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# Recent Advances in Distributed Event-Triggered Communication and Coordinated Control of Multi-Agent Systems

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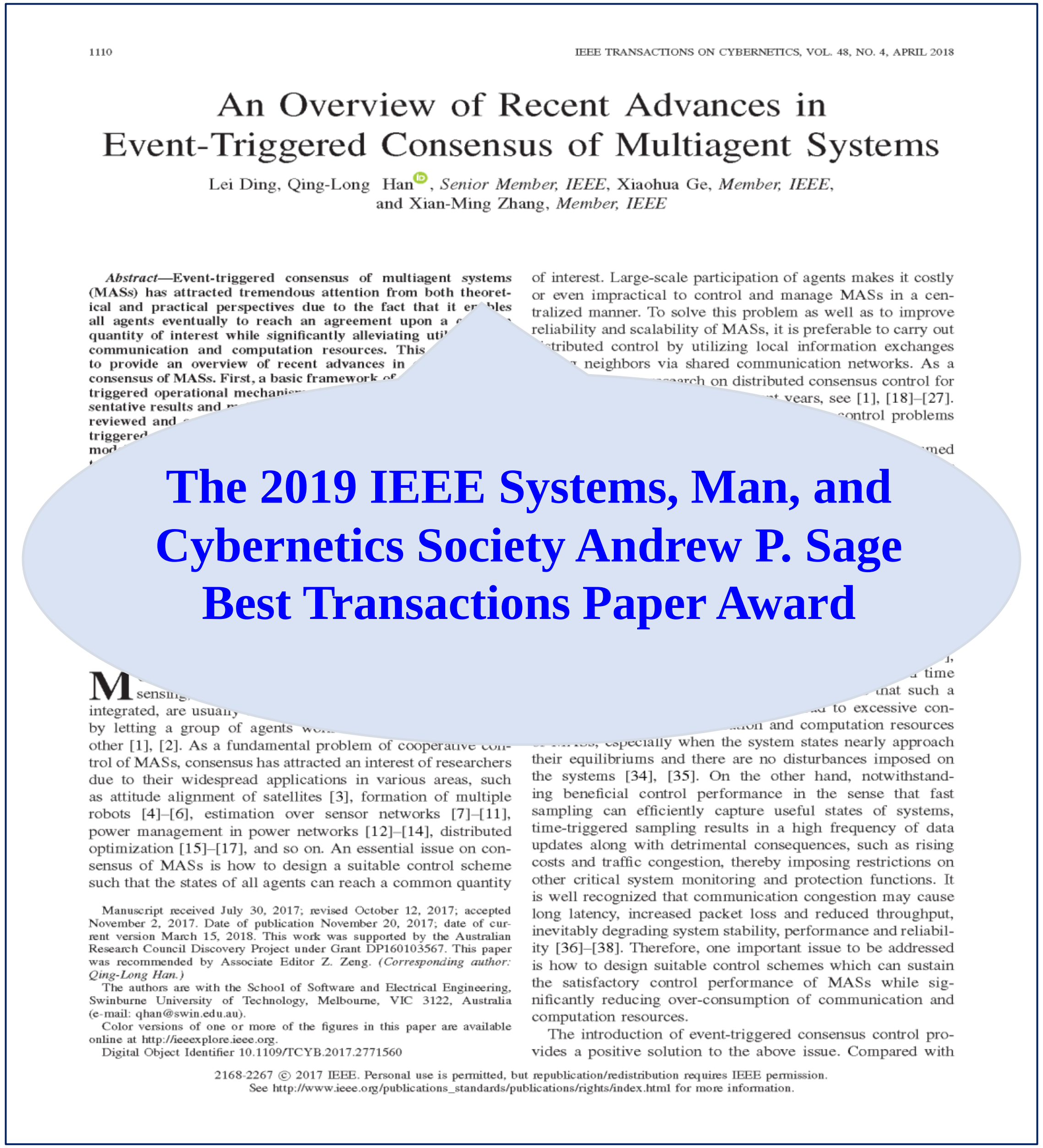

1110 IEEE TRANSACTIONS ON CYBERNETICS, VOL. 48, NO. 4, APRIL 2018

An Overview of Recent Advances in Event-Triggered Consensus of Multiagent Systems

Lei Ding, Qing-Long Han, *Senior Member, IEEE*, Xiaohua Ge, *Member, IEEE*, and Xian-Ming Zhang, *Member, IEEE*

other [1], [2]. As a fundamental problem of cooperative control of MASs, consensus has attracted an interest of researchers due to their widespread applications in various areas, such as attitude alignment of satellites [3], formation of multiple robots [4]–[6], estimation over sensor networks [7]–[11], power management in power networks [12]–[14], distributed optimization [15]–[17], and so on. An essential issue on consensus of MASs is how to design a suitable control scheme such that the states of all agents can reach a common quantity of interest. Large-scale participation of agents makes it costly or even impractical to control and manage MASs in a centralized manner. To solve this problem as well as to improve reliability and scalability of MASs, it is preferable to carry out distributed control by utilizing local information exchanges

their equilibriums and there are no disturbances imposed on the systems [34], [35]. On the other hand, notwithstanding beneficial control performance in the sense that fast sampling can efficiently capture useful states of systems, time-triggered sampling results in a high frequency of data updates along with detrimental consequences, such as rising costs and traffic congestion, thereby imposing restrictions on other critical system monitoring and protection functions. It is well recognized that communication congestion may cause long latency, increased packet loss and reduced throughput, inevitably degrading system stability, performance and reliability [36]–[38]. Therefore, one important issue to be addressed is how to design suitable control schemes which can sustain the satisfactory control performance of MASs while significantly reducing over-consumption of communication and computation resources.

The introduction of event-triggered consensus control provides a positive solution to the above issue. Compared with

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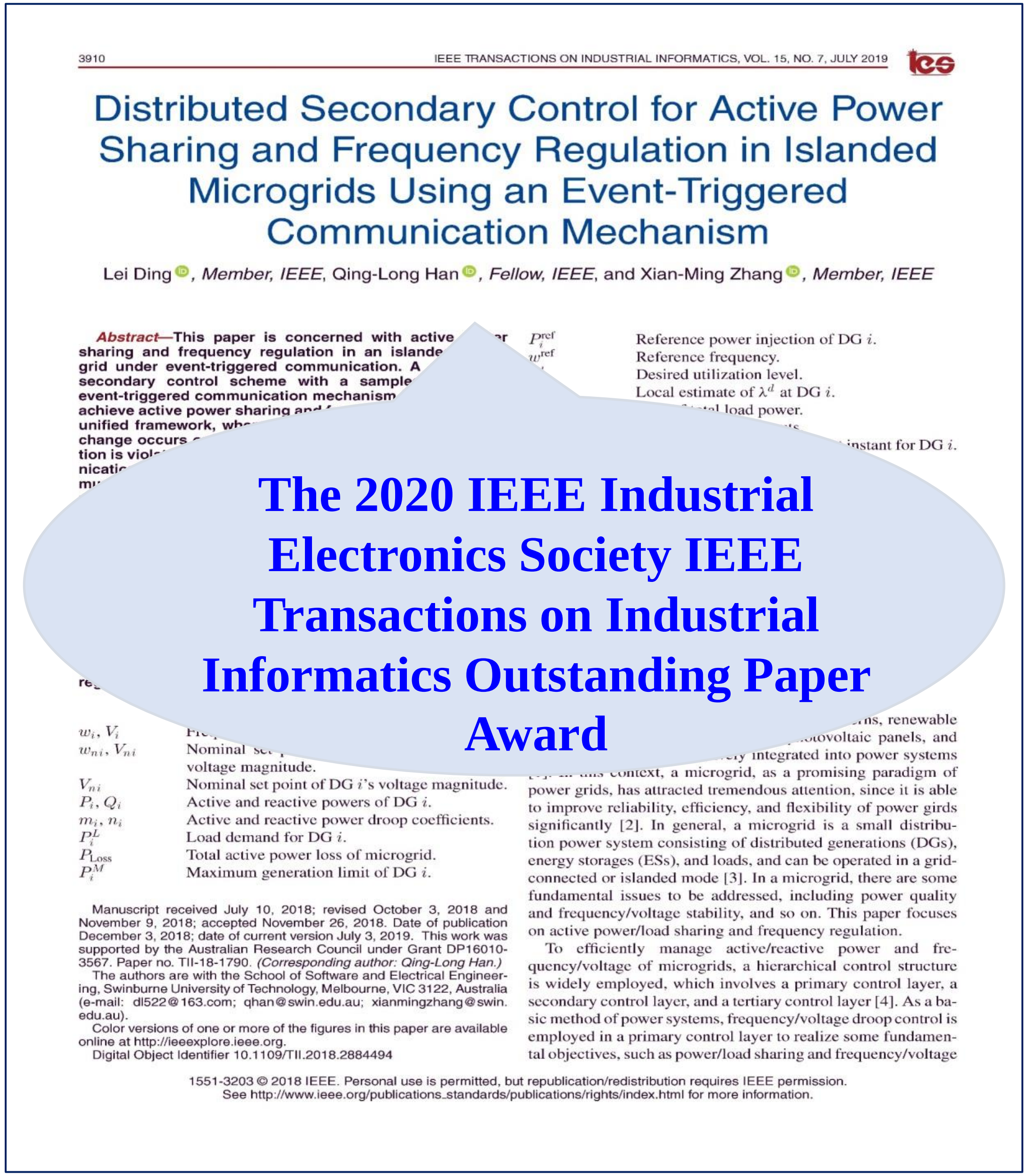
**The 2019 IEEE Systems, Man, and Cybernetics Society Andrew P. Sage Best Transactions Paper Award**



3910 IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, VOL. 15, NO. 7, JULY 2019

Distributed Secondary Control for Active Power Sharing and Frequency Regulation in Islanded Microgrids Using an Event-Triggered Communication Mechanism

Lei Ding, *Member, IEEE*, Qing-Long Han, *Fellow, IEEE*, and Xian-Ming Zhang, *Member, IEEE*

| | |
|---|---|
| $P_i^{ref}$ | Reference power injection of DG $i$. |
| $w^{ref}$ | Reference frequency. |
| | Desired utilization level. |
| | Local estimate of $\lambda^d$ at DG $i$. |
| $w_{ni}, V_{ni}$ | Nominal set point ... voltage magnitude. |
| $V_{ni}$ | Nominal set point of DG $i$'s voltage magnitude. |
| $P_i, Q_i$ | Active and reactive powers of DG $i$. |
| $m_i, n_i$ | Active and reactive power droop coefficients. |
| $P_i^L$ | Load demand for DG $i$. |
| $P_{Loss}$ | Total active power loss of microgrid. |
| $P_i^M$ | Maximum generation limit of DG $i$. |

... power grids, has attracted tremendous attention, since it is able to improve reliability, efficiency, and flexibility of power girds significantly [2]. In general, a microgrid is a small distribution power system consisting of distributed generations (DGs), energy storages (ESs), and loads, and can be operated in a grid-connected or islanded mode [3]. In a microgrid, there are some fundamental issues to be addressed, including power quality and frequency/voltage stability, and so on. This paper focuses on active power/load sharing and frequency regulation.

To efficiently manage active/reactive power and frequency/voltage of microgrids, a hierarchical control structure is widely employed, which involves a primary control layer, a secondary control layer, and a tertiary control layer [4]. As a basic method of power systems, frequency/voltage droop control is employed in a primary control layer to realize some fundamental objectives, such as power/load sharing and frequency/voltage

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The authors are with the School of Software and Electrical Engineering, Swinburne University of Technology, Melbourne, VIC 3122, Australia (e-mail: dl522@163.com; qhan@swin.edu.au; xianmingzhang@swin.edu.au).

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Digital Object Identifier 10.1109/TII.2018.2884494



**The 2020 IEEE Industrial Electronics Society IEEE Transactions on Industrial Informatics Outstanding Paper Award**

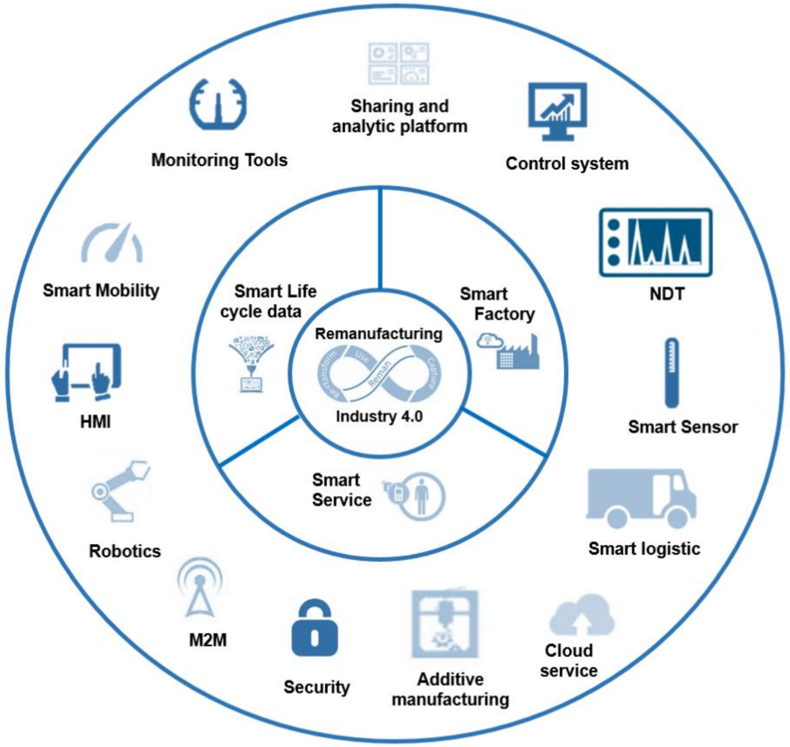
# OUTLINE

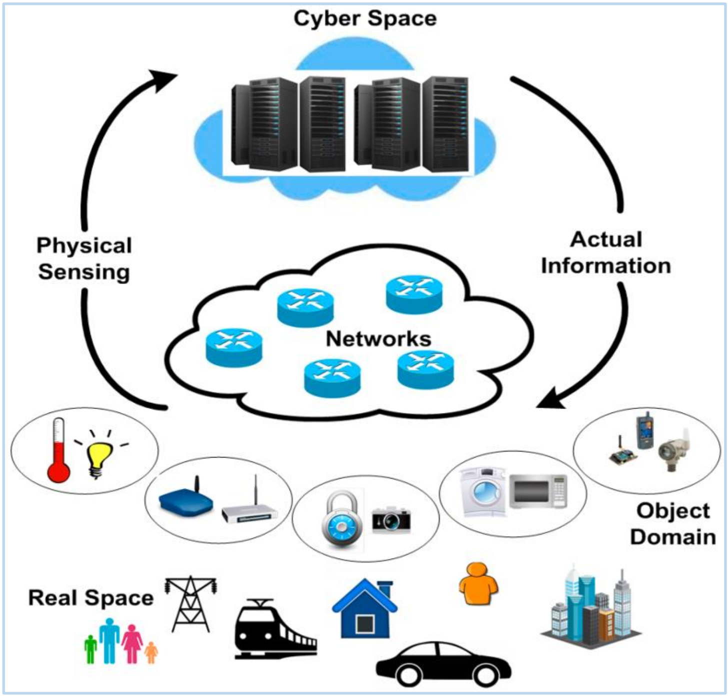
01

# Multi-Agent Systems

# Multi-Agent Systems

**Industry 4.0** refers to the transformation of industry through the intelligent networking of machines and processes with the help of information and communication technology.




Multi-agent systems (MASs) are the basis and enabler of Industry 4.0.

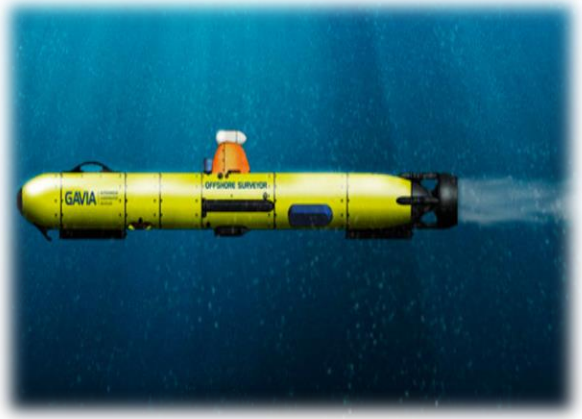
# Multi-Agent Systems

An MAS is a system that consists of multiple autonomous agents communicating with one another through a network medium so as to perform a coordinated task or achieve a desirable collective behaviour.

**Agent**: Pioneer 3-DX

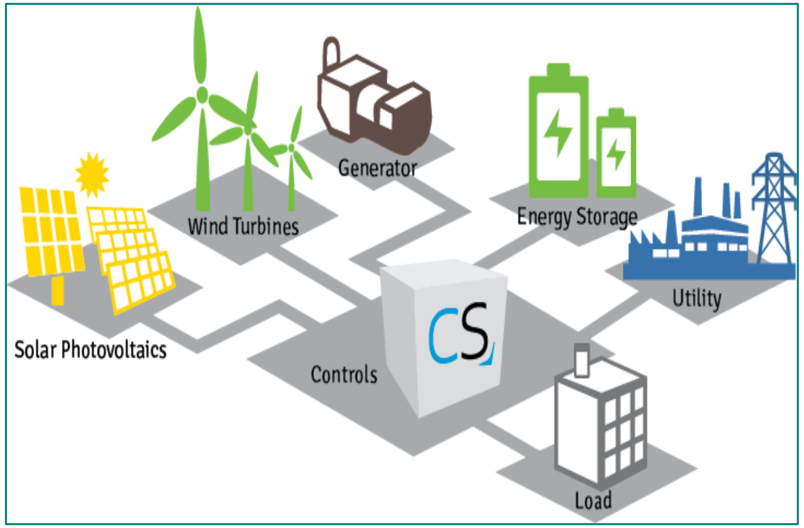
**Agent**: MQ9-Reaper

**Agent**: DJI Phantom Unmanned Aerial Vehicle (UAV)

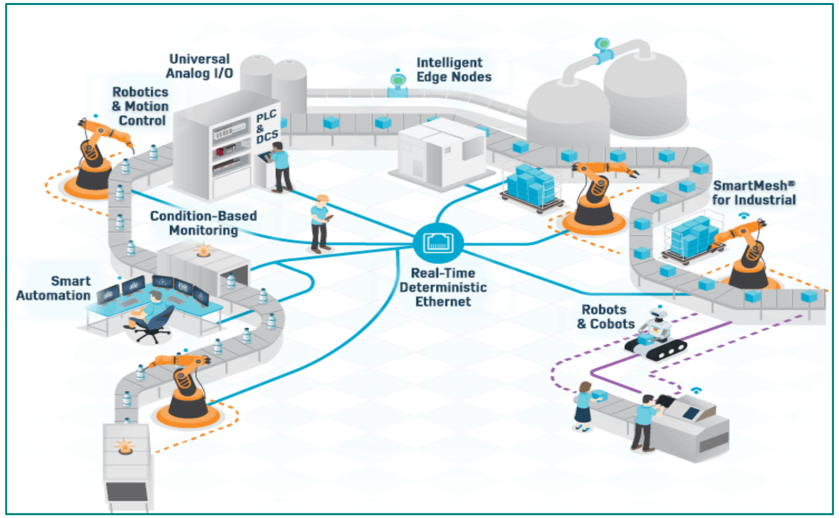


**Agent**: Gavia-Surveyor Autonomous Underwater Vehicle (AUV)

# Multi-Agent Systems




Smart Grids




Industrial Manufacturing

Practical applications

MAS

Intelligent Transportation

Multi-UAVs

# Multi-Agent Systems

Several key features

**MAS**

### Inter-Agent Communication

- ✓ Networked structure
- ✓ Local information exchange among neighbours
- ✓ Distributed

### Coordinated Behaviour

- ✓ Consensus (Rendezvous)
- ✓ Flocking
- ✓ Coverage control
- ✓ Containment control
- ✓ Formation control

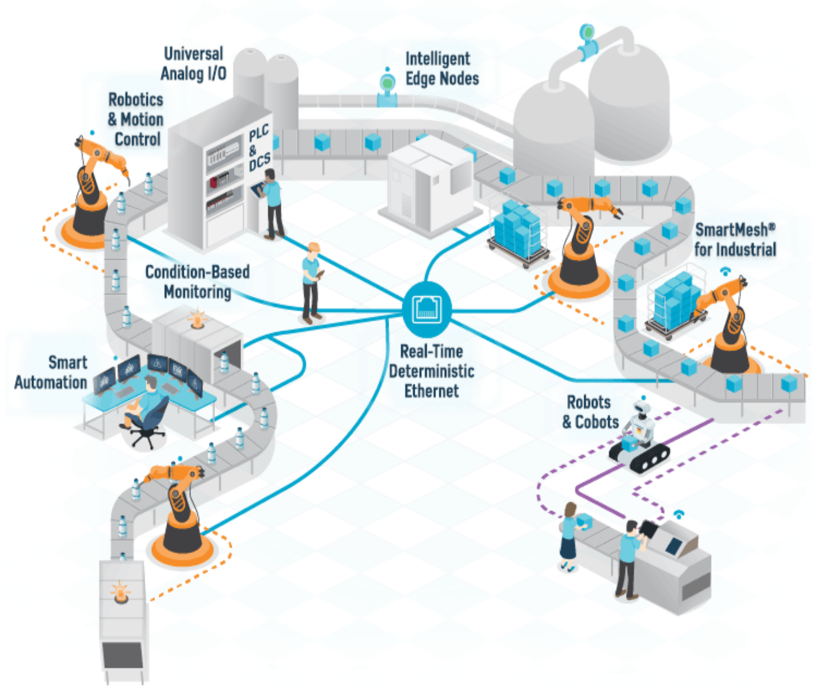
### Advantages

- ✓ Achieving complicated and dangerous missions
- ✓ High efficiency
- ✓ Reliability, Scalability, Robustness

# Multi-Agent Systems

## Communication and Coordinated Control in MASs

### A typical MAS




### Communication Networks

Unit control → Coordinated control

- Large number
- Spatially distributed
- Communication and computation burden

Centralized control

Distributed control

# Multi-Agent Systems

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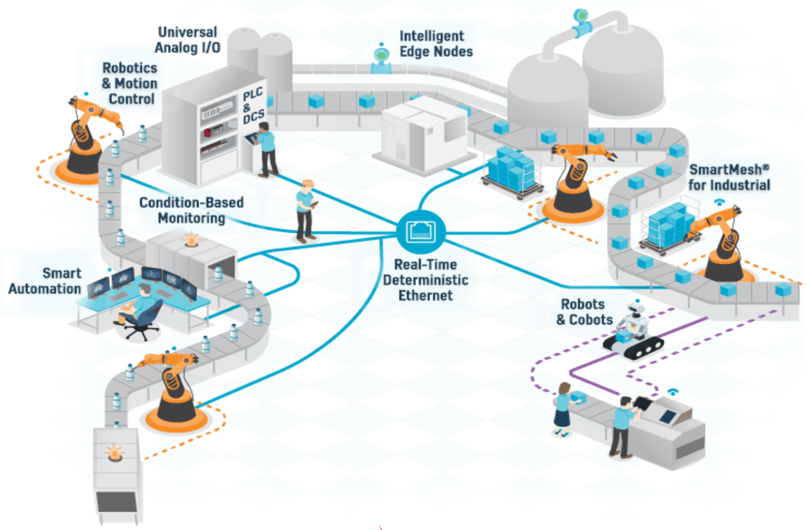
## Challenging Issues

### A typical MAS




### Communication and control design

- ✓ Achieving satisfactory control performance ← **Control Objective**
- ✓ Making efficient use of communication and computation resources. ← **Communication Objective**

**There is a tradeoff between these two objectives**

**How to design a suitable control scheme which can achieve these two objectives simultaneously?**

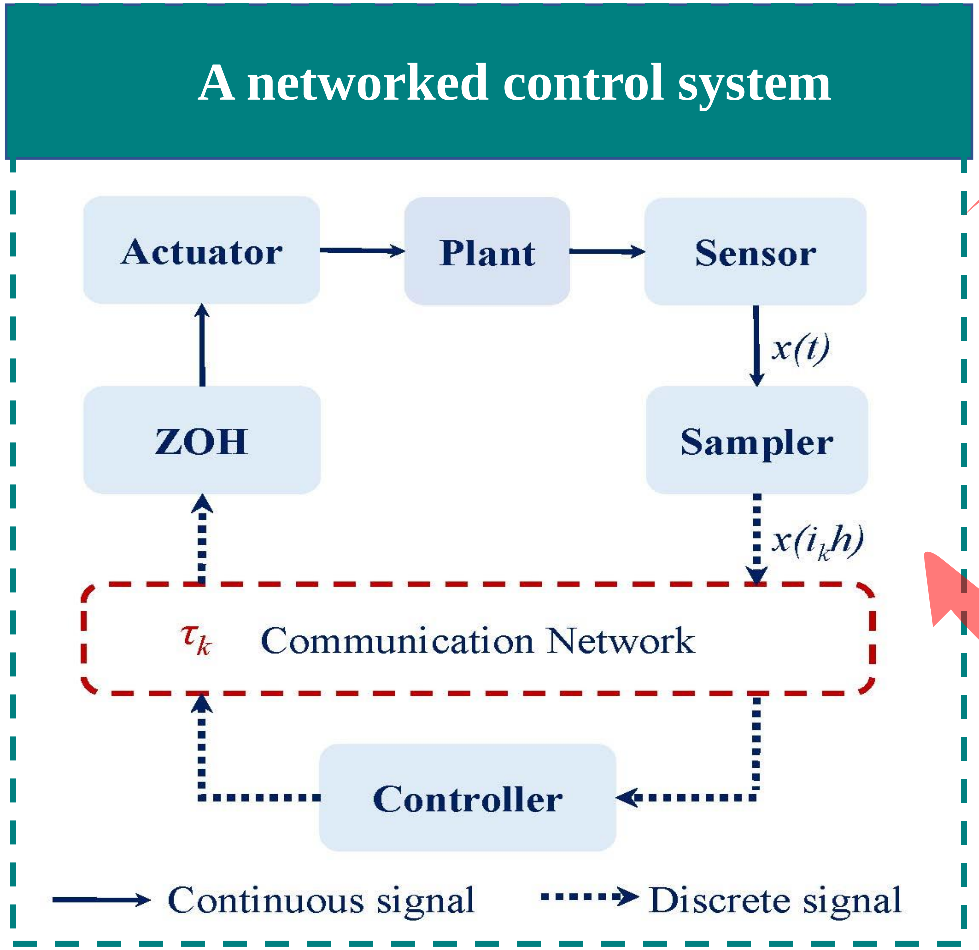
**Solution** →

**Distributed event-triggered coordinated control scheme**

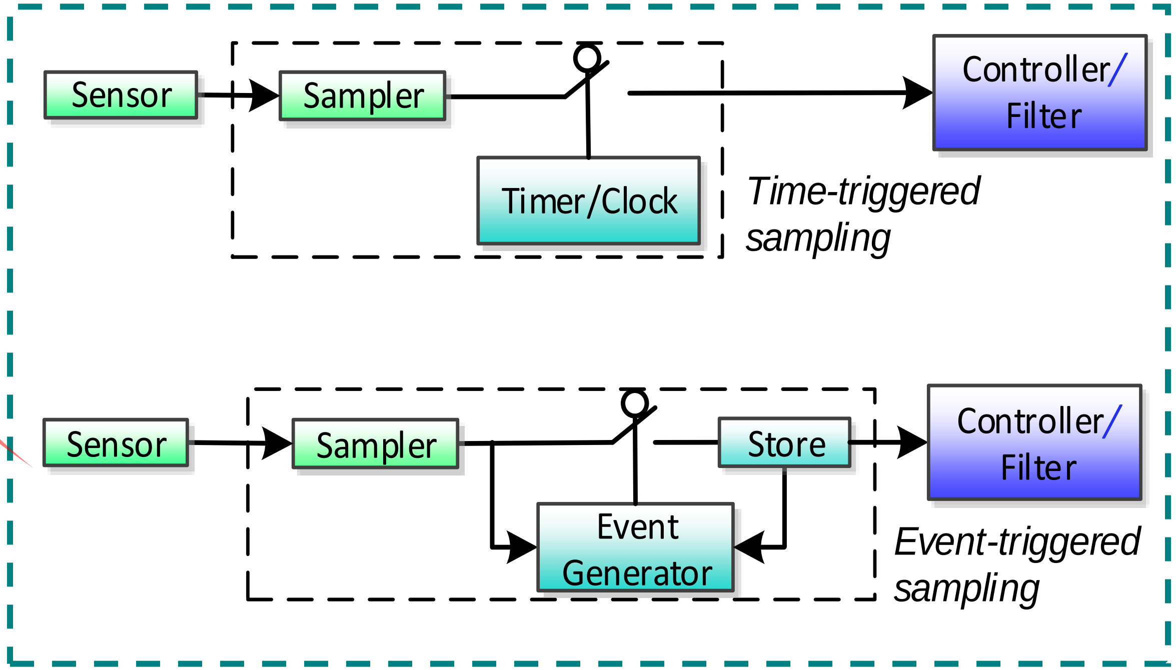
02

# Event-Triggered Communication

# Event-Triggered Communication

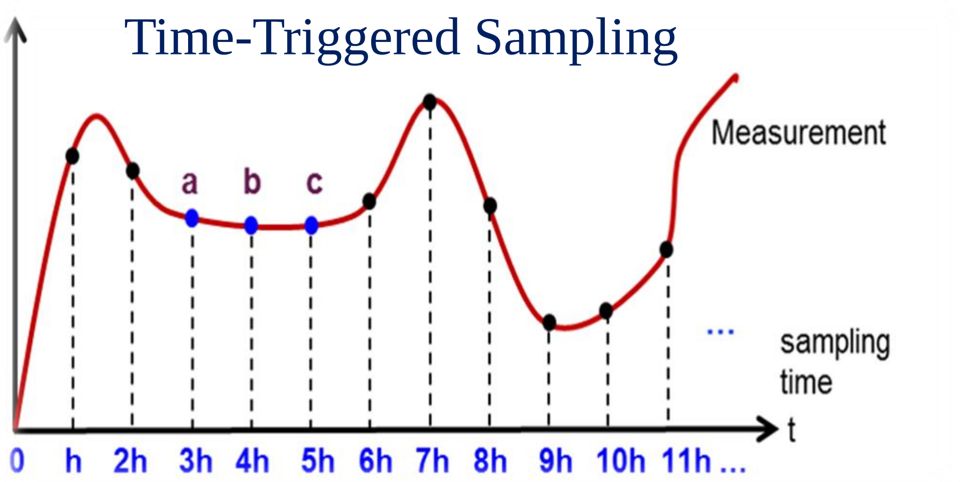


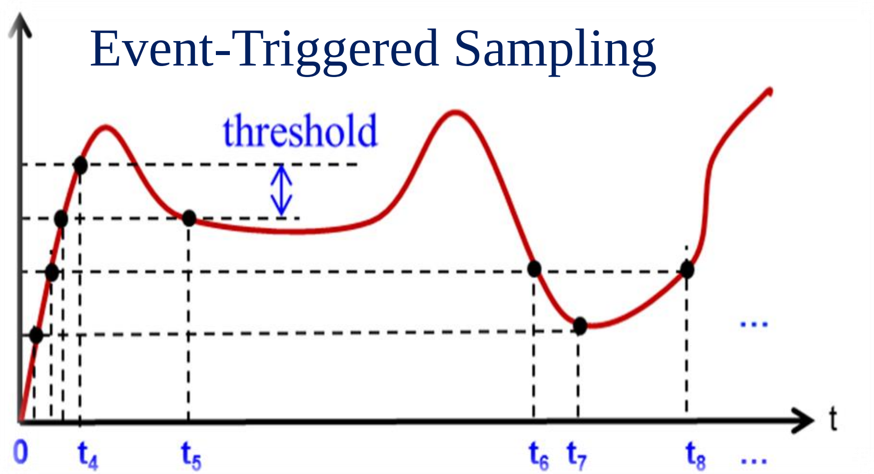

- When to sample?
- When to transmit?



# Event-Triggered Communication

## Time-Triggered Sampling VS Event-Triggered Sampling



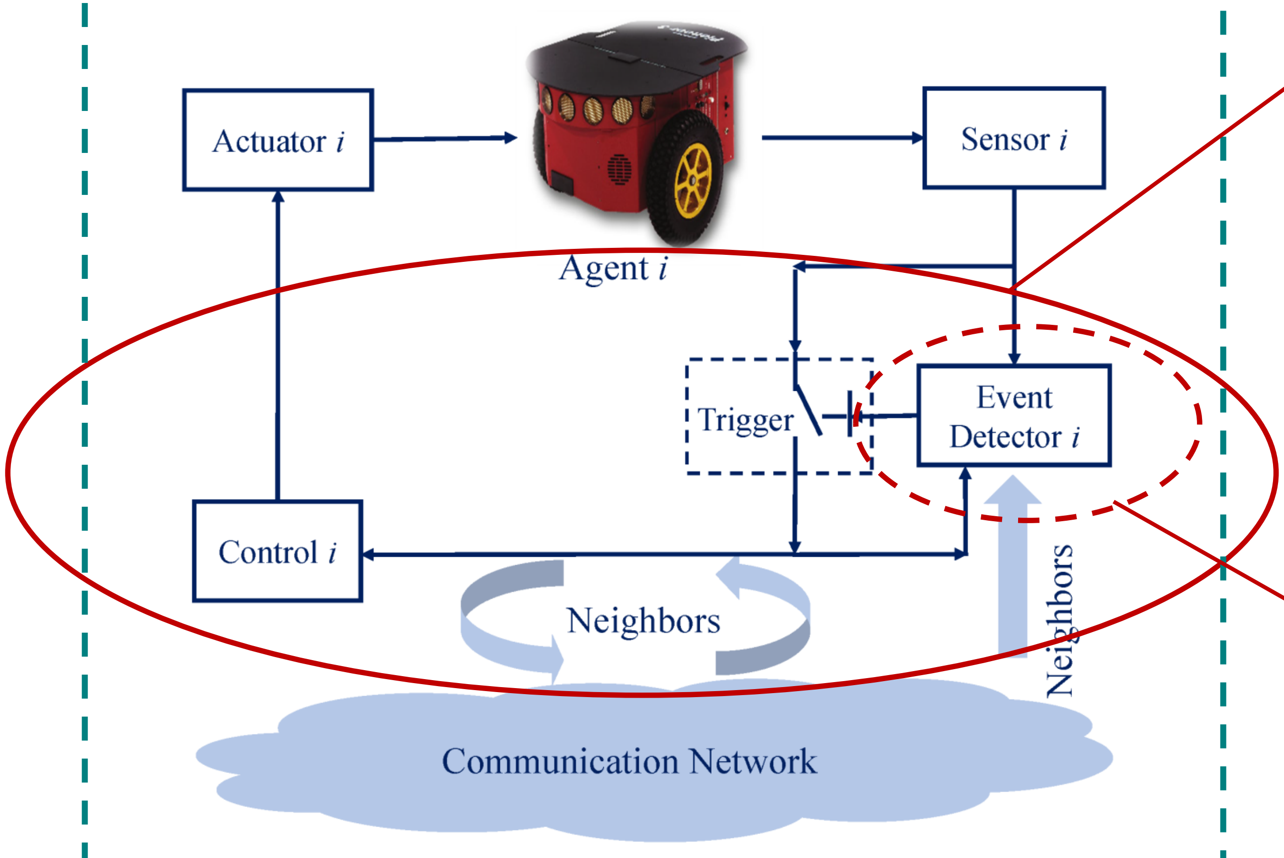




- Periodical sampling instants
- Irrespective of real-time network resource utilization and dynamic system evolution
- Resource-wasteful (e.g., little fluctuation at points: a, b, c)

- Sample only when an event occurs, e.g., a threshold is violated
- Dynamic and intelligent sampling
- Resource-efficient

# Event-Triggered Communication

**Event-triggered coordinated control for MASs**



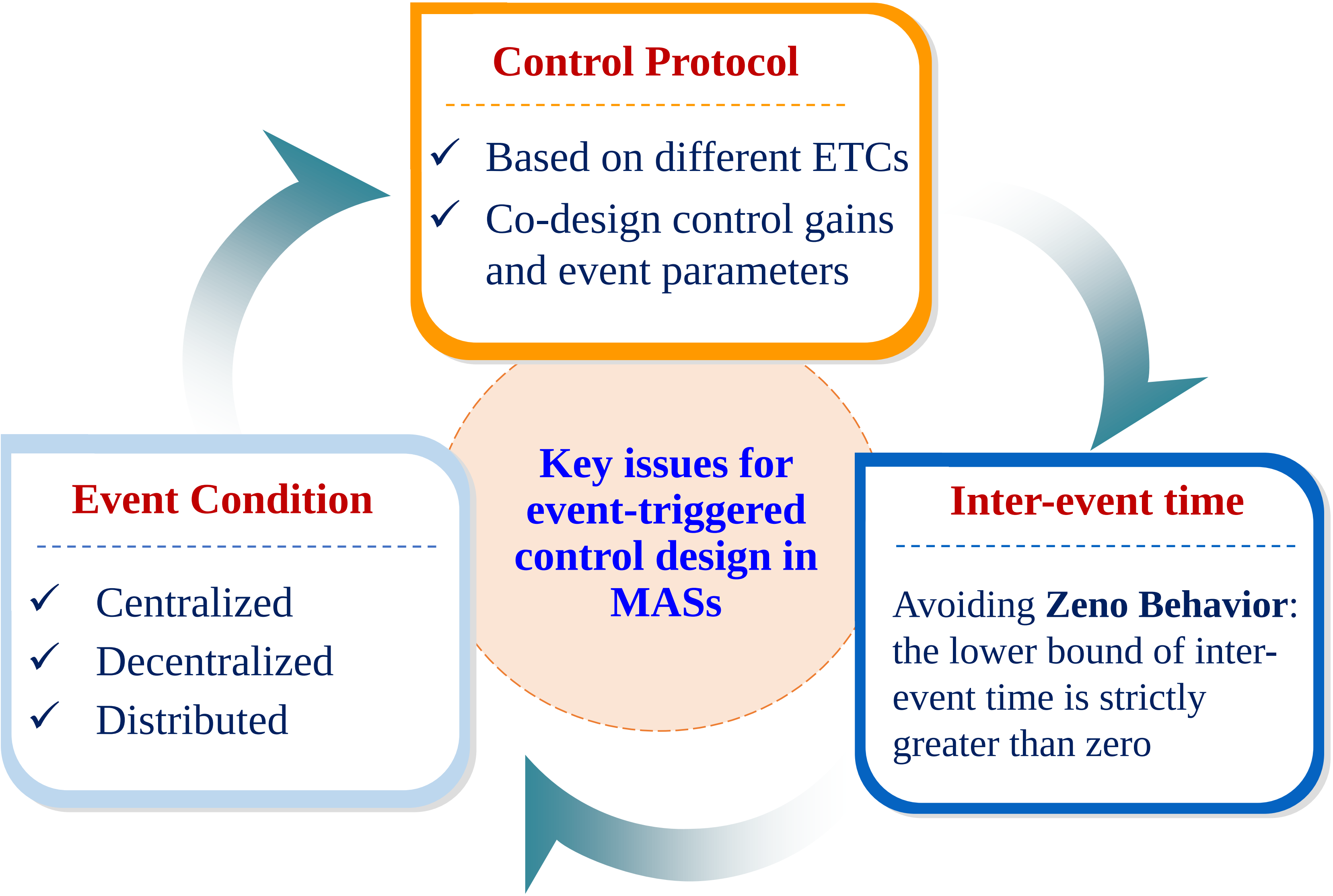

**Event-Triggered Control Scheme**

- ✓ Event-triggered sampling/communication module
- ✓ Control module

**Event Detector**

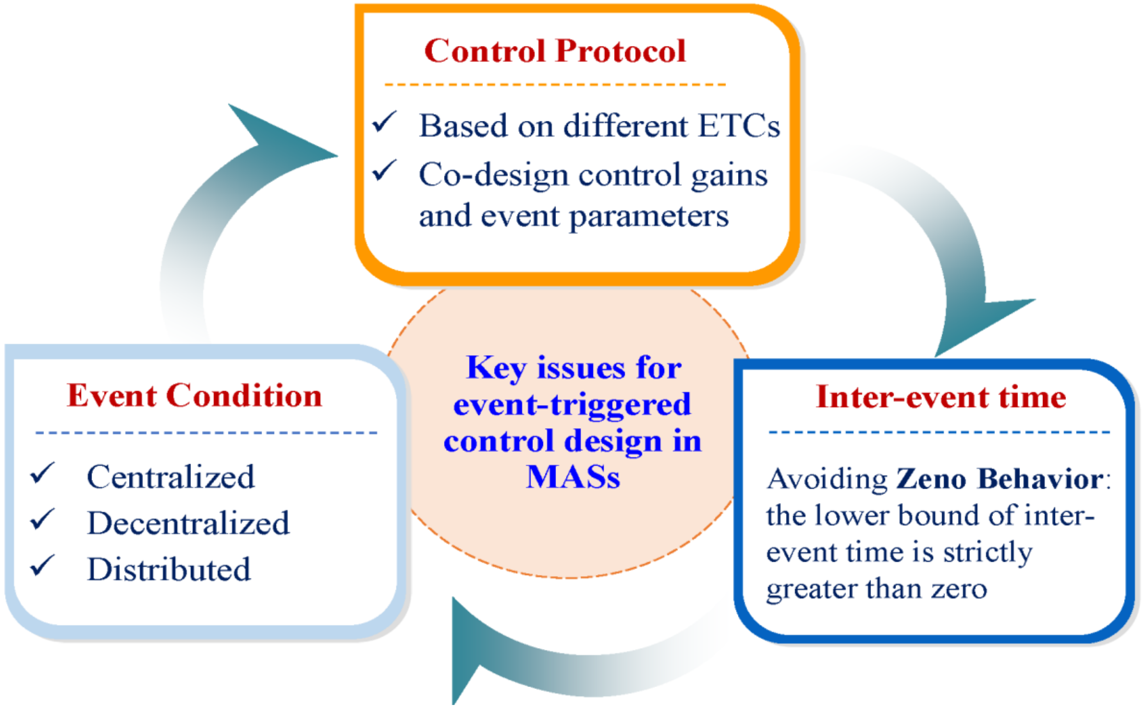
- ✓ Presetting or embedding an event-triggering condition (ETC)
- ✓ Collecting all measurements;
- ✓ Making a decision;
- ✓ Generating an execution signal.

# Event-Triggered Communication



# Event-Triggered Communication

## MAS *VS* Single-Agent System




### Difficulties

- ✓ **Strong information coupling** in distributed control protocol
- ✓ **High complexity** in designing distributed ETCs
- ✓ **Complicated analysis** on excluding Zeno behavior

**It is more complicated and challenging to design event-triggered control scheme for MASs**

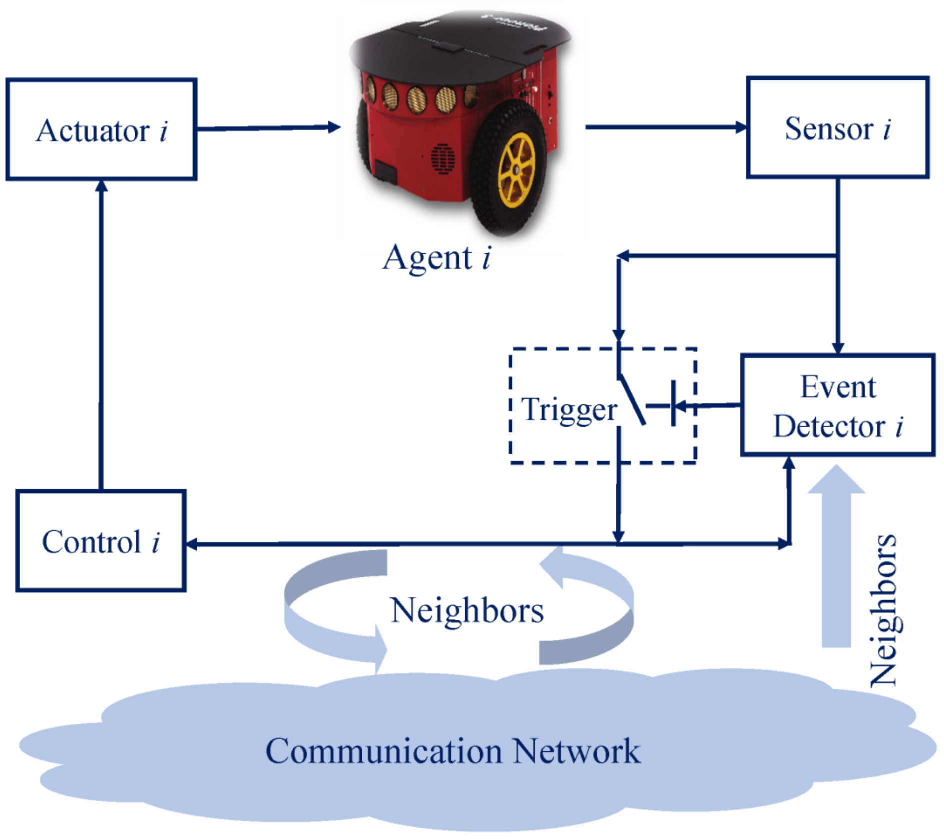
03

# Distributed Event-Triggered Consensus

# Distributed Event-Triggered Consensus

## Consensus issues

### Event-triggered coordinated control for MASs




### Agents' dynamics and control protocol

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

$$u_i(t) = -K \sum_{j \in N_i} a_{ij}(t)(x_i(t) - x_j(t))$$

### Communication topology

- ✓ Directed or undirected
- ✓ Fixed or time-varying

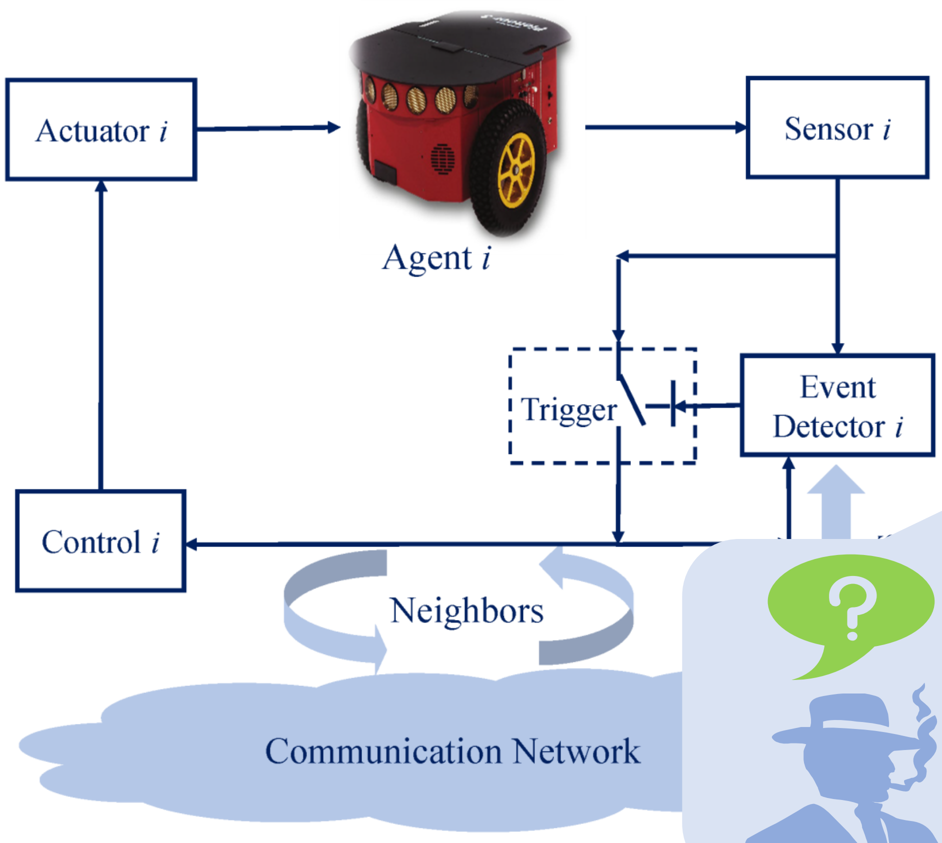
### Consensus objective

$$\lim_{t \to \infty} \|x_i - x_j\| = 0$$

# Distributed Event-Triggered Consensus

## Consensus issues

### Event-triggered coordinated control for MASs




### Agents' dynamics and control protocol

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

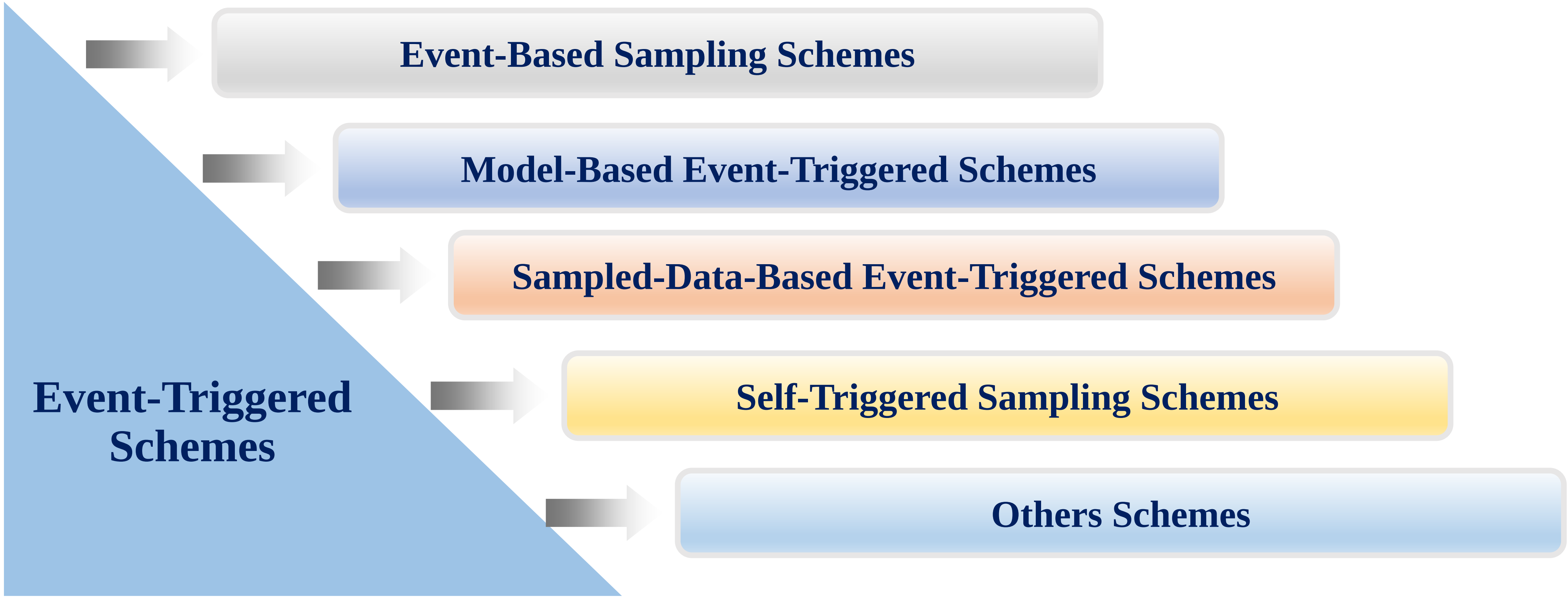
$$u_i(t) = -K \sum_{j \in N_i} a_{ij}(t)(x_i(t) - x_j(t))$$

### Communication topology

✓ Directed or undirected

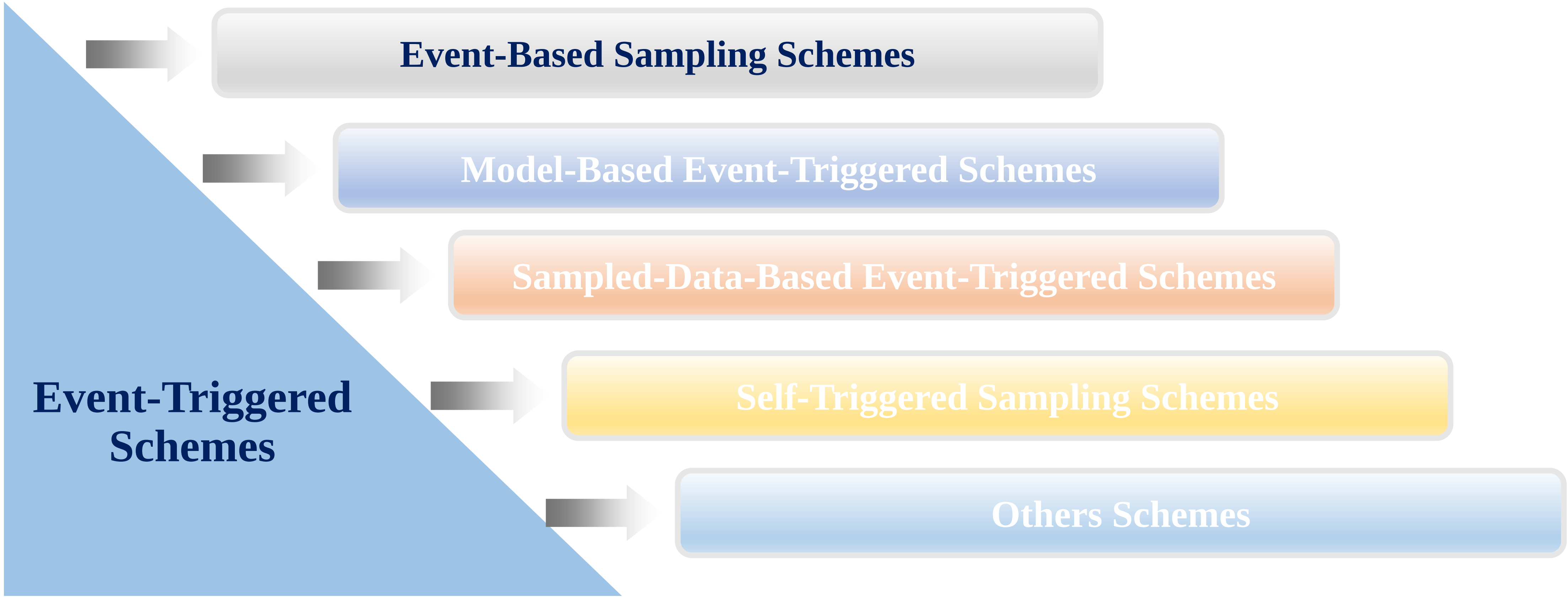
**How to design a distributed event-triggered scheme in this consensus framework**

# Distributed Event-Triggered Consensus




L. Ding, Q.-L. Han, X. Ge, and X.-M. Zhang, “An overview of recent advances in event-triggered consensus of multi-agent systems,” *IEEE Transactions on Cybernetics*, vol.48, no.4, pp. 1110-1123, 2018.

# Distributed Event-Triggered Consensus

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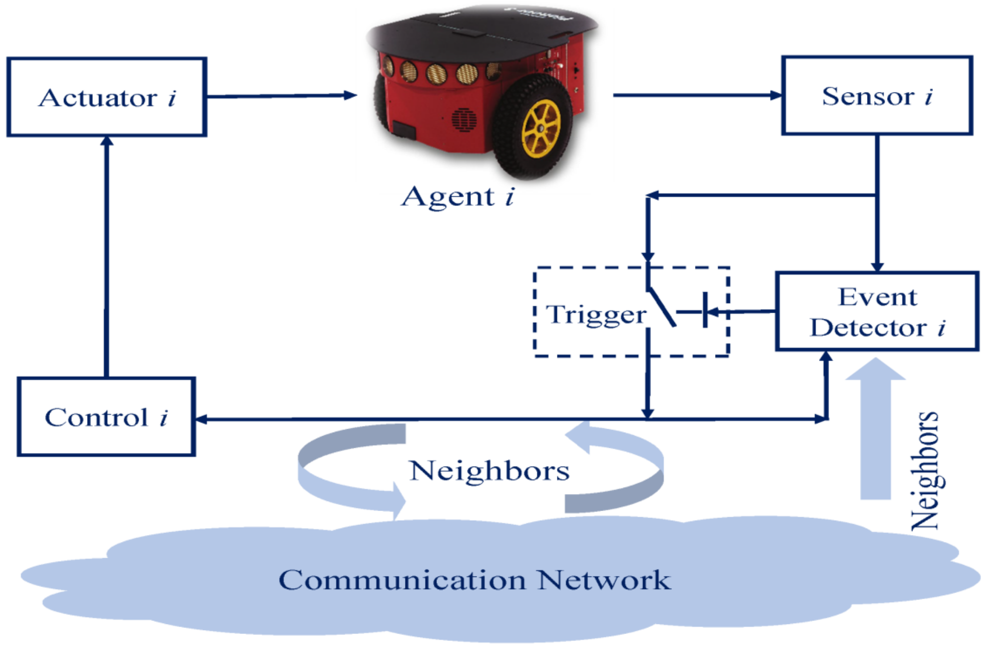
# Distributed Event-Triggered Consensus

## Event-Based Sampling Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

The event-triggered consensus scheme was proposed in [D. Dimarogonas, IEEE TAC, 57(5), pp. 1291-1297, 2012.]

**Control protocol:**

$$u_i(t) = -K \sum_{j \in N_i} a_{ij}(x_i(t_k^i) - x_j(t_{k(t)}^j))$$

**ETC:**

$$f_i(\|e_i(t)\| \leq \Delta_i(z_i(t))$$

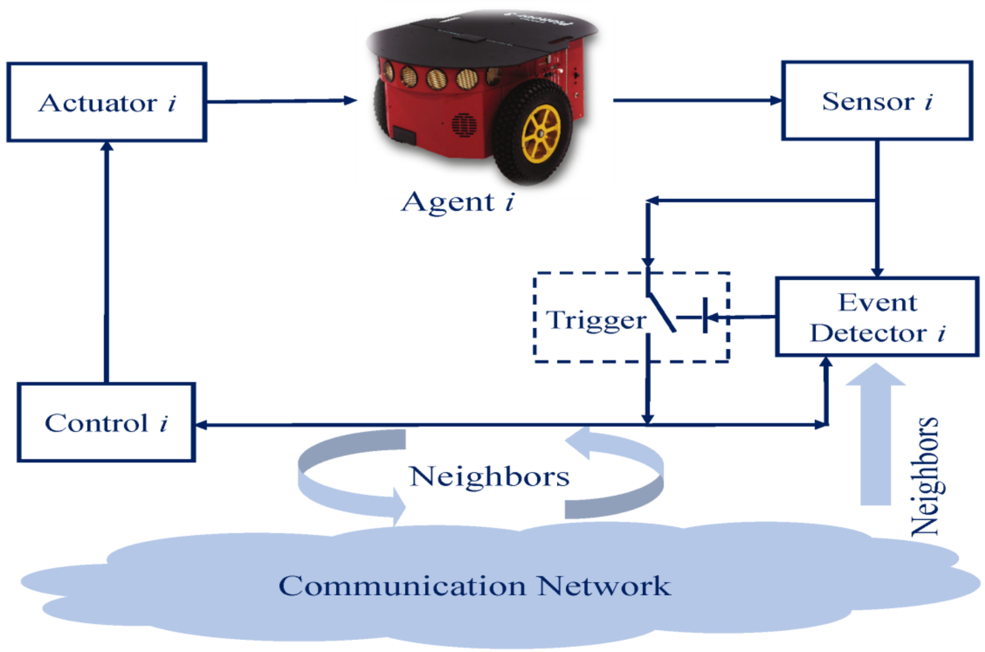
$$e_i(t) = x_i(t_k^i) - x_i(t)$$

$$z_i(t) = \sum_{j \in N_i} a_{ij}(x_i(t) - x_j(t))$$


D. Dimarogonas, E. Frazzoli, and K. Johansson, "Distributed event-triggered control for multi-agent systems," *IEEE Trans. Autom. Control*, vol. 57, no. 5, pp. 1291-1297, 2012.

# Distributed Event-Triggered Consensus

## Event-Based Sampling Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

The event-triggered consensus scheme was proposed in [D ... 57(5), pp. 1291-1297

Depending on its neighbors' event instants

**Control protocol:**

$$u_i(t) = -K \sum_{j \in N_i} a_{ij}(x_i(t_k^i) - x_j(t_{k(t)}^j))$$

**ETC:**

$$f_i(\|e_i(t)\| \leq \Delta_i(z_i(t))$$

$$e_i(t) = x_i(t_k^i) - x_i(t)$$

$$z_i(t) = \sum_{j \in N_i} a_{ij}(x_i(t) - x_j(t))$$

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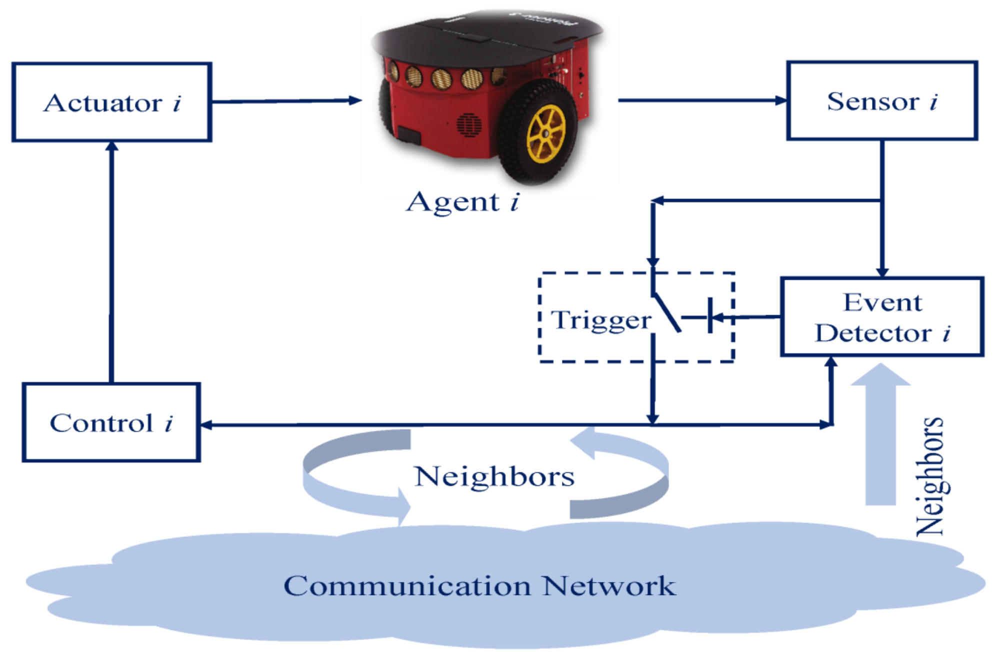
## Event-Based Sampling Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

The event-triggered consensus scheme was proposed in [D. Dimarogonas, IEEE TAC, 57(5), pp. 1291-1297, 2012.]

**Control protocol:**

$$u_i(t) = -K \sum_{j \in N_i}$$

The threshold function requires continuous communication

**ETC:**

$$f_i(\|e_i(t)\| \leq \Delta_i(z_i(t))$$

$$e_i(t) = x_i(t_k^i) - x_i(t)$$

$$z_i(t) = \sum_{j \in N_i} a_{ij}(x_i(t) - x_j(t))$$

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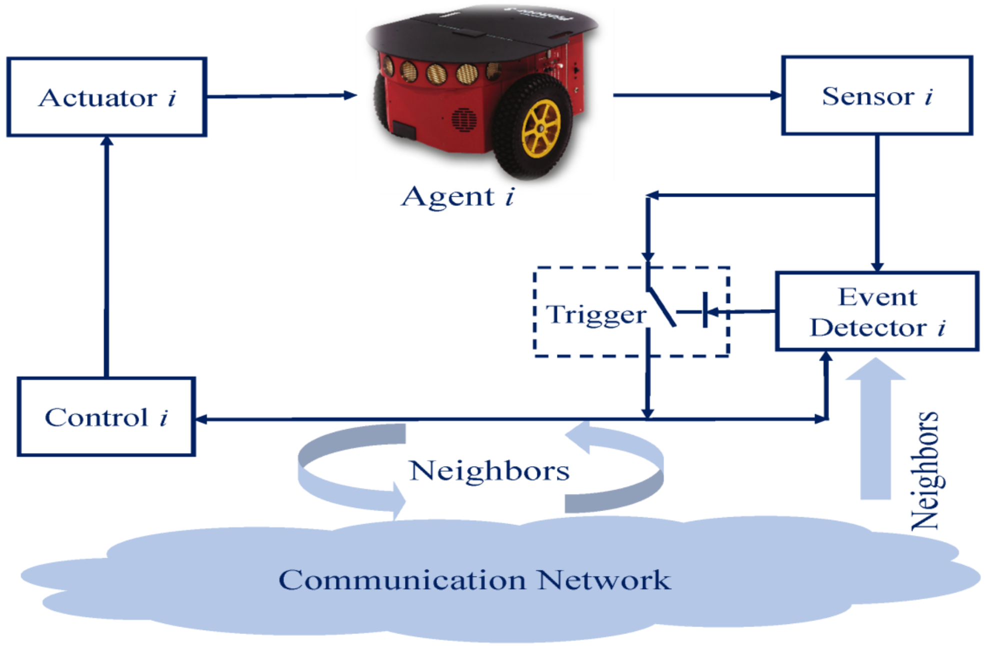
# Distributed Event-Triggered Consensus



## Event-Based Sampling Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

The event-triggered consensus scheme was proposed in [D. Dimarogonas, IEEE TAC, 57(5), pp. 1291-1297, 2012.]

**Contro**

$$u_i( \ldots {}^{j}_{k(t)}))$$

Requiring that $e_i(t) \to 0$ as $z_i(t) \to 0$, otherwise, Zeno behaviour will happen

**ETC:**

$$f_i(\|e_i(t)\| \leq \Delta_i(z_i(t))$$

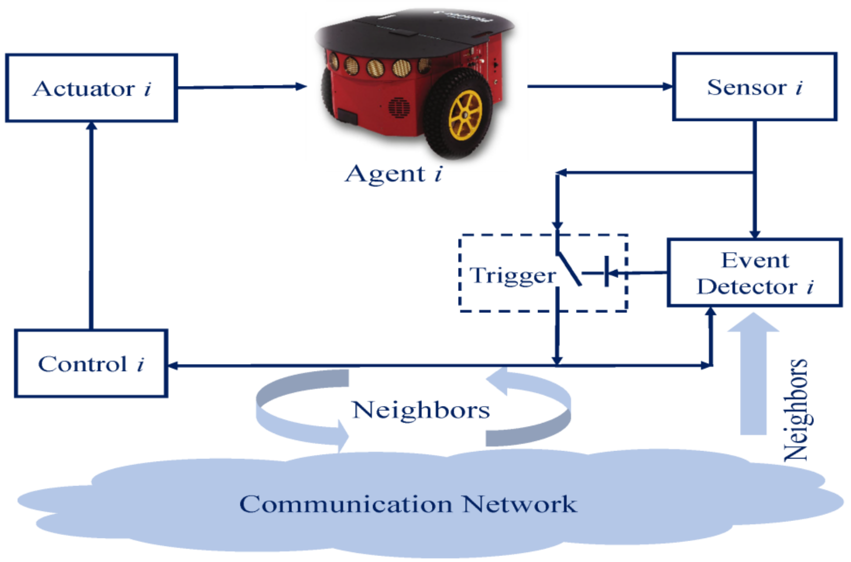
$$e_i(t) = x_i(t_k^i) - x_i(t)$$

$$z_i(t) = \sum_{j \in N_i} a_{ij}(x_i(t) - x_j(t))$$

D. Dimarogonas, E. Frazzoli, and K. Johansson, "Distributed event-triggered control for multi-agent systems," *IEEE Trans. Autom. Control*, vol. 57, no. 5, pp. 1291-1297, 2012.

# Distributed Event-Triggered Consensus

## Event-Based Sampling Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**Control protocol:** [D. Dimarogonas, IEEE TAC, 57(5), pp. 1291-1297, 2012.]

$$u_i(t) = -K \sum_{j \in N_i} a_{ij}(x_i(t_k^i) - x_j(t_{k(t)}^j))$$

**ETC:** $f_i(\|e_i(t)\| \leq \Delta_i(z_i(t))$

## Limitations

**Limitation 1**

High frequency of control updates

**Limitation 2**

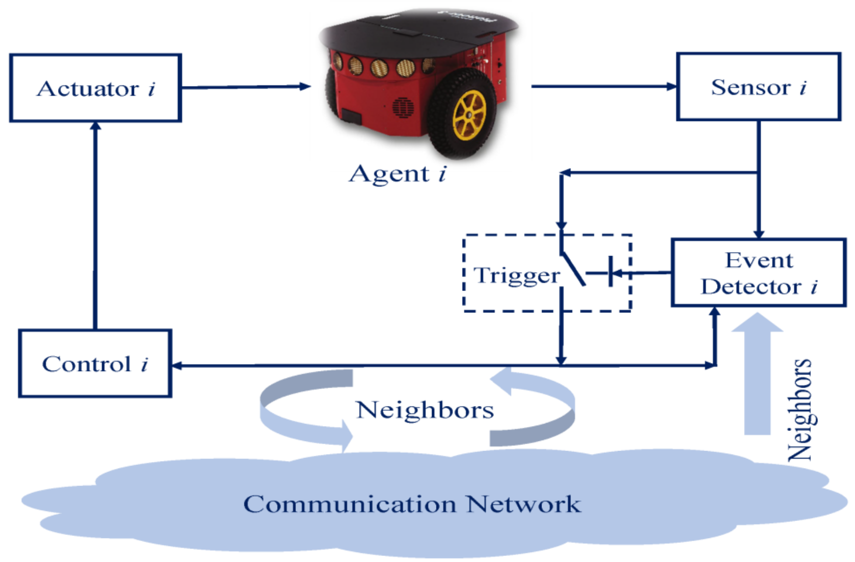
Requirement on continuous communication

**Limitation 3**

Restriction on system dynamics

# Distributed Event-Triggered Consensus

## Event-Based Sampling Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**Limitation 1**

High frequency of control updates

To

**Solution**

The c
updates
only at its o
event instant


- ✓ Y. Fan, G. Feng, Y. Wang, and C. Song, "Distributed event-triggered control of multi-agent systems with combinational measurements," *Automatica*, vol. 49, no. 2, pp. 671–675, 2013.
- ✓ W. Zhu, Z.-P. Jiang, and G. Feng, "Event-based consensus of multi-agent systems with general linear models," *Automatica*, vol. 50, no. 2, pp. 552–558, 2014
- ✓ W. Zhu and Z.-P. Jiang, "Event-based leader-following consensus of multi-agent systems with input time delay," *IEEE Trans. Autom. Control*, vol. 60, no. 5, pp. 1362–1367, May 2015.

# Distributed Event-Triggered Consensus

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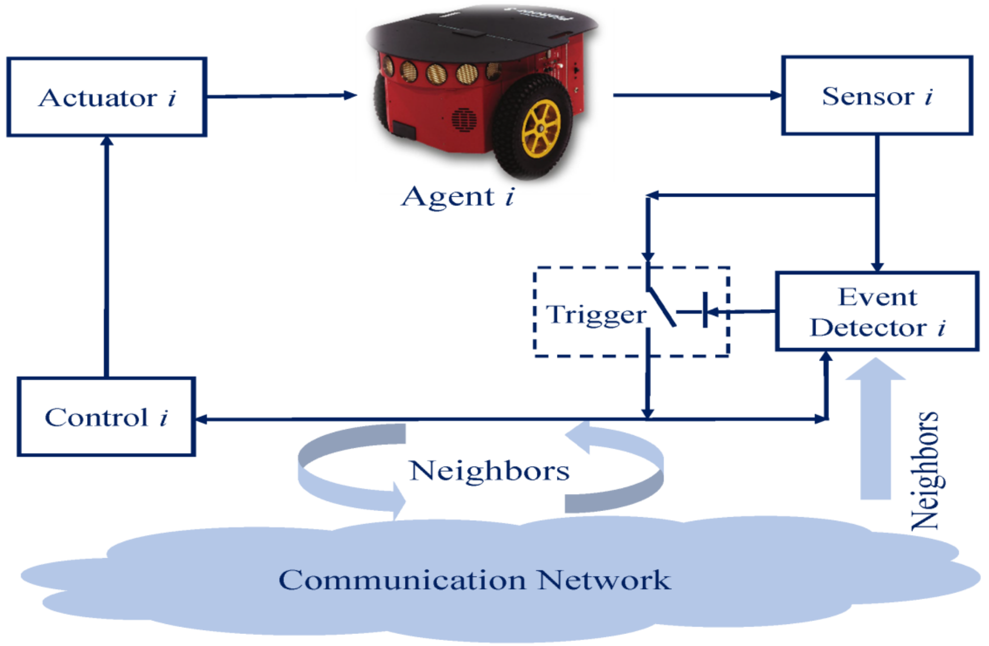
## Event-Based Sampling Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**Solution 1 to avoiding high frequency of control updates**

**Control protocol:**

$$u_i(t) = -K \sum_{j \in N_i} a_{ij}(x_i(t_k^i) - x_j(t_k^i))$$

**ETC:**

$$f_i(\|e_i(t)\| \leq \Delta_i(z_i(t))$$

$$e_i(t) = z_i(t_k^i) - z_i(t)$$

$$z_i(t) = \sum_{j \in N_i} a_{ij}(x_i(t) - x_j(t))$$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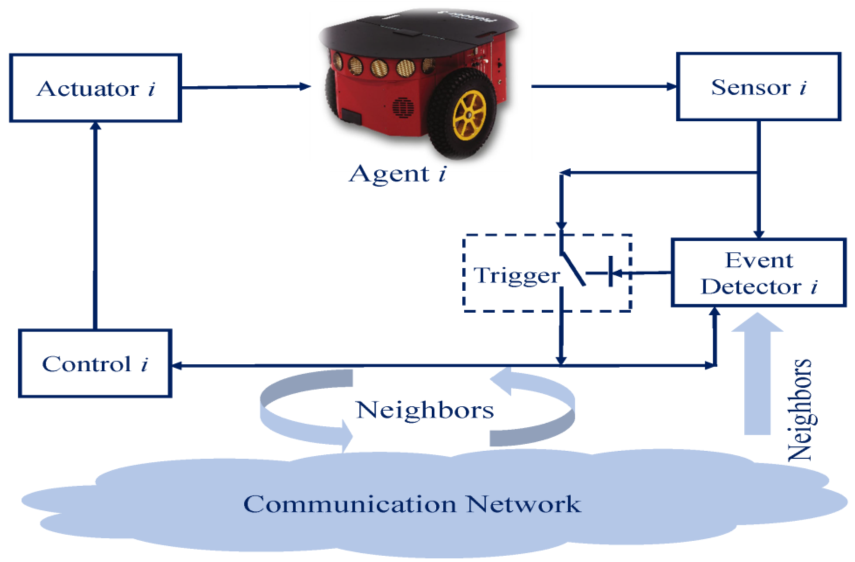
# Distributed Event-Triggered Consensus

## Event-Based Sampling Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$


- ✓ C. Nowzari and J. Cortés, "Distributed event-triggered coordination for average consensus on weight-balanced digraphs," *Automatica*, vol. 68, pp. 237–244, Jun. 2016.
- ✓ S. S. Kia, J. Cortés, and S. Martínez, "Distributed event-triggered communication for dynamic average consensus in networked systems," *Automatica*, vol. 59, pp. 112–119, Sep. 2015.
- ✓ H. Yu and P. J. Antsaklis, "Output synchronization of networked passive systems with event-driven communication," *IEEE Trans. Autom. Control*, vol. 59, no. 3, pp. 750–756, Mar. 2014.
- ✓ G. S. Seyboth, D. V. Dimarogonas, and K. H. Johansson, "Event-based broadcasting for multi-agent average consensus," *Automatica*, vol. 49, no. 1, pp. 245–252, 2013.

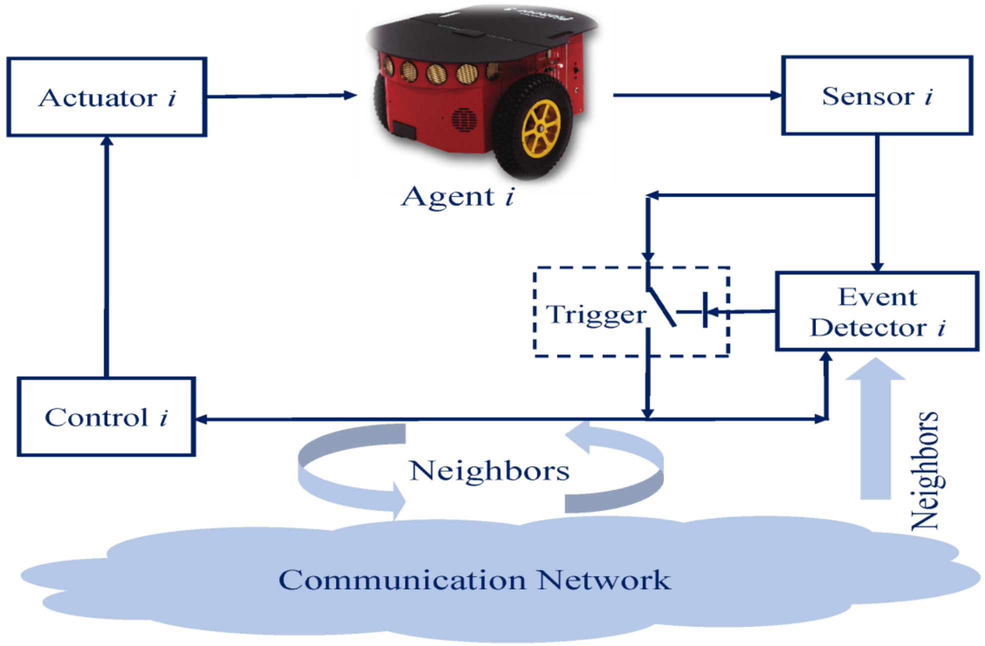

The control updates happen only at its own event instants

…hreshold uses the triggered signals;

✓ State-independent threshold;

# Distributed Event-Triggered Consensus

## Event-Based Sampling Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**Solution 2 to avoiding continuous communication**

**Control protocol:**

$$u_i(t) = -K \sum_{j \in N_i} a_{ij}(x_i(t_k^i) - x_j(t_{k(t)}^j))$$

**ETC:**

$$f_i(\|e_i(t)\| \leq \Delta_i(\hat{z}_i(t))$$

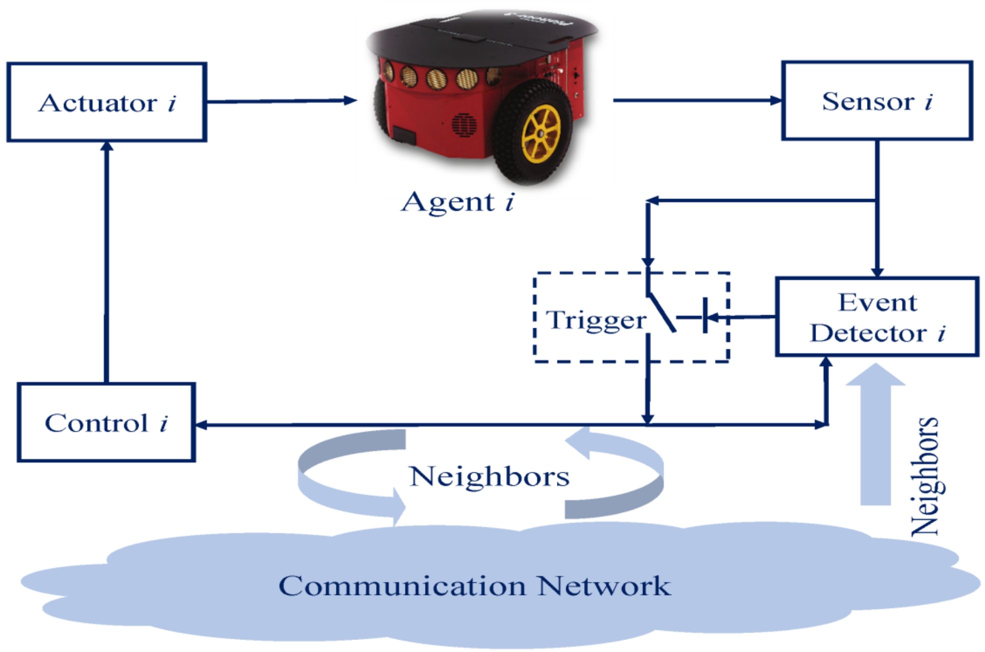
$$e_i(t) = x_i(t_k^i) - x_i(t)$$

$$\hat{z}_i(t) = \sum_{j \in N_i} a_{ij}(x_i(t_k^i) - x_j(t_{k(t)}^j))$$

C. Nowzari and J. Cortés, "Distributed event-triggered coordination for average consensus on weight-balanced digraphs," *Automatica*, vol. 68, pp. 237–244, Jun. 2016.

# Distributed Event-Triggered Consensus

## Event-Based Sampling Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**Solution 2 to avoiding continuous communication**

**Control protocol:**

$$u_i(t) = -K \sum_{j \in N_i} a_{ij}(x_i(t_k^i) - x_j(t_{k(t)}^j))$$

**ETC:**

$$f_i(\|e_i(t)\| \leq \Delta_i(t)$$

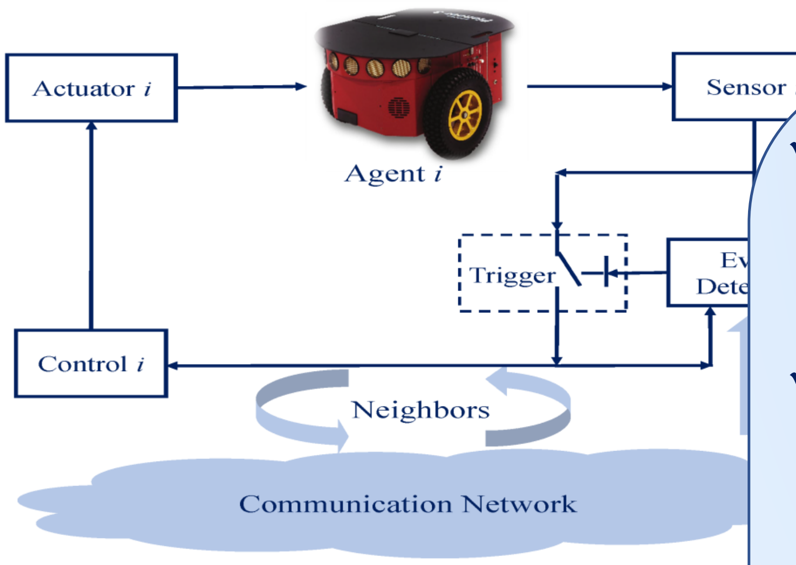
$$e_i(t) = x_i(t_k^i) - x_i(t)$$

$$\Delta_i(t) = c_1 e^{-\alpha_i t} + c_0^i$$

G. S. Seyboth, D. V. Dimarogonas, and K. H. Johansson, "Event-based broadcasting for multi-agent average consensus," *Automatica*, vol. 49, no. 1, pp. 245–252, 2013.

# Distributed Event-Triggered Consensus

## Event-Based Sampling Schemes




**Agents' dynamics**

$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdot$

**Limitation 1**

High frequency of control

**Limitation 2**

Requirement on continuous ...ation

**Limitation 3**

Restriction on system dynamics

...itations

...2

...ndent

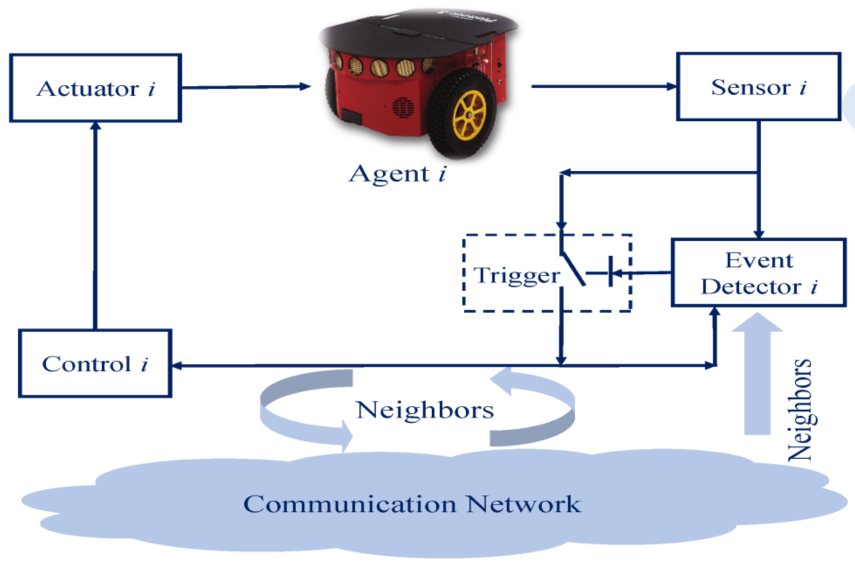
**Solution 3**

Model-based event-triggered control schemes

- ✓ E. Garcia, Y. Cao, and D. W. Casbeer, "Decentralized event-triggered consensus with general linear dynamics," *Automatica*, vol. 50, no. 10, pp. 2633–2640, 2014.
- ✓ D. Yang, W. Ren, X. Liu, and W. Chen, "Decentralized event-triggered consensus for linear multi-agent systems under general directed graphs," *Automatica*, vol. 69, pp. 242–249, Jul. 2016.
- ✓ T.-H. Cheng, Z. Kan, J. R. Klotz, J. M. Shea, and W. E. Dixon, "Event triggered control of multiagent systems for fixed and time-varying network topologies," *IEEE Trans. Autom. Control*, vol. 62, no. 10, pp. 5365–5371, Oct. 2017.

# Distributed Event-Triggered Consensus

## Event-Based Sampling Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**Limitation 1** | **Limitation 2** | **Limitation 3**

...tion on
...em
...ics

**It should be emphasized that there are no any schemes which can overcome all three limitations**

**To overcome ... se limitations**

**Solution 1**

The control updates happen only at its own event instants

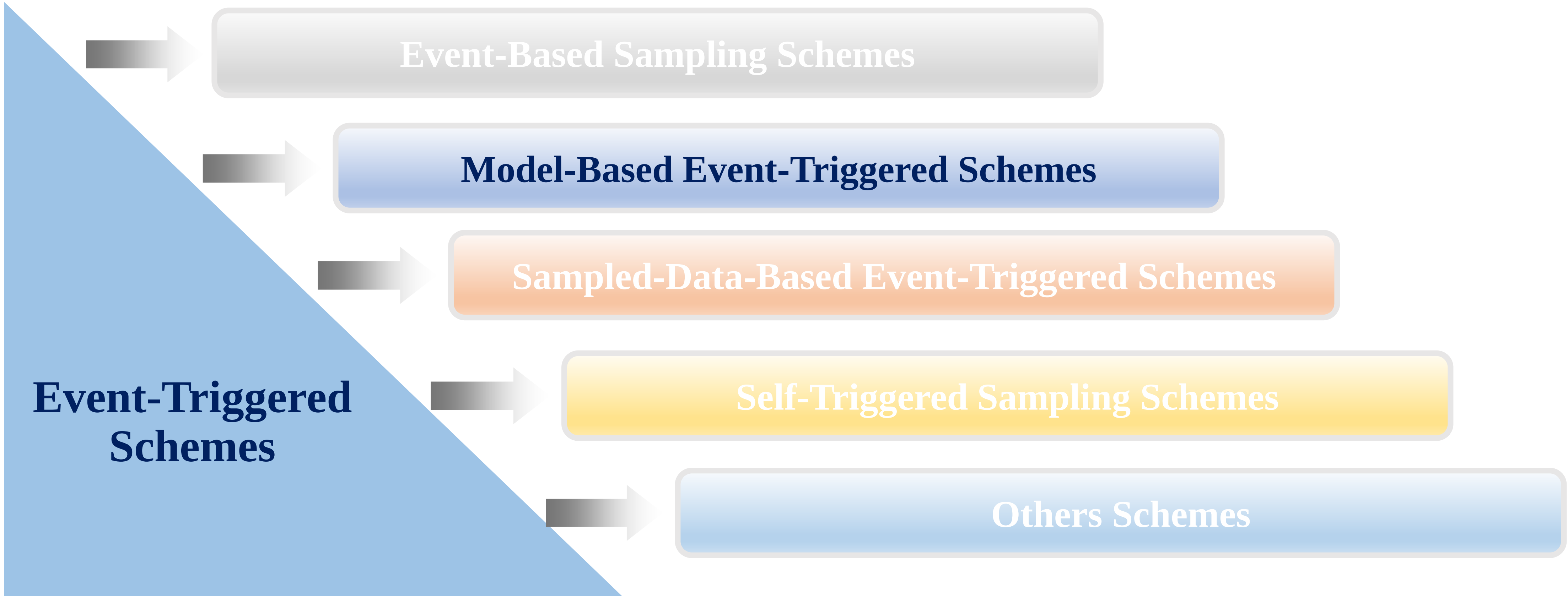
**Solution 2**

- ✓ Threshold uses the triggered signals;
- ✓ State-independent threshold;

**Solution 3**

Model-based event-triggered control schemes

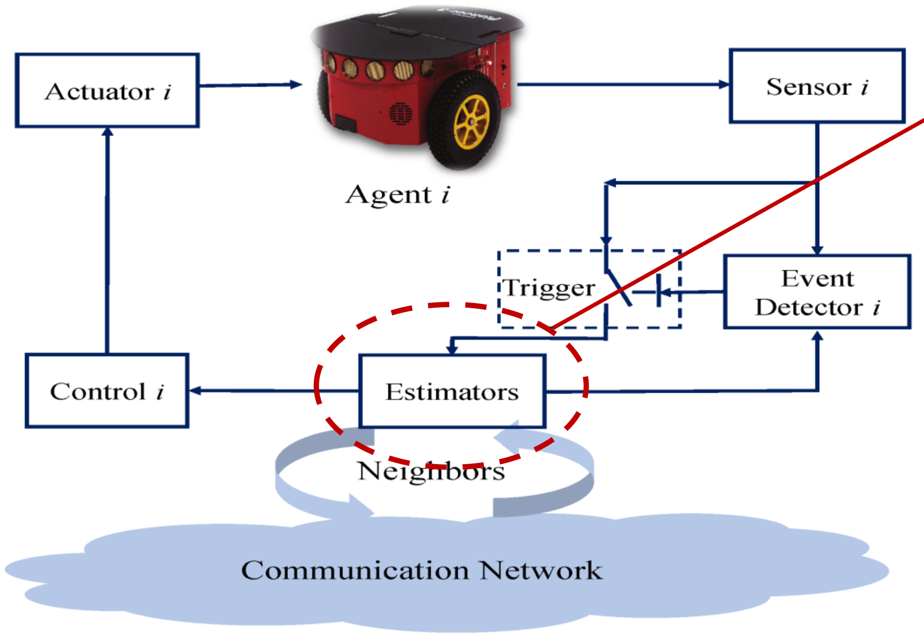
# Distributed Event-Triggered Consensus




L. Ding, Q.-L. Han, X. Ge, and X.-M. Zhang, “An overview of recent advances in event-triggered consensus of multi-agent systems,” *IEEE Transactions on Cybernetics*, vol.48, no.4, pp. 1110-1123, 2018.

# Distributed Event-Triggered Consensus

## Model-Based Event-triggered Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**Function of estimators**

- ✓ To predict its own and neighbors' states based on the received information at last triggered instants
- ✓ The ETC is based on its estimation error

**Estimation approach**

- **Open-loop estimation approach** [Garcia *et al.* (2014)], [Yang *et al.* (2014)]
- **Closed-loop estimation approach** [D. Liuzza *et al.* (2016)]

# Distributed Event-Triggered Consensus

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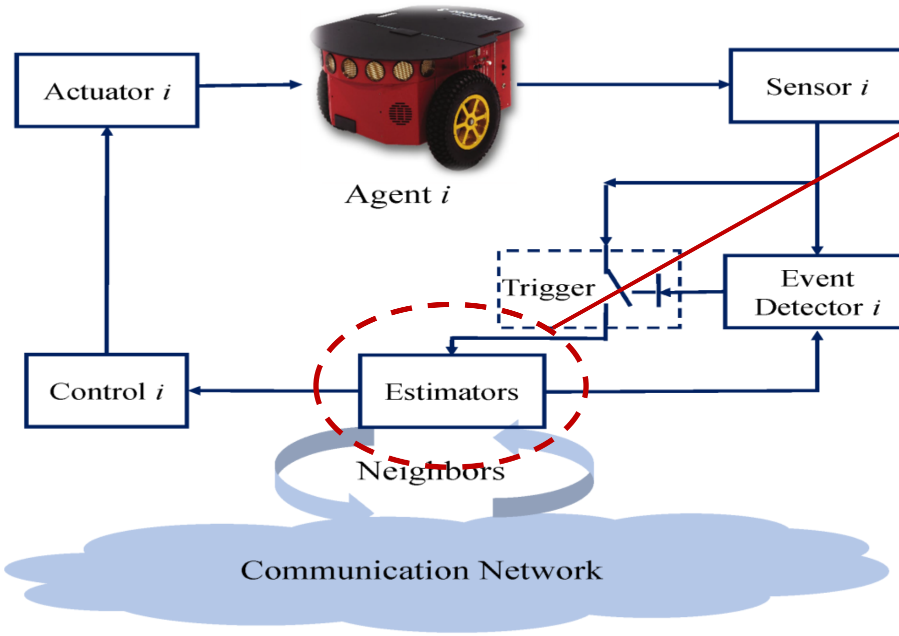
## Model-Based Event-triggered Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

## Open-loop estimation approach

**Estimator:**

$$\dot{\hat{x}}_j(t) = A\hat{x}_j(t), t \in [t_k^j, t_{k+1}^j)$$

$$\hat{x}_j(t) = x_j(t_k^j), j \in N_i$$

**Control protocol:**

$$u_i(t) = -K \sum_{j \in N_i} a_{ij}(\hat{x}_i(t) - \hat{x}_j(t))$$

**ETC:** $f_{ij}(\|e_{ij}(t)\| \leq \Delta_i(\hat{z}_{ij}(t))$

$$e_{ij}(t) = \hat{x}_i(t) - x_i(t)$$

$$z_i(t) = \sum_{j \in N_i} a_{ij}(\hat{x}_i(t) - \hat{x}_j(t))$$

D. Yang, W. Ren, X. Liu, and W. Chen, "Decentralized event-triggered consensus for linear multi-agent systems under general directed graphs," *Automatica*, vol. 69, pp. 242–249, Jul. 2016.

# Distributed Event-Triggered Consensus

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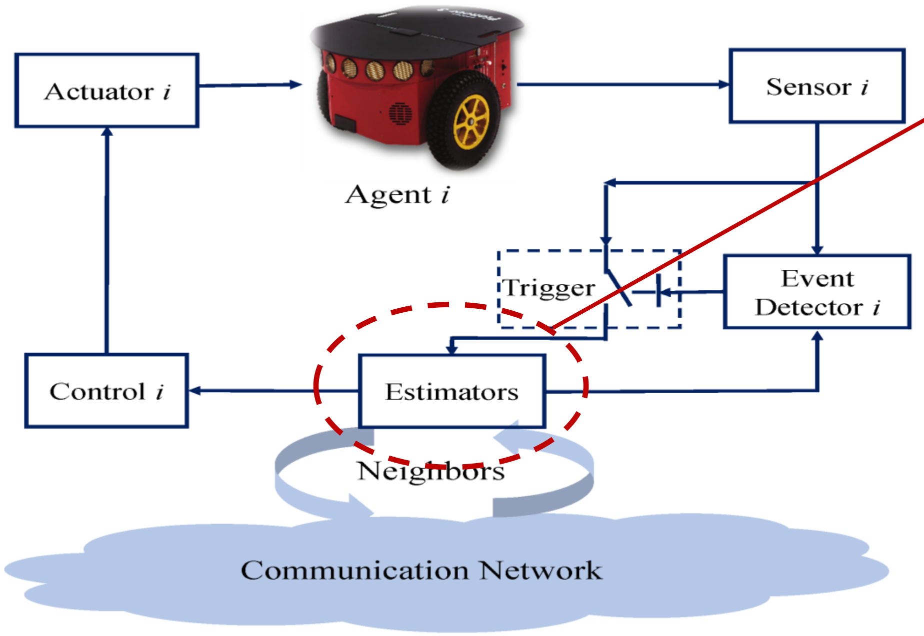
## Model-Based Event-triggered Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

## Closed-loop estimation approach

**Estimator:**

$$\dot{\hat{x}}_j(t) = A\hat{x}_j(t) + Bu_{ij}(t_k^{ij}), t \in [t_k^{ij}, t_{k+1}^{ij})$$

$$\hat{x}_j(t) = x_j(t_k^{ij}), j \in N_i$$

**Control protocol:**

$$u_i(t) = -K \sum_{j \in N_i} a_{ij}(\hat{x}_i(t_k^{ij}) - \hat{x}_j(t_k^{ij}))$$

**ETC:** $f_{ij}(\|e_{ij}(t)\| \le \Delta_{ij}(z_{ij}(t))$

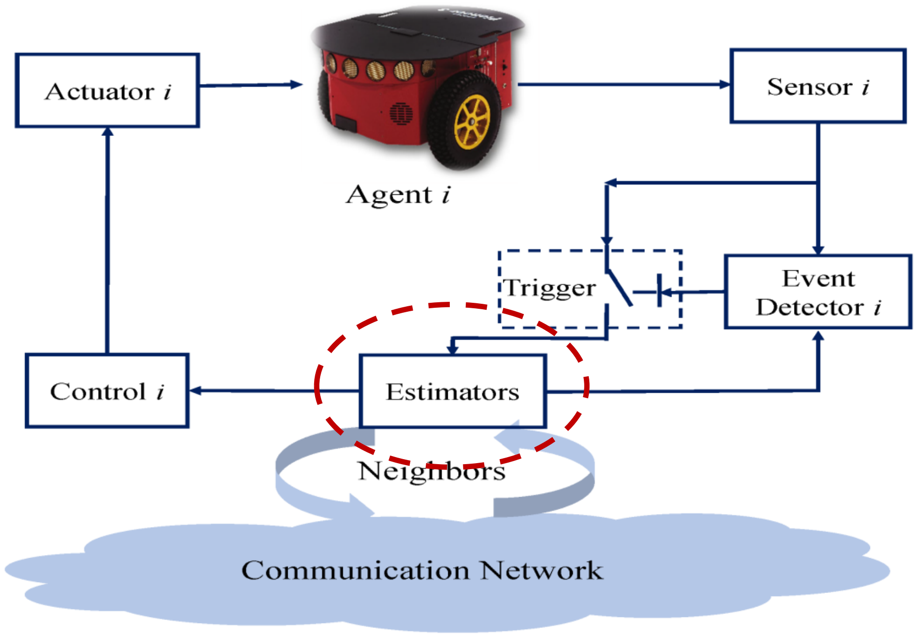
$$e_{ij}(t) = z_{ij}(t_k^{ij}) - z_{ij}(t)$$

$$z_{ij}(t) = \hat{x}_i(t) - \hat{x}_j(t)$$

D. Yang, W. Ren, X. Liu, and W. Chen, "Decentralized event-triggered consensus for linear multi-agent systems under general directed graphs," *Automatica*, vol. 69, pp. 242–249, Jul. 2016.

# Distributed Event-Triggered Consensus

## Model-Based Event-triggered Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**Advantages**

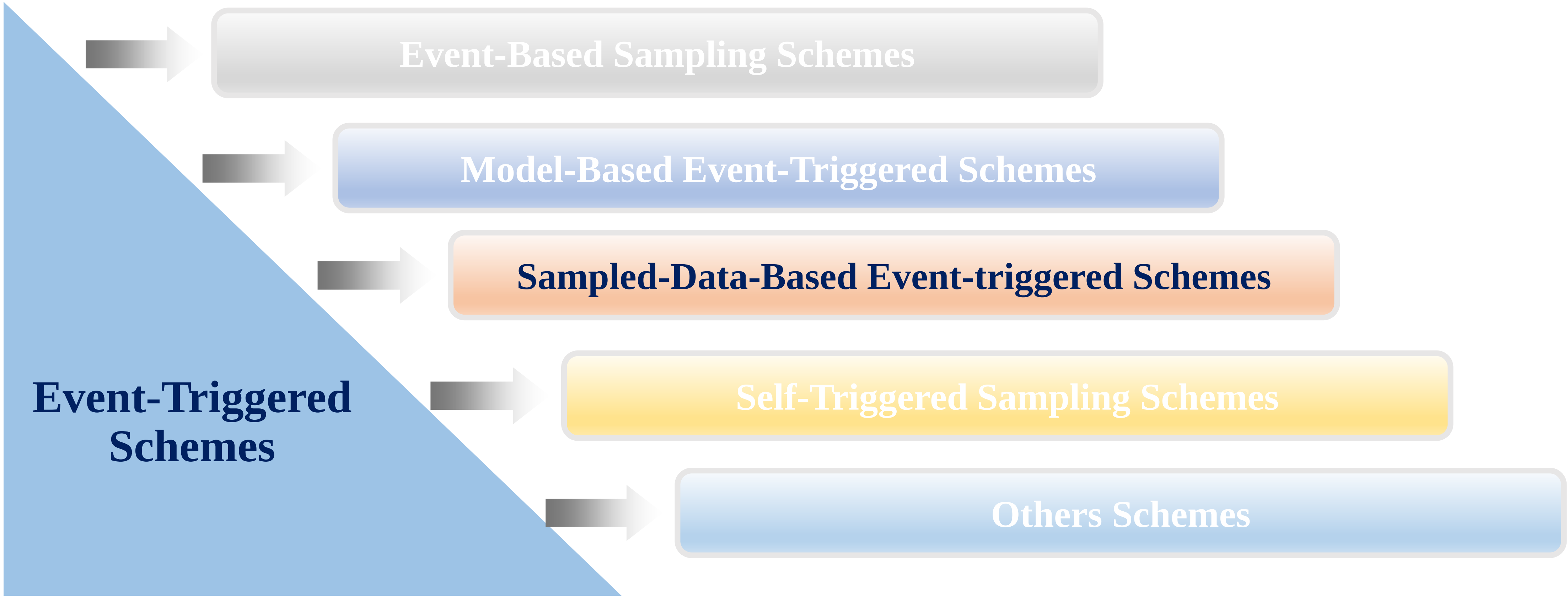
- ✓ Continuous communication is no longer needed;
- ✓ System dynamics is not limited.

***VS***

**Disadvantages**

- ✓ Costs and complexity are increasing due to the deployment of estimators;
- ✓ The system dynamics matrix should be known *a prior*.

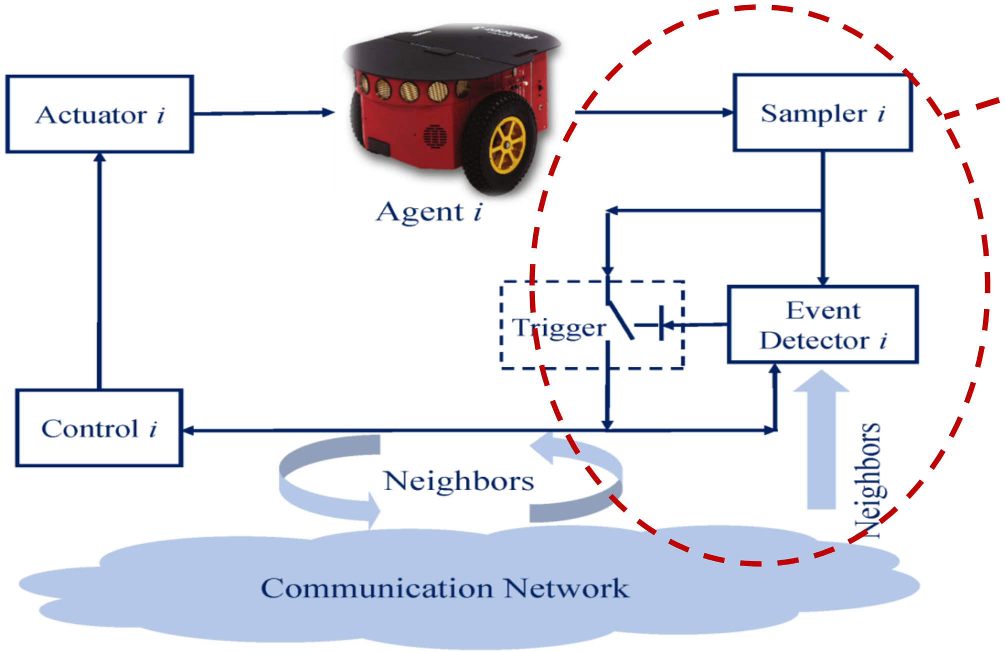
# Distributed Event-Triggered Consensus




L. Ding, Q.-L. Han, X. Ge, and X.-M. Zhang, “An overview of recent advances in event-triggered consensus of multi-agent systems,” *IEEE Transactions on Cybernetics*, vol.48, no.4, pp. 1110-1123, 2018.

# Distributed Event-Triggered Consensus

## Sampled-Data-Based Event-triggered Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**Key characteristics**

- ✓ The event detection is only carried out at each sampling instants;
- ✓ The ETC is based on its sampled-data error.

**Control protocol:**

$$u_i(t) = -K \sum_{j \in N_i} a_{ij}(x_i(t_k^i h) - x_j(t_{k(t)}^j h))$$

**ETC:** $f_i(\|e_i(kh)\| \leq \Delta_i(z_i(kh))$

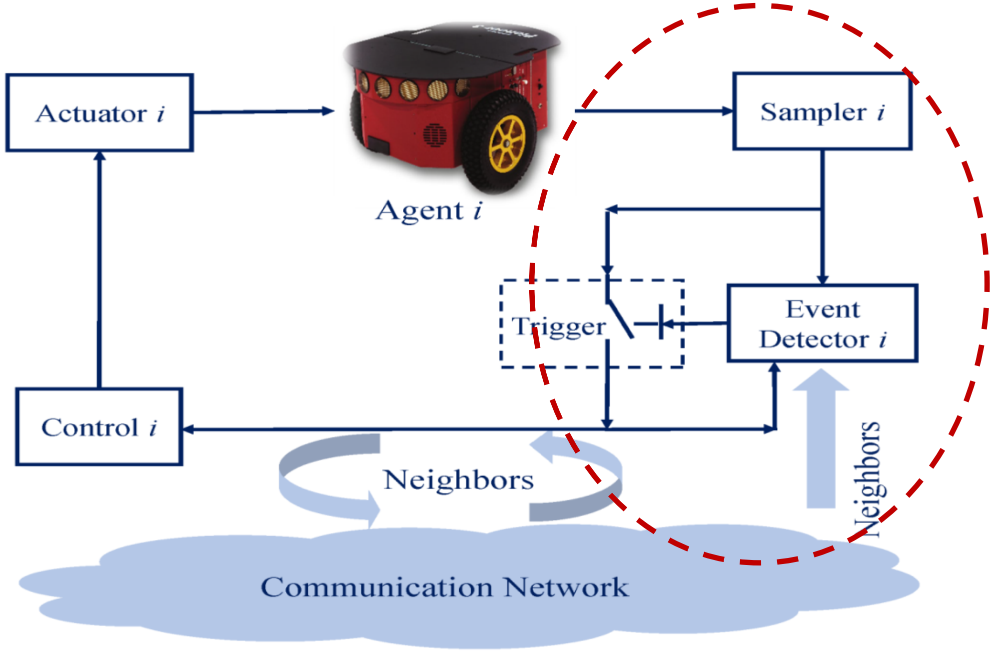
$$e_i(kh) = x_i(t_k^i h) - x_i(kh)$$

$$z_i(kh) = \sum_{j \in N_i} a_{ij}(x_i(t_k^i h) - x_j(t_{k(t)}^j h))$$

G. Guo, L. Ding, and Q.-L. Han, "A distributed event-triggered transmission strategy for sampled-data consensus of multi-agent systems," *Automatica*, 50(5), pp. 1489-1496, 2014.

# Distributed Event-Triggered Consensus

## Sampled-Data-Based Event-triggered Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**A codesign algorithm**

Transmission rate on time interval [0, *Th*]:

$$J = \frac{1}{T \sum_I^N N_i} \sum_{k=0}^{T-1} \sum_{i=1}^{N} N_i \rho_k^i$$

$$\rho_k^i = \begin{cases} 1 & \text{If transmitted successfully} \\ 0 & \text{Otherwise} \end{cases}$$

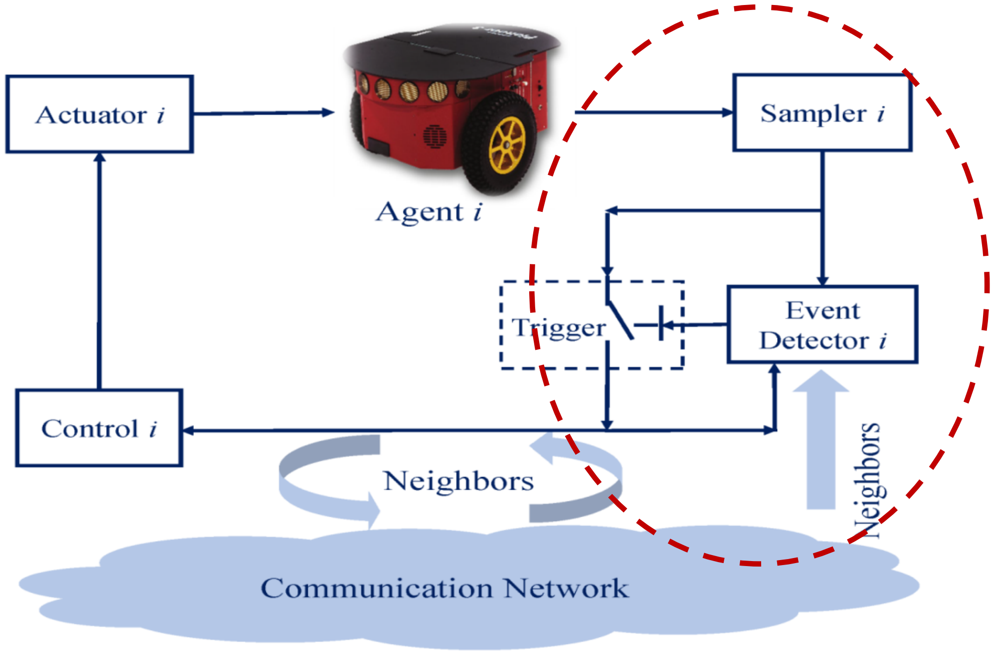
The co-design issue comes to designing the event parameters and the controller gain $K$ simultaneously

$$\min \; \|J - J^*\|$$

G. Guo, L. Ding, and Q.-L. Han, "A distributed event-triggered transmission strategy for sampled-data consensus of multi-agent systems," *Automatica*, 50(5), pp. 1489-1496, 2014.

# Distributed Event-Triggered Consensus

## Sampled-Data-Based Event-triggered Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**Advantages**

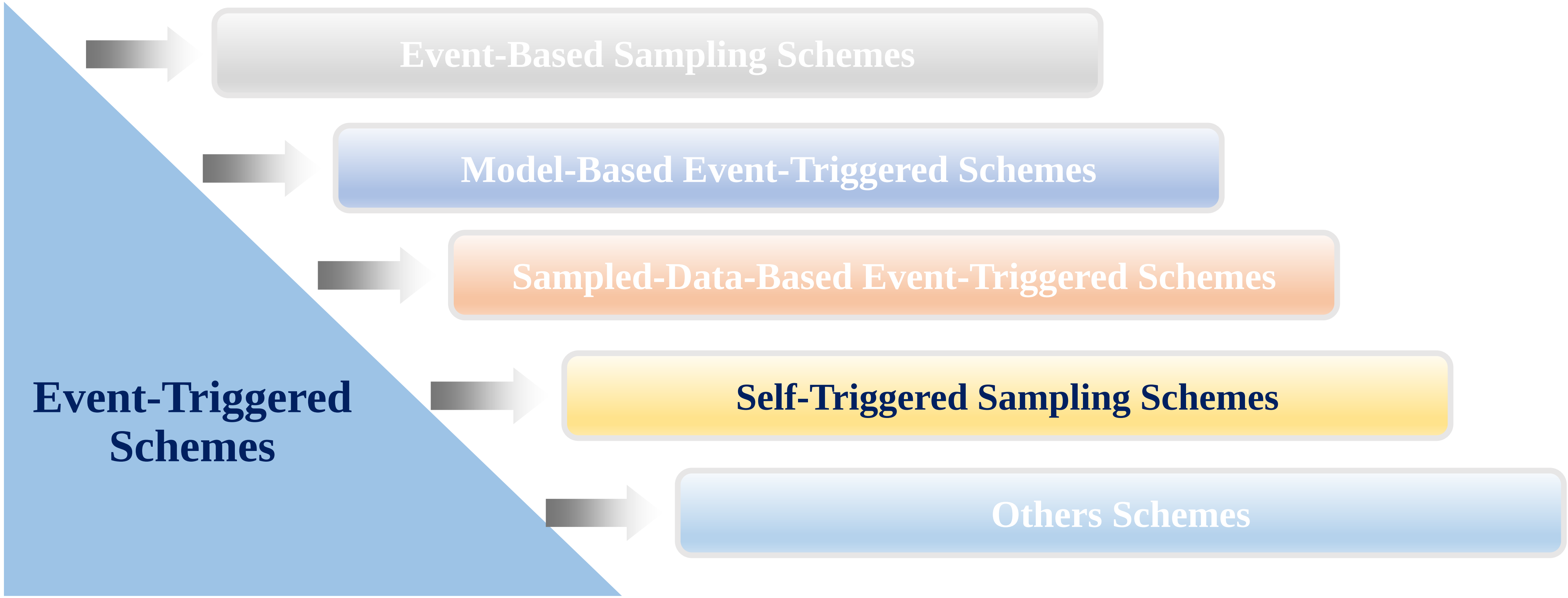
- ✓ Continuous monitoring and computation are no longer needed;
- ✓ Zeno behavior is naturally excluded.

***VS***

**Disadvantages**

- ✓ The sampling period is required to be identical for all agents;
- ✓ It inherits the shortcoming of sampled-data systems, such as some useful states may be ignored.

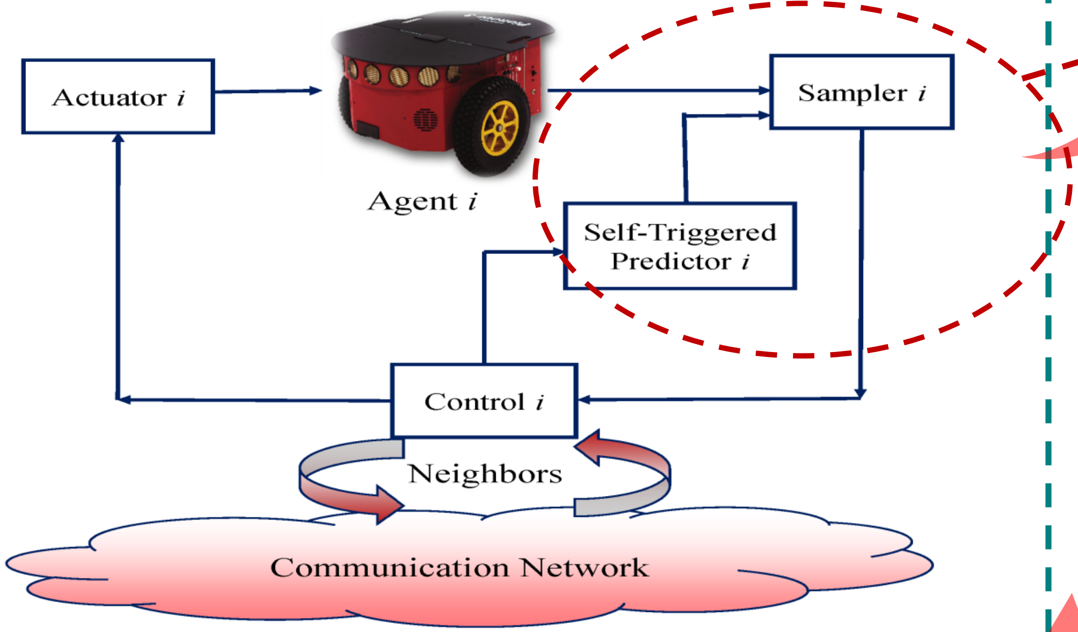
# Distributed Event-Triggered Consensus




L. Ding, Q.-L. Han, X. Ge, and X.-M. Zhang, "An overview of recent advances in event-triggered consensus of multi-agent systems," *IEEE Transactions on Cybernetics*, vol.48, no.4, pp. 1110-1123, 2018.

# Distributed Event-Triggered Consensus

## Self-triggered Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

The next sampling instant is predicted based on the last triggered data and the knowledge of plant dynamics.

**Control Protocol:**

$$u_i(t) = -K \sum_{j \in N_i} a_{ij}\left(x_i(t_k^i) - x_j(t_{k(t)}^j)\right)$$

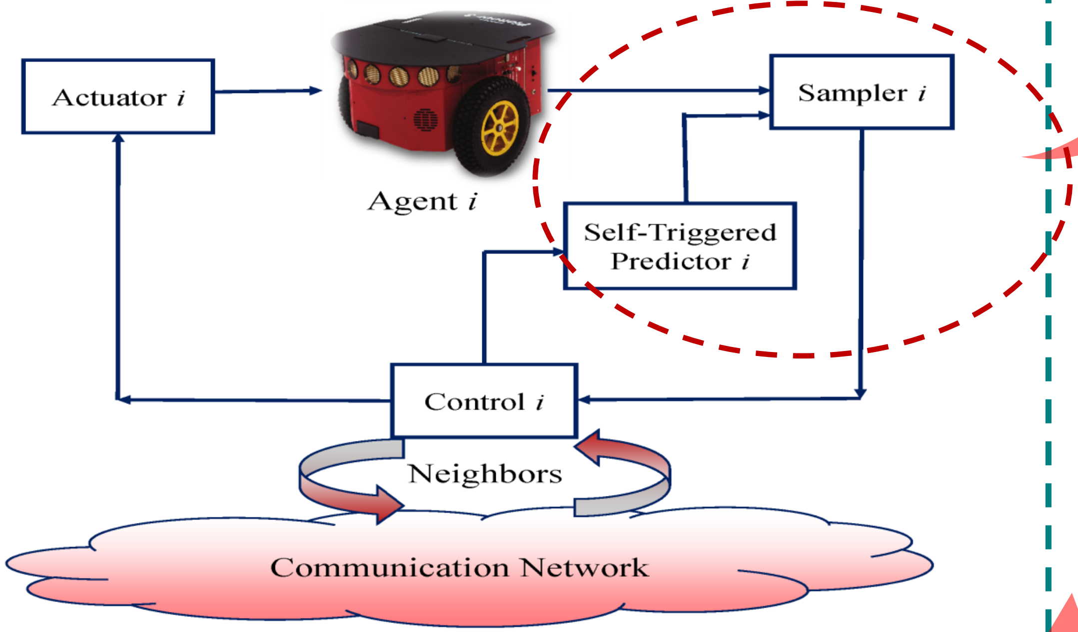
**Update instants:**

$$t_{k+1}^i = t_k^i + h_i\left(x_i(t_k^i), x_j(t_{k(t)}^j)\right)$$


D. Dimarogonas, E. Frazzoli, and K. Johansson, "Distributed event-triggered control for multi-agent systems," *IEEE Trans. Autom. Control*, vol. 57, no. 5, pp. 1291-1297, 2012.

# Distributed Event-Triggered Consensus

## Self-triggered Schemes




**Agents' dynamics**

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t), i = 1, 2, \cdots, N$$

**Advantages**

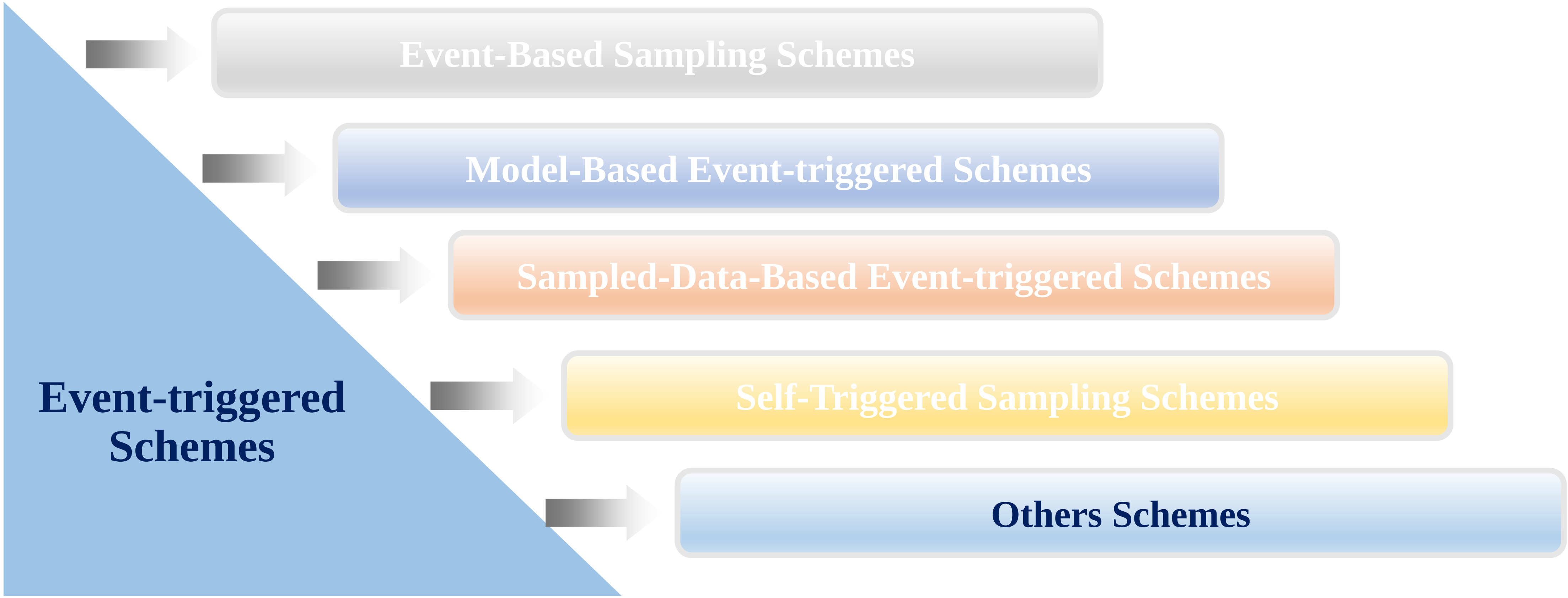
- ✓ Avoiding continuous event monitoring and computation.

***VS***

**Disadvantages**

- ✓ Over-approximation by individual agent on the state of environment and the network;
- ✓ More conservative than the event-triggered schemes.

# Distributed Event-Triggered Consensus




L. Ding, Q.-L. Han, X. Ge, and X.-M. Zhang, “An overview of recent advances in event-triggered consensus of multi-agent systems,” *IEEE Transactions on Cybernetics*, vol.48, no.4, pp. 1110-1123, 2018.

# Distributed Event-Triggered Consensus

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## Some other types of event-triggered schemes

### Adaptive Event-Triggered Schemes

Event parameters can be adjusted based on the changes of system dynamics.

X. Yin, etc., *Int. J. Control*, 89(4), 653-667, 2016.

X. Ge, etc., *IEEE Trans. Ind. Electron*., 64(10) 8118-8127, 2017.

### Dynamic Event-Triggered Schemes

Threshold function is dynamically adjusted based on the changes of system dynamics.

X. Ge, etc., *IEEE Trans. Syst., Man, and Cybern. Syst.*, 50(9), 3112-3124, 2020.

### Team-Triggered Schemes

Combing both event- and self-triggered schemes.

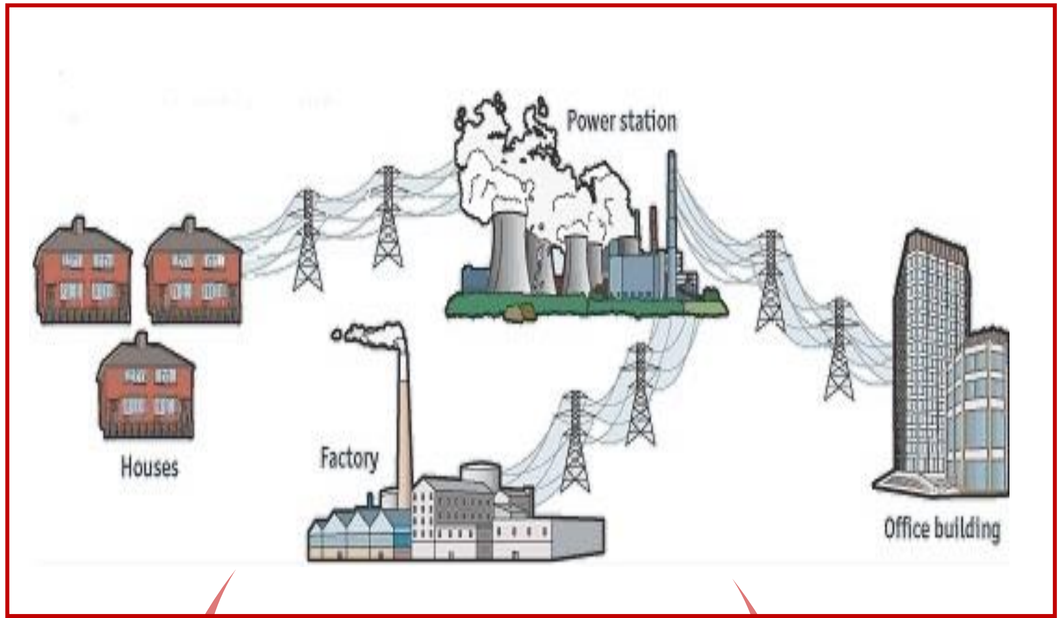
C. Nowzari, etc., *IEEE Trans. Autom. Control*, 61(1), 34-47, 2016.

04

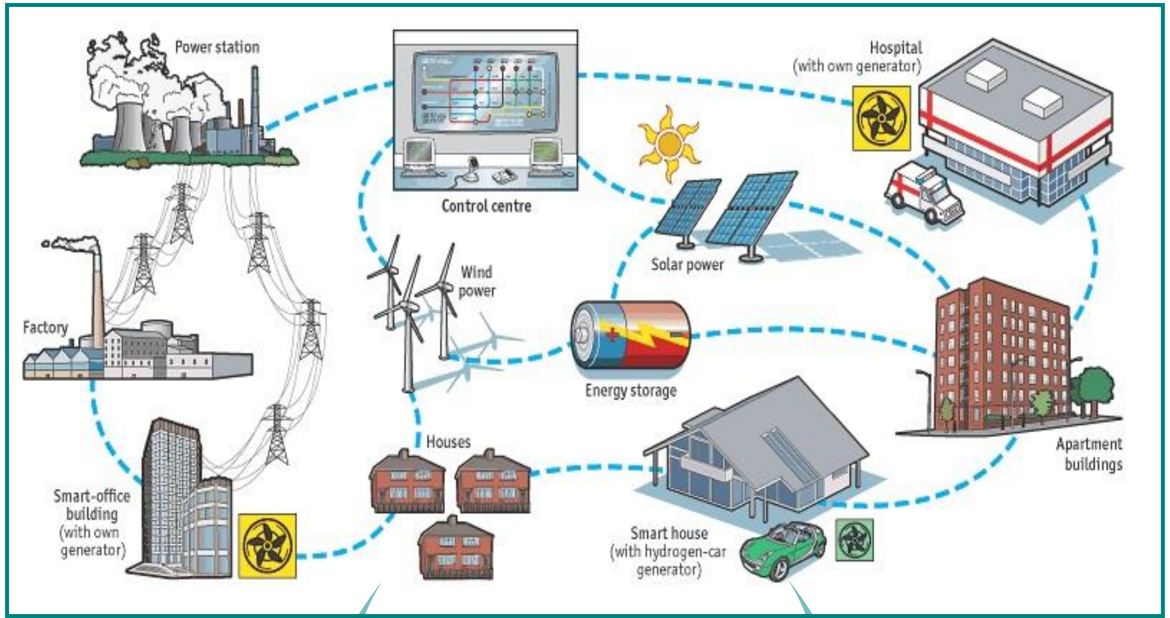
# Practical Example in Microgrids

# Practical Example in Microgrids

## A huge revolution of power grids




Traditional grids




Smart grids

- Centralized power generation
- One-way power flow
- Few customer options

*VS*

- Centralized and distributed generation
- Two-way power flow
- Flexibility in demand

# Practical Example in Microgrids

Energy Storage

EV Storage

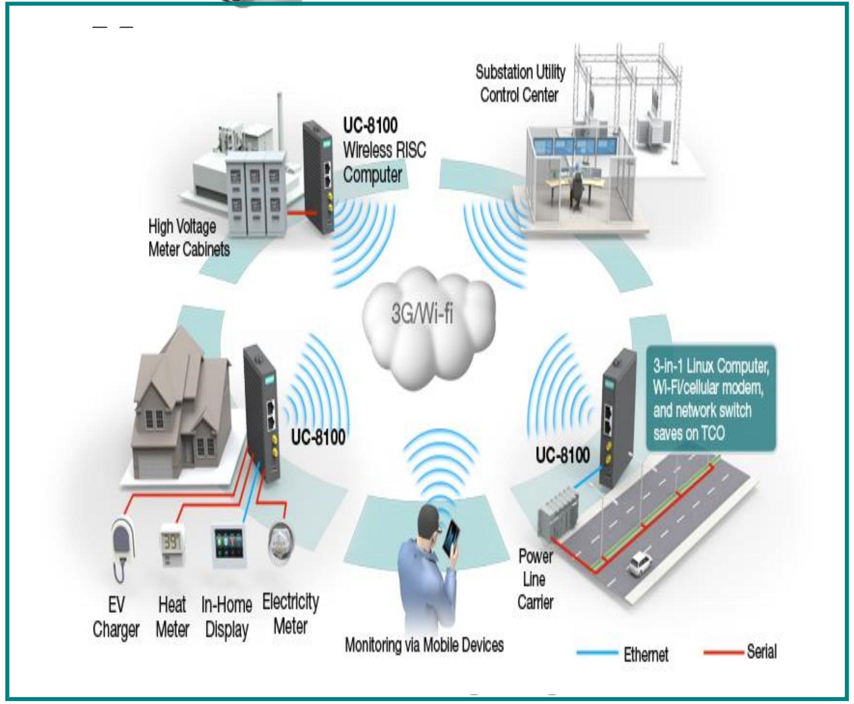
Municipal
Customers

Residential
Renewable

Local
Generator

Wind
Farms

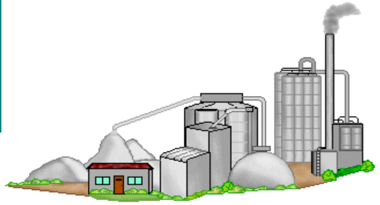
Solar
Farms




Community
Customers

Residential
Customers

Commercial
Customers



Industry
Customers

Smart
Meter
(AMI)


PMU

# Practical Example in Microgrids

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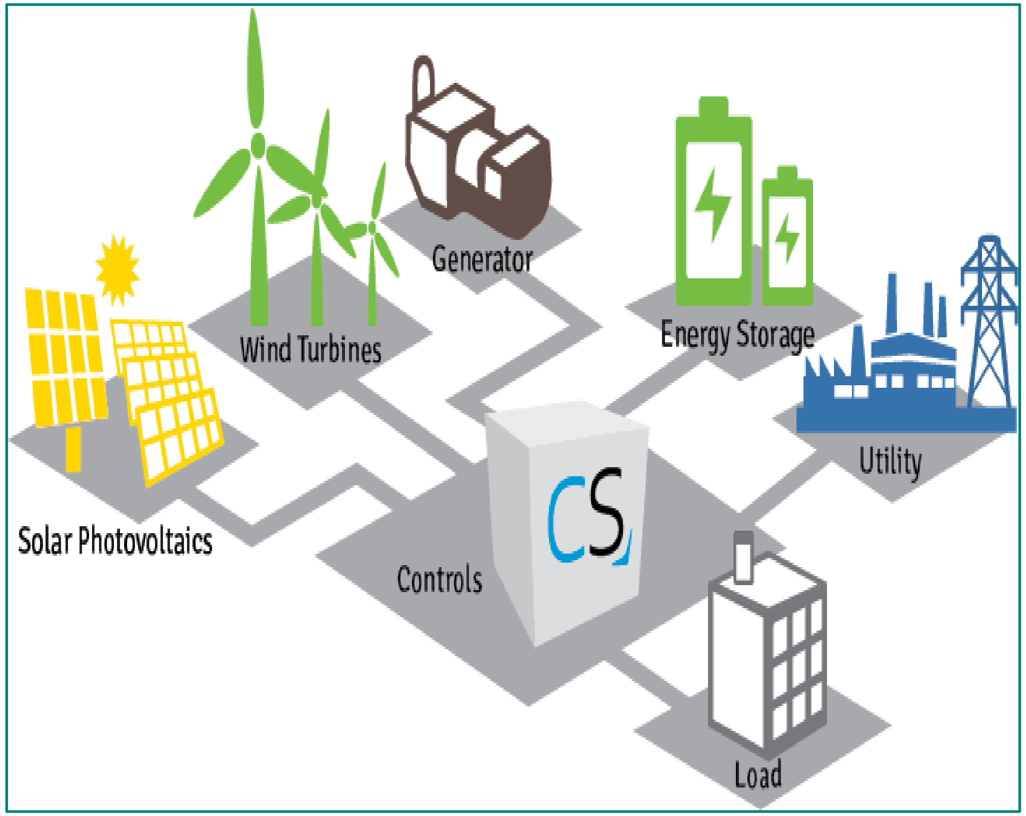
## Microgrid




**Characteristics:**

- Low-voltage distribution networks
- Grid-connected & islanded

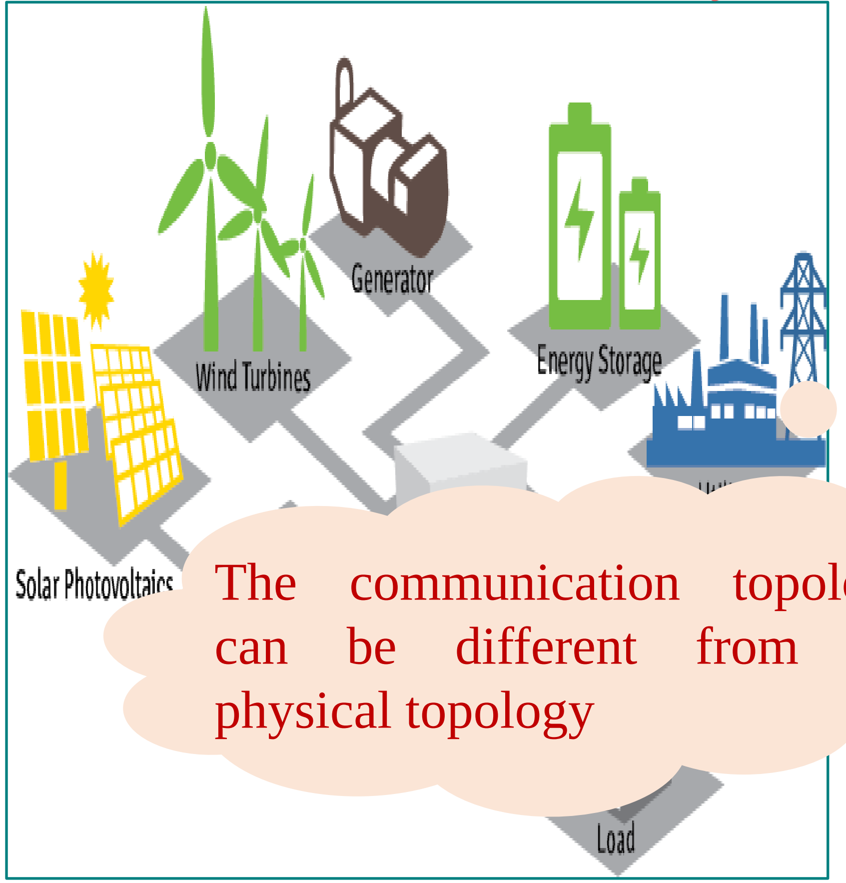
**Fundamental control issues:**

- Frequency synchronization
- Power sharing
- Voltage regulation
- Economic dispatch

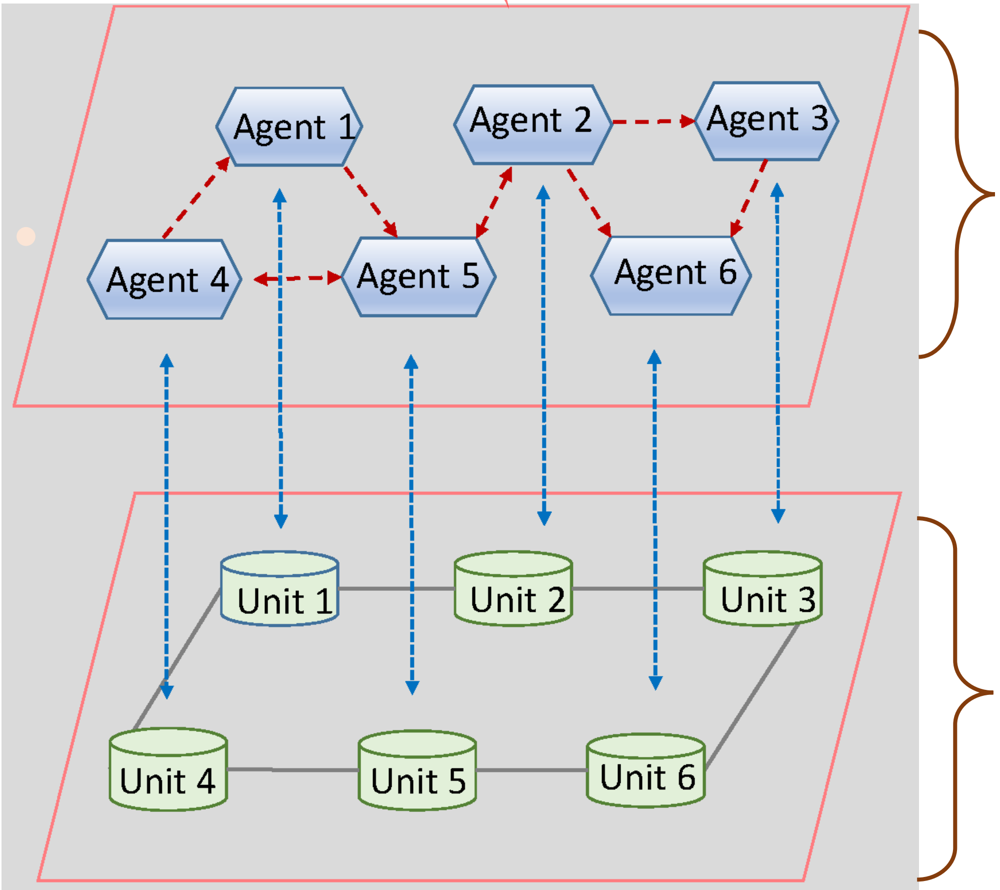
**Various applications:** Hospitals, campuses and isolated communities

# Practical Example in Microgrids

**Cyber-Physical System (CPS)**




The communication topology can be different from the physical topology



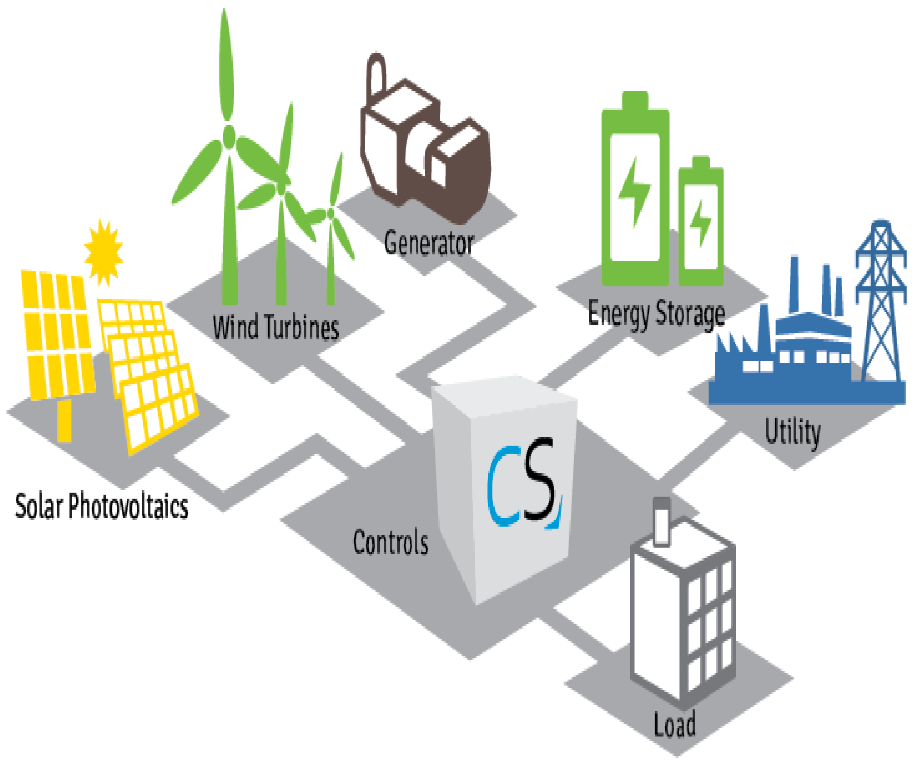

**Cyber layer:** Agents exchange information via a communication network

**Physical layer:** Units in MGs are connected by transmission lines

# Practical Example in Microgrids

## Hierarchical Control  Framework of Microgrids

### Microgrid




### Tertiary Control

- To manage and optimize power dispatch
- Centralized & distributed

### Secondary Control

- To compensate the deviation of frequency and voltage
- Centralized, decentralized & distributed

### Primary Control

- To maintain voltage and frequency stability, and power sharing
- Decentralized

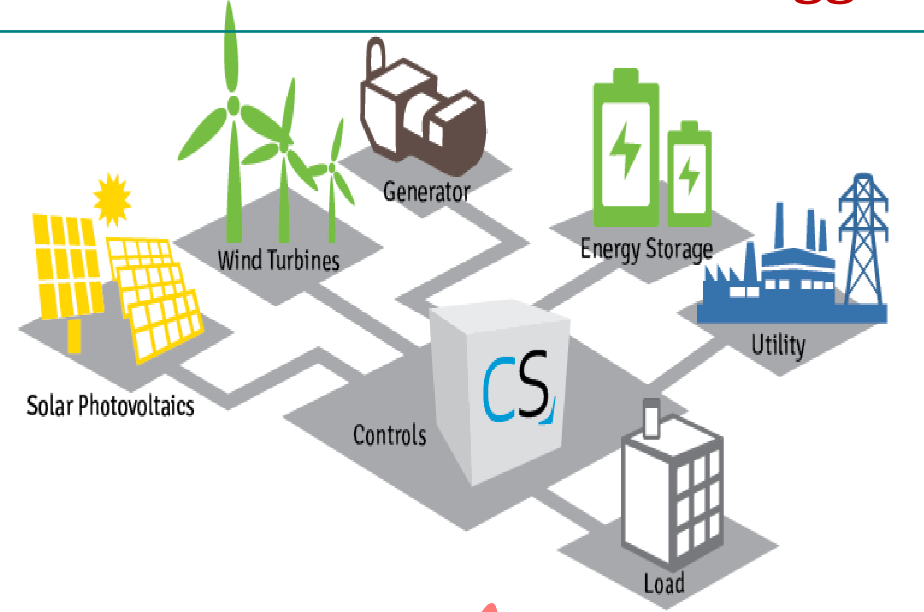
Slower

Time scale

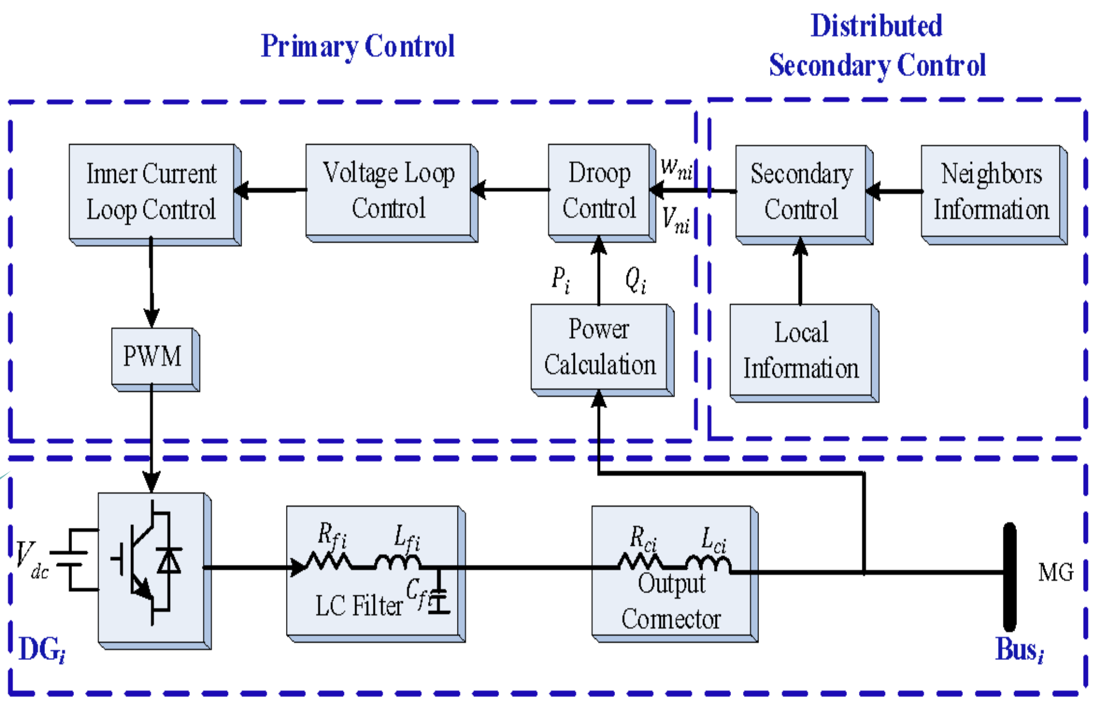
Faster

# Practical Example in Microgrids

## Distributed event-triggered secondary control in AC microgrids




- Each DG can be regarded as an agent which can communicate with neighbors



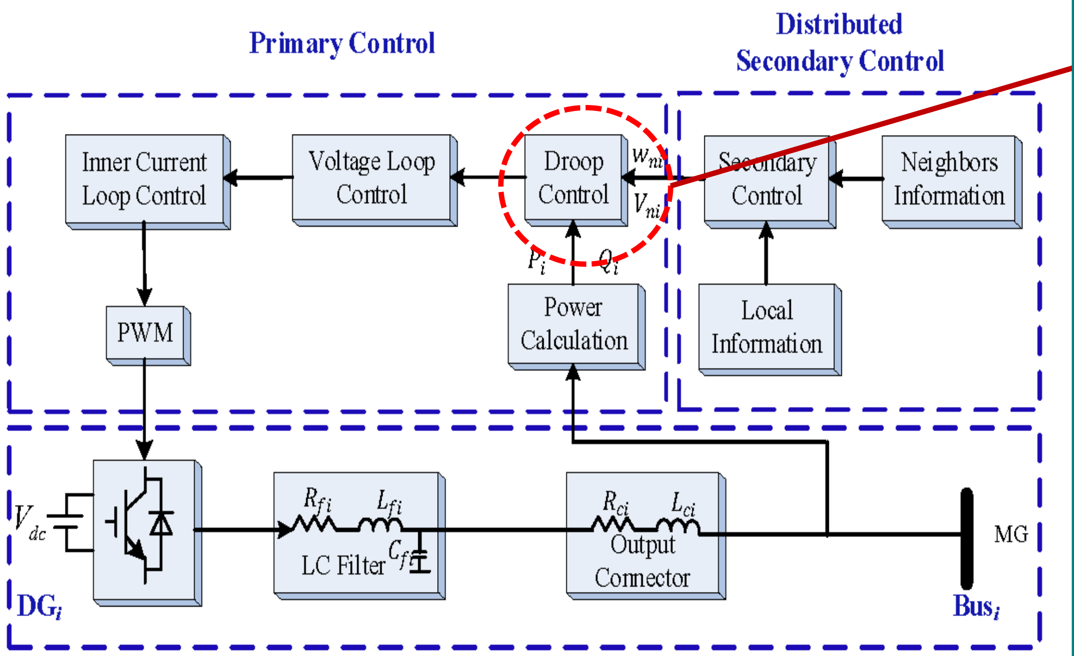

- **Primary Control:** power sharing and frequency/voltage stability;
- **Secondary Control:** regulate the frequency and voltage to reference values


L. Ding, Q.-L. Han, and X.-M. Zhang, "Distributed secondary control for active power sharing and frequency regulation in islanded microgrids using an event-triggered communication mechanism," *IEEE Transactions on Industrial Informatics*, vol.15, no.7, pp. 3910-3922, 2019.

# Practical Example in Microgrids

## Distributed event-triggered secondary control in AC microgrids

### Hierarchical control of DG $i$




### Primary Control

$$w_i = w_{ni} - m_i P_i$$

$$V_i = V_{ni} - n_i Q_i$$

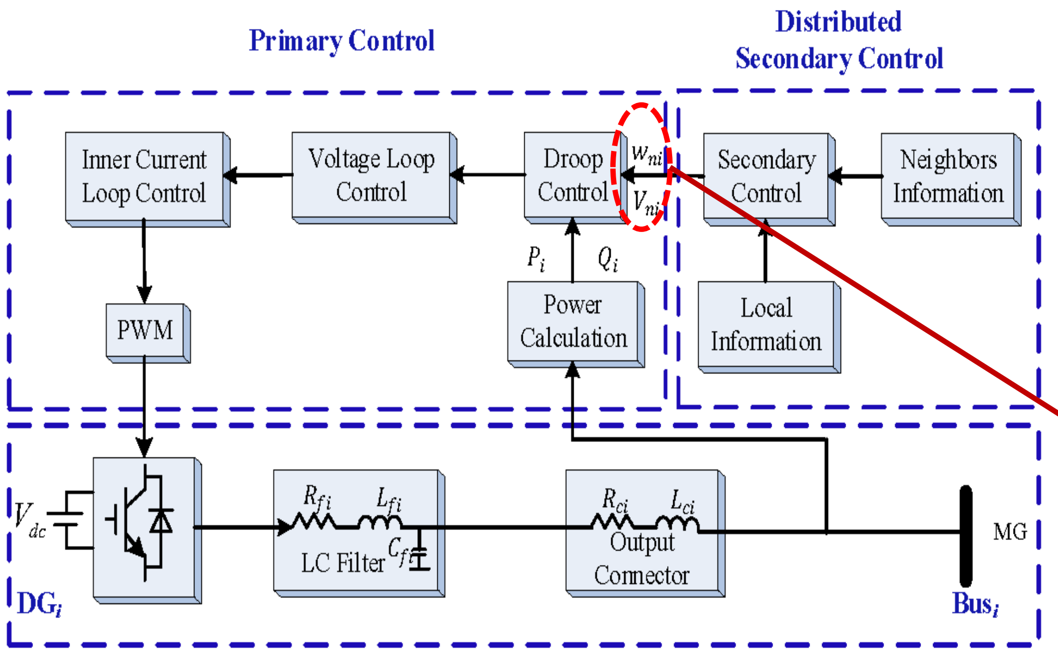
$w_i$: the output frequency;
$V_i$: the magnitude of output voltage;
$w_{ni}$: the nominal set point of frequency;
$V_{ni}$: the nominal set point of voltage magnitude;
$P_i$: the active power output;
$Q_i$; the reactive power output;
$m_i$: the frequency droop control coefficient;
$n_i$: the voltage droop control coefficient.

L. Ding, Q.-L. Han, and X.-M. Zhang, "Distributed secondary control for active power sharing and frequency regulation in islanded microgrids using an event-triggered communication mechanism," *IEEE Transactions on Industrial Informatics*, vol.15, no.7, pp. 3910-3922, 2019.

# Practical Example in Microgrids

## Distributed event-triggered secondary control in AC microgrids

### Hierarchical control of DG *i*




### Secondary Control

$$w_i = w_{ni} - m_i P_i$$

$$V_i = V_{ni} - n_i Q_i$$

Taking derivative of $w_i$ yields

$$\dot{w}_i = \dot{w}_{ni} - m_i \dot{P}_i = u_i^w$$

where $u_i^w$ is the auxiliary control input of $w_i$. Then, the nominal set point is determined by

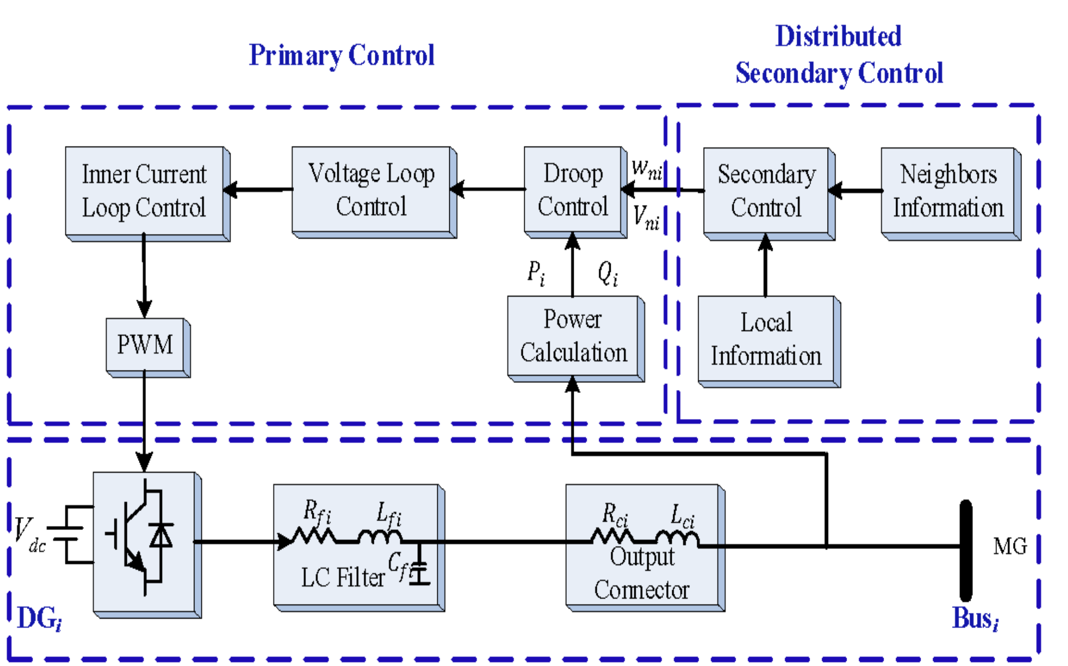
$$w_{ni} = \int (u_i^w + m_i \dot{P}_i)\, ds$$

L. Ding, Q.-L. Han, and X.-M. Zhang, "Distributed secondary control for active power sharing and frequency regulation in islanded microgrids using an event-triggered communication mechanism," *IEEE Transactions on Industrial Informatics*, vol.15, no.7, pp. 3910-3922, 2019.

# Practical Example in Microgrids

SWINBURNE UNIVERSITY OF TECHNOLOGY

## Hierarchical control of DG *i*




## Active power reference

The balance between the total generation active power, load demand and power losses can be described by

$$\sum_{i=1}^{N} P_i = \sum_{i=1}^{N} P_i^L + P_{loss}$$

where $P_i^L$ is the load demand at bus i, and $P_{loss}$ =$\alpha \sum_{i=}$ ... al active ... with $\alpha$ bei... re... injection is se...

Maximum generation

Desired utilization level

$$P_i^{ref} = (1+\alpha)\lambda^d P_i^M$$

$$\lambda^d = \frac{\sum_{i=1}^{N} P_i^L}{\sum_{i=1}^{N} P_i^M}$$

**Proportional active power sharing**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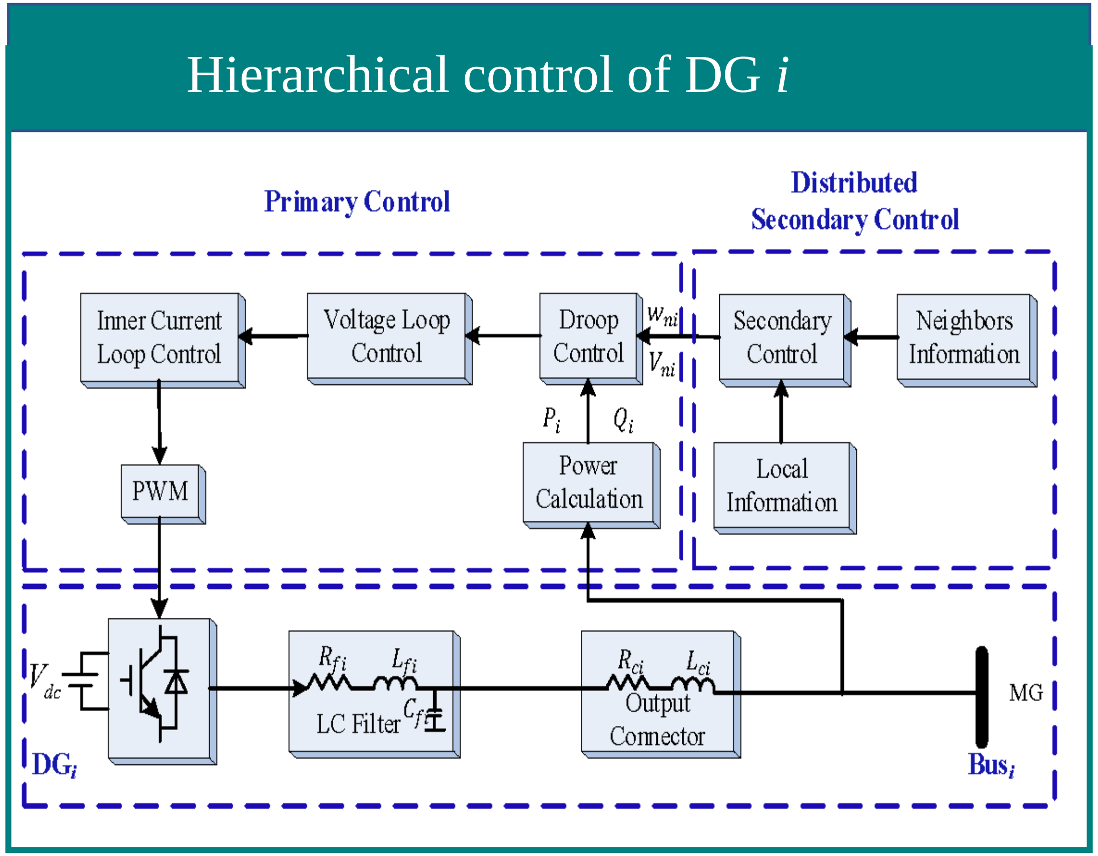
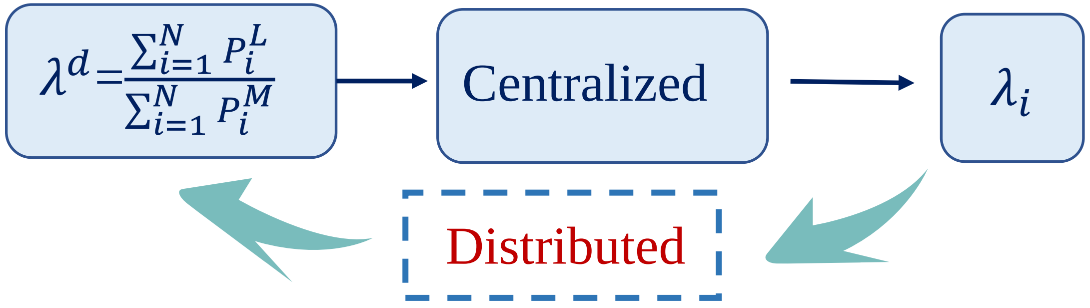
# Practical Example in Microgrids




## Control objectives




**Control objectives:** design distributed secondary controllers to achieve:

- ✓ Frequency regulation

$$\lim_{t \to \infty} \left| w_i - w^{ref} \right| = 0$$

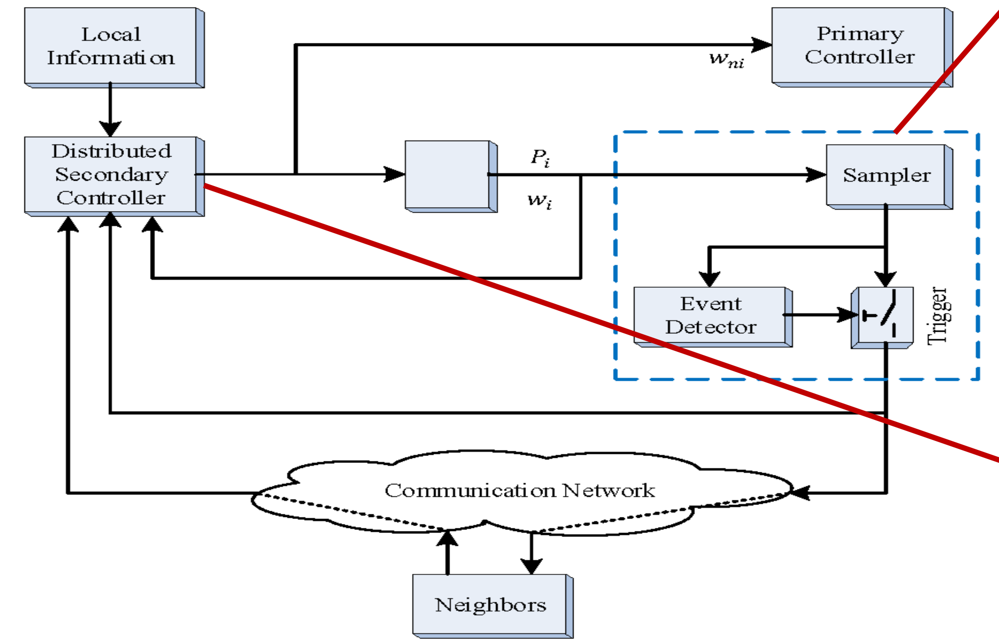
- ✓ Active power sharing

$$\lim_{t \to \infty} \left| \lambda_i - \lambda^d \right| = 0$$


L. Ding, Q.-L. Han, and X.-M. Zhang, "Distributed secondary control for active power sharing and frequency regulation in islanded microgrids using an event-triggered communication mechanism," *IEEE Transactions on Industrial Informatics*, vol.15, no.7, pp. 3910-3922, 2019.

# Practical Example in Microgrids

Distributed control of DG $i$ with event-triggered communication




**Event-triggered communication**

$$t_{k+1}^{i}h = \inf\{kh \mid f_i^P(kh) > 0 \,||\, f_i^w(kh) > 0\}$$

**Frequency controller**

$$u_i^w = -k_5 \sum_{j\in N_i} a_{ij}\left(w_i\left(t_k^i h\right) - w_j\left(t_{k(t)}^j h\right)\right) - k_5 b_i\left(P_i^M w_i(t) - w^{ref}\right)$$

**Active power controller**

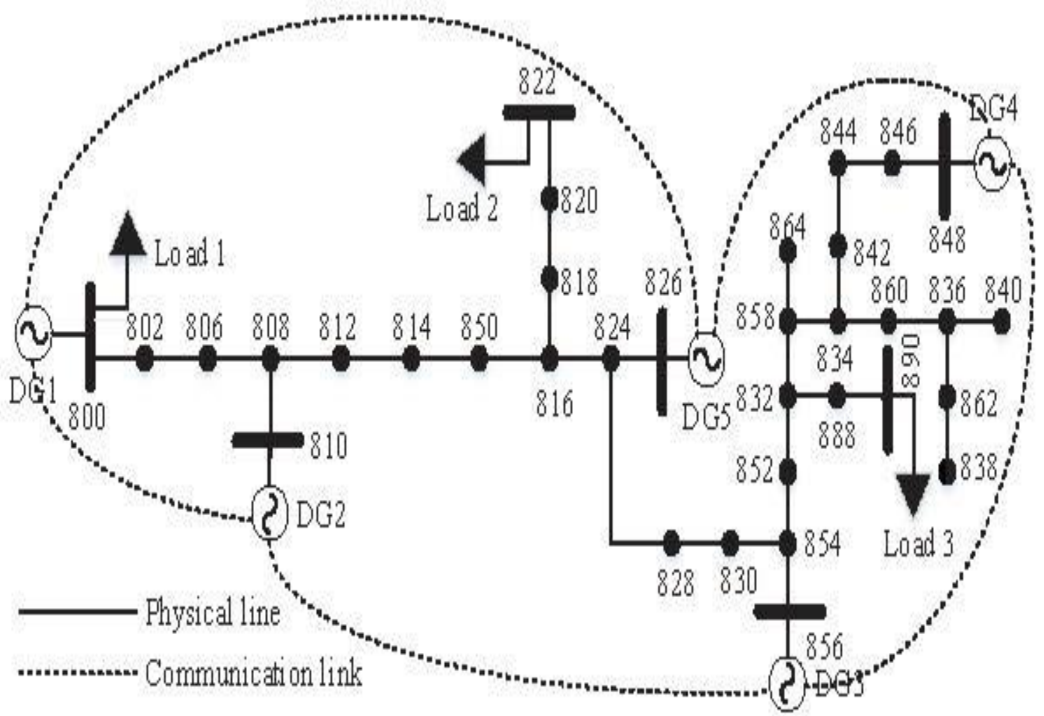
$$u_i^\lambda = -k_1\left(P_i^M \lambda_i(t) - P_i^L\right) - k_2 \textstyle\sum_{j\in N_i} a_{ij}\left(\lambda_i\left(t_k^i h\right) - \lambda_j\left(t_{k(t)}^j h\right)\right) + k_3 \textstyle\sum_{j\in N_i} a_{ij}\left(z_i\left(t_k^i h\right) - z_j\left(t_{k(t)}^j h\right)\right)$$

$$\dot{z}_i = k_4 \textstyle\sum_{j\in N_i} a_{ij}\left(z_i\left(t_k^i h\right) - z_j\left(t_{k(t)}^j h\right)\right)$$

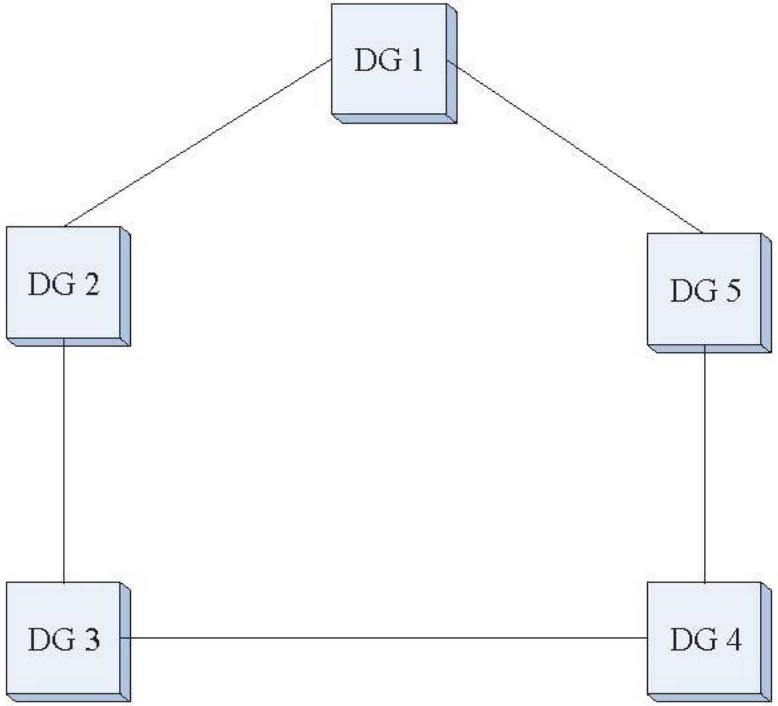

L. Ding, Q.-L. Han, and X.-M. Zhang, "Distributed secondary control for active power sharing and frequency regulation in islanded microgrids using an event-triggered communication mechanism," *IEEE Transactions on Industrial Informatics*, vol.15, no.7, pp. 3910-3922, 2019.

# Practical Example in Microgrids

## Case studies




A modified IEEE 34-bus test system

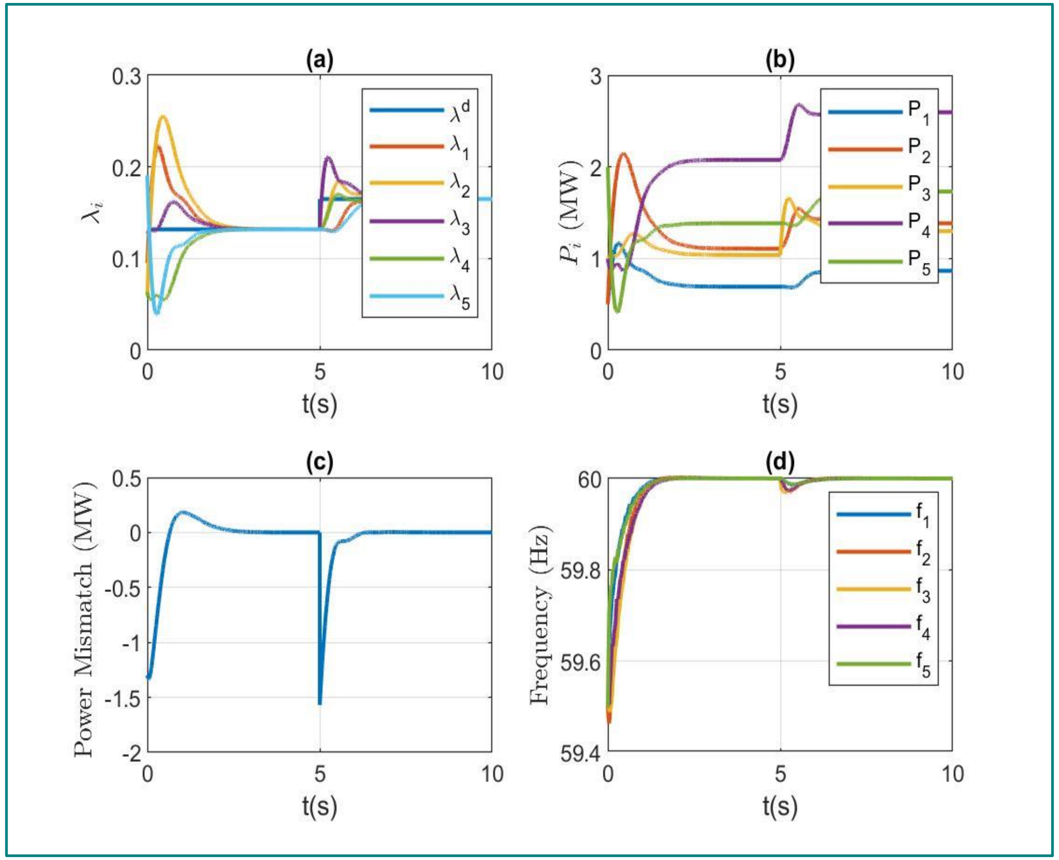


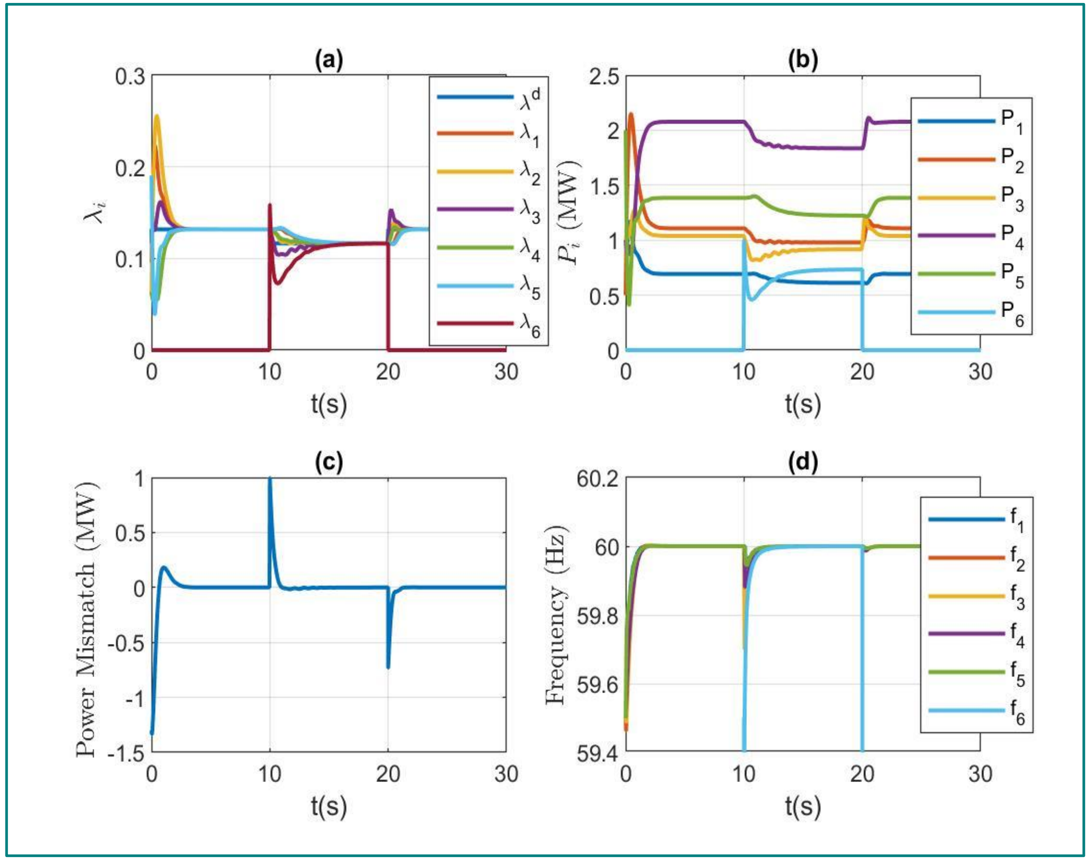

Communication topology

L. Ding, Q.-L. Han, and X.-M. Zhang, “Distributed secondary control for active power sharing and frequency regulation in islanded microgrids using an event-triggered communication mechanism,” *IEEE Transactions on Industrial Informatics*, vol.15, no.7, pp. 3910-3922, 2019.

# Practical Example in Microgrids

## Case studies



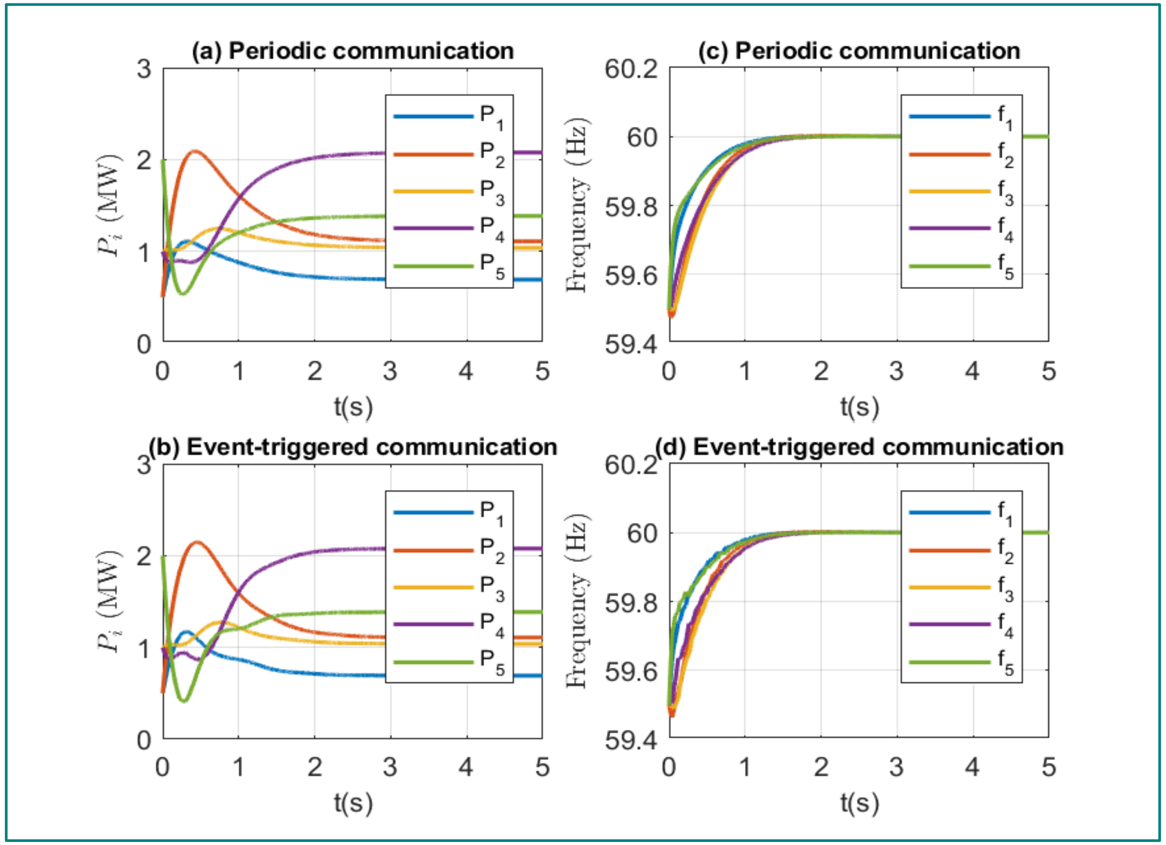

Impact of load changes: load 3 is doubled at 5s

Plug-and-Play ability: at t=10s, DG 6 is plugged into the MG and is removed at t=20s

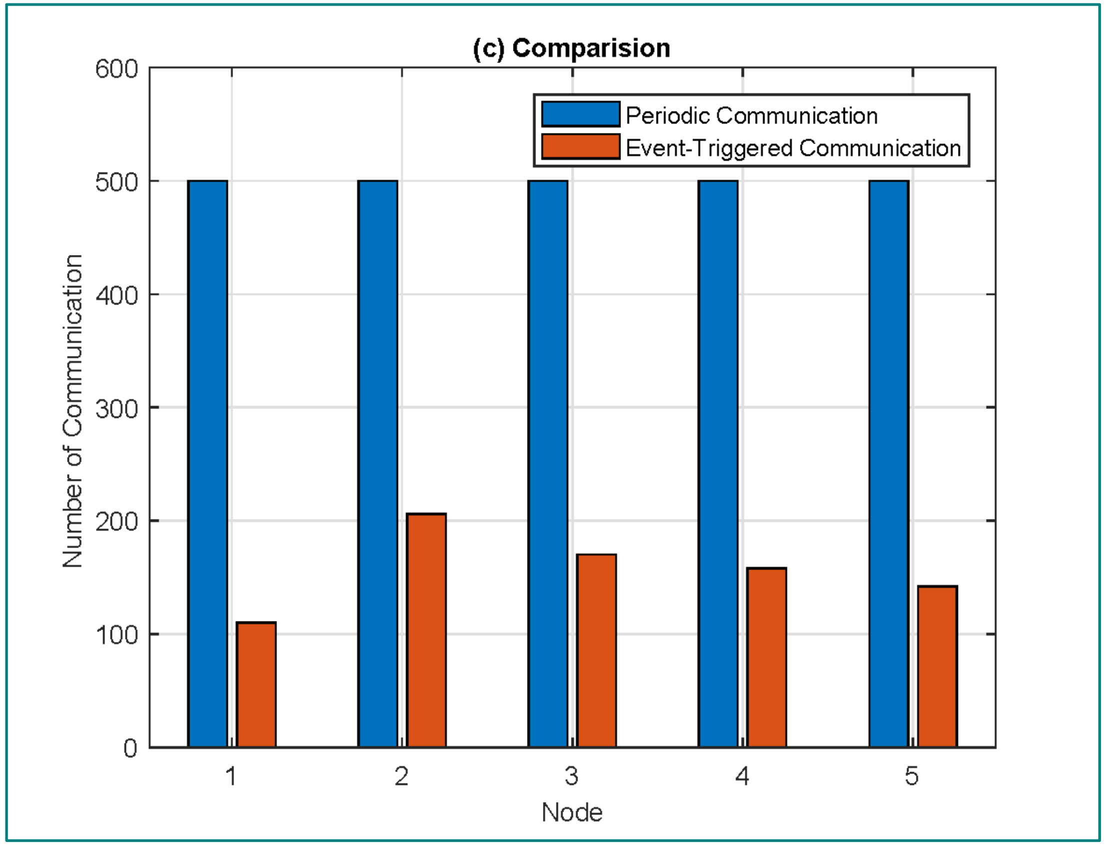

L. Ding, Q.-L. Han, and X.-M. Zhang, "Distributed secondary control for active power sharing and frequency regulation in islanded microgrids using an event-triggered communication mechanism," *IEEE Transactions on Industrial Informatics*, vol.15, no.7, pp. 3910-3922, 2019.

# Practical Example in Microgrids

## Case studies




Comparison of control performance




Comparison of communication performance

L. Ding, Q.-L. Han, and X.-M. Zhang, "Distributed secondary control for active power sharing and frequency regulation in islanded microgrids using an event-triggered communication mechanism," *IEEE Transactions on Industrial Informatics*, vol.15, no.7, pp. 3910-3922, 2019.

04

# Challenging Issues

# Challenging Issues

Fixed-time/prescribed time event-triggered consensus is more practical since it can ensure a fast convergence rate while reducing utilization of communication and computation resources.

The stochasticity may exist in many different forms such as stochastic process/measurement/communication noise, stochastic communication topologies


To reveal the relationship between constrained objective functions and utilization of resources in distributed optimization problems

Devise resilient and secure event-triggered control schemes to deal with various failure/attacks in system data transmission channels

# Survey Papers


- Y. Miao, C. Chen, L. Pan, Q.-L. Han, J. Zhang, and Y. Xiang, “Machine learning based cyber attacks targeting on controlled information: A survey,” *ACM Computing Surveys*, vol. 54, no. 7, Article No. 139, pp. 1-36, July 2021, DOI: 10.1145/3465171
- D. Ding, Q.-L. Han, X. Ge, and J. Wang, “Secure state estimation and control of cyber-physical systems: A survey,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 51, no. 1, pp. 176-190, January 2021, DOI: 10.1109/TSMC.2020.3041121
- Z. Peng, J. Wang, D. Wang, and Q.-L. Han, “An overview of recent advances in coordinated control of multiple autonomous surface vehicles,” *IEEE Transactions on Industrial Informatics*, vol. 17, no. 2, pp. 732-745, February 2021, DOI: 10.1109/TII.2020.3004343
- G. Lin, S. Wen, Q.-L. Han, J. Zhang, and Y. Xiang, “Software vulnerability detection using deep neural networks: A survey,” *Proceedings of the IEEE*, vol. 108, no. 10, pp. 1825-1848, October 2020, DOI: 10.1109/JPROC.2020.2993293
- X. Ge, Q.-L. Han, L. Ding, Y.-L. Wang, and X.-M. Zhang, “Dynamic event-triggered distributed coordination control and its applications: A survey of trends and techniques,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 50, no. 9, pp. 3112-3125, September 2020, DOI: 10.1109/TSMC.2020.3010825

# Survey Papers


- R. Coulter, Q.-L. Han, L. Pan, J. Zhang, and Y. Xiang, “Data driven cyber security in perspective - intelligent traffic analysis,” *IEEE Transactions on Cybernetics*, vol. 50, no. 7, pp. 3081-3093, July 2020, DOI: 10.1109/TCYB.2019.2940940
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- H. Yang, Q.-L. Han, X. Ge, L. Ding, Y. Xu, B. Jiang, and D. Zhou, “Fault tolerant cooperative control of multi-agent systems: A survey of trends and methodologies,” *IEEE Transactions on Industrial Informatics*, vol. 16, no. 1, pp. 4-17, January 2020, DOI: 10.1109/TII.2019.2945004

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- D. Ding, Q.-L. Han, Z. Wang, and X. Ge, "A survey on model-based distributed control and filtering for industrial cyber-physical systems," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 5, pp. 2483-2499, May 2019, DOI: 10.1109/TII.2019.2905295
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- Z. Zuo, Q.-L. Han, B. Ning, X. Ge, and X.-M. Zhang, "An overview of recent advances in fixed-time cooperative control of multi-agent systems," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 6, pp. 2322-2334, June 2018, DOI: 10.1109/TII.2018.2817248
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- X.-M. Zhang, Q.-L. Han, and B.-L. Zhang, "An overview and deep investigation on sampled-data-based event-triggered control and filtering for networked systems," *IEEE Transactions on Industrial Informatics*, vol. 13, no. 1, pp. 4-16, February 2017, DOI: 10.1109/TII.2016.2607150.

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- L. Ma, Z. Wang, Q.-L. Han, and Y. Liu, "Consensus control of stochastic multi-agent systems: A survey," *SCIENCE CHINA Information Sciences*, vol. 60, no. 12, pp. 120201:1–120201:15, December 2017, DOI: 10.1007/s11432-017-9169-4
- X. Ge, F. Yang, and Q.-L. Han, "Distributed networked control systems: A brief overview," *Information Sciences*, vol. 380, pp. 117-131, February 2017, DOI: 10.1016/j.ins.2015.07.047
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# Thank You !

***Questions?***