Coalition-Based Cooperative Packet Delivery Under Uncertainty: A Dynamic Bayesian Coalitional Game

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Introduction

- **Problem**: A base station has packets to transmit to a mobile node. However, this mobile node may not be in the transmission range of the base station. Then, other mobile nodes can help forward packets to the mobile node.
- Similar to the **delay-tolerant networking (DTN)** problem.
- A base station transmits data to the mobile nodes inside its coverage area of transmission and then these mobile nodes carry-and-forward the data to the destination mobile nodes when there is no end-to-end connectivity among the mobile nodes and the base station.
- The key assumption in the existing schemes is that the mobile nodes which are located near each other always help for data delivery.

Introduction

- Consequently, cooperation among the nodes in a group would be dynamic, and the dynamics of the formation of groups among cooperative nodes (or coalitions) needs to be analyzed.
- The theory of coalitional games is used to analyze how the coalitions are formed among mobile nodes for cooperative packet delivery.
- The mobile nodes in the same coalition agree to help each other for packet delivery based on the agreement.
- However, some misbehaving mobile nodes may break the agreement and may not help other nodes (e.g., to reduce their transmission costs and improve their own benefits).

Introduction

- ***Bayesian Nash-stable coalition structure:*** No player will have an incentive (i.e., a better payoff without making the others get worse payoffs) to move from its current coalition to any other coalition that makes the coalitional structure to change.

- ***Bayesian Core****:* A set of payoffs corresponding to a grand coalition (i.e., a coalition of all the players) upon which no other coalition can improve, and therefore, no player has an incentive to leave the grand coalition.

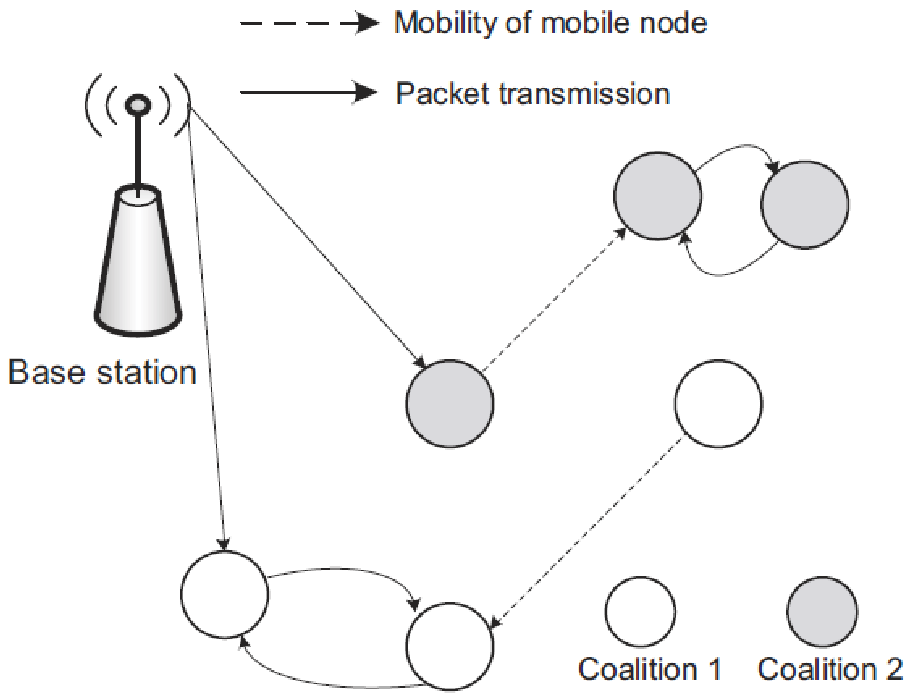
- ***Perfect Bayesian equilibrium :***
  - The players' beliefs are updated according to *Bayes' theorem* and the players make their optimal actions with respect to their beliefs .
  - Bayesian Nash-stable coalitional structure for each subgame is called perfect Bayesian equilibrium.

Contributions

- The major contributions of the work can be summarized as follows:
  - formulation of a Bayesian coalitional game to model the uncertainty in node behavior for cooperative packet delivery in wireless mobile networks,
  - analysis of two solution concepts, namely, Nash-stable equilibrum and Bayesian core, for the proposed Bayesian coalitional game, and
  - extension of the static Bayesian coalitional game to a multi-stage dynamic coalitional game and proposal of a belief update mechanism for the dynamic Bayesian coalitional game,

System Model and Assumptions

- Mobile nodes can form coalitions to help forward data from a base station to other mobile nodes which are out of the transmission range of the base station.



System Model and Assumptions

- We consider a scenario with *N* rational mobile nodes which can form coalitions among them for cooperative packet delivery to/from the base stations.

- We assume that each mobile node will carry-and-forward packets to other mobile nodes in the same coalition when they meet each other.

- We assume that, over a period of time, the patterns of mobility and inter-encounter time of each mobile node can be predicted.

- Any mobile node *i* receives packets from the base station or from another mobile node *j* in the same coalition at the cost of c^{r}_{ij} per packet.

System Model and Assumptions

- Mobile node *i* then forwards the packets to their destination or to another
- mobile node *j′* in the same coalition which does not have these packets. For mobile node I, the cost of this transmission is $c^{\mathrm{f}}_{ij'}$ per packet.
- Let d_i denote the packet delivery delay which is the duration from when a packet is originally transmitted from the base station to when the packet is received by its destination.
- Given the benefit of smaller delay due to cooperative packet delivery at the cost of relaying packets to the other mobile nodes in the same coalition, a coalitional game-theoretic approach is applied to analyze the coalition formation process among mobile nodes.

Uncertainty in Node Behavior for Cooperative Packet Delivery

- A ***well-behaved*** node always helps to deliver packets to the other nodes in the same coalition.
- A ***misbehaving*** node does not always help to deliver packets to other nodes. In particular, a misbehaving node may refuse to deliver a packet of other nodes in the same coalition with a probability.
- A mobile node does not know the types of other mobile nodes.
- A mobile node cannot observe whether a packet sent to the next mobile node will be forwarded to other mobile nodes or not.
- But a mobile node itself directly experiences the packet forwarding from other mobile nodes and uses its observations to estimate the types of other mobile nodes.

Formulation of the Bayesian Coalitional Game Model

- A Bayesian coalitional game with *non-transferable utility* is defined as

$$G = \langle \mathbb{N}, \mathbb{T}, \mathcal{P}, (\bar{u}_i)_{i \in \mathbb{N}}, (\succeq_i)_{i \in \mathbb{N}} \rangle.$$

- *Players:* The set of players consists of *N* rational mobile nodes and is denoted by $\mathbb{N} = \{1, \ldots, N\}$

- *Type:* The type space is denoted by $\mathbb{T} = \mathbb{T}_1 \times \cdots \times \mathbb{T}_M$ where $\mathbb{T}_i = \{T_w, T_m\}$ denotes a player's possible type set. T_w is for well-behaved nodes and T_m is for misbehaving nodes.

- *Probability Distribution:* $\mathcal{P}$ is a common a priori probability over the type in $\mathbb{T}$.

Formulation of the Bayesian Coalitional Game Model

- Mobile node *i*'s belief probabilities about mobile node *j* over types T_w *and* T_m *are denoted by* p_{ij} *and* $1-p_{ij}$*, respectively.*

- Also, the probability of packet delivery refusal ς_{ij} for a misbehaving mobile node is unknown to the other mobile nodes.

- *Preference*: $\succeq_i$ describes player *i's* preference. For example, $S_1 \succeq_i S_2$ means that player *i* prefers to be a member of coalition S_2 at most as much as S_1 .

- *Action:* The action of each player is to make a decision on which coalition to form (i.e., to join or leave a coalition) based on its own payoff and the payoffs of other players in the current coalition as well as the new coalition.

Formulation of the Bayesian Coalitional Game Model

- *Payoff:* $\bar{u}_i(\mathcal{S}, \vec{\mathrm{t}}^i_{\mathcal{S}})$ is defined as the expected payoff of mobile node *i* which is the difference between the average utility and the average cost given the beliefs of node *i* about the types of all players in the coalition $\mathcal{S}$.

$$\bar{u}_i(\mathcal{S}, \vec{\mathrm{t}}^i_{\mathcal{S}}) \quad = \quad E[\alpha_i R_i(\mathcal{S}, \vec{\mathrm{t}}^i_{\mathcal{S}}) - \beta_i C_i(\mathcal{S}, \vec{\mathrm{t}}^i_{\mathcal{S}})]$$

- The utility of mobile node *i* is defined as the following equation.

$$R_i(\mathcal{S}, \vec{\mathrm{t}}^i_{\mathcal{S}}) = \begin{cases} \max\left(0, 1 - \frac{d_i(\mathcal{S})}{\min(\hat{d}_i, d_i^{TTL})}\right), & |\mathcal{S}| > 1 \\ 0, & \text{otherwise} \end{cases}$$

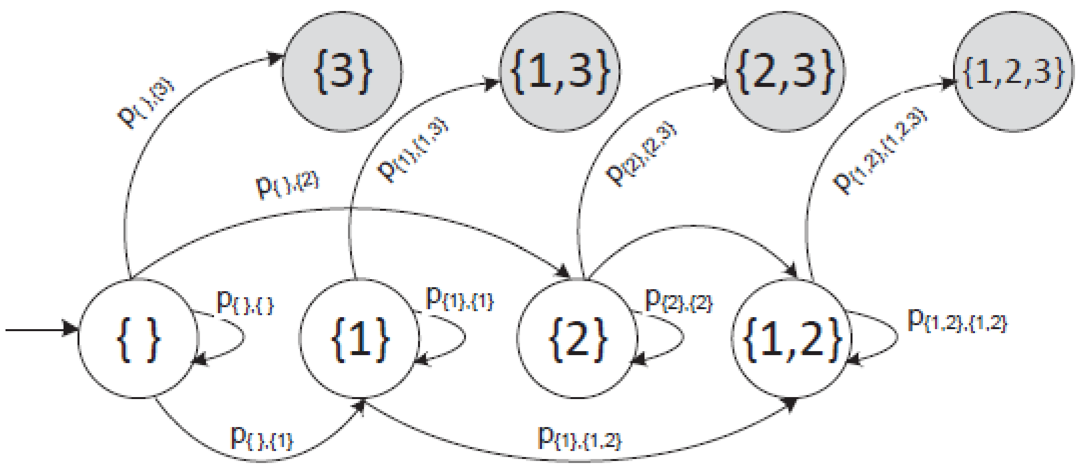
- The average cost of mobile node *i* for delivering a packet to any mobile node *j* in the same coalition can be expressed as the following equation.

$$C_i(\mathcal{S}, \vec{\mathrm{t}}^i_{\mathcal{S}}) = \begin{cases} \sum_{j \in \mathcal{S}, j \neq i} c_{ij}(\mathcal{S}), & |\mathcal{S}| > 1 \\ 0, & \text{otherwise} \end{cases}$$

Formulation of the Bayesian Coalitional Game Model

- We formulate a discrete-time Markov chain model to find the utility and the average cost (and hence the expected payoff) of each mobile node under uncertainty about other mobile nodes' *types*.

- The figure shows the DTMC for a packet delivery scenario when there are 3 mobile nodes in the same coalition. Mobile nodes 1 and 2 help the base station to deliver a packet to mobile node 3.



Nash-Stable Coalitional Structure and Bayesian Core

- **Definition 1:** A coalitional structure $\Upsilon = \{\mathcal{S}_1, \ldots, \mathcal{S}_l, \ldots, \mathcal{S}_s\}$ is Nash-stable if $\forall i \in \mathbb{N}, \mathcal{S}_l^i \succeq_i \mathcal{S}_k \cup \{i\}\ for\ all\ \mathcal{S}_k \in \Upsilon \setminus \mathcal{S}_l^i \cup \{\emptyset\}$.
- No player *i* has an incentive to leave its current coalition $\mathcal{S}_l^i$ and act alone. This implies that no player believes that she will be better off (in terms of expected payoff) by acting alone.
- Given a player's beliefs about the other players, no player *i* will have an incentive to move from its current coalition $\mathcal{S}_l^i$ to any other coalition that makes the coalitional structure to change. This implies no player believes that she will be better off by joining the new.

Algorithm 1: Distributed coalition formation algorithm

Initialize $\phi = 0$ and $\Upsilon(\phi) = \{\mathcal{S}_1(\phi), \ldots, \mathcal{S}_s(\phi)\}$
loop
  At time ϕ, mobile node i is randomly selected to make a decision to leave $\mathcal{S}_l^i(\phi)$ and join any coalition $\mathcal{S}_k \in \Upsilon(\phi) \setminus \mathcal{S}_l^i(\phi) \cup \{\emptyset\}$.
  Mobile node i computes its expected payoff $\bar{u}_i(S_l^i(\phi), \vec{\mathbf{t}}^i_{S_l^i(\phi)})$
  Mobile node i randomly selects one of coalitions, i.e., $\mathcal{S}_k$, to join.
  Mobile node i computes its expected payoff $\bar{u}_i(\mathcal{S}_k(\phi) \cup \{i\}, \vec{\mathbf{t}}^i_{\mathcal{S}_k(\phi)\cup\{i\}})$
  if $\bar{u}_i(\mathcal{S}_k(\phi) \cup \{i\}, \vec{\mathbf{t}}^i_{\mathcal{S}_k(\phi)\cup\{i\}}) > \bar{u}_i(S_l^i(\phi), \vec{\mathbf{t}}^i_{S_l^i(\phi)})$
    Mobile node i sends its request to the central coordinator to join $\mathcal{S}_k(\tau)$.
    Mobile node $j \in \mathcal{S}_k(\phi)$ computes and sends its expected payoff $\bar{u}_j(\mathcal{S}_k(\phi) \cup \{i\}, \vec{\mathbf{t}}^j_{\mathcal{S}_k(\phi)\cup\{j\}})$ to the central coordinator.
    if $\mathcal{S}_k(\phi) \cup \{i\} \succ_i \mathcal{S}_l^i(\phi)$ is true
      Mobile node i joins $\mathcal{S}_k(\phi)$
      $\Upsilon(\phi+1) = (\Upsilon(\phi) \setminus \{\mathcal{S}_l^i(\phi), \mathcal{S}_k(\phi)\}) \cup \{\mathcal{S}_k(\phi) \cup \{i\}\} \cup \{\mathcal{S}_l^i(\phi) \setminus \{i\}\}$
    else
      $\Upsilon(\phi+1) = \Upsilon(\phi)$
    end
  else
    $\Upsilon(\phi+1) = \Upsilon(\phi)$
  end
  $\phi = \phi + 1$
end loop when a Nash-stable coalitional structure Υ^* is obtained

Nash-Stable Coalitional Structure and Bayesian Core

- Starting with any coalitional structure , if any mobile node *i* still prefers to move to a new coalition, then the current coalitional structure is not Nash-stable.

- The current coalitional structure changes to a new coalitional structure after mobile node *i* joins a new coalition.

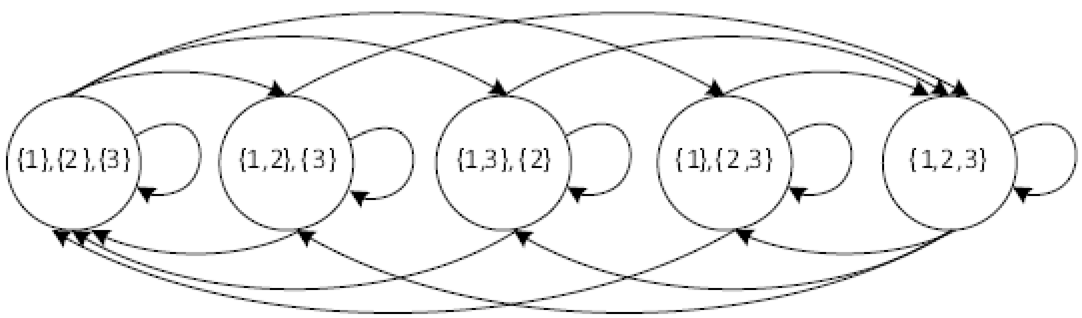
- There are maximum 2^{N-1} coalitions including an empty coalition for each mobile node *i* to possibly join.

- The worst case is that if mobile node *i* cannot find any non-empty coalition to join, mobile node *i* then forms its singleton coalition.

Nash-Stable Coalitional Structure and Bayesian Core

- The DTMC follows Algorithm 1 when the state (i.e., coalitional structure) changes based on individual preferences of the players.

- As an example, with three players, the state transition diagram of the DTMC for coalition formation is shown in the below figure.



Dynamic Bayesian Coalitional Game

- A player can update her beliefs (i.e., probabilities) about the *types* of other players as the game evolves according to Bayes' rules.

- Also, it can update the probabilities of packet delivery refusal ς_{ij} that for misbehaving mobile nodes based on an exponential moving average method.

- The update is made based on each player's imperfect observations about others' behaviors (i.e., there can be *false positive observation error*).

- When the coalitional game with belief update mechanism is repeatedly played, the solution of each subgame (i.e., *Bayesian Nash-stable coalitional structure*), which can be called a *perfect Bayesian equilibrium*, is obtained.

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Dynamic Bayesian Coalitional Game

- Mobile node *i* can update its belief probability about mobile node *j*'s well-behaved *type* according to Bayes' theorem as shown

$$p_{ij}^{\tau_{ij}+1}(\chi_{ij}(\omega_c=\Omega_c)) = \frac{p_{ij}^{\tau_{ij}}(1-p_e)}{p_{ij}^{\tau_{ij}}(1-p_e)+(1-p_{ij}^{\tau_{ij}})(1-\varsigma_{ij}^{\tau_{ij}+1})(1-p_e)}.$$

$$p_{ij}^{\tau_{ij}+1}(\chi_{ij}(\omega_n)) = \frac{p_{ij}^{\tau_{ij}}p_e}{p_{ij}^{\tau_{ij}}p_e+(1-p_{ij}^{\tau_{ij}})(\varsigma_{ij}^{\tau_{ij}+1}+(1-\varsigma_{ij}^{\tau_{ij}+1})p_e)}.$$

$$\varsigma_{ij}^{\tau_{ij}+1} = w_1\varsigma_{ij}^{\tau_{ij}+1\dagger}+w_2\varsigma_{ij}^{\tau_{ij}}$$

$$\varsigma_{ij}^{\tau_{ij}+1\dagger} = \begin{cases} \left(\dfrac{(1-p_e)-\frac{|\chi_{ij}(\omega_c=\Omega_c)|^{\tau_{ij}+1}}{|\chi_{ij}|^{\tau_{ij}+1}}}{(1-p_{ij}^{\tau_{ij}})(1-p_e)}\right), & |\chi_{ij}(\omega_c=\Omega_c)|^{\tau_{ij}+1}>0 \\ \left(\dfrac{\frac{|\chi_{ij}(\omega_n)|^{\tau_{ij}+1}}{|\chi_{ij}|^{\tau_{ij}+1}}-p_e}{(1-p_{ij}^{\tau_{ij}})(1-p_e)}\right), & |\chi_{ij}(\omega_n)|^{\tau_{ij}+1}>0. \end{cases}$$

Algorithm 2: Distributed algorithm for dynamic Bayesian coalitional game with belief update mechanism

1: Mobile node i initializes the counter τ_{ij} for all $j \in \mathbb{N}$ and $j \neq i$. τ_{ij} is the τ_{ij}-th time of observation of helping behavior of mobile node j observed by mobile node i (i.e., $\tau_{ij} = 0, \forall j$).

2: Mobile node i initializes its beliefs $P_j^i(t_j = T_m) = p_{ij}^{\tau_{ij}}$ and $P_j^i(t_j = T_w) = 1 - p_{ij}^{\tau_{ij}}$ for all $j \in \mathbb{N}$ and $j \neq i$, where $0 < p_{ij}^{\tau_{ij}} < 1$.

3: The coalition formation algorithm, **Algorithm 1**, is run.

4: **loop**

5: Mobile node i in $\mathcal{S}_l^i \in \Upsilon$ helps others to deliver packet according to the current stable coalitional structure Υ.

6: Mobile node i observes the helping behavior $\chi_{ij}^{\tau_{ij}}$ of mobile node j.

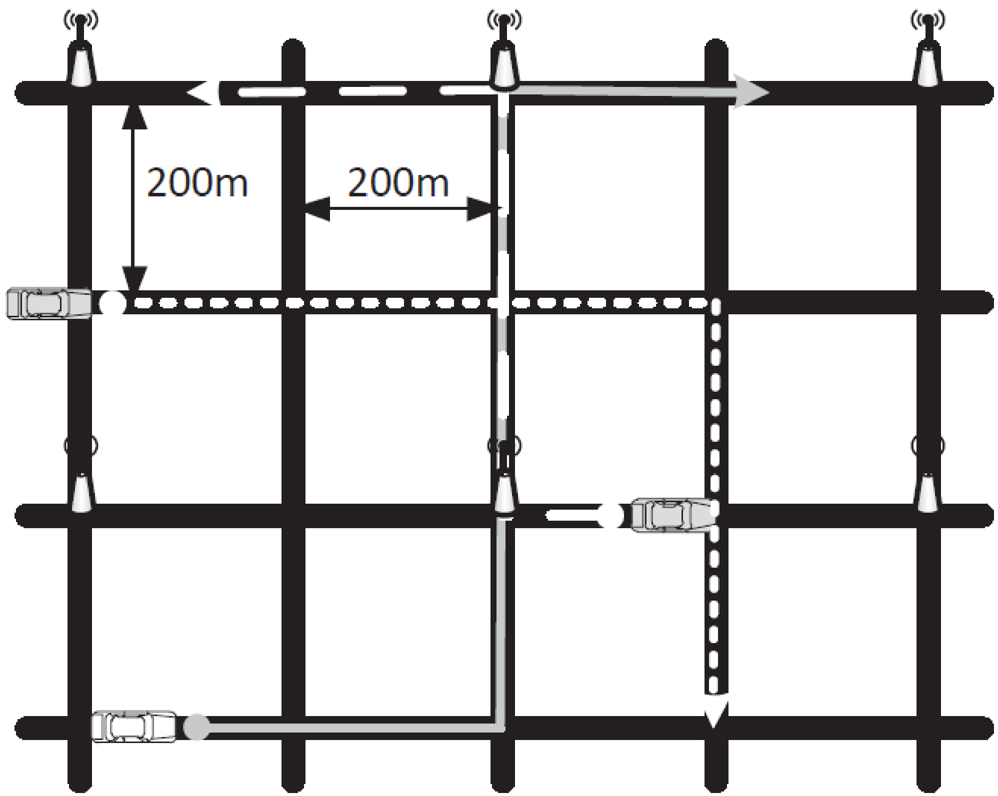
7: Mobile node i updates its the belief probability of packet delivery to be refused by other mobile node j, if mobile node j is a misbehaving node, i.e., $\varsigma_{ij}^{\tau_{ij}+1}(\chi_{ij}^{\tau_{ij}}(\omega_n))$.

8: Mobile node i updates its probabilistic belief about another mobile node j's type $p_{ij}^{\tau_{ij}+1}(\chi_{ij}^{\tau_{ij}})$.

9: **end loop** until packet delivery is done or network state changes

10: Go to Step 3.

Performance Evaluation



- Apply this cooperative packet delivery in vehicle-to-roadside (V2R) communications as the example.
- To find the encounter information among vehicles and base stations, we use a traffic simulator named “SUMO” and then use MATLAB to simulate the cooperative game

Performance Evaluation

DEFAULT VALUES OF PARAMETERS

Parameter	Description/value
Communication range of base station	Radius of 100 m
Communication range of vehicle	Radius of 50 m
Maximum speed on roads	50 km/h (31.25 mph)
Vehicle's acceleration	0.8 m/s^2
Vehicle's deceleration	4.5 m/s^2

15 DIFFERENT COALITIONAL STRUCTURES FOR 4 VEHICLES

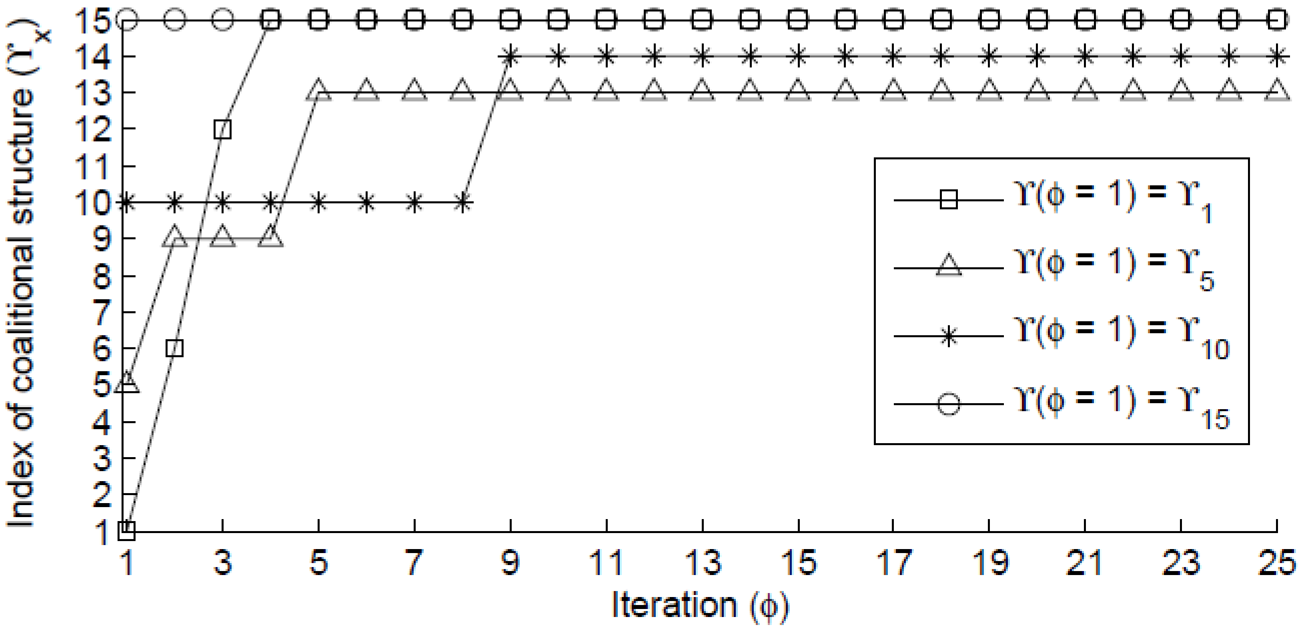
Coalitional structure					
Υ_1	$\{1\},\{2\},\{3\},\{4\}$	Υ_2	$\{1,2\},\{3\},\{4\}$	Υ_3	$\{1\},\{2\},\{3,4\}$
Υ_4	$\{1,3\},\{2\},\{4\}$	Υ_5	$\{1\},\{3\},\{2,4\}$	Υ_6	$\{1,4\},\{2\},\{3\}$
Υ_7	$\{1\},\{4\},\{2,3\}$	Υ_8	$\{1,2\},\{3,4\}$	Υ_9	$\{1,3\},\{2,4\}$
Υ_{10}	$\{1,4\},\{2,3\}$	Υ_{11}	$\{1,2,3\},\{4\}$	Υ_{12}	$\{1,2,4\},\{3\}$
Υ_{13}	$\{1,3,4\},\{2\}$	Υ_{14}	$\{1\},\{2,3,4\}$	Υ_{15}	$\{1,2,3,4\}$

RATES (r_{ij}) PER SECOND THAT EACH VEHICLE MEETS OTHER VEHICLES AND AN RSB ON A ROAD

Rate	RBS	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4
RSB	-	0.0339	0.0345	0.0299	0.0308
Vehicle 1	0.0339	-	0.0103	0.0108	0.0104
Vehicle 2	0.0345	0.0103	-	0.0122	0.0145
Vehicle 3	0.0299	0.0108	0.0122	-	0.0247
Vehicle 4	0.0308	0.0104	0.0145	0.0247	-

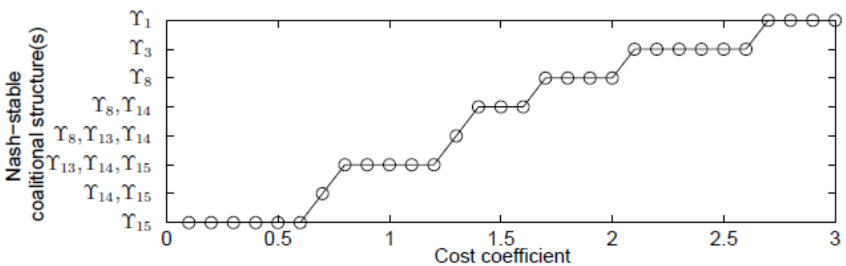
Performance Evaluation

- Nash-stable coalitional structure obtained from the individual preference-based algorithm.

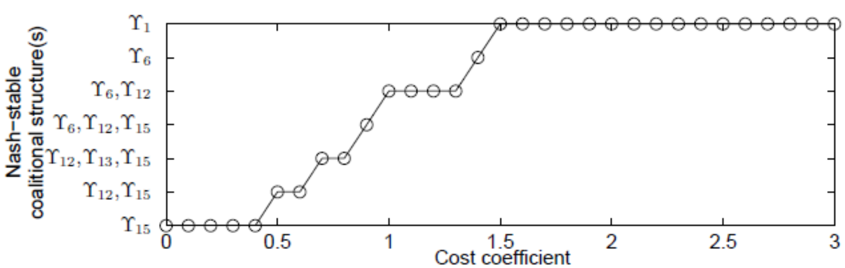


Performance Evaluation

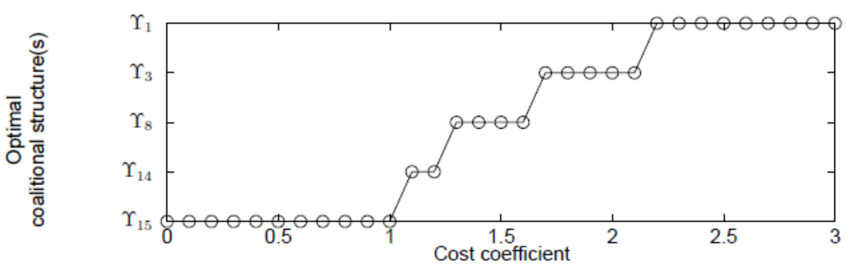
Nash-stable coalitional structure



(a)



(b)



(c)

- (a) Nash-stable coalitional structures with incomplete information
- (b) Nash-stable coalitional structures with complete information, and

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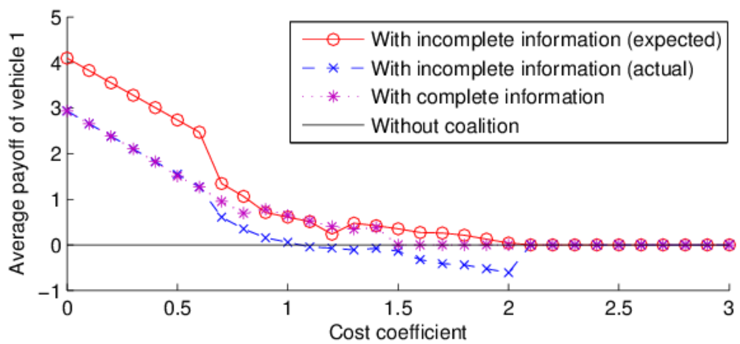
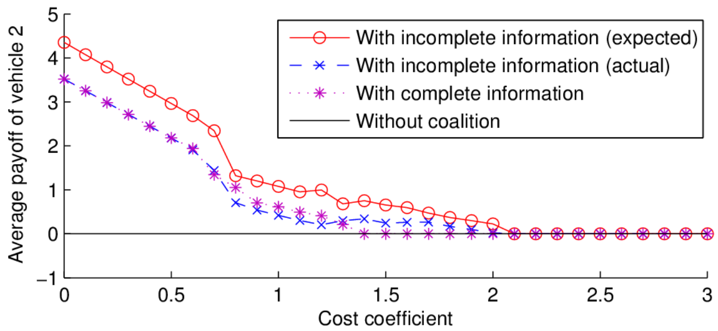
- (c) optimal coalitional structures under different values of cost coefficient.

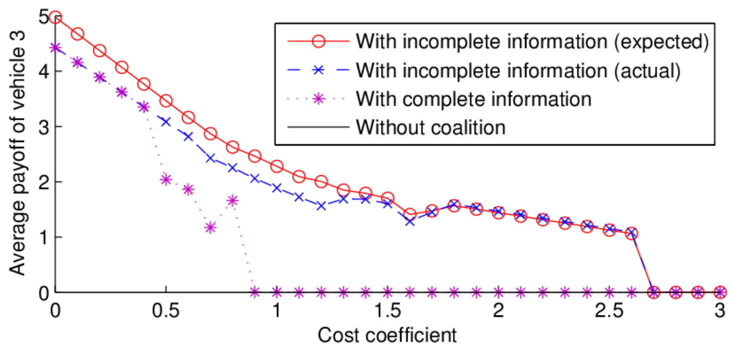
Performance Evaluation

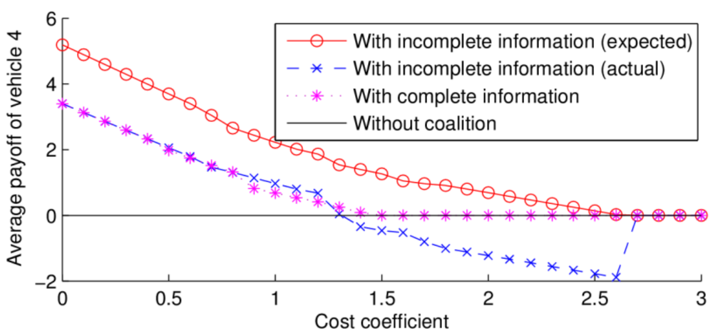
Average payoff

- With incomplete information, in some cases, the actual payoff can be lower than zero due to lack of true information about other users' *types*.



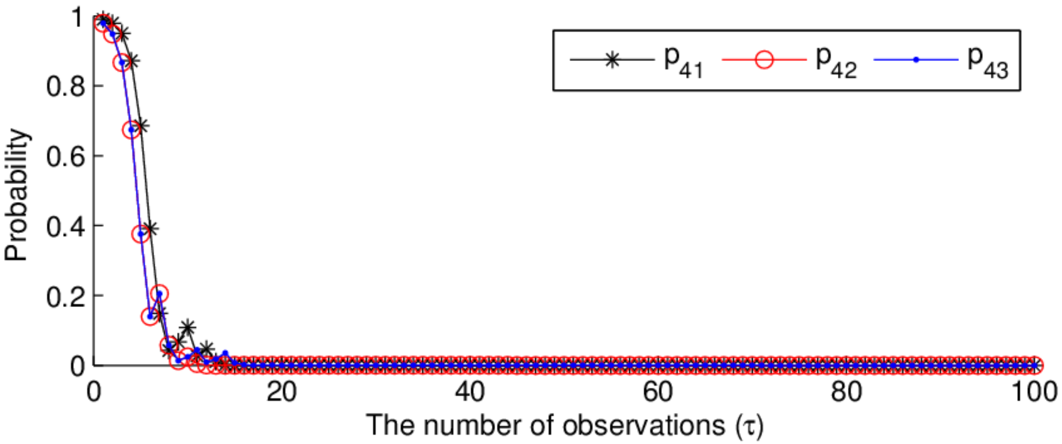




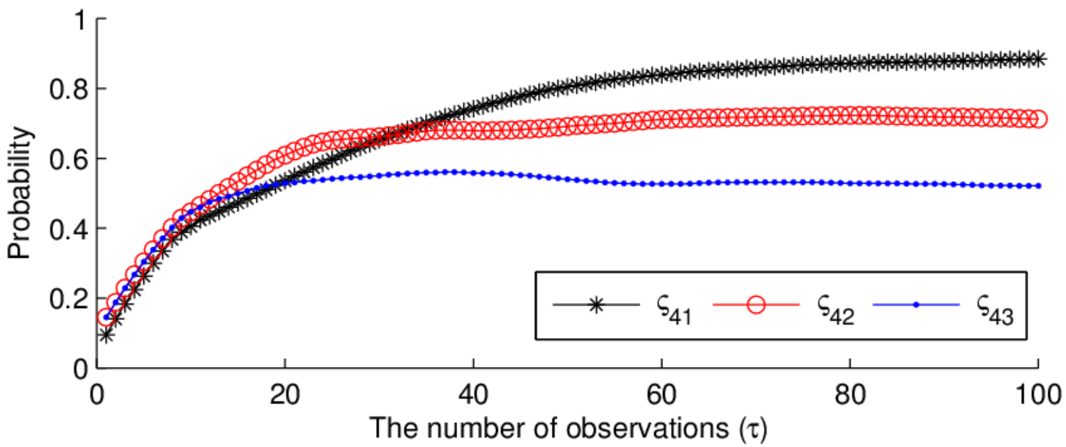


Performance Evaluation

Dynamic belief update



- (a) Vehicle 4's belief probabilities that vehicles 1, 2, and 3 are well behaved (i.e., p_{41}, p_{42}, p_{43})



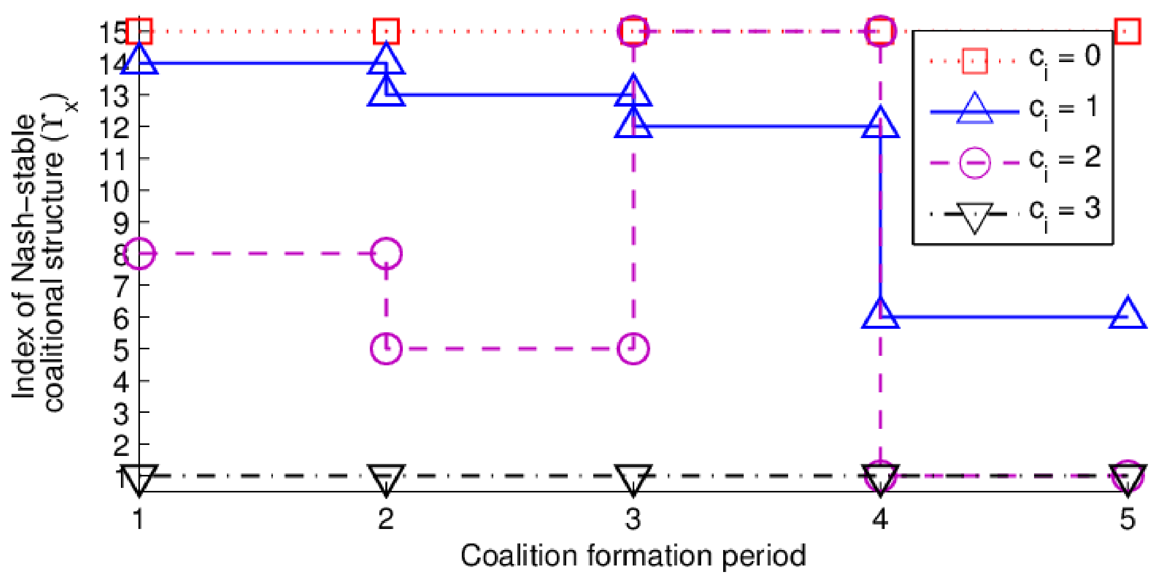
- (b) Vehicle 4's belief probabilities that vehicles 1, 2, and 3 will refuse to deliver a packet (i.e., ς_{41}, ς_{42}, ς_{43}).

- Using Bayes' theorem to update the beliefs about the other vehicles in the same coalition, the probabilistic beliefs of the vehicles will converge to the actual values.

Performance Evaluation

Dynamic belief update

- If all of the vehicles' beliefs converge to the actual values, the actual payoffs from the dynamic Bayesian coalitional game will converge to the same values of payoff obtained from the coalitional game with complete information.



- In the worst case, the vehicle acts alone after the vehicle can learn some other vehicles' actual *types. Hence, the actual payoff is not lower* than the payoff when the vehicle acts alone.

Conclusion

- A dynamic Bayesian coalitional game for coalition-based cooperative packet delivery among mobile nodes in a mobile network under uncertainty in node behavior (i.e., selfishness of nodes) has been presented.

- A Nash-stable coalitional structure, which is the solution of this coalitional game, can be obtained by using the individual preference-based algorithm.

- Moreover, a belief update mechanism based on Bayes' theorem has been proposed. Each mobile node can update its beliefs about the other mobile nodes' types (i.e., well-behaved and misbehaving) under the proposed Bayesian coalitional game.

Thank you