Coordinating users of shared facilities via data-driven predictive assistants and game theory

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Recently, forecasts for more efficient e.g. congested shared facilities

When can ML help? For which ‘socio-aware’ concept of objective? Which algorithms do provably help?
Setting

Facility users’ decisions – assistant-based and ideal

**Assistant-based system:**

- **assistant**
  - signal $V$
  - policy $\pi$
  - forecast $A$

- **users (priv.)**
  - state $X$
  - signals $(W_i)_{i \in I}$
  - actions $(B_i)_{i \in I}$
  - “best response to A”

- **outcome $Y$**

User $i \in I$ picks (time)slot $B_i \in \{1, \ldots, K\}$, $\mathbb{E}$-optimal under her utility $U_i$ and forecast $A$

**Benchmark Bayesian game $G$:**

- **users (priv.)**
  - signal $V$
  - state $X$
  - signals $(W_i)_{i \in I}$
  - actions $(B_i)_{i \in I}$
  - “play BNE”

Users have ‘true’ prior $P(X, V, W)$, know all utility functions, are fully rational [1]

**Predictive objective (simple, obs.):** minimize $\| \pi(V) - P_\pi(Y|V) \|$

**Coordination objective (users’-utilities-aware):** $(P_\pi(B_i|V, W_i))_{i \in I}$ should be Bayesian Nash eq. of $G$ (BNE; “solution w.r.t. util. $U_i$“)

Geiger, Besserve, Winkelmann, Proissl, Schoelkopf: Coordinating users of shared facilities
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Motivation

Setting

What is the utility of predictions for user coordination?

Which assistant algorithms provably reach optimal predictions?

Further

Conclusions
What is the utility of predictions for user coordination?

Self-fulfilling prophecy characterization

Assumptions:

- “\( Y \perp \perp W_i \mid V \)” (“assistant-separable”)
- “\( U_i \perp \perp X \mid W_i, Y \)” (“inference-assistable”)
  (plus additional details)

Theorem

*If* the assistant policy \( \pi \) is a self-fulfilling prophecy

\( \| \pi(V) - P_\pi(Y \mid V) \| = 0 \)

*then* the corresponding strategy profile \( ((P_\pi(B_i \mid V, W_i))_{i \in I}) \) is a Bayesian Nash equilibrium (BNE) of the benchmark game.

Q: But when does a self-fulfilling prophecy exist?
What is the utility of predictions for user coordination?

Self-fulfilling prophecy existence

“Large-scale/aggregated setting”

- set of user types $I = [0, 1]$
  ($\rightarrow$ nonatomic benchmark game [3])
- $V, W$ constant
- $Y_k := \int [B_i = k]r(i|X)di$ (fraction of user types choosing slot $k$)
- $U_i(k, y) - U_i(l, y) = \sum_m i^m q_m(y)$, with one $q_m$ constant, $\neq 0$

Theorem

There exists a self-fulfilling prophecy assistant policy $\pi$
in this large-scale setting.

Proof idea Weak-* topology on distributions $A$,Leray-Schauder-Tychonoff fixed point theorem

Corollary Nonatomic game Bayesian Nash eq. existence result
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**Assistant algorithm with guarantees, experiment**

Assume dynamic large-scale, linear utilities (→ **point forecast** $A$ of $Y$)

**Algorithm “Expodamp”:** For all stages $t \geq 1$, output

$$A^t := \pi(A^{t-1}, Y^{t-1})$$
$$:= A^{t-1} + \alpha(Y^{t-1} - A^{t-1})$$

**Proposition:** Expodamp’s $A_t$ converges to self-fulfilling prophecy ($Y_t$ to Nash).

**Large real-world experiment in our campus cafeteria:** confirms Expodamp against baseline
Related work and further results and

Closest related work:

- **Learning in (congestion) games** [1] studies interacting agents, but without “assistant”
- **Control-theoretic** approaches for congestion in *smart cities* via “assistants” [2], but unaware of individual users’ utilities
- Complementary: *fairness in ML, social welfare optimization*
- (Google’s “Popular times” algorithms etc. – unknown to us)
- *(Exponential smoothing – no non-influential predictions)*

Omitted parts of the paper: small-scale setting with algorithm, stochastic optimality guarantees for Expodamp

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Take home message

ML for collective challenges – need analysis aware of social context

Here: predictive assistants – game theory, algorithms w. guarantees

Potentially many more such mechanisms with interesting analysis!

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