Random Access Protocols for Correlated Users

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1. Introduction and Motivation

- Random access protocols are usually designed under the assumption that users are independent, and are derivatives of the original framed ALOHA [1].
- With the advent of Machine-Type Communication (MTC), some users are likely to exhibit correlation, e.g. if the users observe some common physical phenomenon [2].
- We show how correlated user activity can be exploited in ALOHA-based random access protocols to improve the throughput using a semi-scheduled random access procedure.

2. System Model and Problem Definition

- Time is divided into frames of K slots; collisions are observed as erasures.
- Activity of user i within a frame is defined by $x_i \in \{0, 1\}$:

$$\Pr(\mathbf{x}) = \Pr(x_1, x_2, \dots, x_N).$$

- We introduce the allocation matrix $\mathbf{A} \in \mathbb{R}^{N\times K}$ where A_{ij} is the probability that user i will transmit in slot j conditioned on activation, and $\sum_j A_{ij} = 1$.
- The throughput is given by the expected number of slots in which exactly one user transmits:

$$\mathrm{TP}(\mathbf{A}) = \sum_{k=1}^{K}\sum_{n=1}^{N}\mathbb{E}_{\mathbf{x}}\left[x_n A_{nk}\prod_{m=1}^{N}(1 - x_m A_{mk})^{\mathbb{1}(n\neq m)}\right].$$

- **Objective:** Find an allocation matrix $\mathbf{A}$ that maximizes throughput assuming $\Pr(\mathbf{x})$ is known.

3. Heuristic Algorithm

- The throughput is bounded using the inclusion-exclusion principle:

$$\mathrm{TP}(\mathbf{A}) \le \sum_{k=1}^{K}\sum_{n=1}^{N}\left(A_{nk}\mathbb{E}[x_n] - \max_{\substack{m=1,\dots,N\\ m\neq n}} A_{nk}A_{mk}\mathbb{E}[x_n x_m]\right),$$

$$\mathrm{TP}(\mathbf{A}) \ge \sum_{k=1}^{K}\sum_{n=1}^{N}\left(A_{nk}\mathbb{E}[x_n] - \sum_{\substack{m=1,\dots,N\\ m\neq n}} A_{nk}A_{mk}\mathbb{E}[x_n x_m]\right).$$

- The user correlation for either bound can be represented by a complete graph with vertices $V = \{v_1, \dots, v_N\}$ and edge weights $W_{ij} = \mathbb{E}[x_i x_j]$.

Algorithm:

1. Merge the vertices (v_p, v_q) connected with the minimum edge weight, and update outgoing edge weights according to one of the following rules corresponding to the upper and lower bounds:

   Min-Max: $W_{pn} = \max\{W_{pn}, W_{qn}\} \quad \forall n,$

   Min-Sum: $W_{pn} = W_{pq} + W_{pn} + W_{qn} \quad \forall n.$

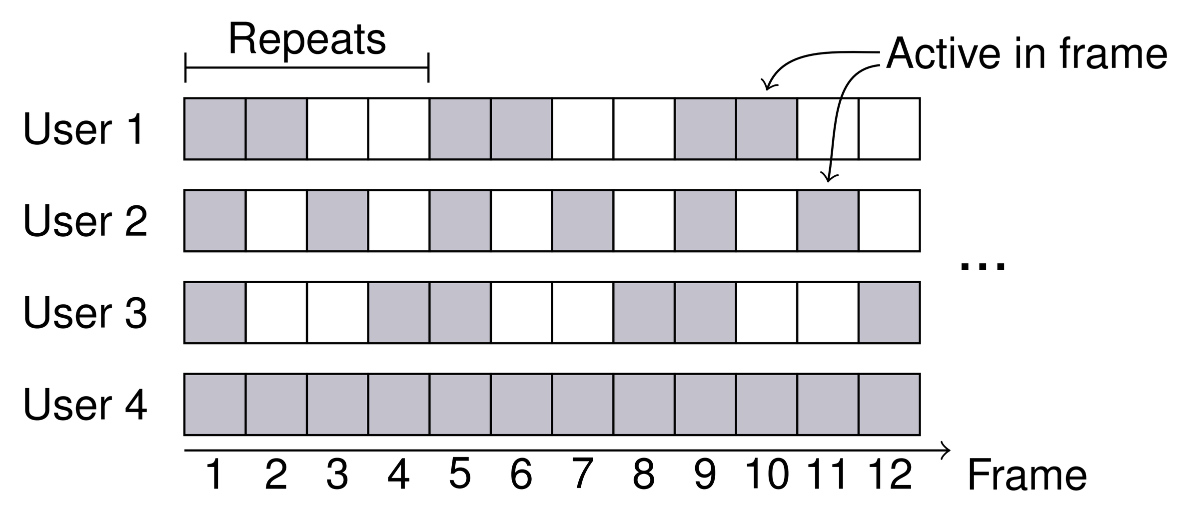
2. Repeat until K vertices remain. The users that have been merged into each of the final K vertices will be assigned to the same slot, and hence the graph implicitly defines $\mathbf{A}$.
3. *Under high load (scaled):* Let S_i denote the slot assigned to user i and $\hat{A}_i \triangleq A_{iS_i}$. Define N_i as the number of users that transmit in slot S_i conditioned on user i being active. We have

$$\mathbb{E}[N_i] = \hat{A}_i + \sum_{n\in\mathcal{N}_{S_i}}\hat{A}_n\mathbb{E}[x_n|x_i] = \hat{A}_i + \frac{1}{\mathbb{E}[x_i]}\sum_{n\in\mathcal{N}_{S_i}}\hat{A}_n\mathbb{E}[x_n x_i],$$

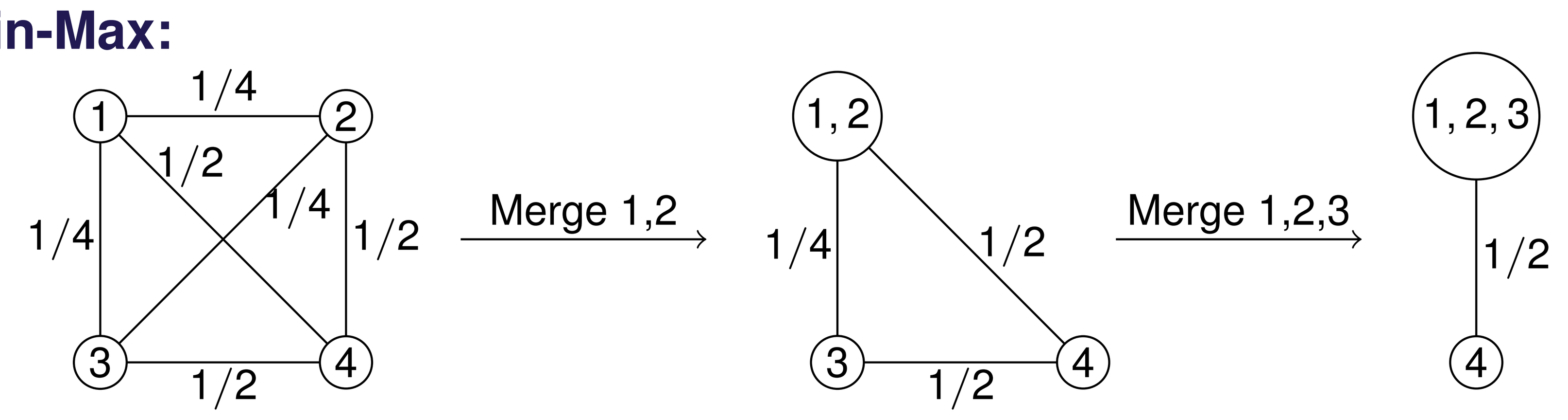
where $\mathcal{N}_{S_i}$ is the set of users assigned to slot S_i. For each slot j, scale $0 \le \hat{A}_i \le 1$ so that the least-squares $\sum_{i\in\mathcal{N}_j}(\mathbb{E}[N_i] - 1)^2$ is minimized.

4. Example

$N = 4$ users, $K = 2$ slots.

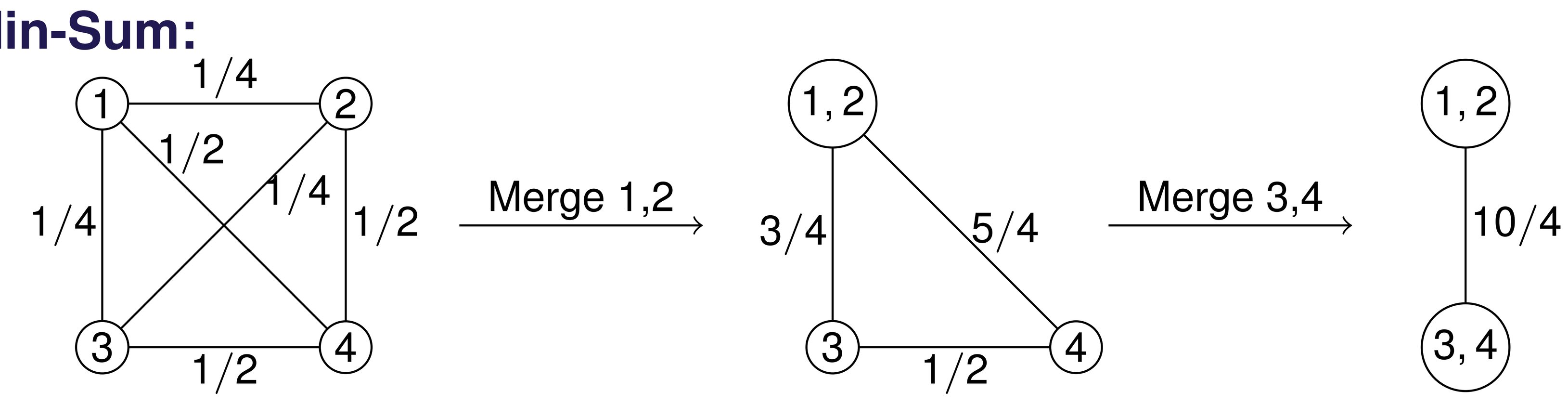


Min-Max:



Resulting throughput: $TP = 7/4$.

Min-Sum:

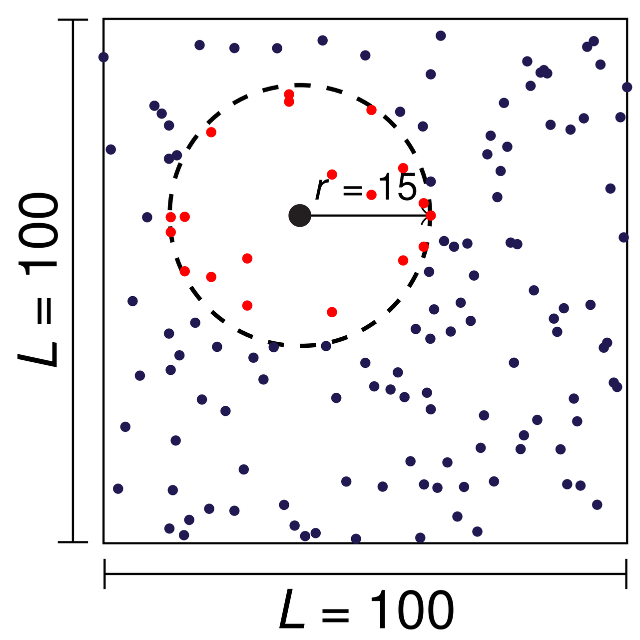


Resulting throughput: $TP = 1$.

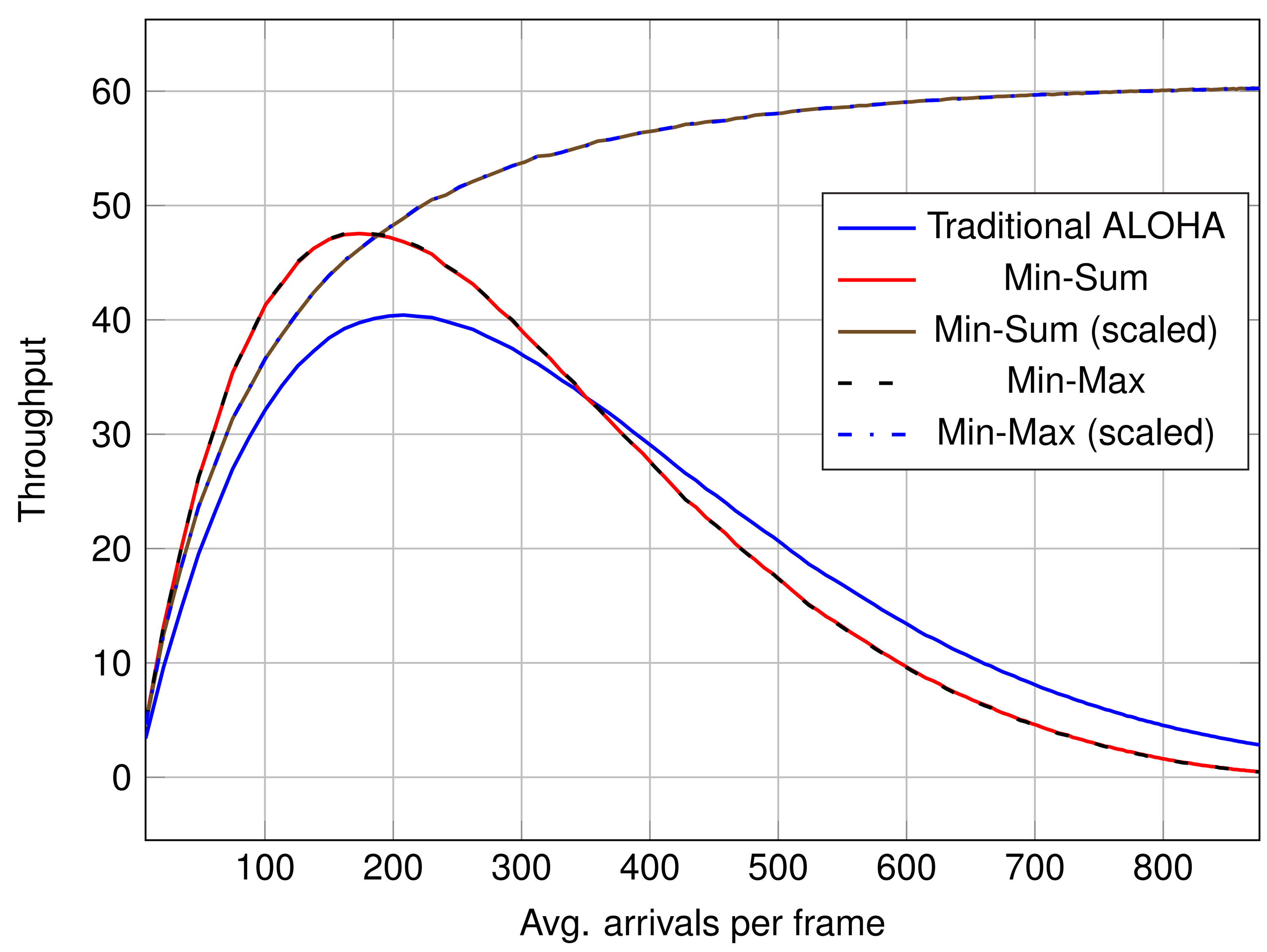
5. Numerical Evaluation

Method:

- $N = 1000$ users are deployed uniformly in a square region with side lengths $L = 100$.
- Events are generated according to a Poisson point process with rate λ.
- All users within a radius $r = 15$ of an event transmit in the following frame.
- Each frame consists of $K = 150$ slots.



Results:



References

[1] L. G. Roberts, "ALOHA packet system with and without slots and capture," *SIGCOMM Comput. Commun. Rev.*, vol. 5, no. 2, pp. 28–42, Apr. 1975.

[2] 3GPP, "Study on RAN improvements for machine-type communications," 3rd Generation Partnership Project (3GPP), Technical Report (TR) TR 37.868, October 2014, v.0.8.1.