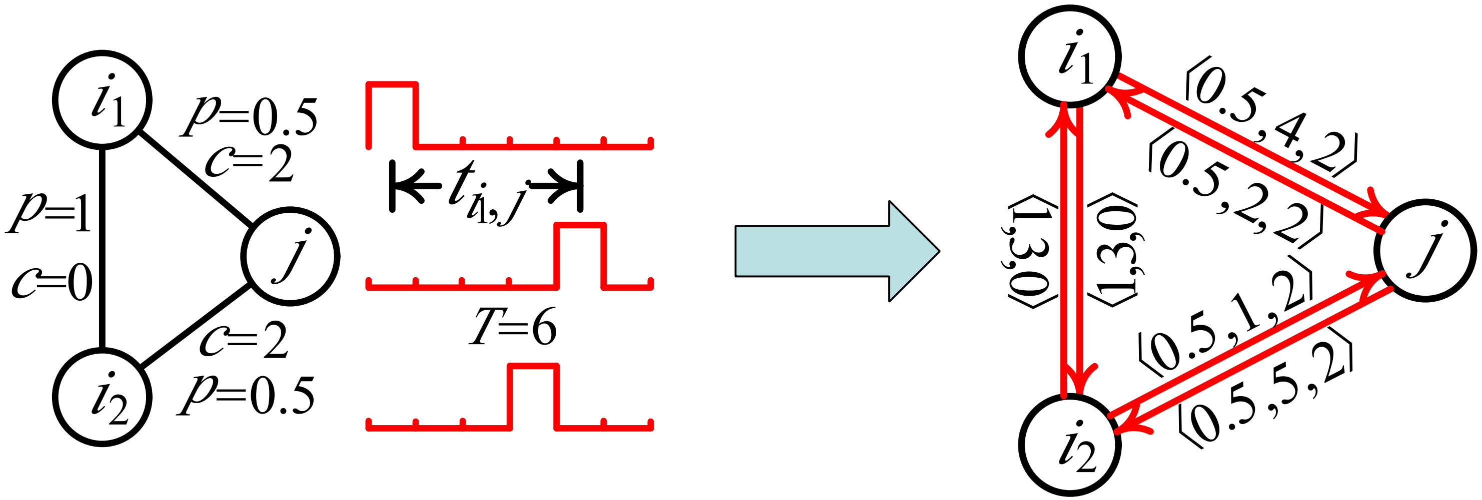
- Duty-cycle WSN
  - Each node has two working states:
    - active: all functions (send/receive, etc.).
    - dormant: can be waked up by a timer to send packets.



  - Each sensor schedules its working states periodically
  - There is a non-negligible delivery delay.

Introduction: duty-cycle WSN

Any duty-cycle WSN can be converted to a direct weighted graph



⟨*p* (reliability), *t* (delay), *c* (cost)⟩

A duty-cycle WSN: ⟨*V*, *W*={⟨*p*, *t*, *c*⟩}⟩

Motivation

Utility-based routing → **Duty-cycle WSN**

delivery delay is an important factor for the routing design

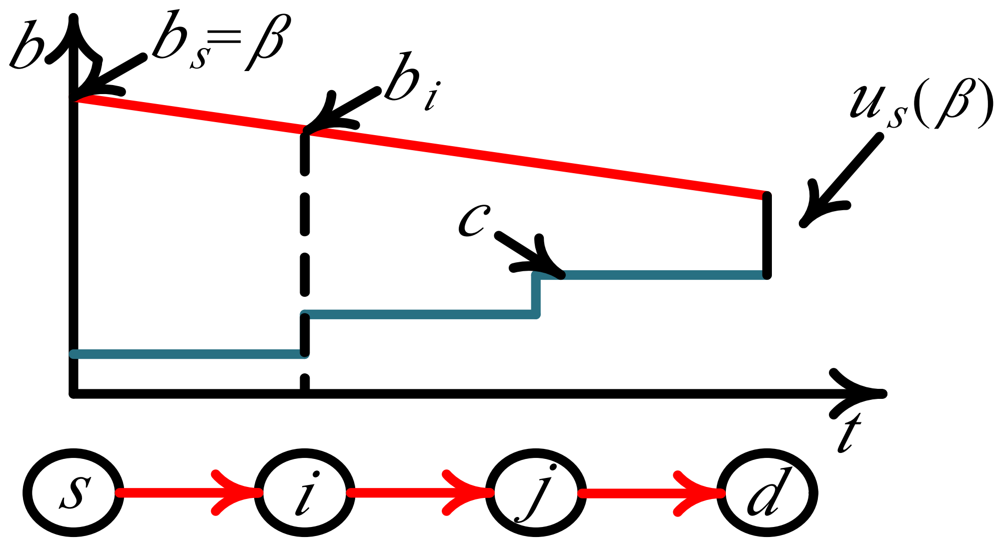
Time-sensitive utility-based routing

Time-sensitive utility model

- **Benefit**: a linearly decreasing reward over time

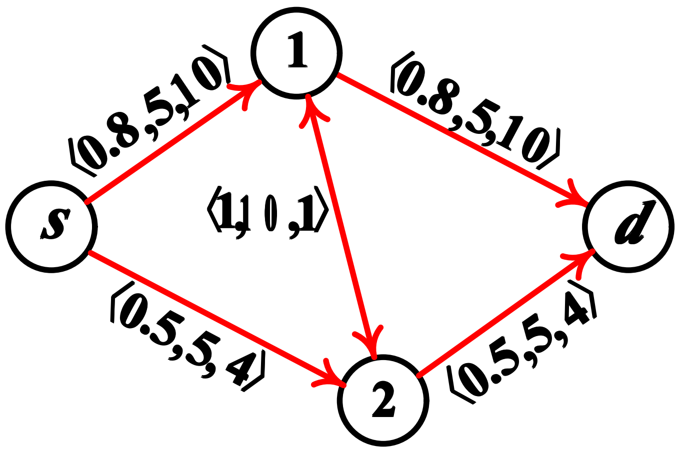
$$b(t) = \begin{cases} \beta - t \cdot \delta, & successful delivery \\ 0, & failed delivery \end{cases}$$

- **Utility**: $u = b(t) - c$
- **Remaining benefit *b* & Expected utility *u(b)***



Problem

- **Time-sensitive utility-based routing**
  - duty-cycle network **G = ⟨ V,W⟩** ,
  - source ***s***, destination ***d***, initial benefit β , benefit decay coefficient δ
  - **Objective**: maximize $u_s(\beta)$.



benefit	path
$50-t$	$s\rightarrow1\rightarrow d$
$40-t$	$s\rightarrow2\rightarrow d$
$30-0.1t$	$s\rightarrow2\rightarrow1\rightarrow d$

Solution

- **Expected utility for a single path**

β=45, δ=1

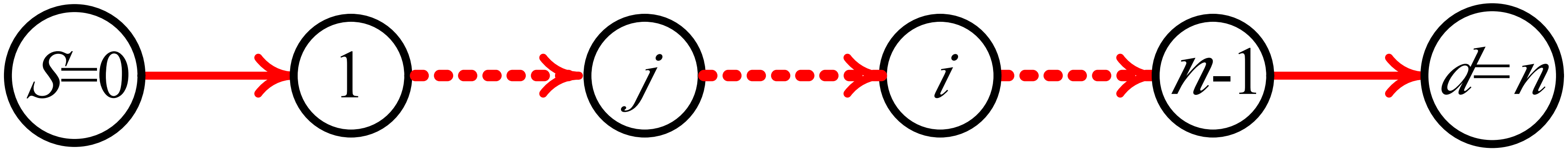
	benefit	cost
Succeed (p):	$45-1*5=40$	10
Fail (1- p) :	0	10
Expected	$0.8*40+0.2*0$	10

– Expected utility: **0.8*40 – 10 = 22**

$$u_s(\beta)=p_{s,d}*(\beta-\delta*t_{s,d})-c_{s,d}$$

Solution

- **Expected utility for a single path**



  - A general formula (Theorem 1)

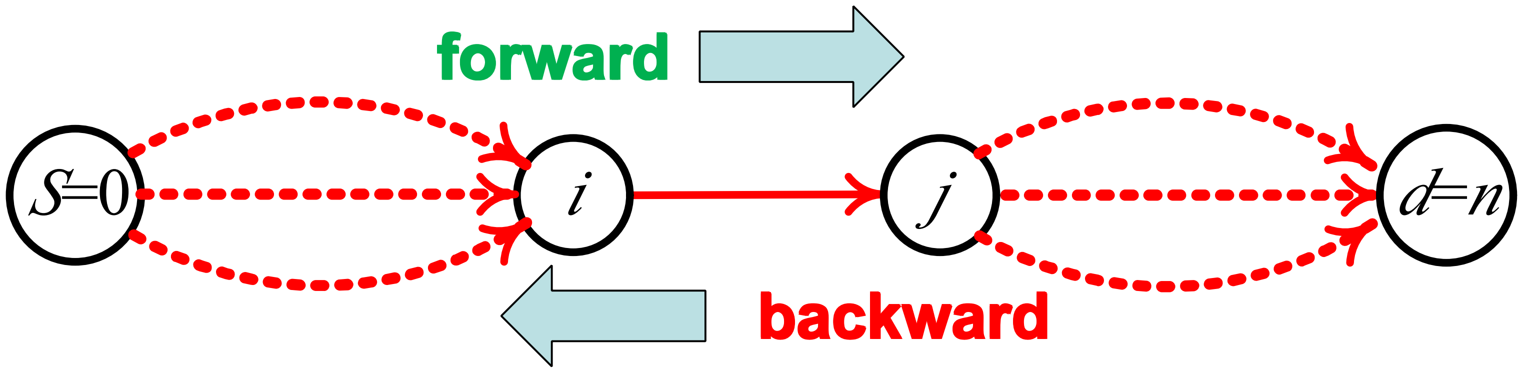
$$u_s(\beta) = \prod_{i=0}^{n-1} p_{i,i+1}\left(\beta - \delta\sum_{i=0}^{n-1} t_{i,i+1}\right) - \sum_{i=0}^{n-1} c_{i,i+1}\prod_{j=0}^{i-1} p_{j,j+1}$$

Require the global information

inefficient for multiple paths

Solution

- **Local iterative formula (Theorem 2)**

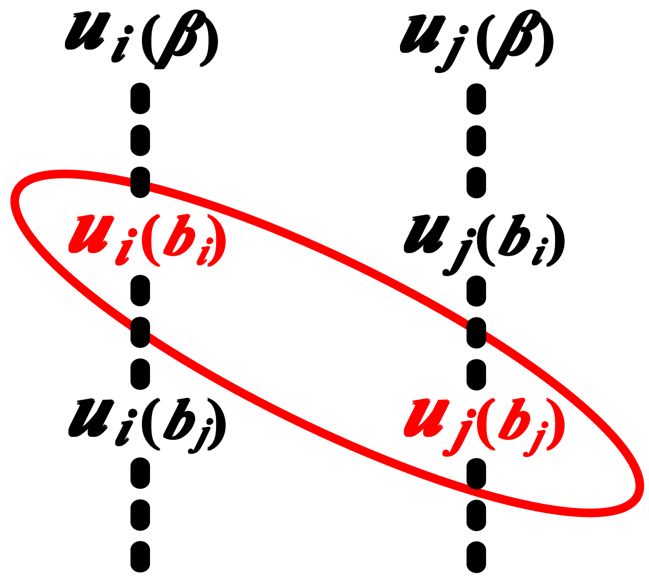


Forward:

$$b_j = b_i - \delta * t_{i,j}$$

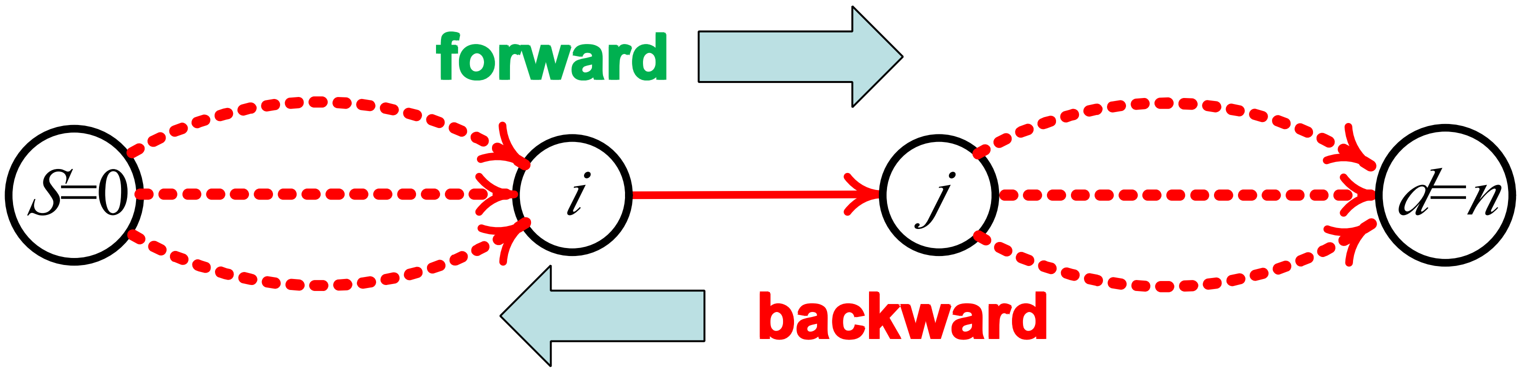
Backward:

$$u_i(b_i) = p_{i,j} * u_j(b_j) - c_{i,j}$$



Solution

- **Local iterative formula (Theorem 2)**

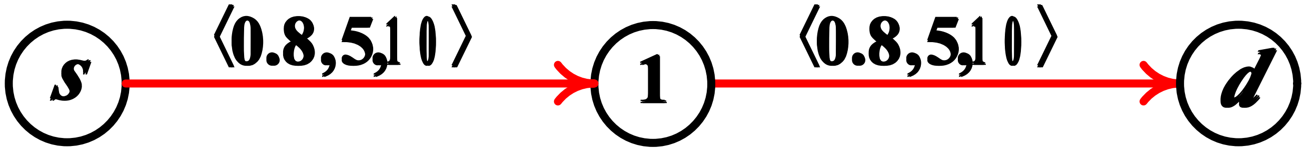


1. The number of b_i needs to be calculated is limited. Especially for a well scheduled duty-cycle WSN, the number is a small value (an example in paper).

2. When we compute b_i and $u_i\,(b_i)$ for the largest β, the b_i and $u_i\,(b_i)$ for other β are also calculated.

Solution

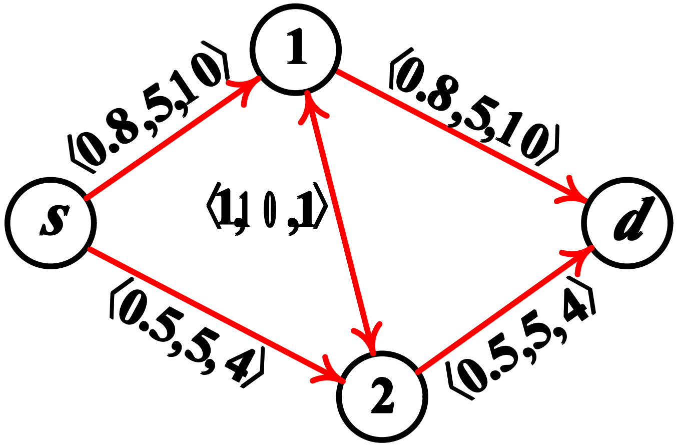
– Example:



benefit	$\beta=50,\ \delta=1$
directly computation	$u_s=0.8\times0.8\times(50-1\times(5+5))-(10+10\times0.8)=7.6$
iteratively computation	$b_s=50,\ b_1=45,\ b_d=40$
	$u_d(b_d)=b_d=40$
	$u_1(b_1)=p_{1,d}\times u_d(b_d)-c_{1,d}=0.8\times40-10=22$
	$u_s(b_s)=p_{s,1}\times u_1(b_1)-c_{s,1}=0.8\times22-10=7.6$

Solution

– Example:



path \ benefit	$50-t$	$40-t$	$30-0.1t$
$s \to 1 \to d$	7.6	1.2	0.56
$s \to 2 \to d$	4	1.5	1.25
$s \to 2 \to 1 \to d$	2.5	-1.5	1.7
$s \to 1 \to 2 \to d$	1.6	-2.4	0.8

Simulation

- **Settings**

Parameter name	Default value	Range
Deployment area S	100m×100m	-
Number of nodes |V|	-	200-600
Transmission probability	-	0.3-0.9
Transmission cost	-	1-10
Scheduling cycle	20	-
Initial benefit	100	10-100
Benefit decay coefficient	0.02	0.02-0.2
Number of messages	10,000	-

Simulation

- Algorithms in comparison
  - MinDelay
  - MaxRatio
  - MinCost
- Metrics
  - Average utility
  - Average delivery delay
  - Average delivery ratio
  - Average delivery cost

Simulation

- Results
  - Average utility vs. initial benefit

Simulation

- Results
  - Average utility vs. benefit decay coefficient

Simulation

- Results
  - Average utility vs.
    initial benefit & benefit decay coefficient

Simulation

- Results
  - Average delay vs.
    initial benefit & benefit decay coefficient

Simulation

- Results
  - Average ratio vs.
    initial benefit & benefit decay coefficient

Simulation

- Results
  - Average cost vs.
    initial benefit & benefit decay coefficient

Conclusion

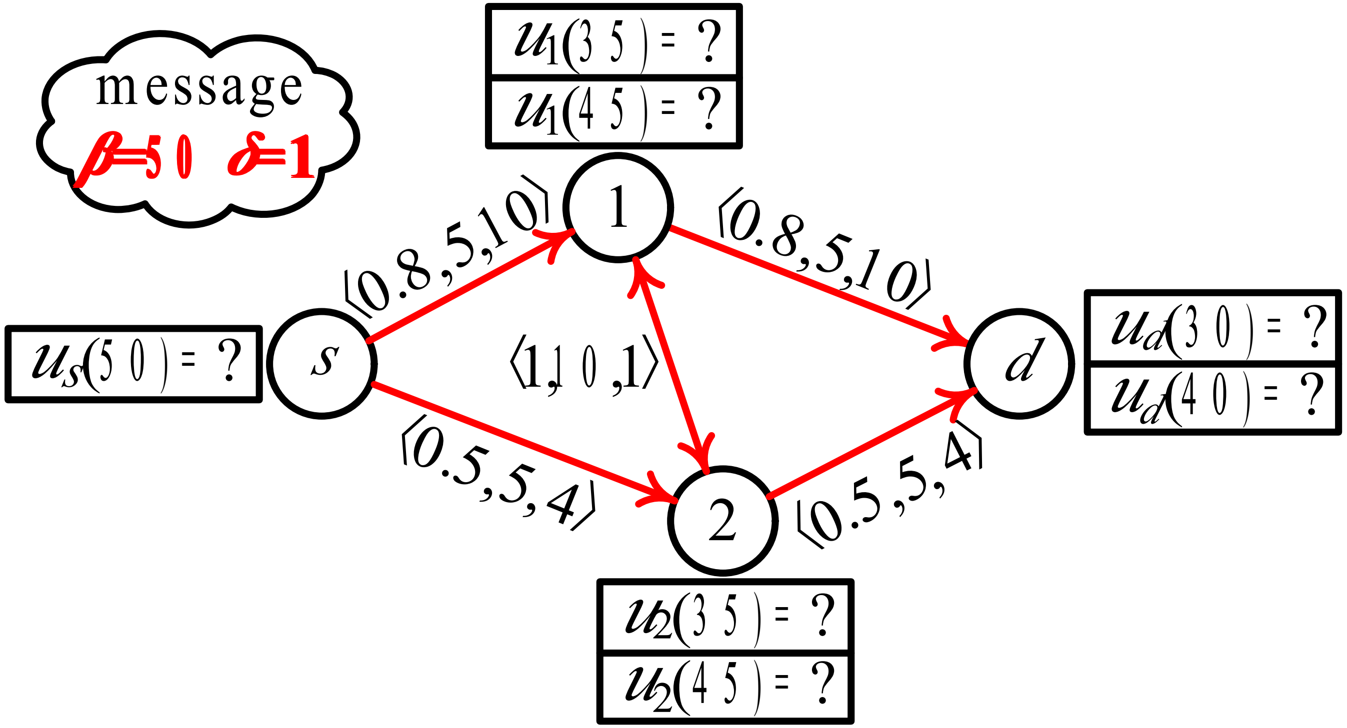
- Our proposed algorithm outperforms the other compared algorithms in utility.
- The larger the initial benefit and the smaller the benefit decay coefficient are, the larger the average utility would be.
- Our proposed algorithm has achieved good performances with reliability, delay, and cost at the same time.

Thanks!

Q&A

Solution

- Example



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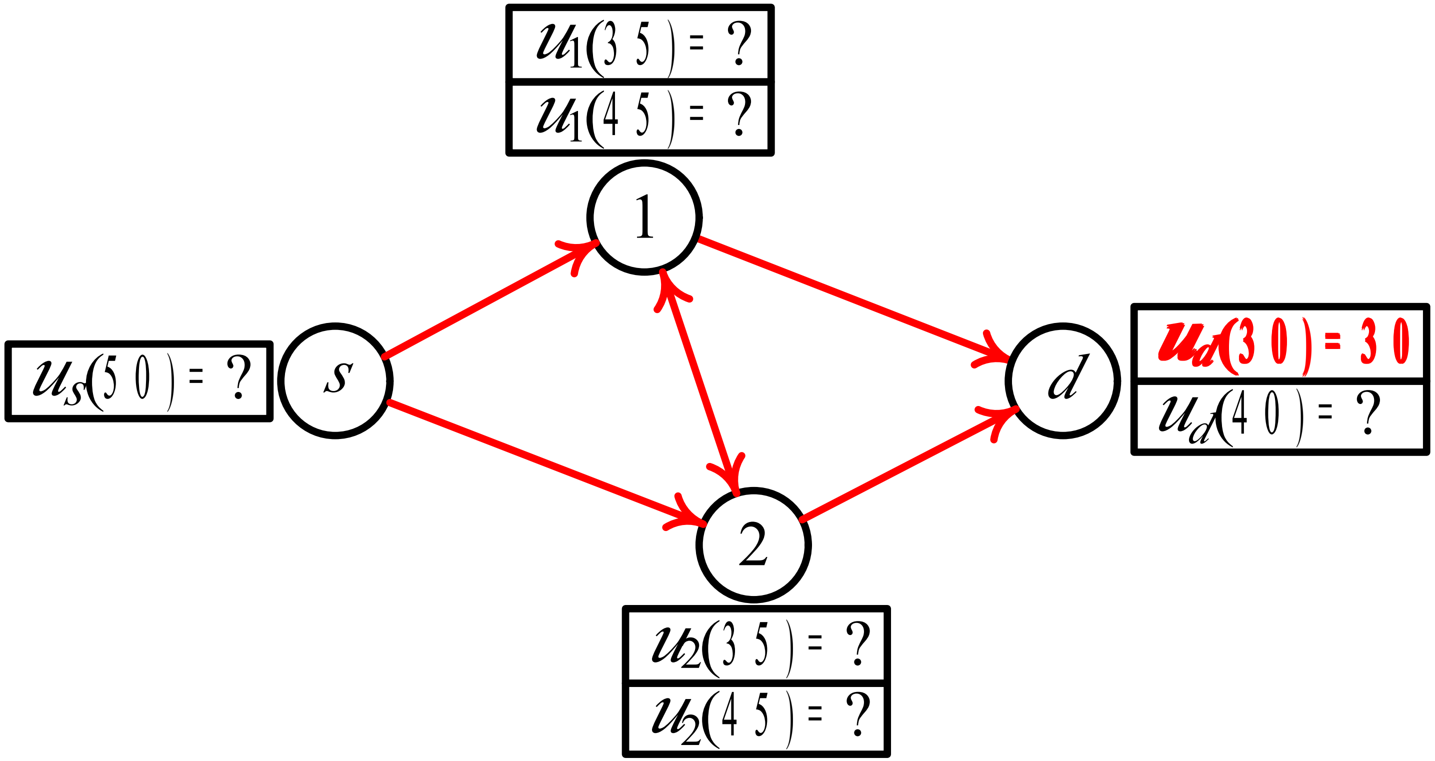

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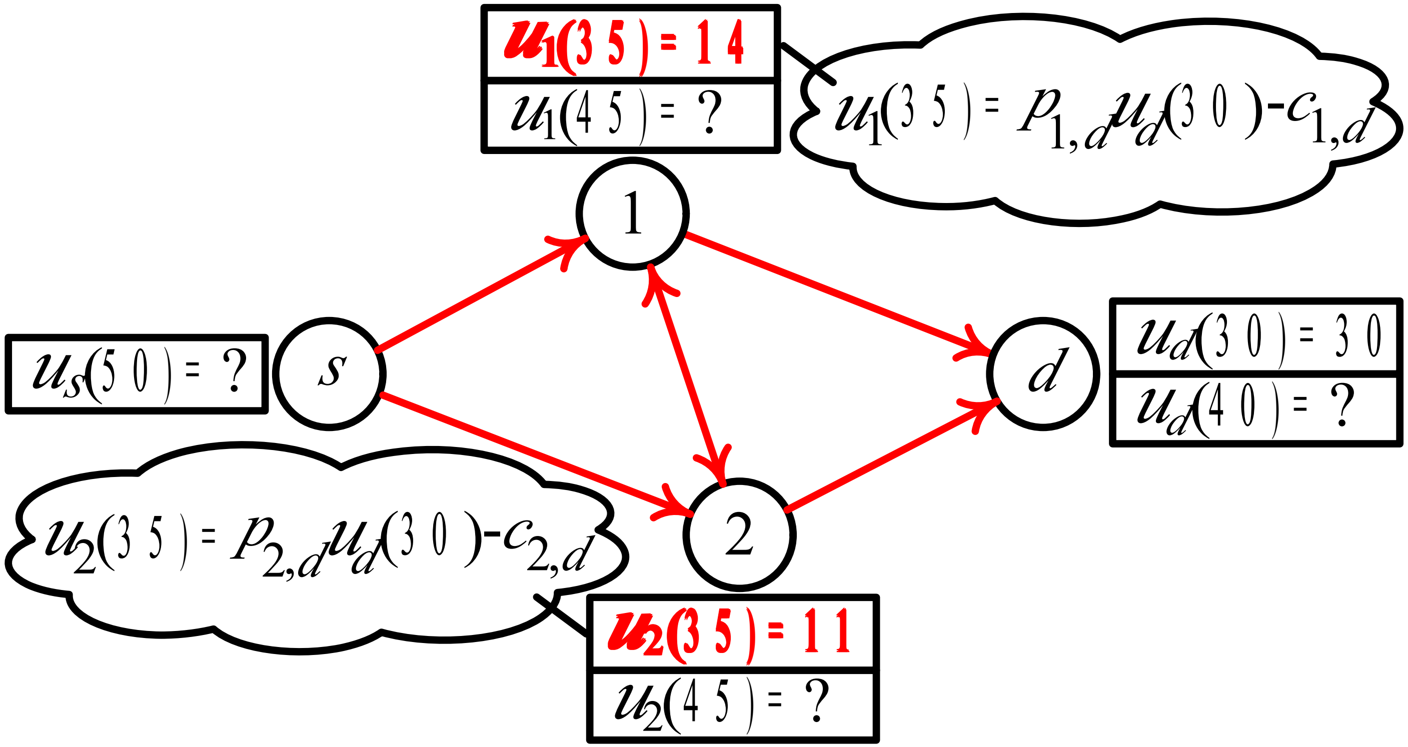

Solution

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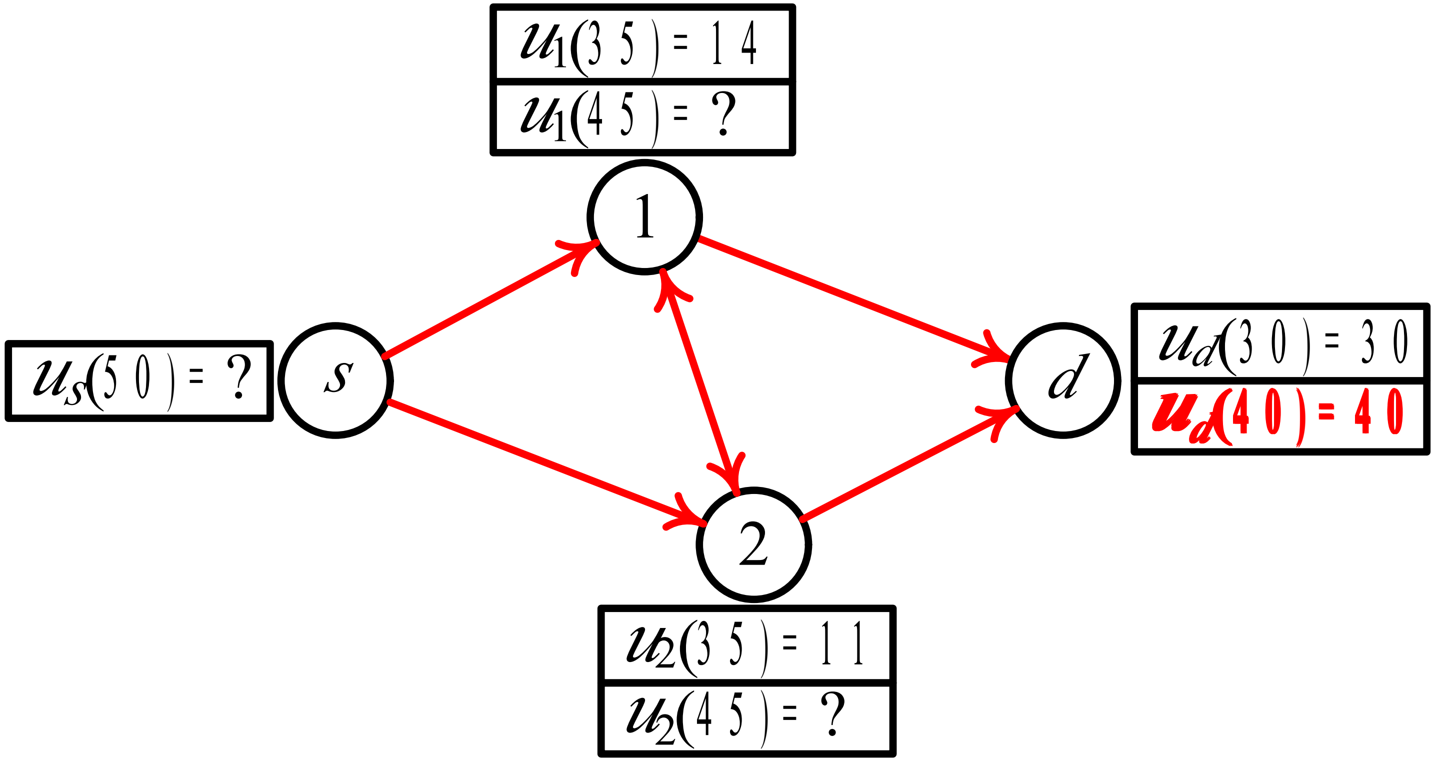
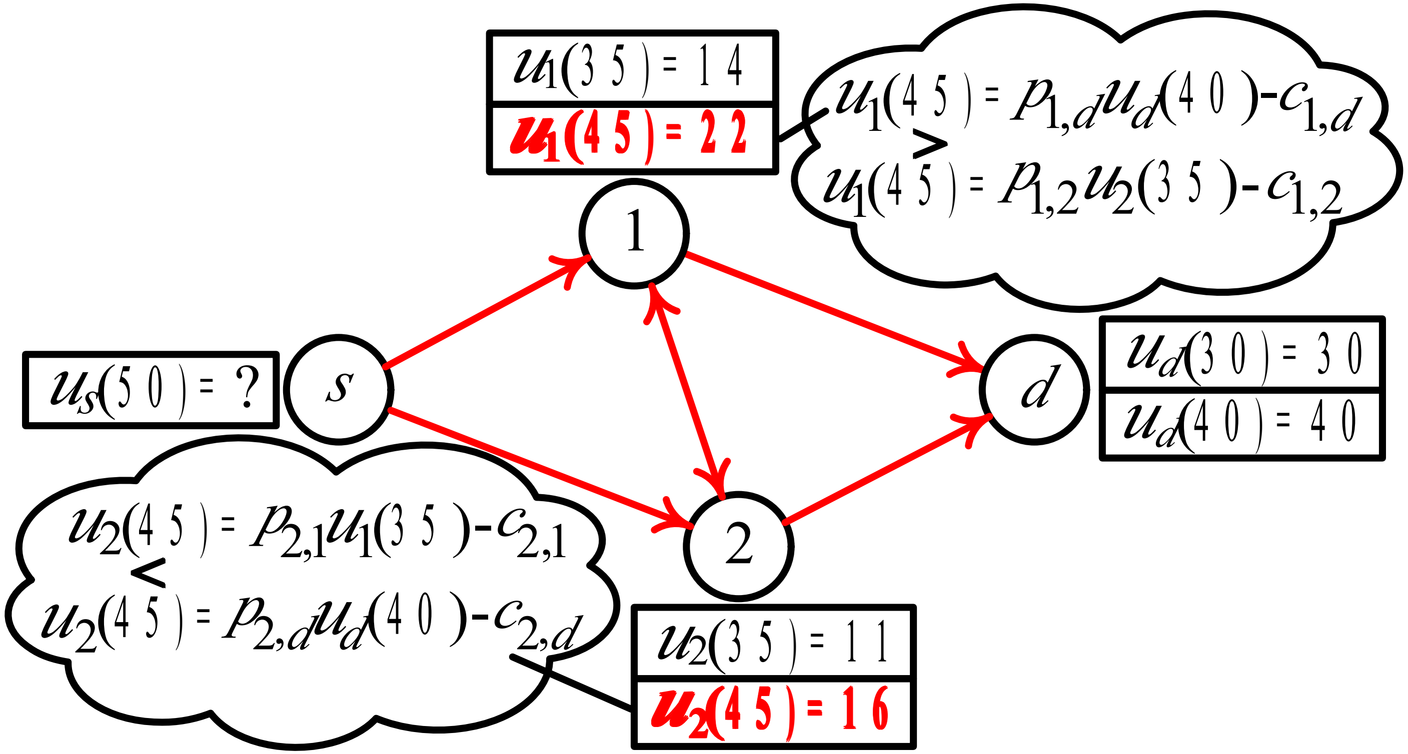


Solution

- Example



Solution

- Example