POWER-Net: Predictive Optimization and Wave Energy Regulation in Networked WEC Systems

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Wave Energy Converters

Image Credit: CorPower Ocean

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A 30 MegaWatt "wave farm" of Pelamis Wave Energy Converters (Business Wire)
Image Credit: salon.com

LITERATURE REVIEW

Over the past decade, WEC control strategies have evolved from single-unit reactive control to centralized and distributed MPC for multi-device arrays. However, a clear research gap remains in the communication protocol between them.

Single-Unit Control

Individual WEC control increases performance up to 300%
(Bacelli et al., 2020)

Multi-WEC Arrays

Arrays suffer destructive interactions (Park effects). (Babarit, 2013; Wang et al., 2016)

Centralized Control

Centralized MPC to control the full array
(Forehand et al., 2016)

Distributed/Decentralized Control

Cooperative MPC to handle complexity and scalability
(Zhang et al., 2023)

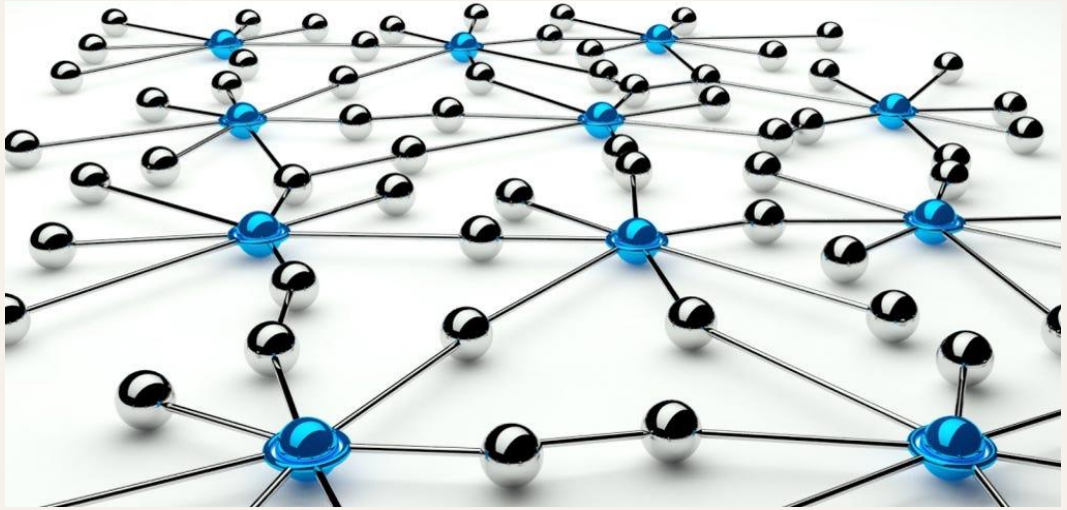
Nonlinear Distributed Control

Nonlinear distributed MPC for better modularity
(Chen et al., 2025)

Research Problem

Centralized and decentralized WEC control strategies often rely on unrealistic assumptions about communication. This work addresses the need for scalable, **communication-aware protocols** that enable real-time coordination under bandwidth constraints.

Image source: eghac.com via Microsoft Bing Images



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Mathematical Modelling for Single WEC

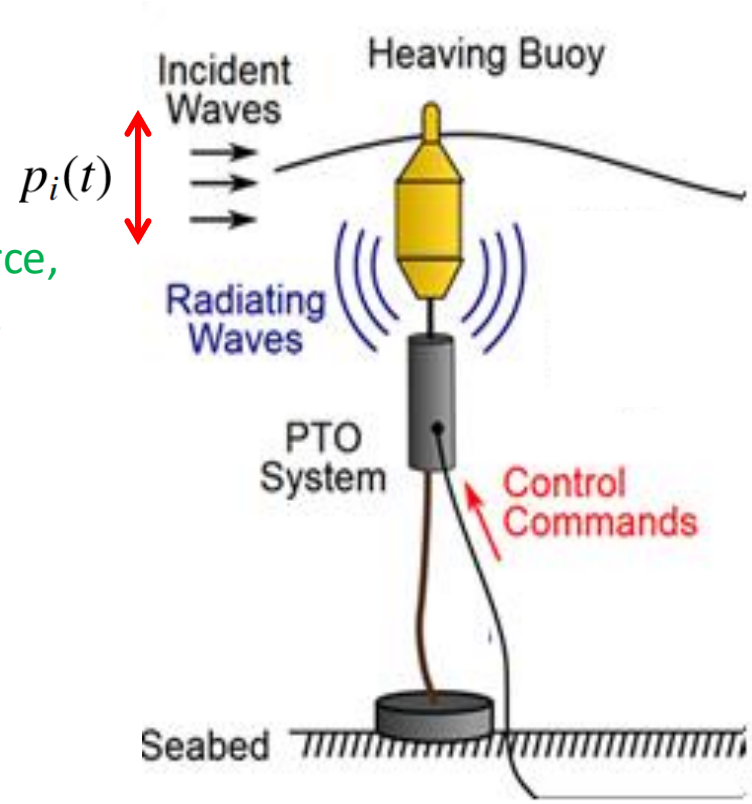
$$m_i \ddot{p}_i(t) = f_i^{\text{exc}}(t) + f_i^{\text{r}}(t) + f_i^{\text{h}}(t) + f_i^{\text{PTO}}(t)$$

Wave excitation force, depends on the wave condition

Radiation force, resulting from the radiating wave generated by the buoy

Restoration force, the buoyancy applied to the body

Power Take-off force, designed by us.



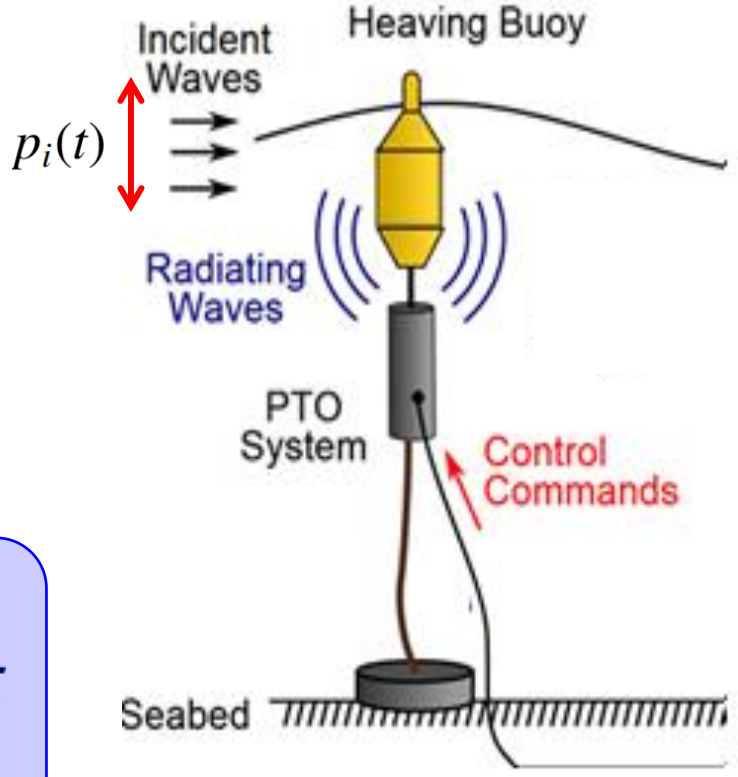
Mathematical Modelling for Single WEC

Optimal Control Problem

$$m_i \ddot{p}_i(t) = f_i^{\text{exc}}(t) + f_i^{\text{r}}(t) + f_i^{\text{h}}(t) + f_i^{\text{PTO}}(t)$$

$$E = -\int_0^T \dot{p}_i(t)\, f_i^{\text{PTO}}(t)\, dt$$

Total energy generated over a duration $[0, T]$



$$f_i^{\text{r}}(t) = -\mu_i\, \ddot{p}_i(t) - \sum_{j=1}^{2} \int_0^t K_{ij}^r(t-\tau)\, \dot{p}_j(\tau)\, \mathrm{d}\tau$$

The hydrodynamic coupling from WEC j to WEC i

Mathematical Modelling for Array

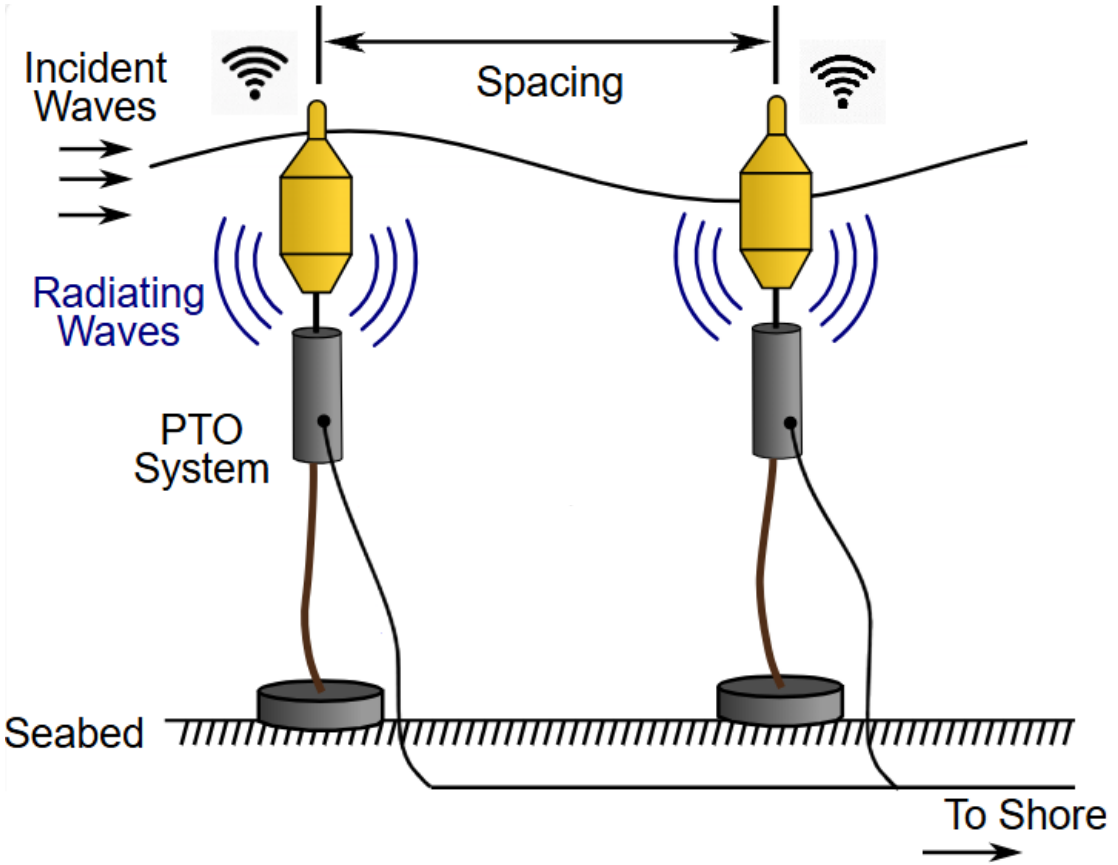
A centralized state-space model

$$\dot{x}(t) = Ax(t) + Bu(t) + B^{\text{exc}} f^{\text{exc}}(t) + B_d w^d(t)$$

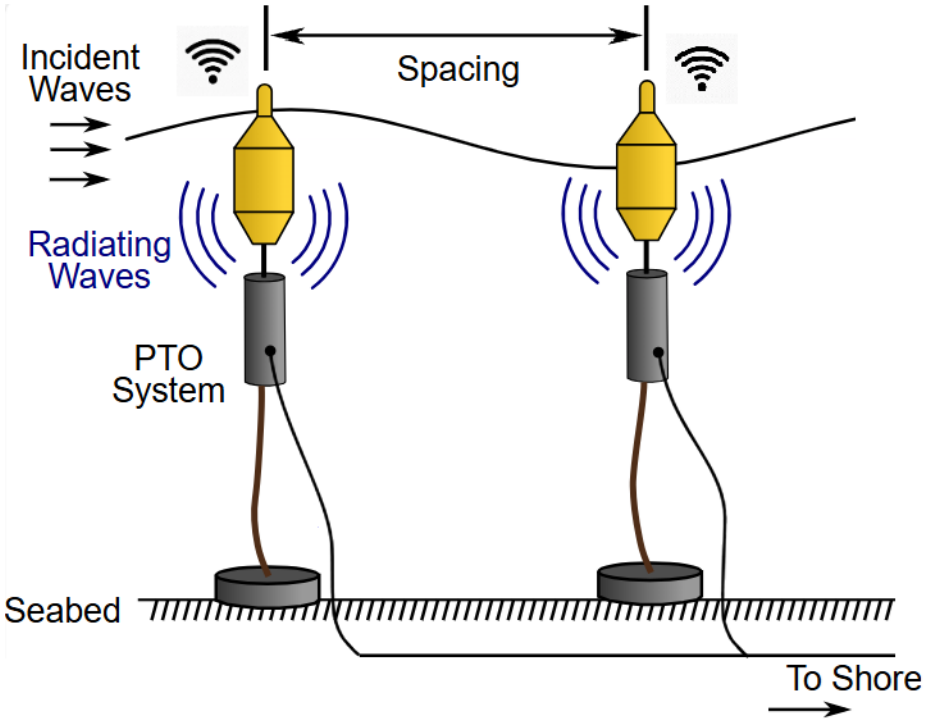
Uncertainties

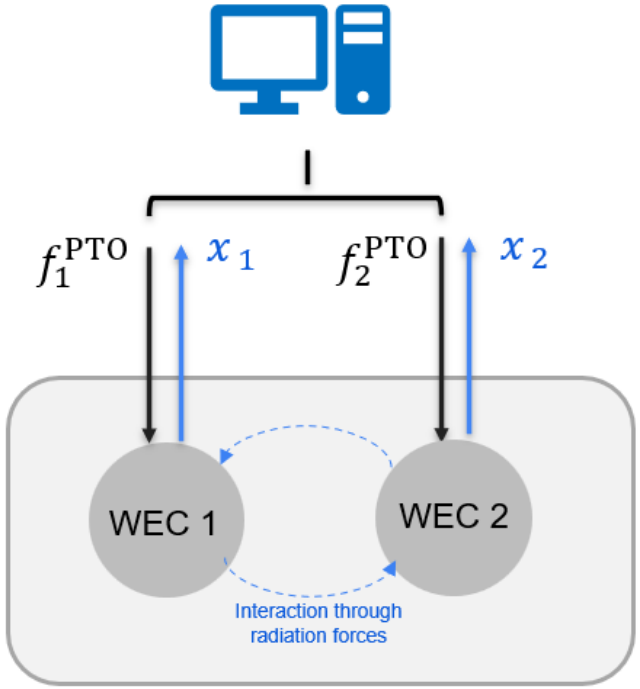
$$P_{\text{total}} = \mathbb{E}\Big[\int_0^T \left(-f_1^{\text{PTO}}(t)\, \dot{p}_1(t) - f_2^{\text{PTO}}(t)\, \dot{p}_2(t) \right) \mathrm{d}t \Big]$$

Total energy generated over a duration $[0, T]$



The communication constrained optimization





$$\max_{f_1^{\mathrm{PTO}}, f_2^{\mathrm{PTO}}} \quad P_{\mathrm{total}} = \mathbb{E}\left[\int_0^T \left(-f_1^{\mathrm{PTO}}(t)\,\dot{p}_1(t) - f_2^{\mathrm{PTO}}(t)\,\dot{p}_2(t)\right)\,\mathrm{d}t\right]$$

$$\text{subject to} \quad \frac{1}{T}\mathbb{E}[m(T)] \leq \bar{m}$$

Communication Protocols Comparison

Continuous Communication 01	Event-Triggered Communication (*Proposed Method*) 02	No Communication 03
Full-state feedback at every time step.	Transmits only when necessary, optimizing the trade-off between **performance and communication cost**.	No updates; control is purely based on internal model predictions.

These scenarios represent the range of bandwidth-accuracy trade-offs in the control applications.

Case Study

Identify Event Trigger

A specific event triggers the need for communication.

Determine Sparse Transmission Times

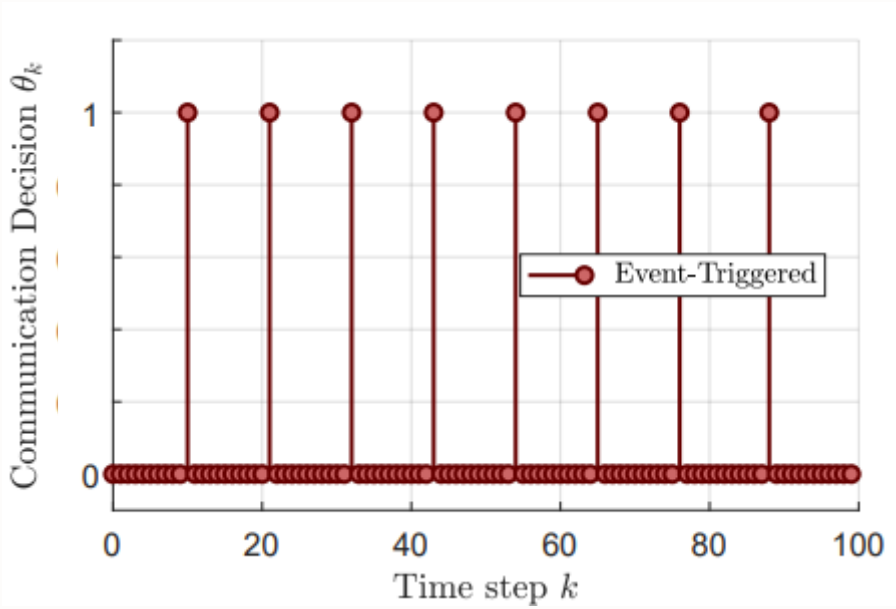
The solution determines the optimal times for communication.

Solve Optimization Problem

An optimization problem is solved to balance Control quality and communication cost.

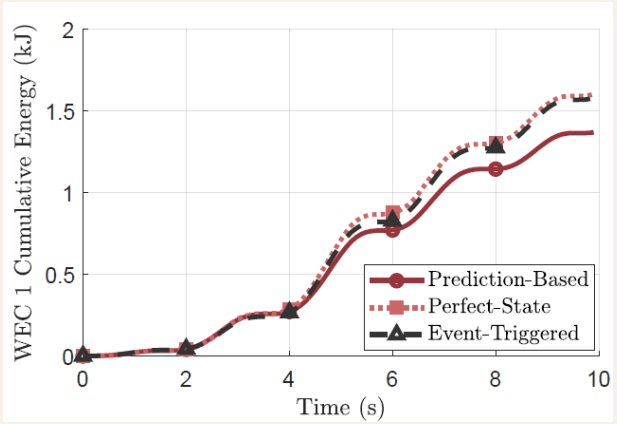
Transmit Data

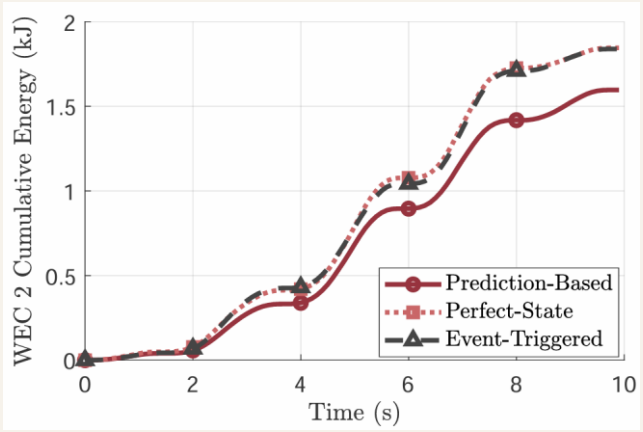
Data is transmitted only at the determined times.

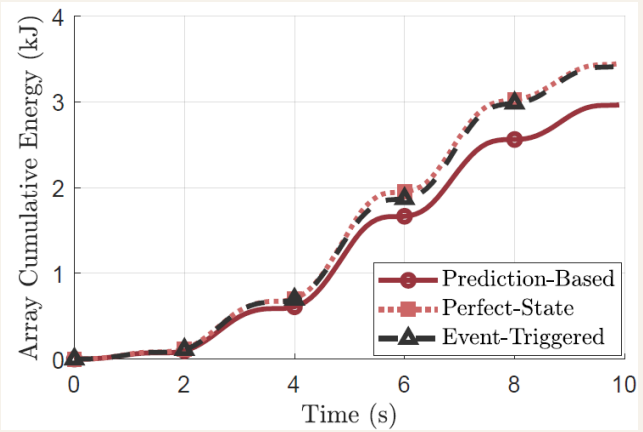


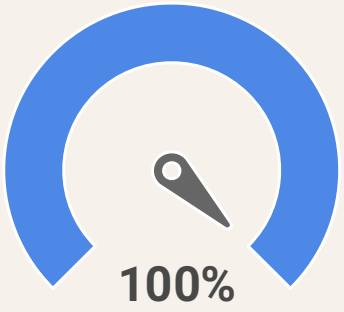
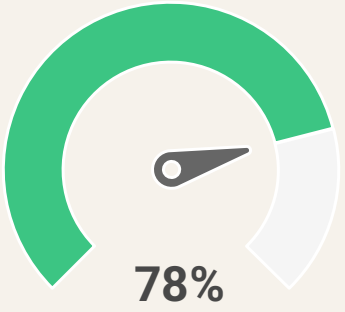
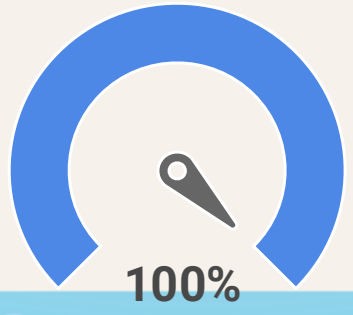
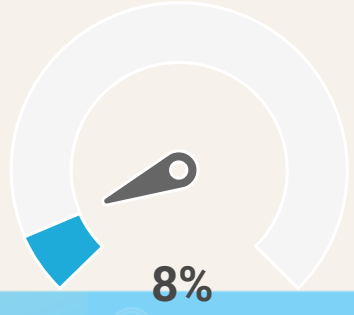
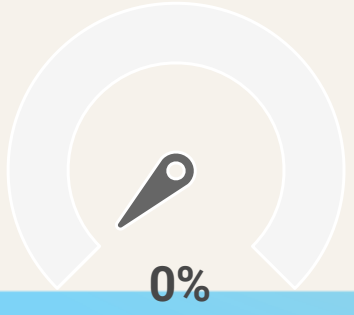
Event-Triggered Communication Scheme

Results:

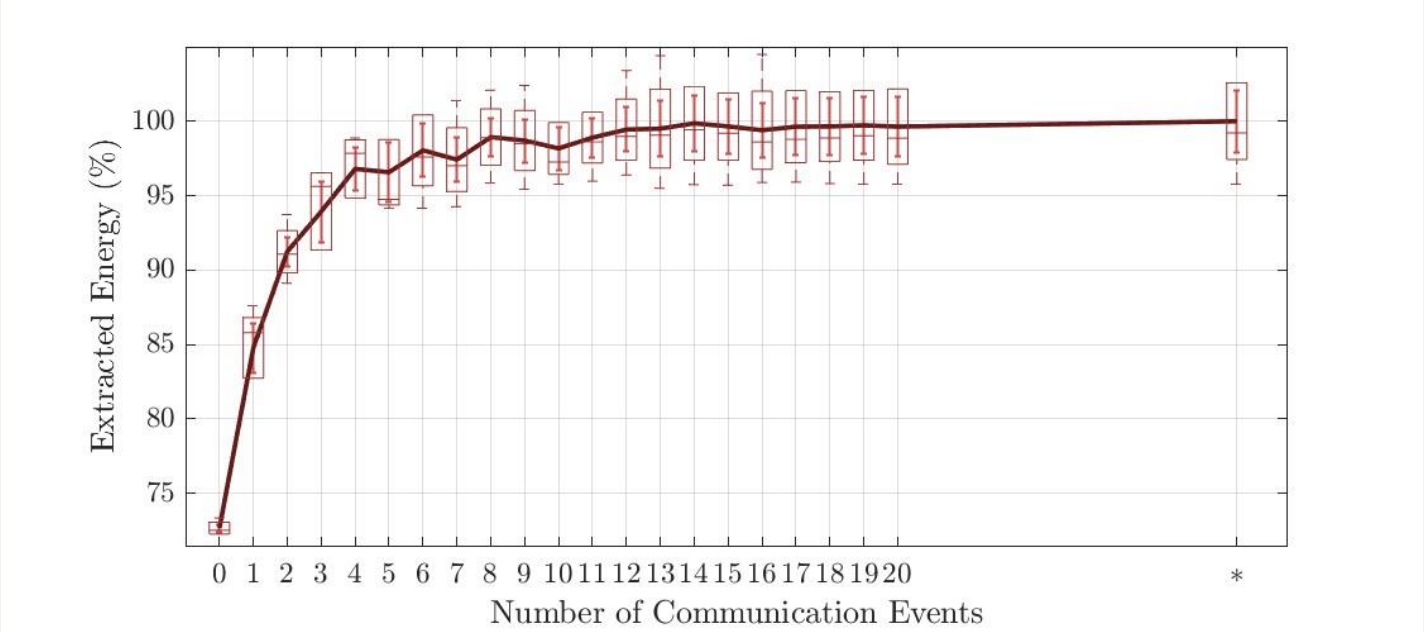






	Continuous Communication	Event-Triggered Communication	No Communication
Energy extracted from the array	 100%	 98%	 78%
Communication	 100%	 8%	 0%

Results:



Optimizing Communication for Energy Extraction

Infrequent Communication

Limited energy extraction efficiency

Increase Communication

Initial power extraction improvement

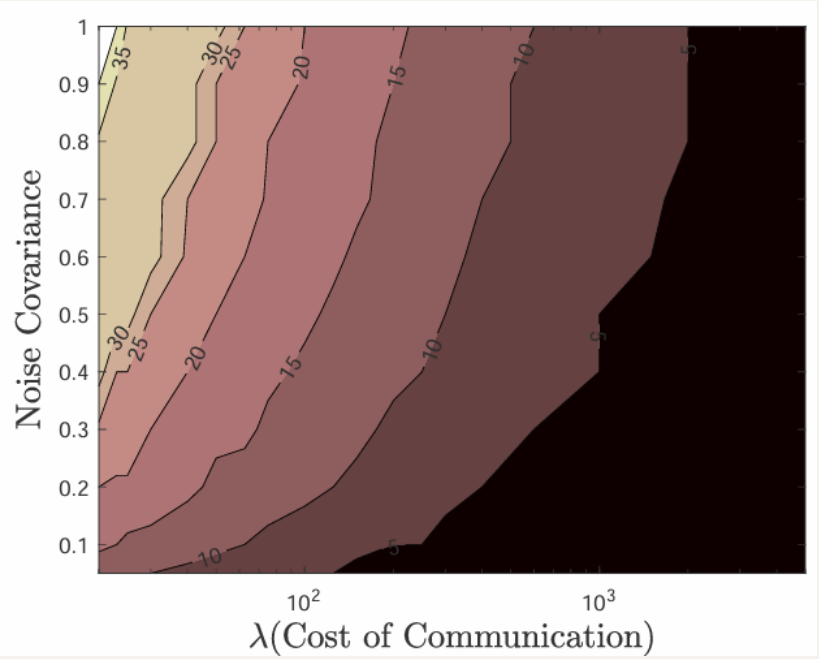
Plateauing Performance

Diminishing returns with over-communication

Moderate Communication

Near-optimal power extraction achieved

Results:



How to balance communication frequency in event-triggered control?

High Communication Cost

Reduces communication events, relying more on predictions.

Low Communication Cost

Increases communication events, enhancing information exchange.

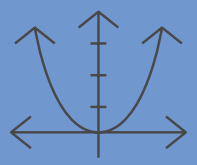
High Noise Covariance

Triggers frequent communication due to uncertainty.

Low Noise Covariance

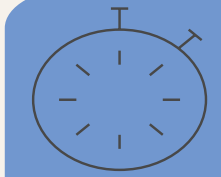
Decreases communication events, trusting predictions.

Conclusion:



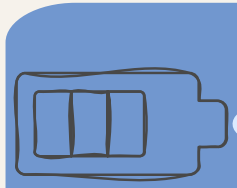
Discrete-Time LQR Control

Optimizes control inputs for efficient energy extraction.



Event-Triggered Communication

Reduces communication frequency while maintaining performance.



Energy Extraction Performance

Maximizes energy capture with minimal communication cost.

Communication Cost Reduction

Significantly lowers communication expense in WEC array

THANK YOU

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