Distributed Control of Autonomous Agents

Can the social sciences help?

Raúl Leonardo Landa Gamiochipi

Networks and Services Research Group
Dept. of Electronic and Electrical Engineering
Rationale

• Propose control algorithms suitable for Networks...
  • Under the control of multiple, unrelated entities
  • In which elements have multiple motivations
  • Formed by large groups of similar agents...
    • Constantly leaving and joining the network
    • Acting in their own “self-interest”
    • Whose software can be modified arbitrarily
The model

• Fluid flow model

• Simple topologies
  • Erdös-Rényi graph and K-Nearest Neighbors map

• Discrete time model

• All peers “produce” a small amount of a “resource”

• Peers are interested in “consuming” a much greater “quota” of this resource. Thus, they must obtain it from their neighboring peers.
The model

- Peers use generalized barter by using *pairwise* currencies
- Price determination is done through a modified *proportional allocation* bidding mechanism
- Resource contribution is rewarded with currency
- Peers are “reserved” an amount of the resource stock of a peer if they had contributed resources to it previously
The Algorithm

$\Gamma_0$:

The neighborhood of peer $i$:

We will also call this the local market of peer $i$.
1. Peers advertise their price level.
The Algorithm

1. Peers advertise their price level.
2. Peers decide how much resource to ask from each of their neighbors, according to the prices that they advertise. Requests are accompanied by bids.
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3. According to past contributions, peers reserve resources for the members of their local market.
4. The peers in the local market then compete for the remaining resources. More resources are assigned to those peers that bid higher.
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4. All peers contribute the reserved and the competition-based resource allocations.
4. Peers hold accounts for their neighbors. The accounts of neighbors that contributed resources to peer $i$ are credited; the accounts of peers that received resource contributions from peer $i$ are debited.
5. A new *price* is calculated by each peer $i$ by taking into account the values of the bids it received. That way, peer $i$ can gauge how valuable its resources are to other peers, and price them accordingly.
6. According to the level of success accomplished with each neighboring peer, \( i \) modifies its bids for the next iteration. If \( i \) obtained everything it wanted from a given peer, it will **reduce** its bid - seeking a lower price later. If not, it will **increase** its bid.
Results
Random (ER)
K-Nearest Neighbors (KNN)
Convergence of Prices
Convergence of Prices

Average Peer Price Level Convergence with Simulation Time

Simulation epoch

Average Peer Price Level

KNN
Resource Buffering Convergence

Average Buffer Occupancy as it varies with simulation epoch

Simulation epoch

Average Buffer Occupancy

ER
Resource Buffering Convergence

![Graph showing average resource buffer convergence with simulation time. The x-axis represents the simulation epoch, ranging from 0 to 100, and the y-axis represents the average peer resource buffer length, ranging from 0 to 250. The graph shows a trend where the average buffer length increases rapidly initially and then levels off as the simulation progresses. The term KNN is highlighted on the graph.](image-url)
Resource Trading Volume Convergence
Resource Trading Volume Convergence

Average Peer Resource Access Convergence with Simulation Time

Simulation epoch

Average Peer Resource Access

KNN
Resource Contribution Ranking

Upload Bandwidth to a single peer

ER
Resource Contribution Ranking

KNN

Upload Bandwidth to a single peer

rank

0 50 100 150 200 250 300 350 400

0

5

10

15

20

25

30

35

40

45

50
Equilibrium Resource Contribution Ranking

Reciprocity-Reserved

Bid-Competition Allocated
Equilibrium Resource Contribution Ranking

Reciprocity-Reserved

Bid-Competition Allocated
Unsatisfied Resource Requests Ranking
Unsatisfied Resource Requests Ranking

KNN
Account Balance Ranking

ER
Account Balance Ranking

KNN
Ok... let’s dive in.

(Time Permitting)
Preferring cheaper alternatives

\[ r_{ij} = \frac{1}{|\Gamma_i| - 1} \left( \frac{p_j}{\sum_{k \in \Gamma_i} p_k} \right) r_i \]

\( r_{ij} \): Amount of resources that peer \( i \) requests from peer \( j \)

- Greater amounts of resources are requested from peers with lower price levels.
Reciprocating past contributions

\[
\rho_{ij} = \left( \frac{w_{ji}}{\sum_{k \in \Gamma_i} w_{ki}} \right) b_i
\]

\(\rho_{ij}\) : Amount of its resources that peer \(i\) reserves for peer \(j\)

\(w_{ji}\) : Account balance of peer \(j\) on peer \(i\)

\(b_i\) : New resources available to peer \(i\) at the current time.
Reciprocating past contributions

\[ \rho_{ij} = \left( \frac{w_{ji}}{\sum_{k \in \Gamma_i} w_{ki}} \right) b_i \]

- \( \rho \) is the basic “tit-for-tat” component of the protocol. It will assign greater amounts of resources to those peers with greater past reciprocation, as measured by their account balances.
Building reciprocal trust

\[ \pi_{i,j} = \min (\rho_{ij}, r_{ji}) \]

\( \pi_{i,j} \): Amount of resources that peer \( i \) delivers to peer \( j \) out of reciprocity

- Providing peers with assured bandwidth gives them an incentive to contribute at some point, so that they can enjoy improved QoS later.
Harnessing selfishness

\[ \gamma_{i,j} = \frac{\beta_{ji}}{\sum_{k \in \Gamma_i} \beta_{ki}} (b_i - \pi_i) \]

\[ \pi_i = \sum_{k \in \Gamma_i} \pi_{ik} \]

\( \gamma_{ij} \): Amount of resources that peer \( i \) delivers to peer \( j \) out of selfishness

- Peers compete for the remaining resources, with higher-bidding peers getting larger allocations.
Cooperation and Competition

\[ c_{ij} = \min (\pi_{ij} + \gamma_{ij}, \alpha_i) \]

- **\( c_{ij} \)**: Amount of its resources that peer \( i \) delivers to peer \( j \)
- **\( \alpha_i \)**: Resource pool available to peer \( i \).
Performance Measures

\[ r_{ij}^\pi = r_{ij} - \pi_{ji} \]

\[ r_{ij}^T = r_{ij} - c_{ji} \]

- These represent the amount of resources that peer \( i \) requested from peer \( j \) which were not delivered.
Paying Up: Creating Wealth

\[ w_{ij}^{(k+1)} = \max \left( w_{ij}^{(k)} + \beta_{ij} c_{ji}^{(k)} - p_j c_{ij}^{(k)}, 0 \right) \]

- \( w_{ij} \): Balance of the account of peer \( i \) on peer \( j \)
- \( \beta_{ij} \): Amount that peer \( i \) will bid when sending requests to peer \( j \)
- \( p_j \): Average price that peer \( j \) reports.
This operation only requires information local to the peer, and it does not require a perfect correspondence with the other peer. The total amount of “currency” can change as a result of this.

\[
 w_{ij}^{(k+1)} = \max \left( w_{ij}^{(k)} + \beta_{ij} c_{ji}^{(k)} - p_j c_{ij}^{(k)}, 0 \right)
\]
Negative Feedback

\[ \beta^{(k+1)}_{ij} = \begin{cases} 
\left( \frac{r^T_{ij}}{r_{ij}} + 1 \right) \beta^{(k)}_{ij} & \text{if } r^T_{ij} > 0 \\
\epsilon \beta^{(k)}_{ij} & \text{if } r^T_{ij} \leq 0; \ \epsilon < 1.
\end{cases} \]

- The bid amount is increased if there was unsatisfied demand, and decreased otherwise.
Prices

\[ p_i = \frac{1}{|\Gamma_i|} \sum_{k \in \Gamma_i} \beta_k \]

- The price is derived from the bids.
Accounting

\[ \delta_i = \zeta_i + \sum_{j \in \Gamma_i} c_{ji} \]

\[ \alpha_{i}^{(k+1)} = \min \left( \alpha_{i}^{(k)} + \delta_{i}^{(k)} - \delta_{i}^{(k-n)} , \eta_i \right) \]

- \( \delta_i \) : Amount of new resources that peer \( i \) obtains for trading on the next round.
- \( \alpha_i \) : Amount of active resources that peer \( i \) has.
- \( \zeta_i \) : Amount of resources that peer \( i \) itself creates per iteration.
\[ \delta_i = \zeta_i + \sum_{j \in \Gamma_i} c_{ji} \]

\[ \alpha_i^{(k+1)} = \min \left( \alpha_i^{(k)} + \delta_i^{(k)} - \delta_i^{(k-n)} , \eta_i \right) \]

\[ \eta_i : \text{ Maximum resource buffer size for peer } i. \]
The End

Questions?