Coalition Formation towards Energy-Efficient Collaborative Mobile Computing

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Collaborative Mobile Computing

- Mobile offloading: migrating the computation-intensive portion of an app to the cloud to execute.
- Gain: trades the relatively low communication energy expense for high computation power consumption.
- Loss: suffers high network latency.
- New features such as *Continuity* made offloading tasks to nearby devices possible.

Coalition Formation of Mobile Users

- Previous works assume fully cooperative mobile users.
- We assume users are:
  - cooperative: collaborates under agreements.
  - individually rational: prefers coalition if it benefits.
- We study the problem of coalition formation among a group of mobile users targeting at the same job.

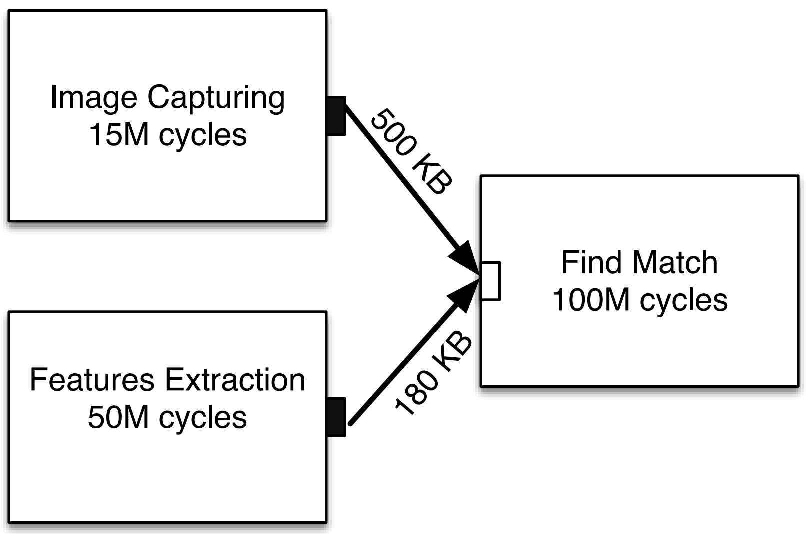
Coalition Formation of Mobile Users

- User case: crowdsourcing, content sharing, indoor localization, etc.
- Key questions:
  - Given a job partitioned into several tasks, how does a group of users form coalitions?
  - Within each coalition, how to distribute the tasks to each user?

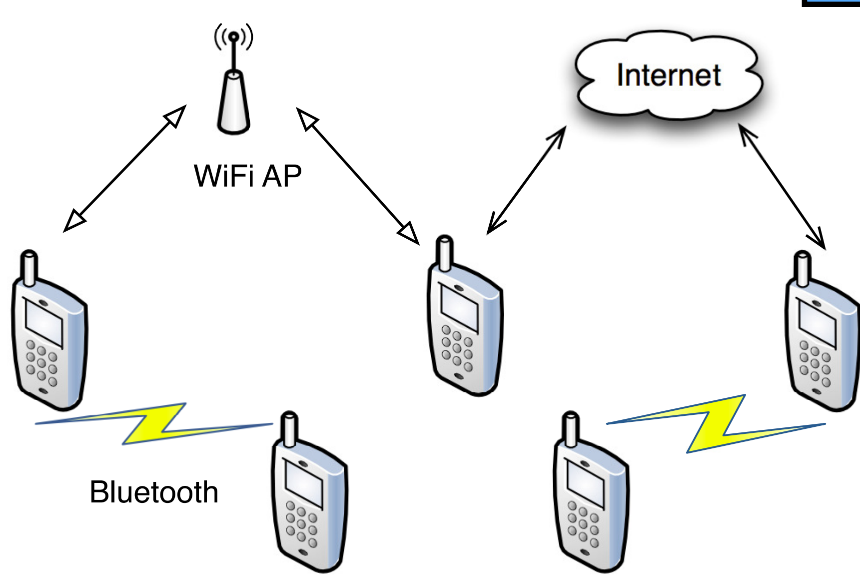
System Model

- A centralized approach: an arbitrator profiles user's info, organizes users into groups, and assigns tasks to each group.
- A distributed scheme: mobile users exchange profiles with users targeting at the same job. Based on the estimated energy cost, users decide to merge into one group or split up.
- A profile is generated by program static analysis tools.

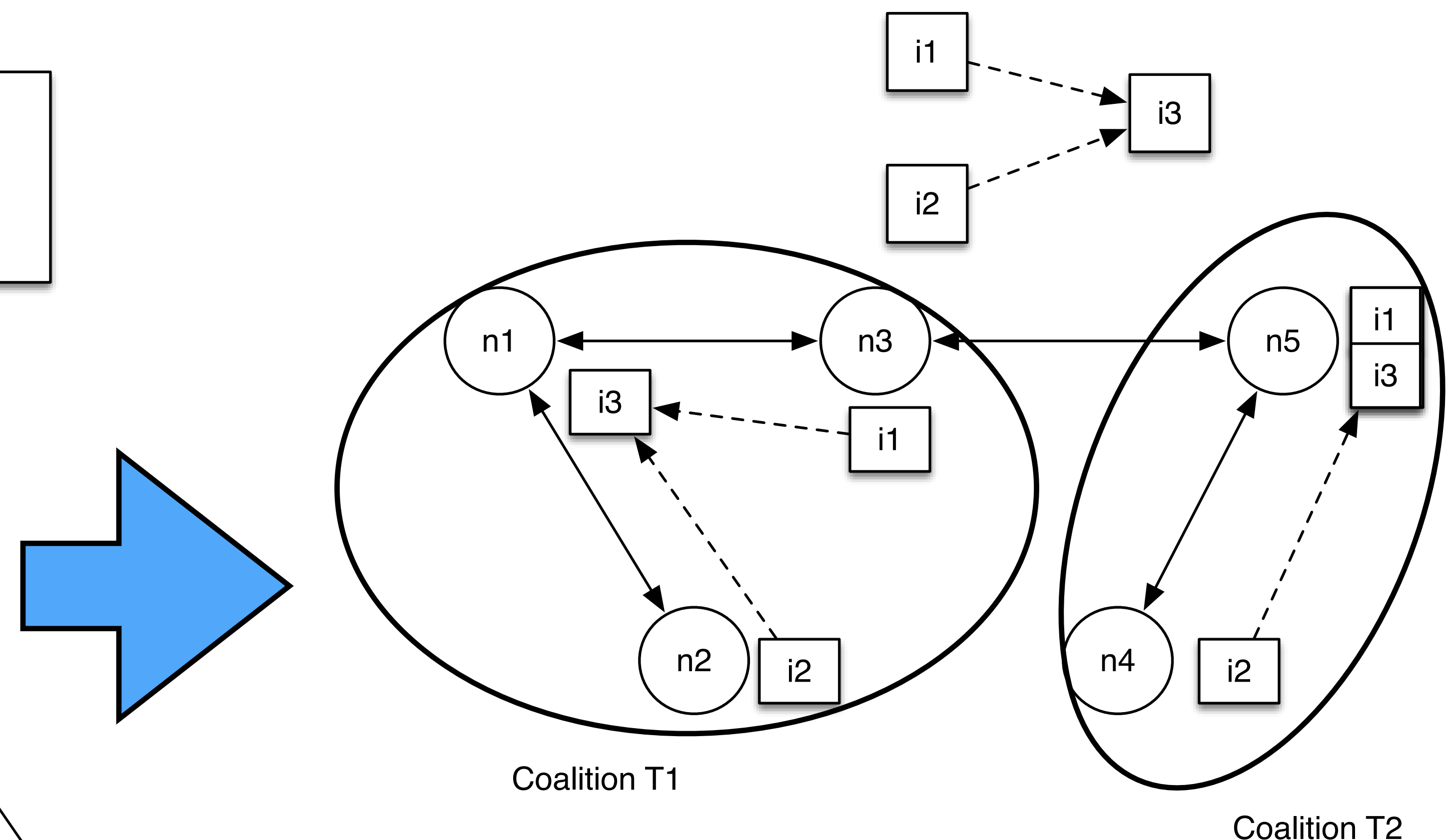
System Model



Task graph



Resource graph



An example of mapping tasks to a set of devices

Task Distribution

- Objective: minimizing the overall energy expense over all partitions of the resource graph with placement constraints.

- B is the set of all partitions. T represents one coalition. C(T) is the sum of the energy expense on all mobile devices in coalition T.

$$\min_{\mathcal{P} \in \mathcal{B}} \sum_{T \in \mathcal{P}} \min C(T).$$

Task Distribution

- To assign the binary variable $s_{i,n}$ representing task i is to be executed on device n.

- Placement constraints:

$$\sum_{n \in T} s_{i,n} = 1, \ \forall i \in \mathbb{V}, \tag{5}$$

$$\sum_{i \in \mathbb{V}} s_{i,n} \geq 1, \ \forall n \in T, \tag{6}$$

$$s_{i,n} s_{j,m} e_{i,j} \leq l_{n,m}, \forall i \neq j, \forall n \neq m, n, m \in T \tag{7}$$

$$s_{i,n} \leq r_{i,n}, \forall i, \forall n \in T, \tag{8}$$

$$s_{i,n} \in \{0, 1\}, \forall n \in T, \forall i \in \mathbb{V}. \tag{9}$$

Coalition Formation

- The centralized approach is non-convex and NP-hard. How about going distributed?
- Collaboration among mobile users is modelled as a non-transferrable utility coalition game (N, v) where N is the entire set of users, and v is the utility for the coalition which is defined as the negative energy cost.
- Partition:

Definition 1: A *collection* is any family $T = \{T_1, ..., T_l\}$ of mutually disjoint coalitions. If additionally $\bigcup_{j=1}^{l} T_j = \mathbb{N}$, the collection T is called a *partition* of $\mathbb{N}$.

Coalition Formation

- Comparison relation:

Definition 2: Assume A and B are partitions of the same set C, a *comparison relation* $\triangleright$ is defined as, $A \triangleright B$ means that the way A partitions C is preferable to the way B partitions C.

- Pareto order: the transformation of coalitions through Pareto order can only happen when it at least strictly improves the utility of one user, i.e., given two partitions T and T', with $\phi(T)$ representing the energy cost of T, the comparison relation is expressed as:

$$T \triangleright T^{'} \iff \forall n, \phi_n(T) \leq \phi_n(T^{'}) \text{ and } \exists m, \phi_m(T) < \phi_m(T^{'})$$

Coalition Formation

- Two rules to transform coalitions:

Merge: $\{T_1, ..., T_k\} \cup P \rightarrow \{\bigcup_{j=1}^{k} T_j\} \cup P$, where $\{\bigcup_{j=1}^{k} T_j\} \triangleright \{T_1, ..., T_k\}$.

Split: $\{\bigcup_{j=1}^{k} T_j\} \cup P \rightarrow \{T_1, ..., T_k\} \cup P$, where $\{T_1, ..., T_k\} \triangleright \{\bigcup_{j=1}^{k} T_j\}$.

- Based on the above rules, we derive the algorithm:

Algorithm 1 Collaborative Computing Game through Merge and Split

Input: Initial partition $T = \{T_1, ..., T_l\} = \mathbb{N}$
Output: Final partition T^{final}
repeat
  T = Merge(T);
  T = Split(T);
until merge and split terminates.
$T^{final} = T$.

Stability Analysis

- Definition: we consider a partition T is stable if for any collection C of the entire user set N that

$$C[T] \triangleright C, \quad (14)$$

where

$$C[T] = \{T_1 \cap \bigcup\{C\}, ..., T_k \cap \bigcup\{C\}\} \backslash \{\emptyset\}.$$

- We prove that the stability defined above implies contractually individual stability, i.e., a state that no player can benefit from moving its coalition to another without making others worse off.

Dc-Stable

- We proved our merge-and-split mechanism is stable if allowing users to transfer between coalitions by merge and split. The stable partition is called Dc-stable partition.

- If a Dc-stable partition T exists, then T is the unique outcome of every iteration of merge and split.

Performance Evaluation

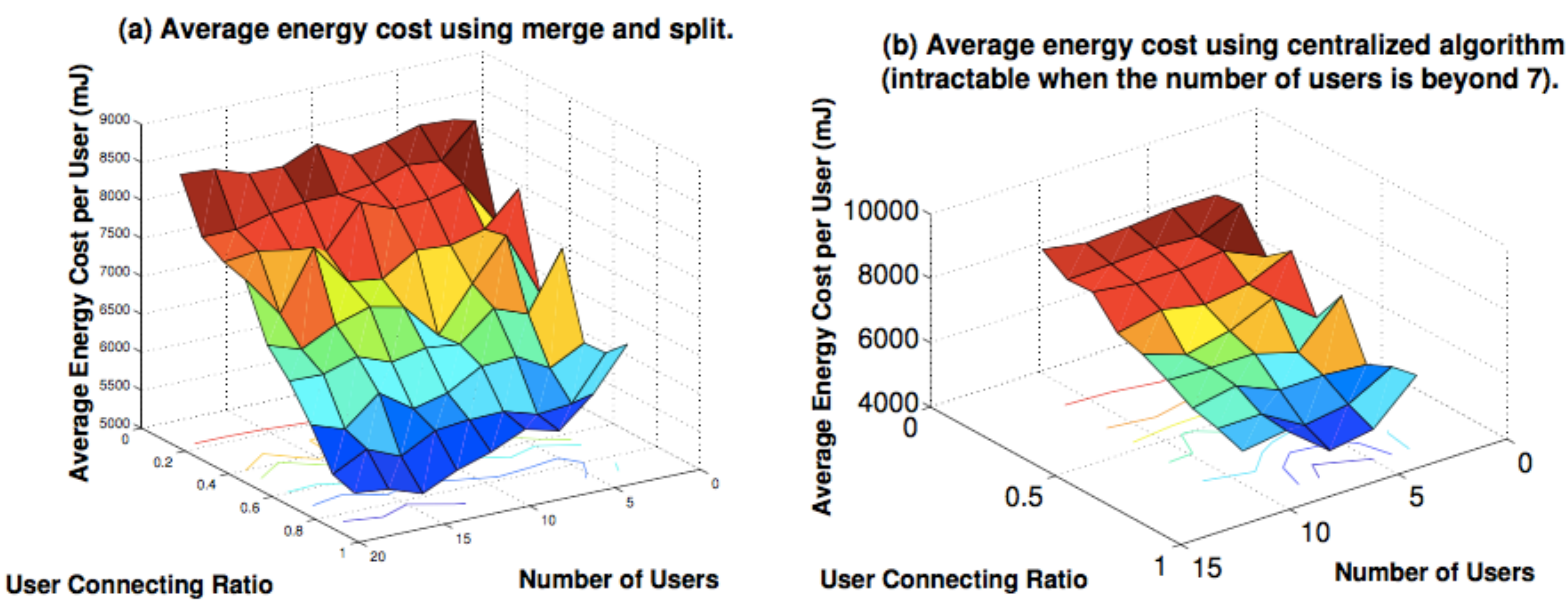
- Setup
  - Computation cycles of each task is 20-100 M cycles.
  - Data transferred is 10-1000 KB on each link.
  - Energy consumption in data transmission is 20-200mJ/KB.
  - Computation energy cost is 40-60 mJ/M cycles.

Performance Evaluation

- Average Energy Cost

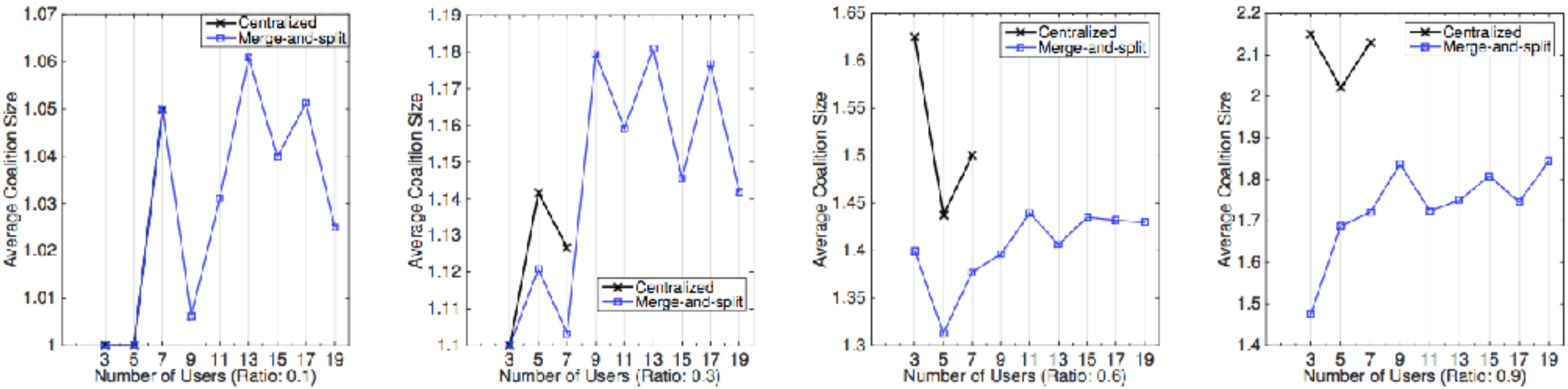
AVERAGE ENERGY COST PER USER OVER ALL CASES

	Non-coop	Centralized	Merge & Split
Energy Cost(J)	8.49	6.86	6.97



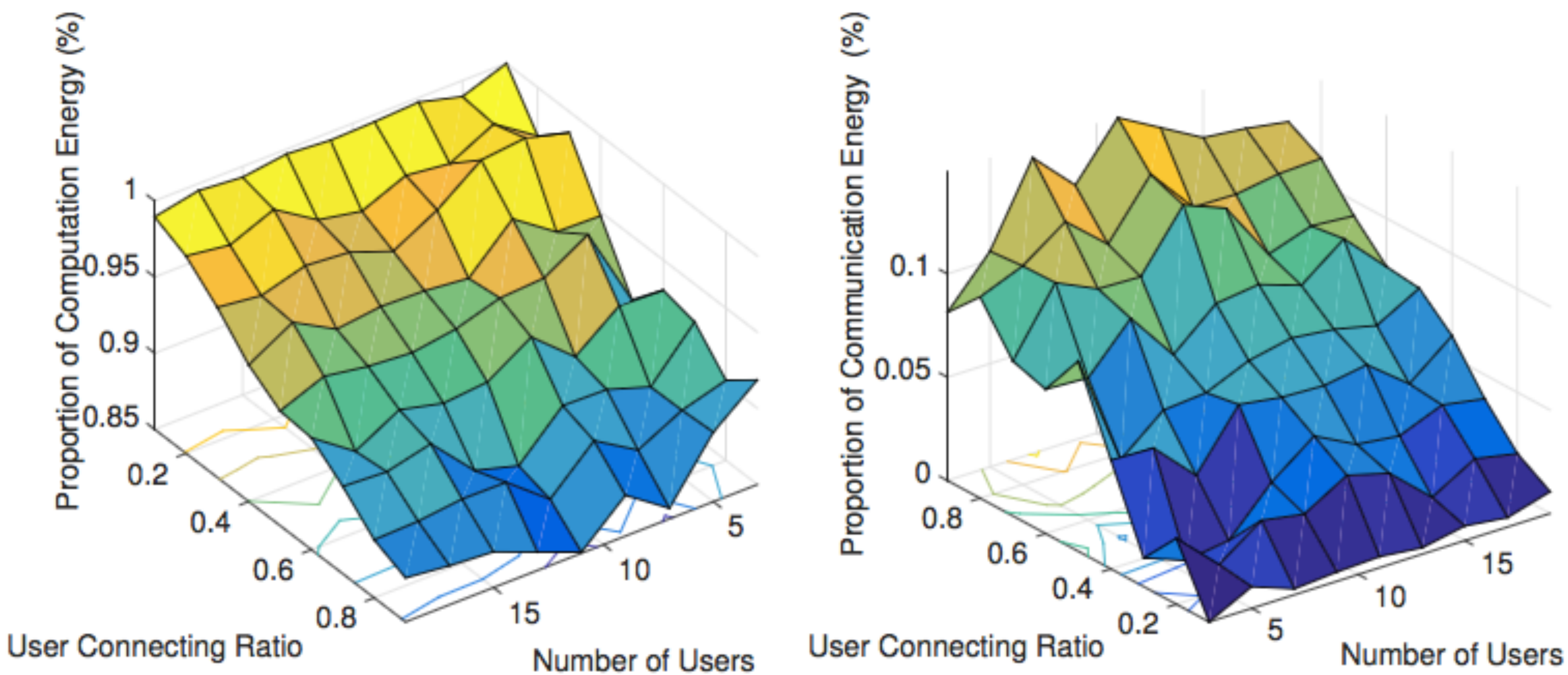
Performance Evaluation

- Average coalition size.



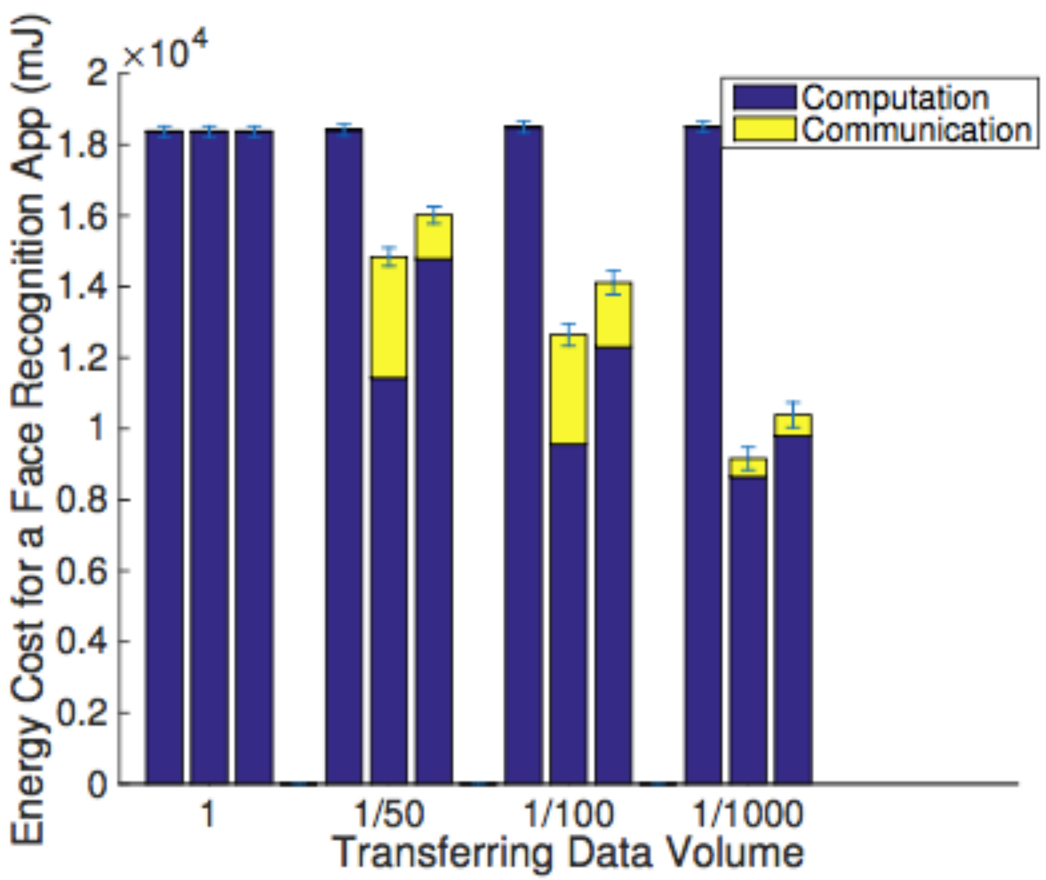
Performance Evaluation

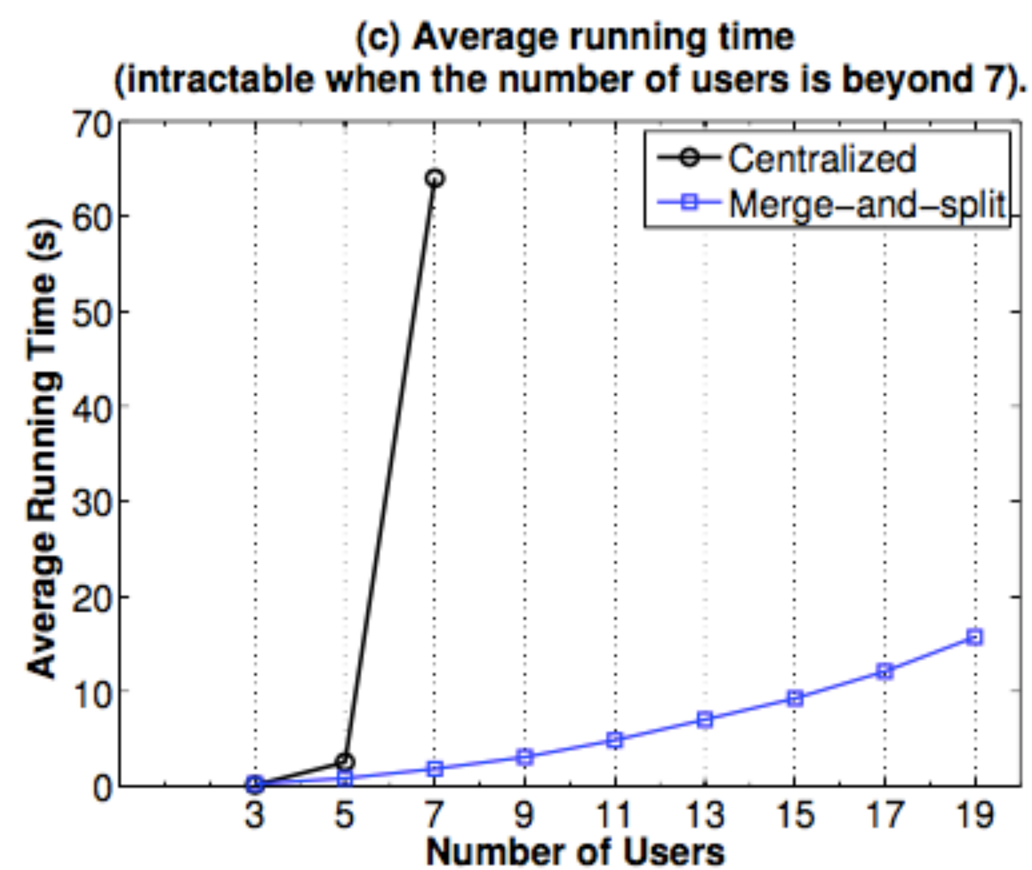
- Average proportion of computation and communication cost.



Performance Evaluation

- Emulation for a real-world app & running time comparison.





Conclusion

- We formulate the task assignment problem as a 0-1 integer programming problem and use heuristic method to solve it.
- We devise a distributed merge-and-split algorithm to allow collaborative and individually rational users to form coalitions.
- We reveal the conditions under which the scheme yields a stable partition.

Q & A.
Thank you.