Wireless Communication in Multi-agent Autonomous Robotic System

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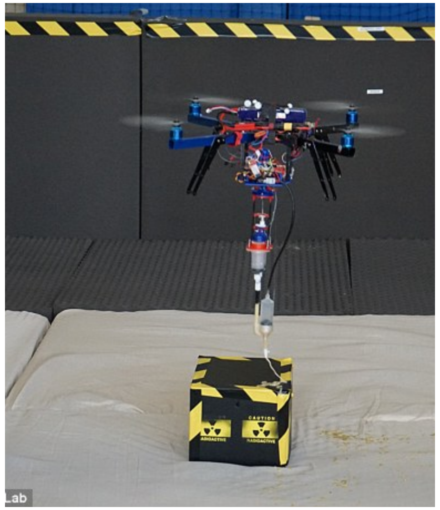
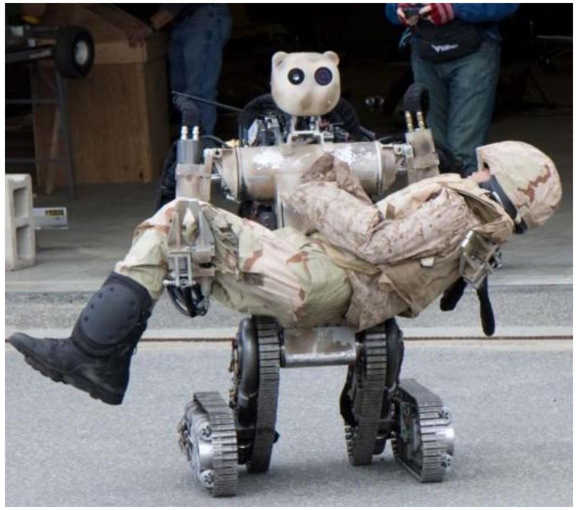
Tasks we could NOT do without a group of robots:

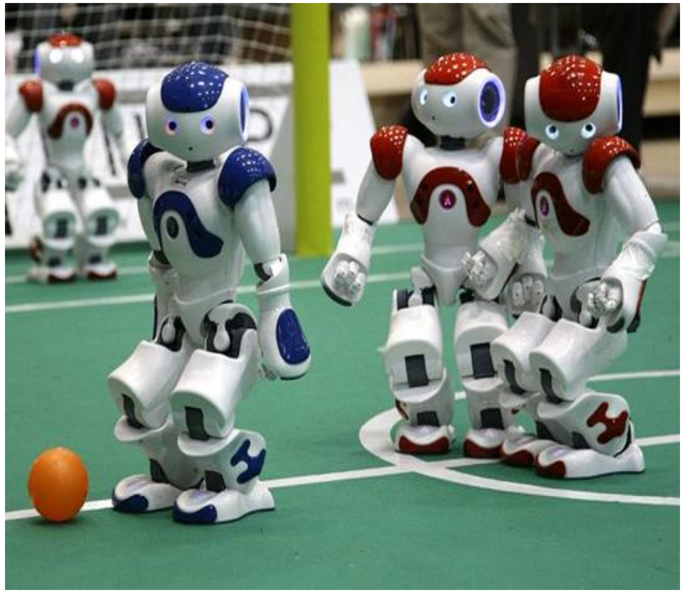
- Military mission in harsh and unknown environment
- Mass production of sensitive and high quality products
- Space exploration
- Remote and Minimally-Invasive Surgery
- Underwater exploration

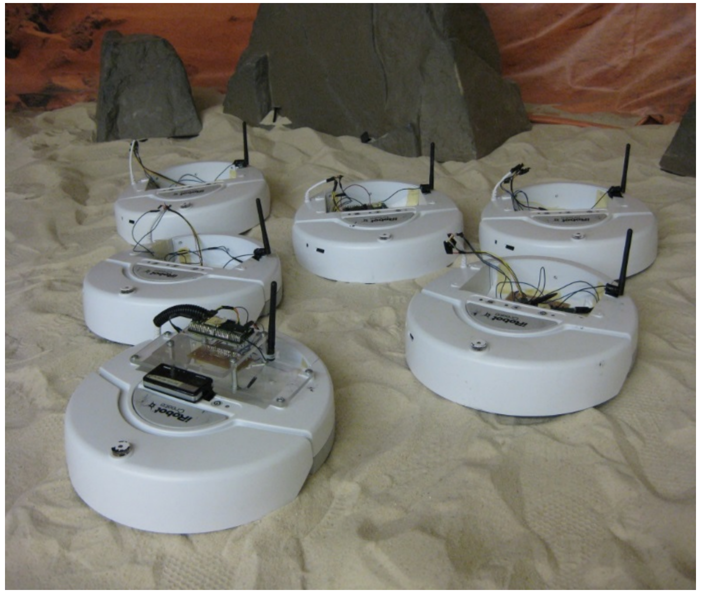




Why communication is important among robots?

- Communication capability among a group of robots is a key necessity to:
  - Negotiate task scheduling
  - Exchange critical information acquired from robots’ sensors
  - Receive and relay the orders from the controller





Specification of different wireless communication protocols among a group of nodes

Protocol	Maximum number of nodes	Frequency Band	Range (m)	Data Rate	Power Consumption
WLAN	N/A	2.4,3.6,5(GHz)	100-300	54 (Mbps)	High
Bluetooth	8 nodes	2.4 (GHz)	100	2.1 (Kbps)	Low
Infrared	N/A	2.4 (GHz)	1	2.4 (Kbps)	Low
ZigBee	255	2.4 (GHz)	75	250 (Kbps)	Very Low
Magnetic Induction	N/A	15 (MHz)	3	100-300(bps)	Very Low

Different types of communication networks

Centralized networks

- There is a main controller node called base station (BS)
- All the nodes communicate with each other through BS
  - Pros: higher number of nodes, more accurate
  - Cons: expensive- overhead signaling- dependency on the BS

Distributed networks (ad-hoc networks)

- The network is established for a very specific application
- Nodes can share information directly
  - Pros: low cost- easy to set up- using unlicensed frequency spectrum
  - Cons: low transmission rate, more susceptible against jamming, dynamic topology

MANET

- Due to the specific nature of robot-based networks, the suitable wireless communication interface should be:
  - Power efficient (battery life is an important factor in wireless nodes)
  - capable of direct communication (in cases of no infrastructure for base station)
  - Self-organizing
  - Decentralized ad-hoc network (Short range communication)
- “Mobile Ad-hoc Communication Network” (MANET) is a group of mobile nodes with limited resources such as, processing capability and storage capacity, which form a **temporary unpredictable** network.
- The network is decentralized and autonomous, where all network activity including discovering the topology and delivering messages must be executed by the nodes themselves.

MANET design requirement

- Distributed Operation and Self Organization
  - No node in the ad hoc network can depend on a network in the background to support the basic functions like routing instead it should be performed in decentralized manner.
  - Since topology changes due to mobility, the network should be self-organized to adapt to the changes.
- Dynamic Routing
  - Table-driven routing
    - It is fast but causes signaling traffic and power consumption
  - Source-initiated on-demand routing
    - Package will wait until route is discovered, but less signaling for update
- Connectivity
  - In connected ad hoc network, for any node there must be a multihop path to any other node.

Game theory and MANET

- Based on the application, the proper communication network can be selected. However, there are many technical challenges to be tackled before establishing the network, namely: power-control, spectrum allocation, security.
- Numerical optimization methods are widely employed to address the mentioned technical problems. However, when the number of independent parameters and the nodes increases, they become less practical in terms of computational complexity and time.
- Thanks to the recent advancements in electronics and software, robots are becoming more and more intelligent, cognitive, and capable of making strategic decisions based on the situation.
- Game theory is a well-know and suitable mathematical framework to model the interactions among the wireless nodes by taking advantage of the robots' aforementioned capabilities.
- Game theory better captures the interactions among the nodes, gives us a better understanding of strategic actions in different situations, and is specially suitable for analyzing the interactions among large number of nodes with different performance function.

A brief introduction to Game Theory

- Game Theory is an strong mathematical tool to model the interaction in an autonomous multi-agent cognitive mobile agents network.

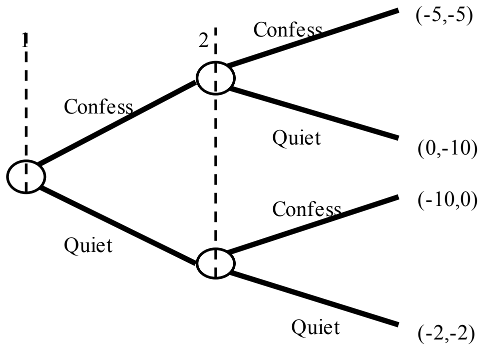
Component of the Game	Elements in a wireless network
Players	Nodes in the wireless network
The set of strategies	modulation scheme, Coding rate, transmit power level, forwarding packet or not.
The set of pay-offs	Performance metrics (e.g. Throughput, Delay, SINR, etc.)

Game Theory

- Non-Cooperative
  - Interaction and decision making among competitive players
  - Each player choose its strategy independently to improve its own performance
  - Possible solution: Nash Equilibrium
- Cooperative
  - Study behavior of rational players when they cooperate
  - Possible solution:
    - Bargaining game
    - formation of coalition

Non-Cooperative game

- Game in Strategic Form
  - Dominating strategy
    - Player's best strategy, regardless of other players' strategy
  - Nash equilibrium $u_i(s_i^*, s_{-i}^*) \geq u_i(s_i, s_{-i}^*), \forall s_i \in \mathcal{S}_i$
  - Mixed strategy
    - Strategies are **pure** if a player *i* selects, in a deterministic manner, one strategy out of its strategy set S_i , if selecting based on **probability distribution** over their set of strategies
- Dynamic non-cooperative game
  - Extensive form
    - the notion of time and information is important
  - Repeated game
    - average utility over time $u_i = (1-\beta)\sum_{t=1}^{\infty} \beta^{t-1} u_i(t)$



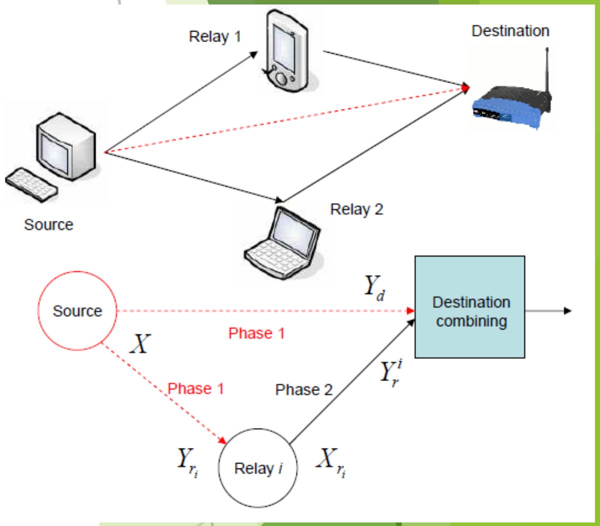
Non-Cooperative Game

- wireless communication non-cooperative scenarios
  - allocation of resources
  - packet forwarding
  - interference management
  - Routing in multi-hop system
    - link qualities, energy efficiency and security
    - Some nodes may not be willing to fully forward the packet
    - Repeated game
  - Relay Selection in cooperative transmission
  - choices of frequencies or transmit power
    - Each node prefer to transmit its maximum power to increase performance, but it increases system interference level and decrease performance. $SINR_j = \frac{h_j P_j}{\sum_{i \neq j} h_i P_i + \sigma^2}$

Cooperative Communication

- transmit cooperatively as a virtual antenna array, thus, providing diversity that can significantly improve system performance
- Transmission in two phases
  - Phase 1, the source broadcasts a message to the destination and relay nodes.
  - In Phase 2, relay nodes send information to the destination (in different time slots or on different orthogonal channels), and the destination combines messages from the source and relays.
- capacity region of his communication channel can be significantly increased

$$Y_d = \sqrt{P_s G_{s,d}} X + n_d \qquad Y_{r_i} = \sqrt{P_s G_{s,r_i}} X + n_{r_i}$$



Direct Transmission

$$\Gamma^{DT}_{s,d} = \frac{P_s G_{s,d}}{\sigma^2}$$

$$R_{s,d} = W \log_2 \left(1 + \Gamma^{DT}_{s,d}\right)$$

cooperative Transmission

$$\Gamma^{AF}_{s,r_i,d} = \frac{P_{r_i} P_s G_{r_i,d} G_{s,r_i}}{\sigma^2 (P_{r_i} G_{r_i,d} + P_s G_{s,r_i} + \sigma^2)}$$

$$R^{AF}_{s,r_i,d} = \frac{1}{2} W \log_2 \left(1 + \Gamma^{DT}_{s,d} + \Gamma^{AF}_{s,r_i,d}\right)$$

Cooperative Communication concerns

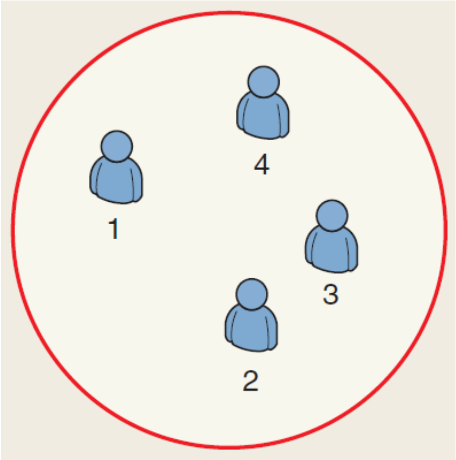
- Relay selection and power control
  - Which relay nodes select as
  - how limited power resources should be distributed over sources and relays
  - Solution: stackelberge :
    - How many nodes should cooperate
    - How much service should be bought

Special type of non-cooperative game

- Stackelberge Game
  - a hierarchy among the players exist
  - one or more of the players (Leader) declare and announce their strategies before the other players(Follower) choose their strategies.
  - Application: Power Control and Relay Section for **Cooperative** Transmission
    - Sender buying the services from the relays to improve its performance, such as the transmission rate
    - Relays selling service, such as power, by setting prices
    - Tradeoffs: price too high, sender buying others; price too low, profit low; sender decides to buy whose and how much to spend
    - Procedures: convergence to the optimal equilibrium
- **Note** : term “non-cooperative” does not always imply that the players do not cooperate, but it means that, any cooperation that might arise must be self-enforcing with no communication or coordination of strategic choices among the players.

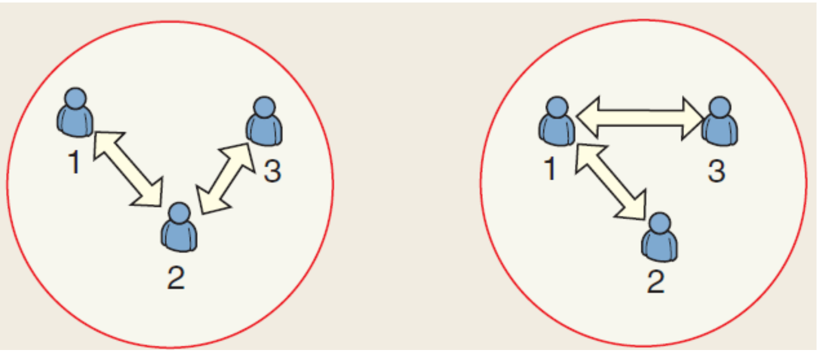
Cooperative Coalitional Game Theory

- Canonical Coalition Game
  - It is beneficial to all players to join the coalition. Grand coalition is the optimal solution
  - Main objective:
    - properties and stability of grand coalition
    - how to distribute gain from cooperation in fair manner between player (Core)
    - Pay-off allocation solution : Core, Shapley value and the nucleolus



Cooperative Coalitional Game Theory

- Coalition Graph Game
  - Internal interactions among players inside each coalition impact the outcome of each coalition
  - Main Objective
    - To drive a low complexity and distributed algorithm for players that wish to build a network graph
    - study the stability, efficiency of the formed network graph.



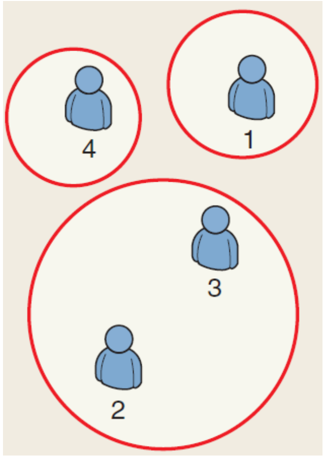
$Coalition\ S = \{1,2,3\}$ $Coalition\ S = \{1,2,3\}$

$Graph\ G_{s1}$ $Graph\ G_{s2}$

$$v(G_{s1}) \neq v(G_{s2})$$

Cooperative Coalitional Game Theory

- Coalition Formation Game
  - Forming a coalition brings gains to its members, but the gains are limited by a cost for forming the coalition (negotiation process or an information exchange), hence the grand coalition is seldom the optimal structure.
  - Main objective
    - optimal coalition size
    - assess the structure's characteristics
  - The coalitional game is subject to environmental changes such as a variation in the number of players, a change in the strength of each player, or other factors that can affect the network's topology.



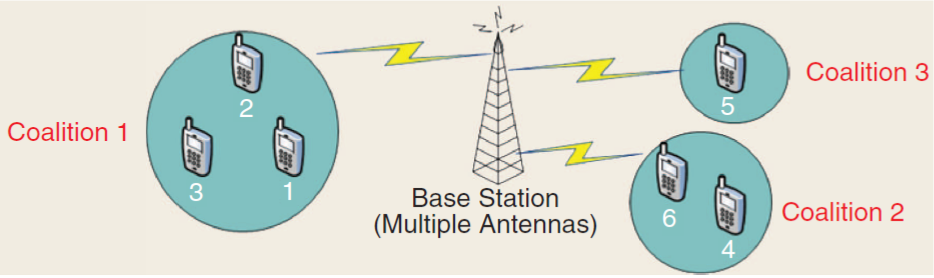
Coalition Formation Game Application

- Virtual MIMO
  - A network of single antenna transmitters that send data in a TDMA system to a multiple antenna receiver.
  - In a non-cooperative approach, each single antenna transmitter sends its data in an allotted slot.

Time Slot 1	Time Slot 2	Time Slot 3	Time Slot 4	Time Slot 5	Time Slot 6
User 1	User 2	User 3	User 4	User 5	User 6

  - For improving their capacity, the transmitters form coalitions, whereby each coalition S is seen as a single user MIMO that transmits in the slots that were previously held by the users of S.

Time Slot 1	Time Slot 2	Time Slot 3	Time Slot 4	Time Slot 5	Time Slot 6
Coal. 1	Coal. 1	Coal. 1	Coal. 2	Coal. 3	Coal. 2



Coalition Formation Game Application

- Virtual MIMO
- To cooperate, users must exchange data, and hence, this exchange of information incurs a cost in terms of power that is increasing by
  - Distances of nodes inside the coalition
    - when two users are far away, information exchange can consume the total power, and the utility for cooperation is smaller than in the non-cooperative case
  - size of coalition

So Grand Coalition is not beneficial.

Value function sum-rate, or capacity, that the coalition can achieve

Coalition Formation Game Application

- Virtual MIMO
- Coalition Formation Algorithm (sequential merge and split)
  - Start with non-cooperative network
  - each user discovers its neighbors (starting with the closest)
    - If cooperation with a neighbor improve its utility then merge
    - if a formed coalition finds out that splitting into smaller coalitions improves the total utility achieved by its users, then a split occurs
  - merge-and-split periodically, and hence, adapt the topology to any environmental change, such as mobility or the joining/leaving of transmitters.
  - end

Application of Game Theory in Robotic Communication

- Sensor sharing
  - Limited facilities and we can equip limited number of robots to sensor network to collect the data from the environment. This robots can be act as leader in system and other robots in vicinity of each of them can form a coalition and interact with this leader in their coalition to use their information to accomplish their task.
- Energy harvesting
  - These energy producer nodes can go through the network and to recharge nodes that demand for energy (consumer nodes) and charge them without human intervention
- Multi hop communication
  - In a defined team work to a group of robots an amount of work would be assigned to each robot, after accomplishing the work it can be act as a relay between other nodes.

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