Secrecy Codes for Wireless Control Systems

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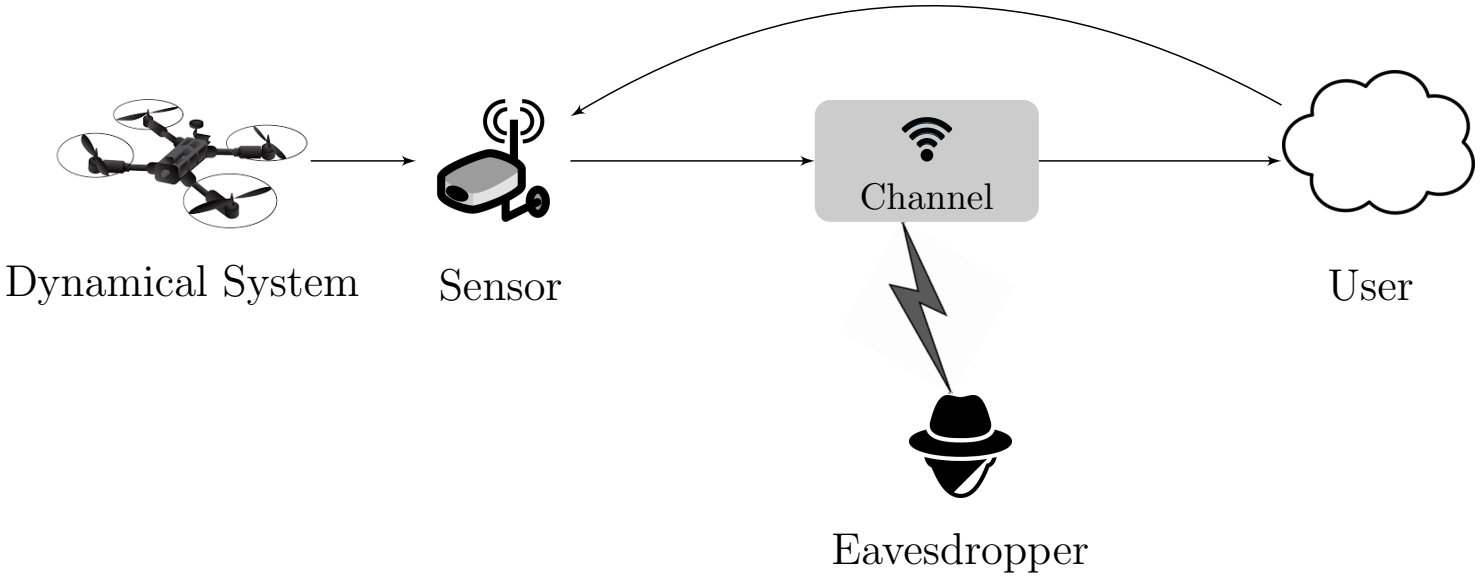
Secrecy Issues in the Internet of Things

- Interconnected sensors and actuators.
- Communication over wireless networks.

The wireless medium may be compromised.

- Broadcast nature.
- Eavesdroppers may intercept sensitive data about the physical system.

Eavesdropping attacks in Dynamical Systems



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- Protect dynamical state information, e.g. position, velocity.

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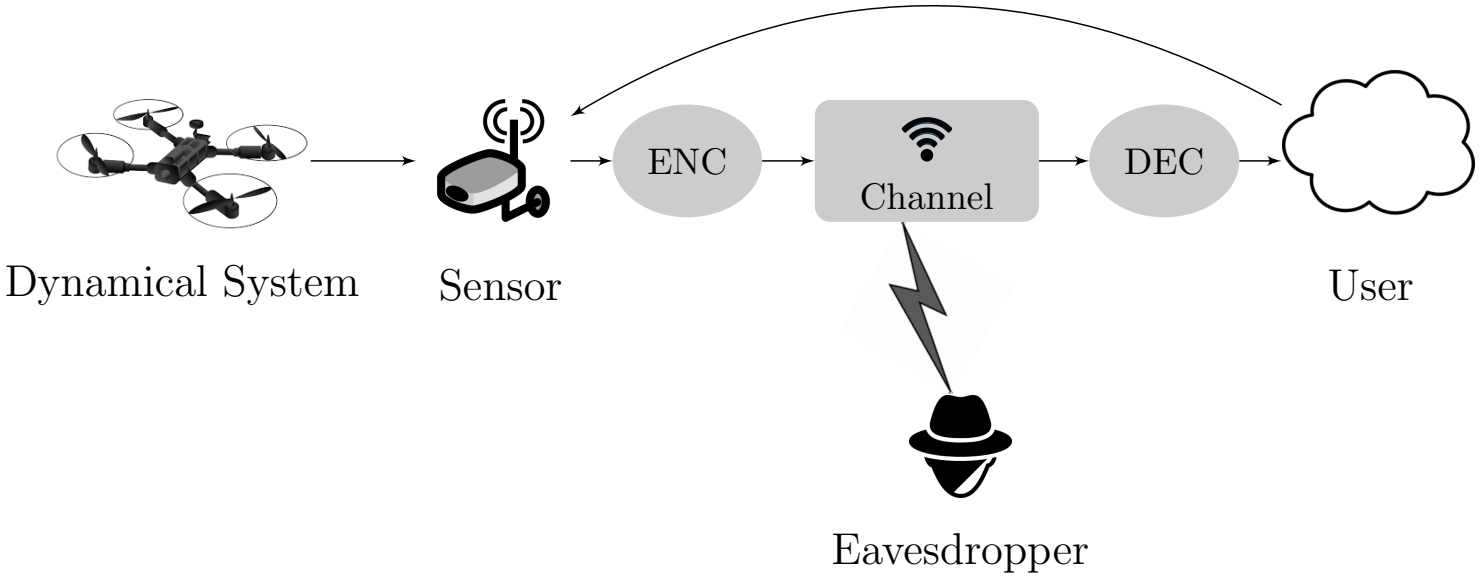

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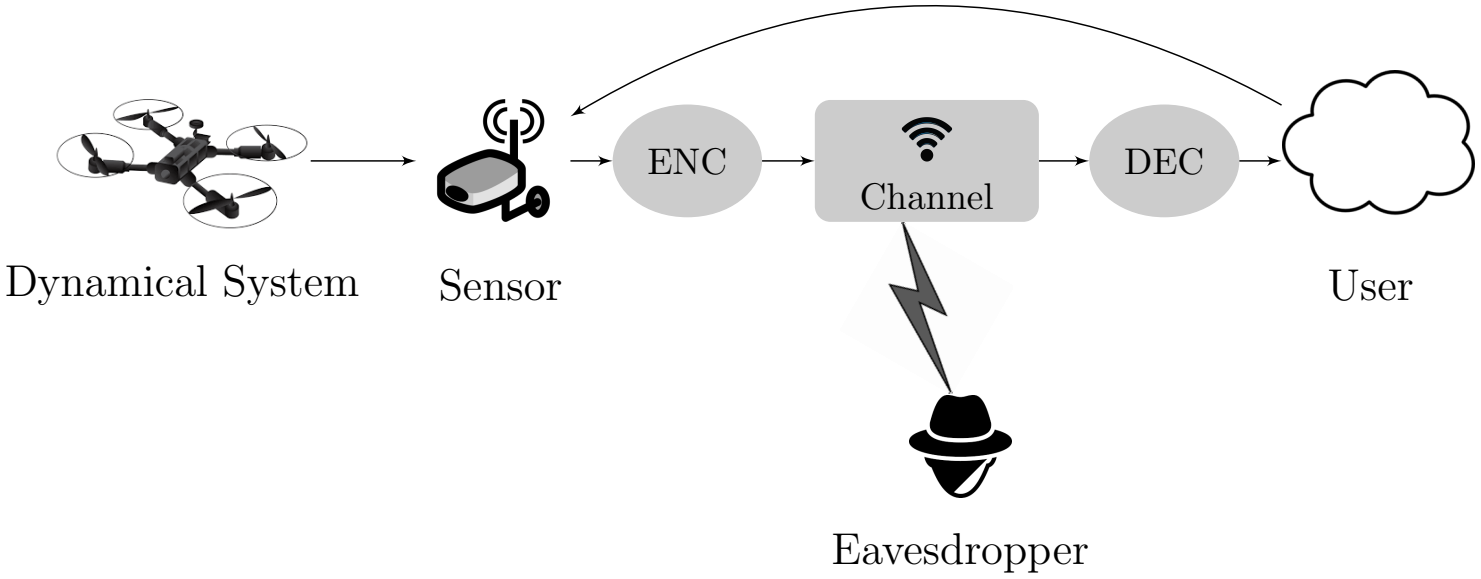

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Challenges

- Tradeoff between security and code complexity.

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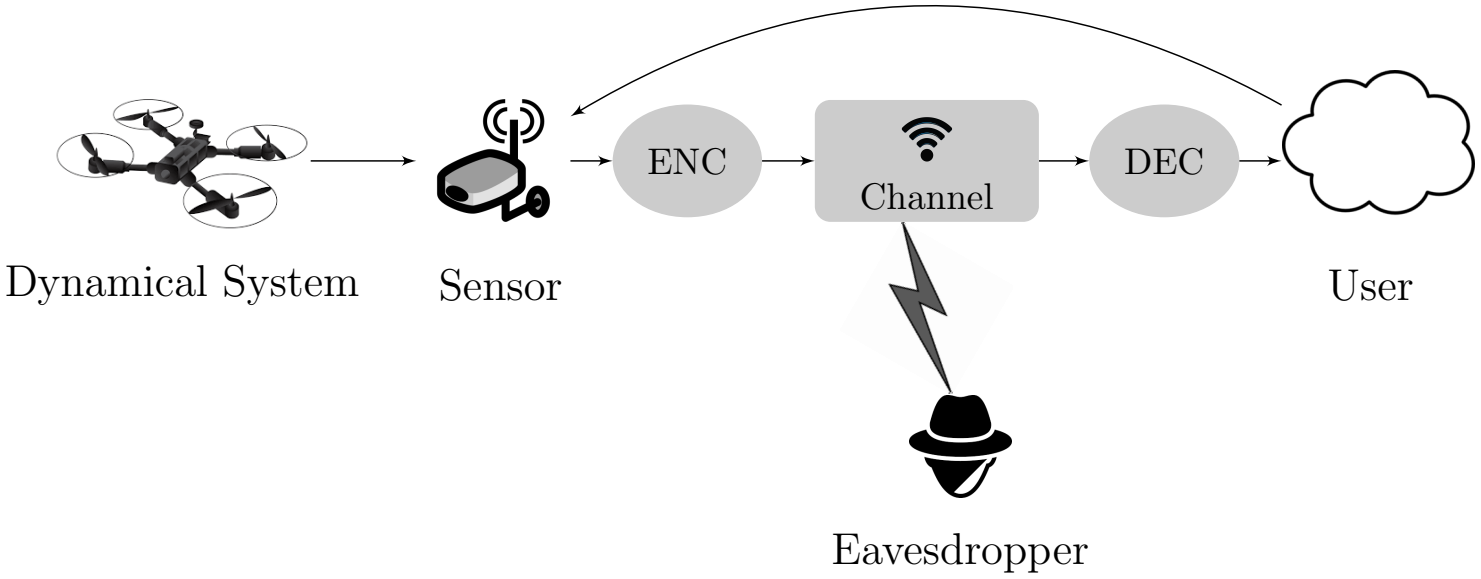

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Approach

- Can we exploit model knowledge/physics for secrecy?

Previous work

Encryption

- Generic tool applied in practice. J. Katz and Y. Lindell. 2014
- Adversary should have bounded computational capabilities.
- Communication/computation overheads.

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Physical layer security

- Information theoretic tools. A. D. Wyner. 1975, M. Wiese et al. 2016
- Provable guarantees.
- Requires eavesdropper's channel model.

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Our approach: State-Secrecy Codes

- Exploit the system dynamics.
- New tradeoff between code complexity and security.
- Simple and fast.
- Strong security guarantees about the current state.

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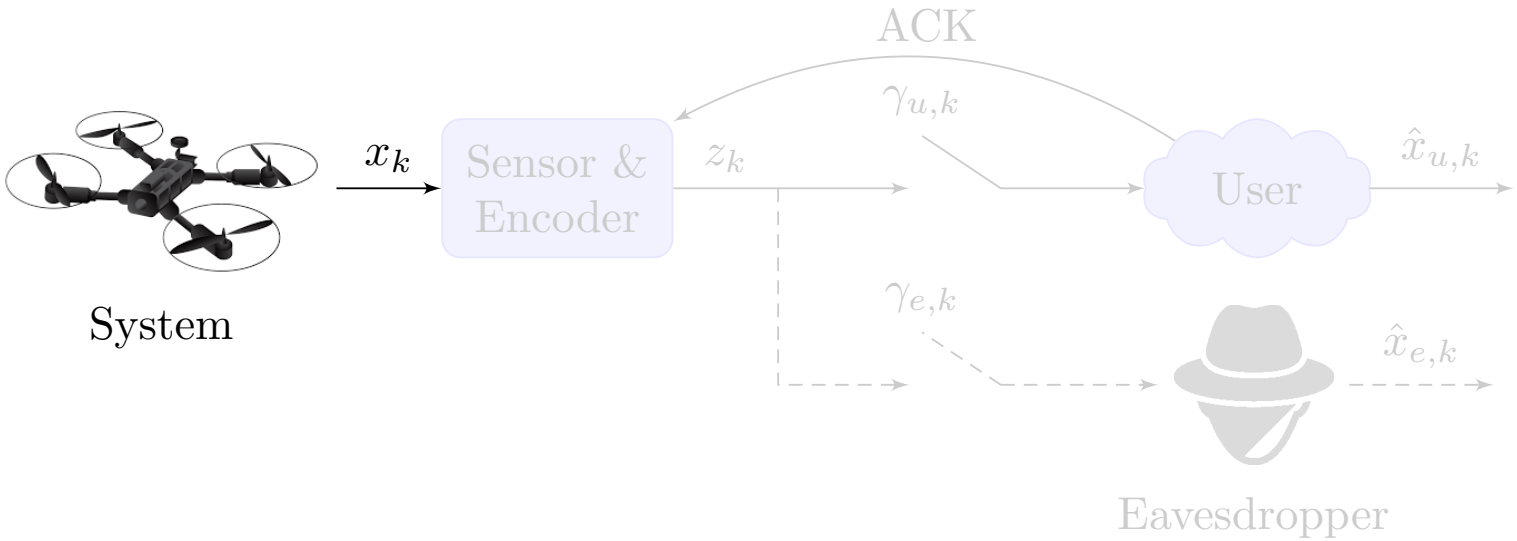
Related work

- Codes for several types of linear systems
  A. Tsiamis et al. CDC 2017, ACC 2018, CDC 2018
- Non-coding approach
  A. S. Leong et al. IFAC 2017, CDC 2017
  A. Tsiamis et al. IFAC 2017

Model



Linear System

- state x_k; e.g. position and velocity at time k

$$x_{k+1} = Ax_k + w_{k+1}, \quad w_k : \text{ Gaussian process noise}$$

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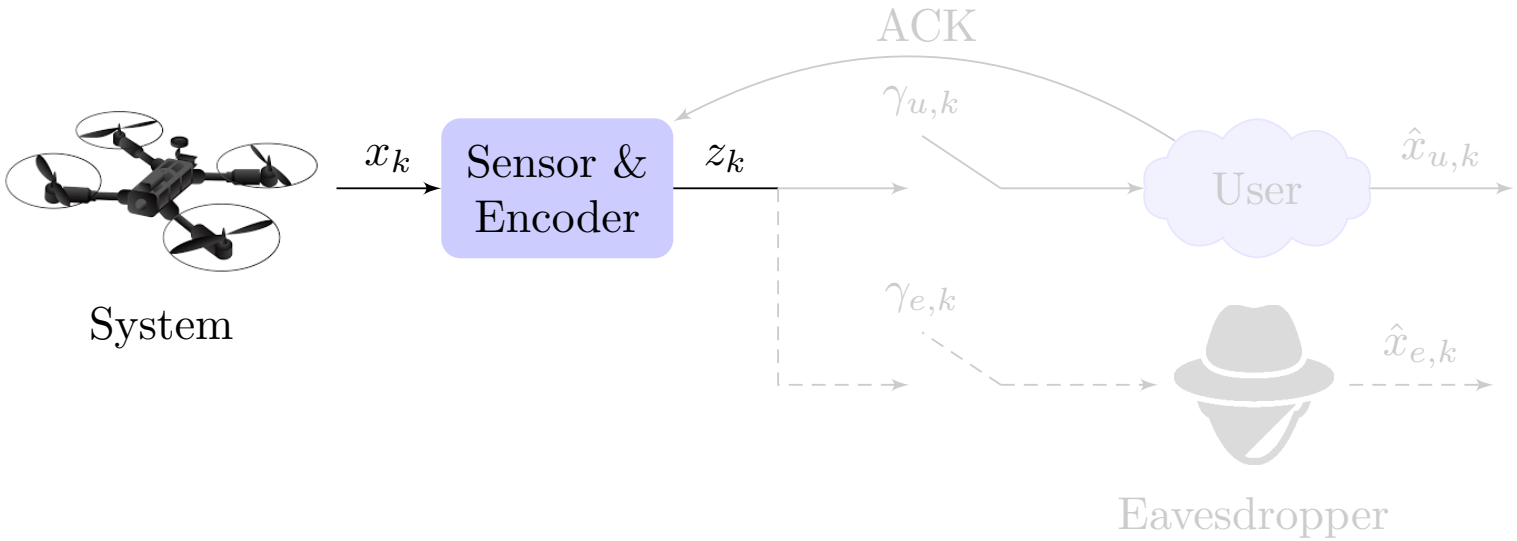

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Sensor and encoder

- z_k encoded version of state x_k.

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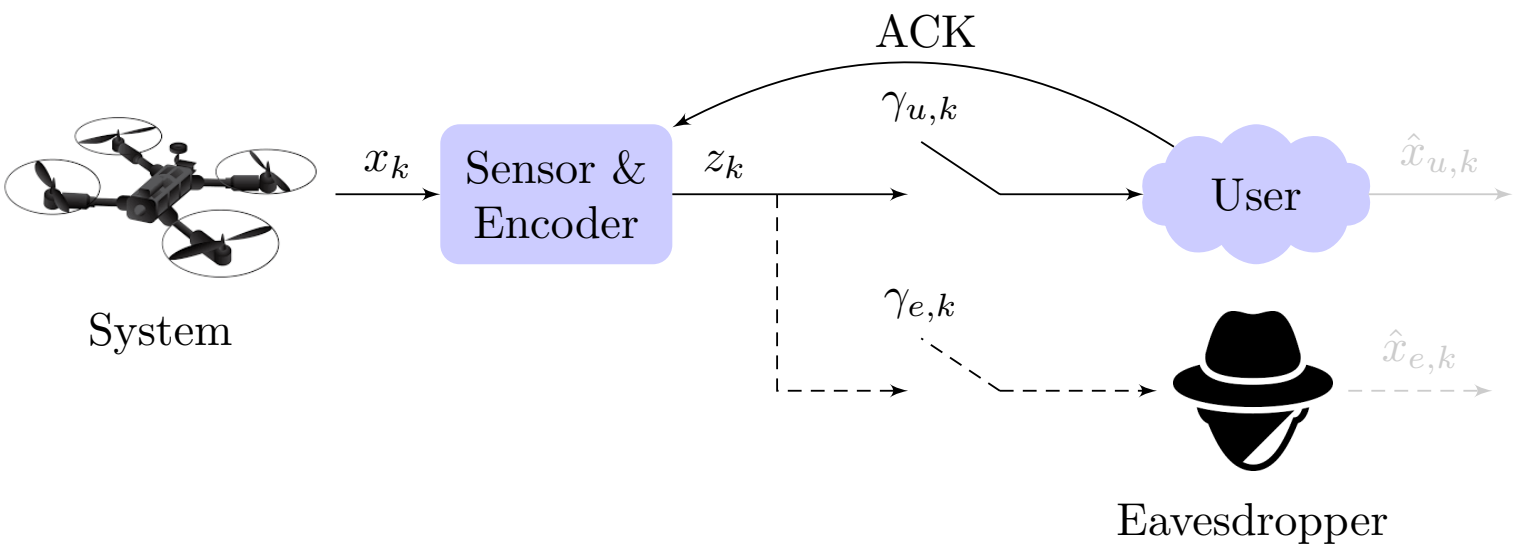
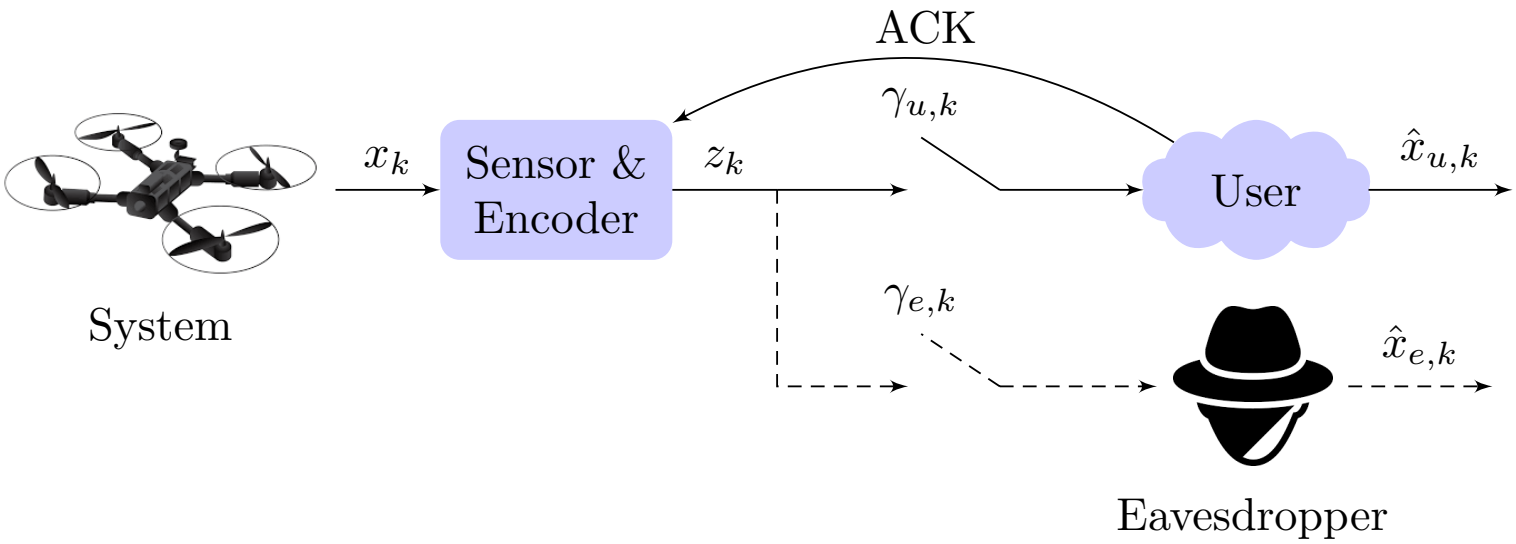


Channel

- Packet drop channels:
  - Message either received intact or dropped.
- $\gamma_{u,k} = 1$: message z_k received.
- $\gamma_{u,k} = 0$: message z_k dropped.
- Acknowledgment signals available.

Model



Decoders: Minimum Mean Square Error Estimators

- Information sets:

$$\mathcal{I}_{u,k} = \{\text{Received messages } z_k\}$$
$$\mathcal{I}_{e,k} = \{\text{Intercepted messages } z_k, \text{User's outcomes } \gamma_{u,k}\}$$

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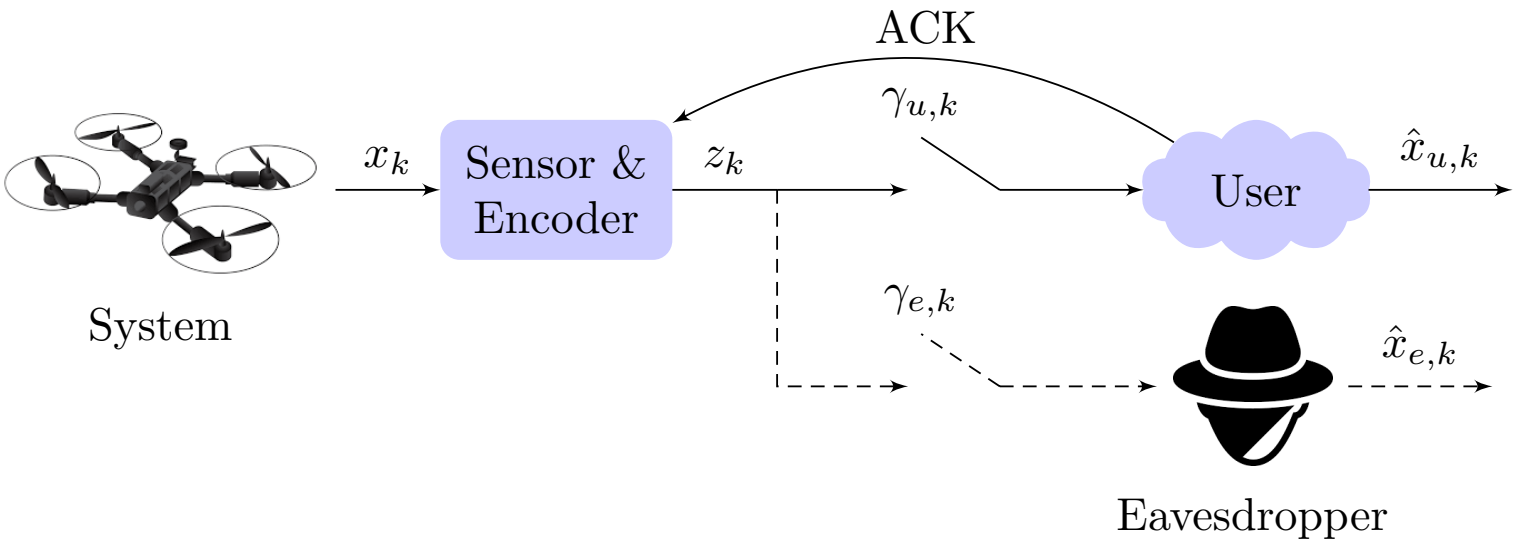

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- Estimation:

$$\hat{x}_{u,k} \text{ minimizes } \mathbb{E}(\|x_k - \hat{x}_{u,k}\|^2 \,|\mathcal{I}_{u,k})$$
$$P_{u,k} \text{ user mmse covariance given } \mathcal{I}_{u,k}$$

Problem: Secrecy

Secrecy

Find a coding scheme such that:

- **Eavesdropper's** minimum mean square error (mmse) for the current state is **maximum** asymptotically.
- **User's** mmse is **optimal**.

Assumptions

- Public A.
- Passive eavesdropper.
- Eavesdropper knows model, coding scheme, acknowledgments.

State-Secrecy Code

Coding Scheme

$$z_k = x_k - L^{k-t_k} x_{t_k}$$

t_k: the most recent message received at the user

- Matrix L depends on the dynamical system's model.
- Choice of L: makes z_k less correlated to x_k for the eavesdropper.
- ACKs: user and sensor agree on t_k.
- Fast and simple.
- Can be used along with encryption.

Example

Code

$$z_k = x_k - L^{k-t_k} x_{t_k}$$

Encoder	**User**	**Eavesdropper**
x_0		

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$x_3 - Lx_2$	✗	$-$	
$x_4 - L^2 x_2$			

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$x_3 - Lx_2$	✗	$-$	
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$x_4 - L^2x_2$	✓	$x_4 - L^2x_2$	✓	$x_4 - L^2x_2$

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$x_4 - L^2x_2$	✓	$x_4 - L^2x_2$	✓	$x_4 - L^2x_2$

- User decodes by adding.

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$x_3 - Lx_2$	✗	$-$	✓	$x_3 - Lx_2$
$x_4 - L^2x_2$	✓	$x_4 - L^2x_2$	✓	$x_4 - L^2x_2$

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- Eavesdropper decodes initially.

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- User decodes by adding.
- Eavesdropper decodes initially.
- Eavesdropper cannot decode for $k > 2$.

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$x_4 - L^2 x_2$	✓	x_4	✓	$x_4 - L^2 x_2$, $x_4 = ?$

Critical event

When the user receives while the eavesdropper misses:

$$\gamma_{u,k} = 1,\ \gamma_{e,k} = 0, \ \text{ for some } k$$

Damages the eavesdropper (here for $k = 2$).

Secrecy guarantees

Theorem 1: Secrecy

If the critical event occurs at time k_0 **secrecy** is achieved:

- **Eavesdropper's** mmse is **asymptotically maximum**:

$$P_{e,k} \rightarrow \text{ maximum value}$$

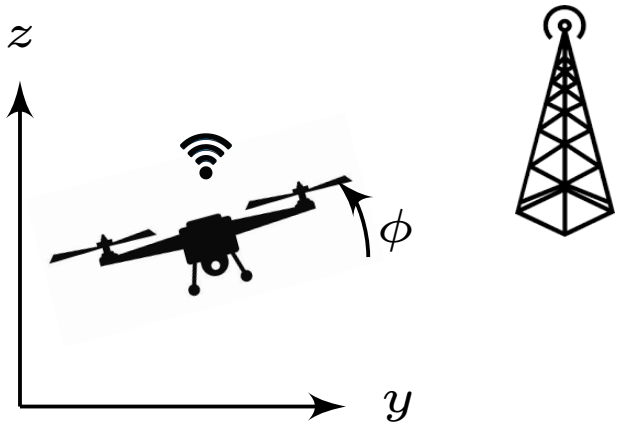
- **User's** mmse remains **optimal**:

$$P_{u,k} = 0, \text{ when user receives. } (\gamma_{u,k} = 1)$$

- One occurrence of the critical event is sufficient.
  (user receives and eavesdropper fails to intercept at some time k.)

- Condition holds for most packet dropping channels.

Simulation scenario



- Linearized dynamics, planar quadrotor
- Hovers around target point $(0, 0, 0)$
- State is position and velocity

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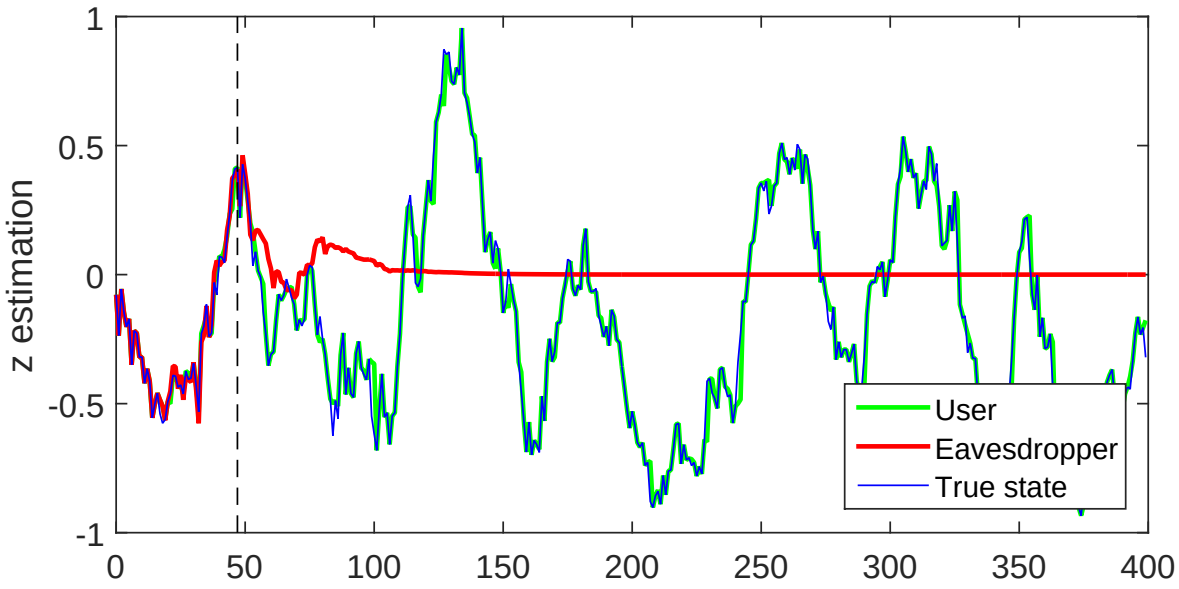

- Height estimation

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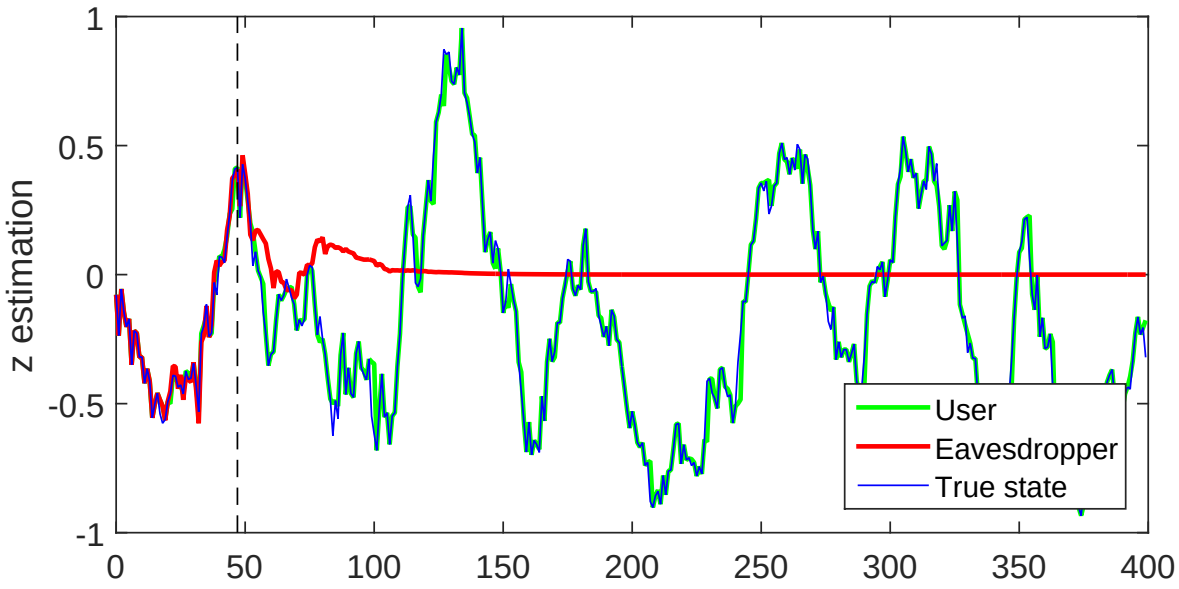

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- Critical event occurs at time $k = 47$

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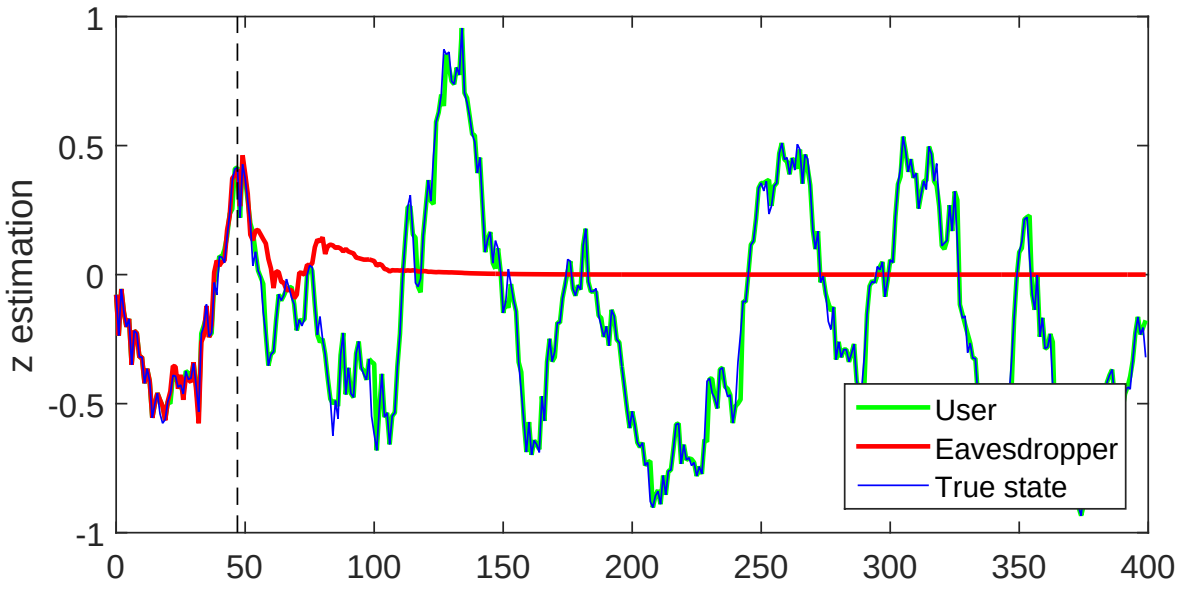

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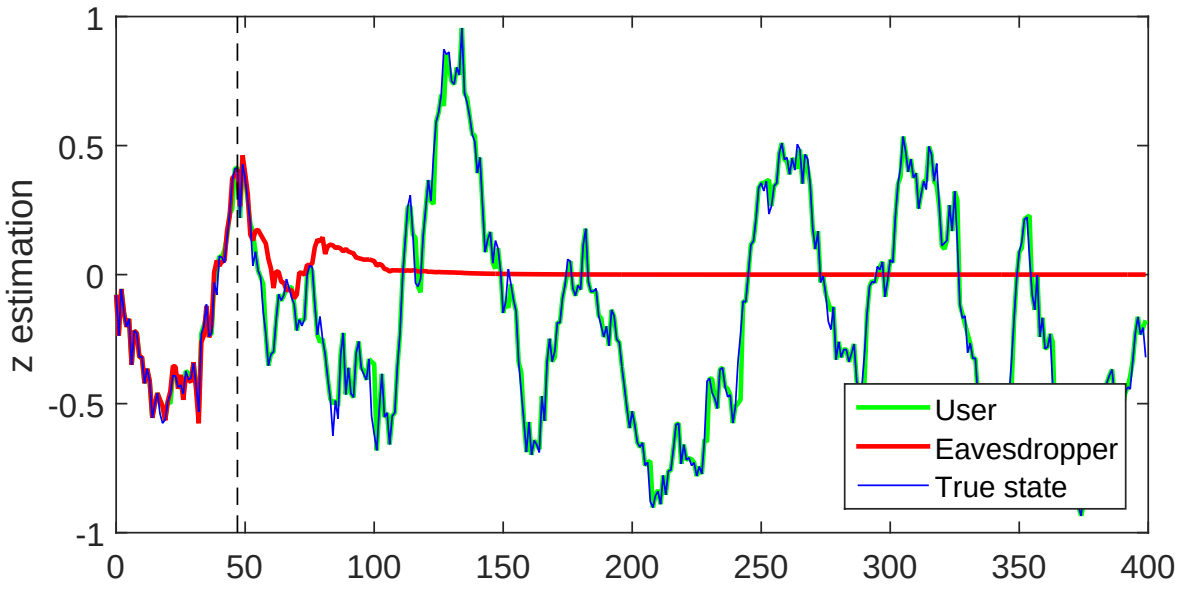

- Height estimation
- Critical event occurs at time $k = 47$
- Eavesdropper gets confused about the state; trivial estimate $x_e = 0$
- User's estimation remains accurate

Conclusion

Summary

- We can exploit the dynamical system model/physics for secrecy.
- Codes specialized for dynamical systems.
- Simple and fast, strong guarantees for the current state.
- Secrecy guarantees for several types of linear systems.

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Future Work

- How to defend against active eavesdroppers?
- How can we combine codes with encryption efficiently?
- How can we apply the codes in closed-loop control systems?
- How can we protect past states?

Thank you!