Robotic Message Ferrying for Wireless Networks using Coarse-Grained Backpressure Control

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Challenge:

*How to design new scheduling algorithms for wireless networks, which combine both robotic control and transmission scheduling?*
In a robotic wireless network,

- $K$ pairs of static sources and sinks cannot communicate directly. Source $i$ receives packets at a constant rate $\lambda_i$.
- $N$ ($N \leq 2K$) controllable robots move around to help transmit data.
- $Q_{src}(i)$: the queue at the source for flow $i$.
- $Q^i_j$: the queue at robot $j$ for flow $i$. No queue at the sinks.

Figure: A network containing 2 pairs of source and sink nodes and 4 robots.
Robots’ Matching

Time:

| epoch 1 | epoch 2 | ....... |

The scheduler

source 1

R_{src(1),3}(t) → robot 3

robot 4

R_{4,sink(2)}(t) → sink 2
Theorem 1

Λ is the achievable capacity region of the network.

\[ \Lambda = \left\{ \lambda \mid 0 \leq \lambda_i < R_{\text{max}}, \quad \forall i, \quad \sum_{i=1}^{K} \lambda_i < \frac{R_{\text{max}} N}{2} \right\} \]  

Figure: Capacity region for a problem with 3 robots and 2 flows
Basis Allocation

Case 1: rate = 0

Case 2: rate = Rmax/2

Case 3: rate = Rmax
Coarse-grained Backpressure based Message Ferrying (CBMF) Algorithm:

At the beginning of each epoch:

- compute the weights $w_{src(i),j} = (Q_{src(i)} - Q^i_j)$ and $w_{sink(i),j} = (Q^i_j)$.
- If the allocation $A(i,j) = 1$, denote $w_{i,j} = w_{src(i),j}$. If $A(i,j) = -1$, denote $w_{i,j} = w_{sink(i),j}$. Else, if $A(i,j) = 0$, $w_{i,j} = 0$.
- Find the allocation $A$ that maximizes $\sum_{i,j} |A(i,j)|w_{i,j}(A(i,j))$ subject to the following three constraints:
  1. $\sum_i |A(i,j)| = 1$,
  2. $\sum_j \mathcal{I}\{A(i,j) = 1\} \leq 1$,
  3. $\sum_j \mathcal{I}\{A(i,j) = -1\} \leq 1$.

The CBFM algorithm works without priori knowledge of arrival rates.
Theorem 2

For any arrival that is strictly within $\Lambda_{IB}(v, T)$, the CBMF algorithm ensures that all source and robot queues are stable (always bounded by a finite value).

$$
\Lambda_{IB}(v, T) = \left\{ \lambda|0 \leq \lambda_i < R_{\text{max}}(1 - \frac{d}{vT}), \right. \\
\forall i, \sum_{i=1}^{K} \lambda_i < \frac{R_{\text{max}}(1 - \frac{d}{vT}) N}{2} \left\} \right.
$$

$d$: the maximum distance between the static nodes.
$v$: the moving velocity of robots.
$T$: the epoch length
Varying Velocity $\nu$

Figure: Delay of flows 1 as we vary $\nu$ for $T = 100$
Varying Epoch Length $T$

Figure: Delay of flows 1 as we vary $T$ for $v = 4 \times \sqrt{2}$
Conclusions

We addressed two fundamental questions:

- What is the throughput capacity region of such systems?
- How can robots be scheduled to ensure stable operation, even without prior knowledge of arrival rates?

Future Work

- Improve our CBFM algorithm to support the entire capacity region.
- Design an adaptive algorithm, probably by adapting epoch length, to satisfy any unknown arrival rates and maintain minimum delay at the same time.
thank you