SWIFT: Instantaneous Feedback-based Adaptive Communications (IFAC) and Networks

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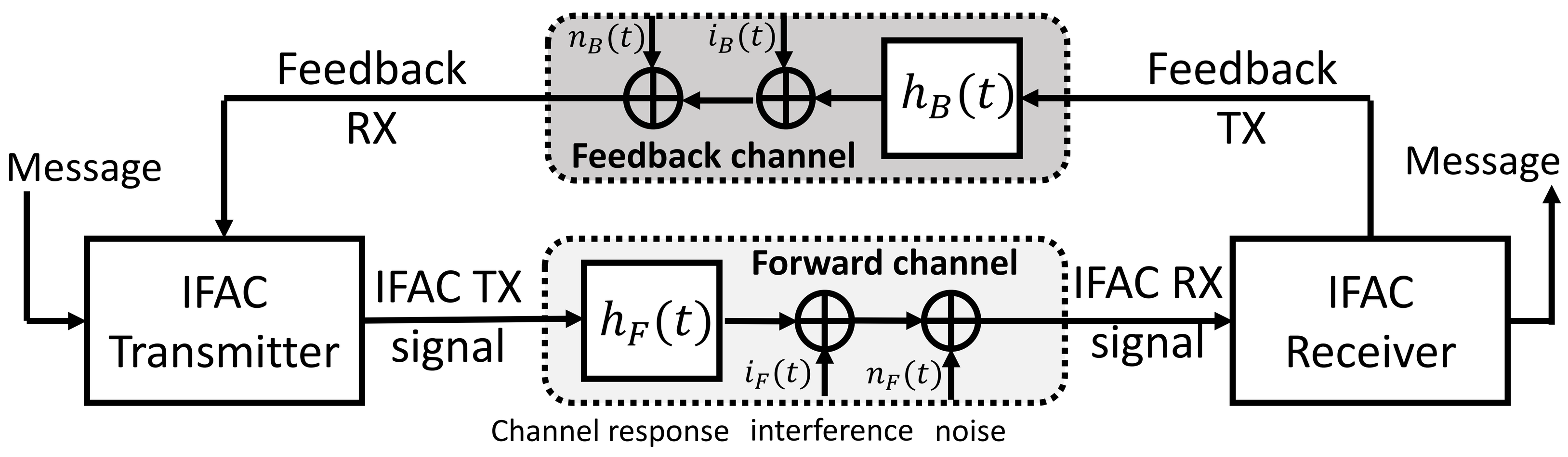
Motivation and Concept

Instantaneous Feedback-based Adaptive Communications (IFAC)

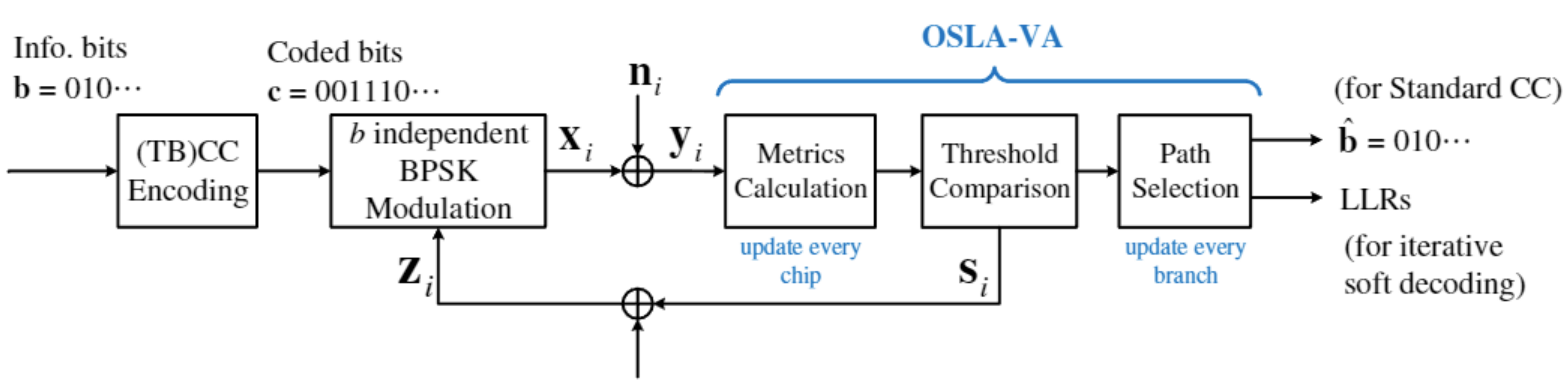


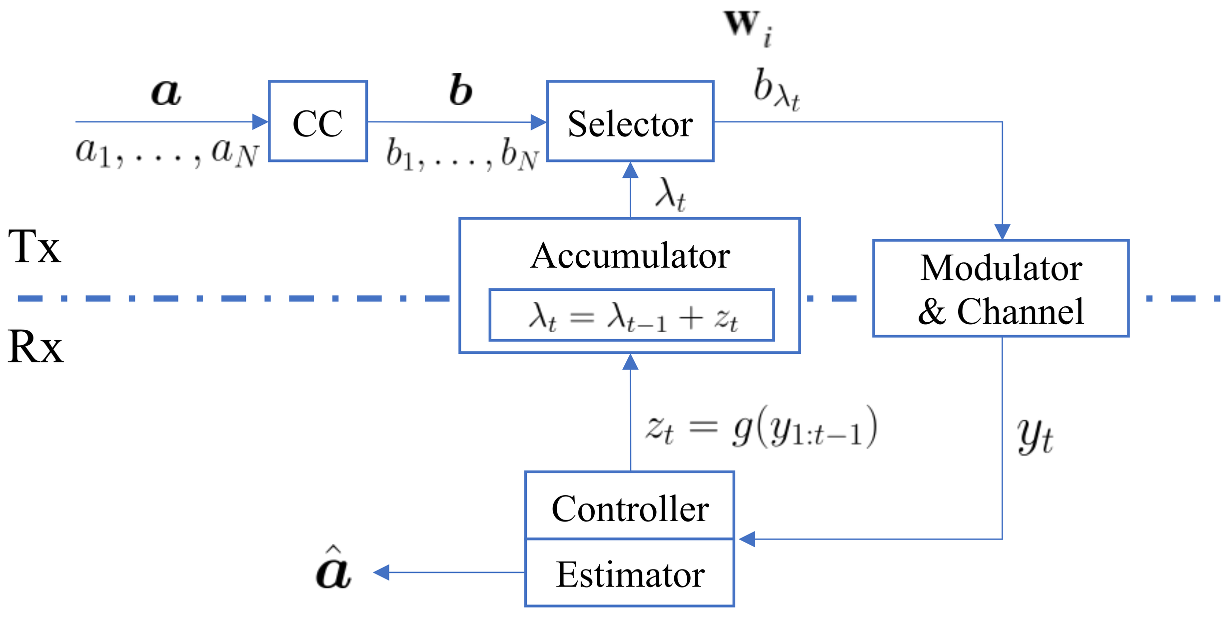
Research Program Structure

- Thrust 1: IFAC physical layer theories, models, and algorithms
- Thrust 2: Data-Driven reinforcement learning based IFAC
- Thrust 3: Prototyping and experiments

Proposed IFAC scheme

- **Opportunistic Symbol Length Adaptation (OSLA)**
- **OSLA combined with tail-biting convolutional codes, turbo codes**
- **Reinforcement learning based feedback and modulation**





In the beginning of every chip t, controller chooses from:
(i) $z_t = 0$, letting transmitter resend the previously transmitted symbol, or
(ii) $z_t = 1$, letting transmitter move forward to the next symbol.

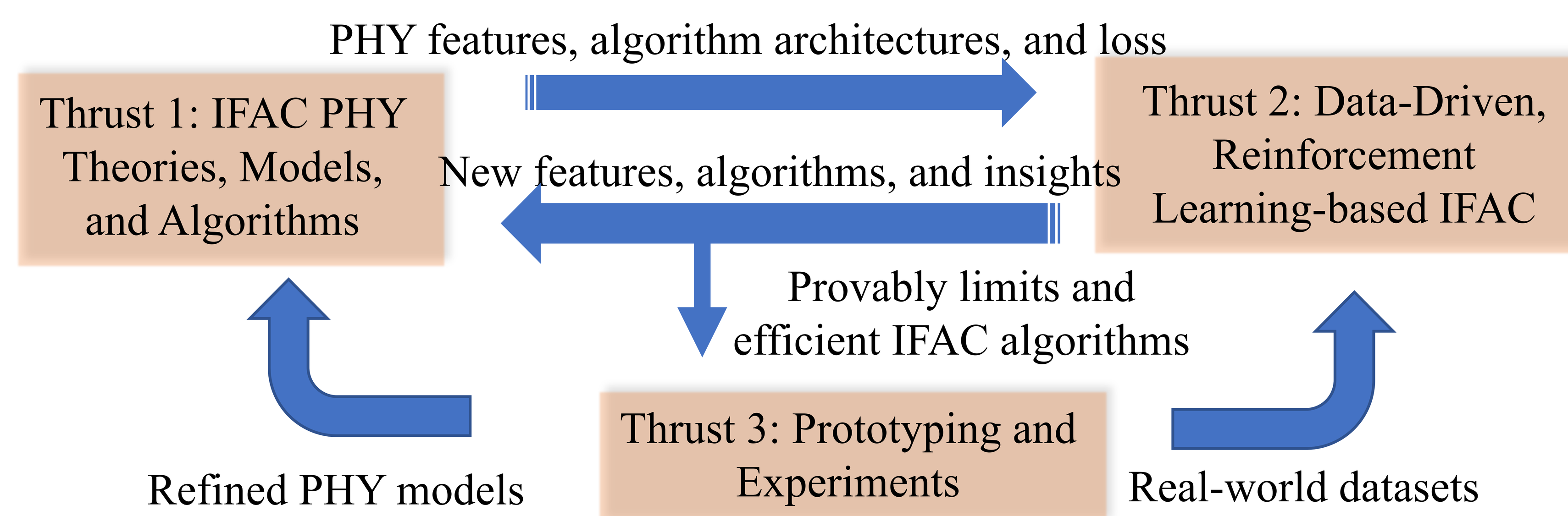
The objective is to find a policy g minimizing the expected packet error rate.

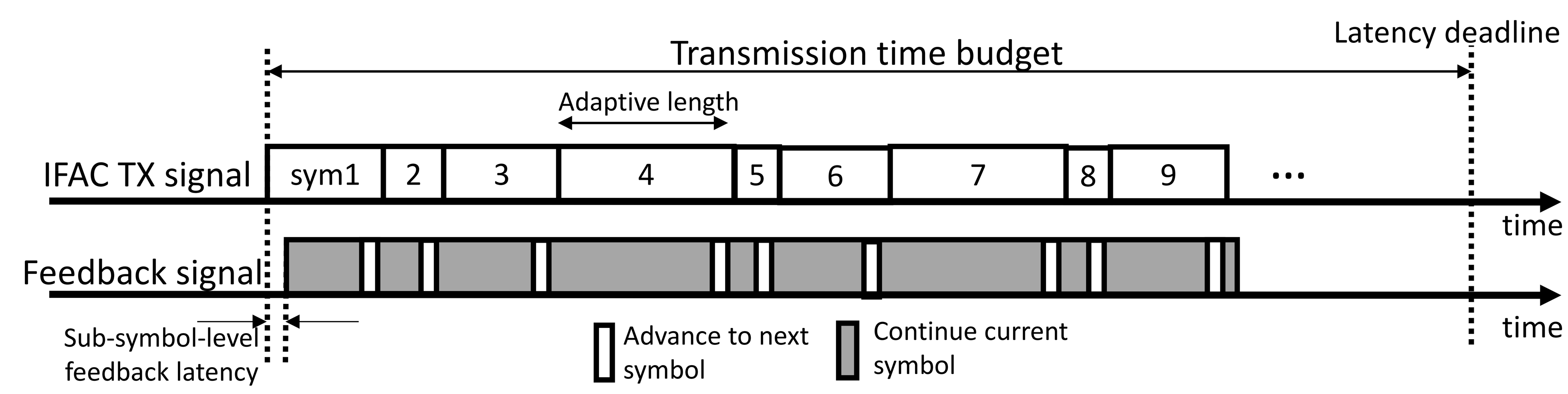
Intellectual merits

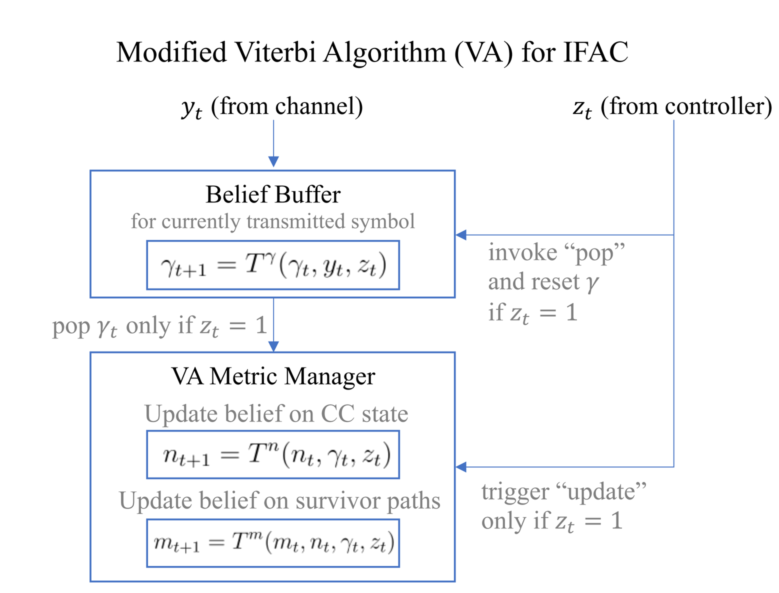
- **Ultra-reliable low latency communication (URLLC) via instantaneous feedback**
- Although feedback cannot increase the capacity of a memoryless AWGN channel, but it can **significantly increase error exponent for short blocklengths**
- **Near-instantaneous feedback feasible thanks to modern digital VLSI performance**

Challenges

- Novel physical layer modulation utilizing (near-)instantaneous feedback
- Reliability against feedback noise in realistic channels







Explanation:
Suppose symbol b_k was transmitted in previous chip $t-1$
$\gamma_t: \mathcal{B} \to [0,1]$: accumulative metric for b_k
$n_t \in \Delta(\mathcal{S})$: posterior belief on CC state s_{k+1}
$m_t \in \Delta(\mathcal{S})$: normalized metric for path ended up with s_{k+1}
m_t is a real-time version of path metric in standard VA.

IFAC problem formulation

$$\min_g \mathbb{E}^g\left[\mathbb{P}^g(\hat{\boldsymbol{A}} \neq \boldsymbol{A}) + \mu T^g\right]$$

$$\text{s.t.} \quad T^g \leq T_{tot}, \text{ w.p.1}$$

μ: energy cost for per chip use
T^g: total number of chips consumed by the packet under control policy g
T_{tot}: the maximal number of chips assigned to the packet

Markov decision process (MDP) formulation
Solving the optimization problem is equivalent to solving the following MDP:

State: $x_t = (\underbrace{m_t, n_t, \gamma_t}_{\text{VA metrics}}, \lambda_{t-1})$

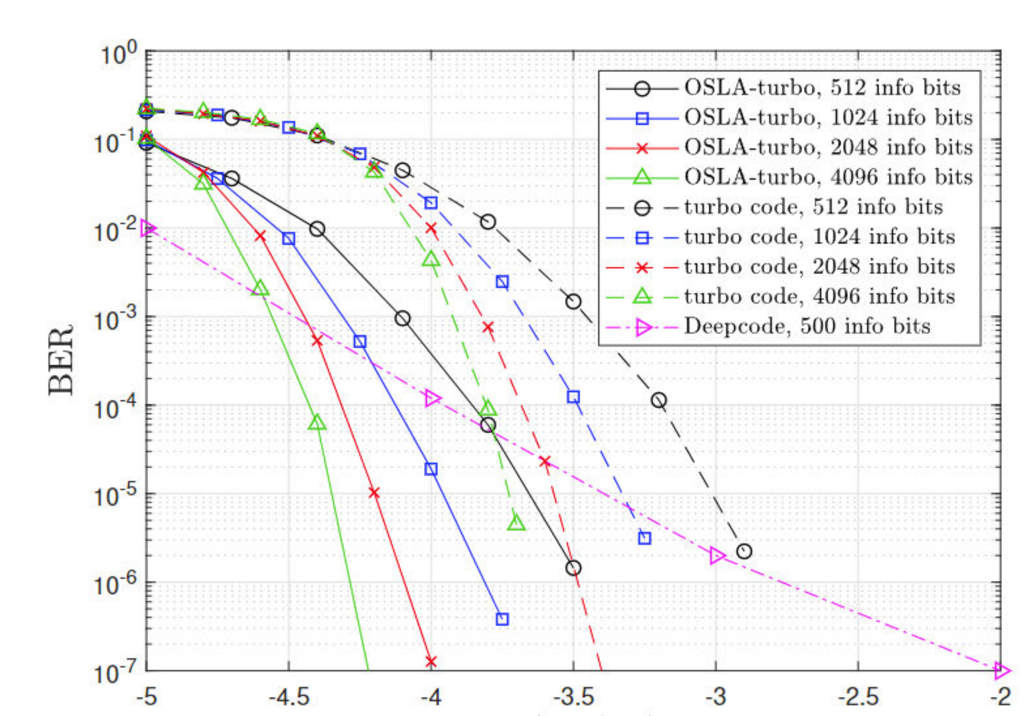
Action: $z_t \in \{0,1\}$

Instantaneous cost:

$$c_t(x_t, z_t) = \begin{cases} \mu, & \text{if } \lambda_{t-1} + z_t \leq N \\ 0, & \text{otherwise} \end{cases}$$

Terminal cost: suppose for time T, either $\lambda_{T-1} = N$ or $T-1 = T_{tot}$

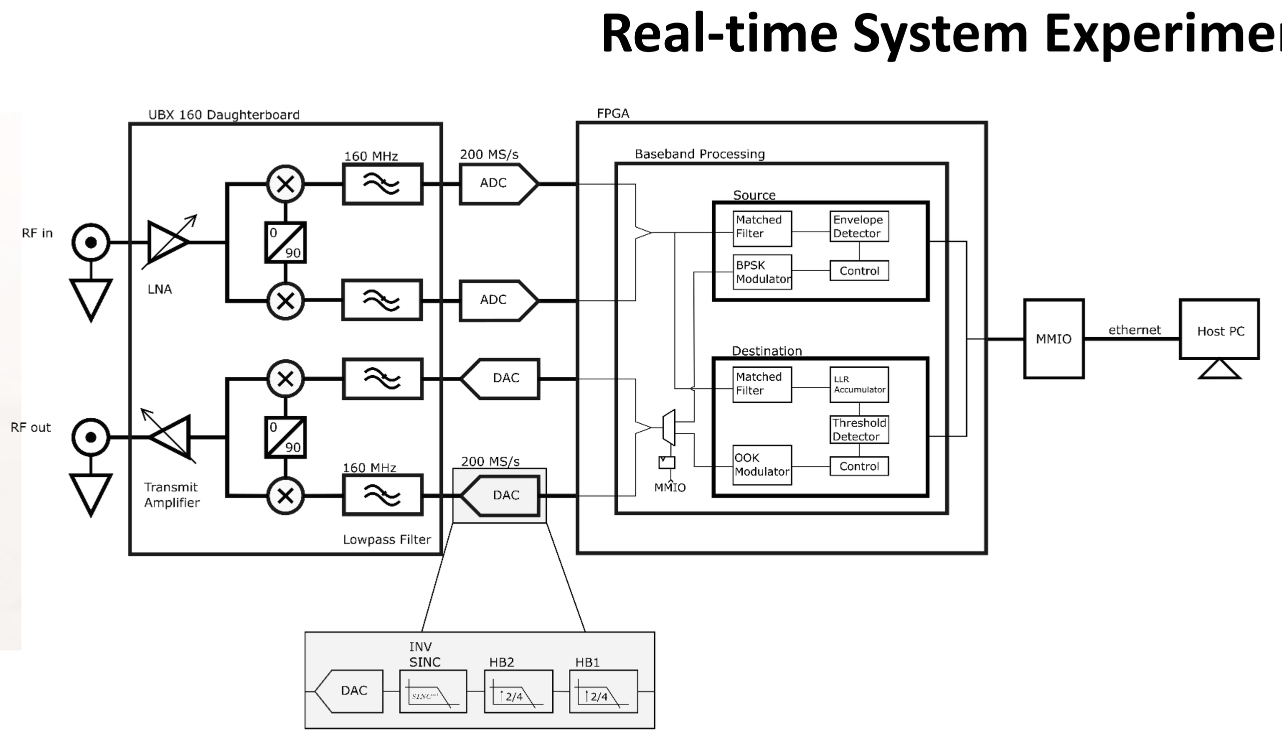
$$c_T(x_T) = \mathbb{P}(\hat{\boldsymbol{A}} \neq \boldsymbol{A} | y_{1:T-1}, z_{1:T-1}) = f(m_T, n_T, \gamma_T, \lambda_{T-1})$$

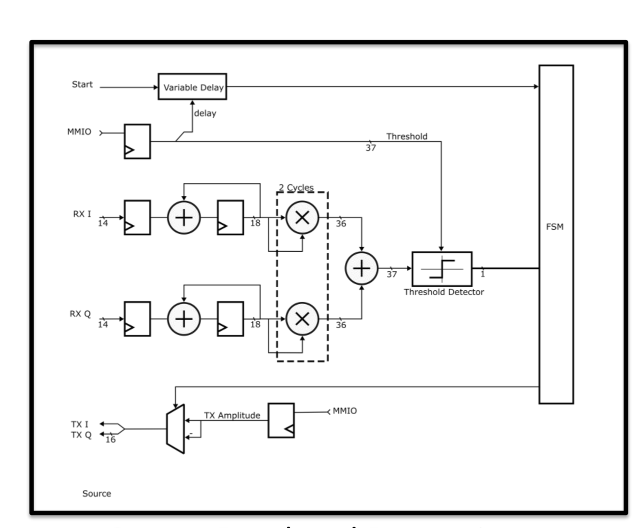


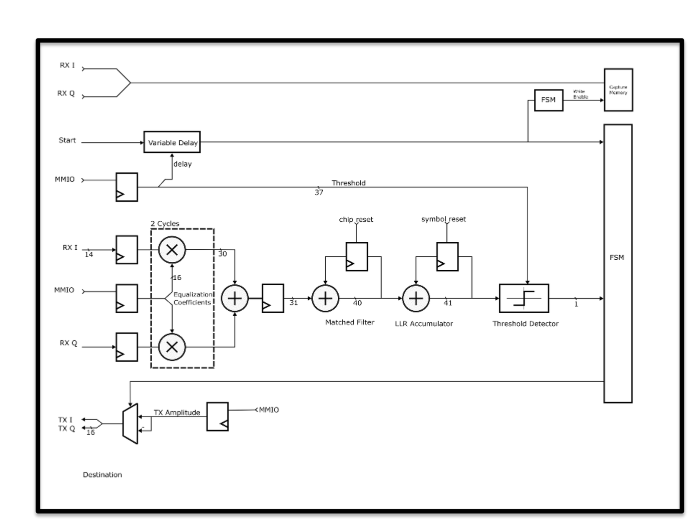
IFAC-OSLA k = 512, 1024, 2048, 4096 bits

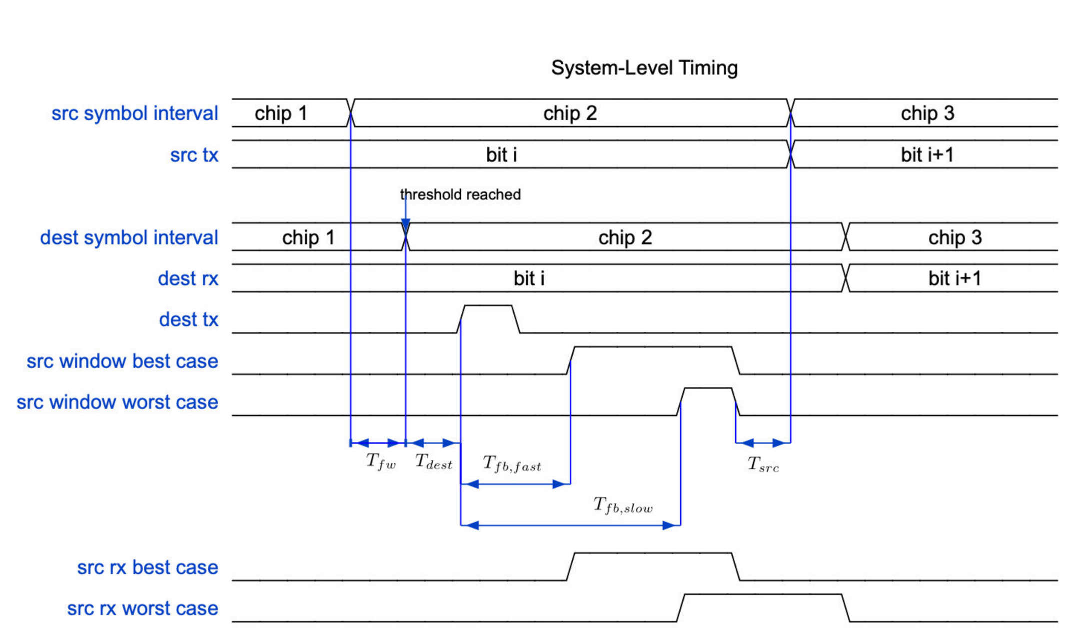
Real-time System Experiments

IFAC on USRP software defined radio (SDR) FPGA platform




Source Baseband Processing


Destination Baseband Processing



Scheme	Error Slope	Feedback Robustness	Blocklength Scalability	Complexity Real-time Feasibility	Arithmetic Imprecision Tolerance	Flexibility*
Non-Feedback	Medium	N/A	Excellent	Good	Good	Excellent
(Modulo-)SK	Excellent	Good**	Poor	Excellent	Poor	Excellent
Burnashev	Excellent	Poor	Poor	Good	Medium	Good
DeepCode	Good	Good	Medium	Poor	Good	Poor
GBAF	Excellent	Good	Medium	Poor	Good	Poor
OSLA	**Good**	**Excellent**	**Excellent**	**Good**	**Good**	**Excellent**

* To adjust code rate or adapt to different SNR conditions.
** When Modulo-SK is used.

Future Directions

- Reinforcement learning for feedback and modulation design
- Novel IFAC schemes with strict URLLC latency constraints
- IFAC schemes with application-specific objective functions
  - Max spectral efficiency given BER vs. Min BER given spectral efficiency
- Real-time demonstration on FPGA hardware in MCity

Educational Agenda

- Interdisciplinary research involving theoretical research, reinforcement learning, and experimental study with hardware implementation → Integration into a coursework: **EECS 598 VLSI for Wireless Communication and Machine Learning**

Broad Impacts

- Spectrally efficient URLLC for mMTC, and V2X communications
- Low latency AR/VR applications including exer-games for people with disabilities

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