Multi-Vehicle Map Fusion using GNU Radio

Optimization and Acceleration Opportunities

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Acknowledgment

- Thanks to the many IBM colleagues who contribute to and support different aspects of this work + our esteemed university collaborators at Harvard, Columbia, and UIUC (Profs. David Brooks, Vijay Janapa Reddi, Gu-Yeon Wei, Luca Carloni, Ken Shepard, Sarita Adve, Vikram Adve, Sasa Misailovic) + many brilliant graduate students and postdocs!

- Special thanks to **Dr. Thomas Rondeau**, Program Manager of the DARPA MTO DSSoC Program

This research was developed, in part, with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions and/or findings expressed are those of the authors and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government. This document is approved for public release: distribution unlimited.

Outline

- **Part 1: Adaptive Swarm Intelligence**
  – A novel computation paradigm

- **Part 2: DARPA-sponsored EPOCHS project**
  – EPOCHS Reference Application for multi-vehicle *cooperative perception*

- **Part 3: 802.11p Transceiver**
  – A methodology to identify acceleration opportunities

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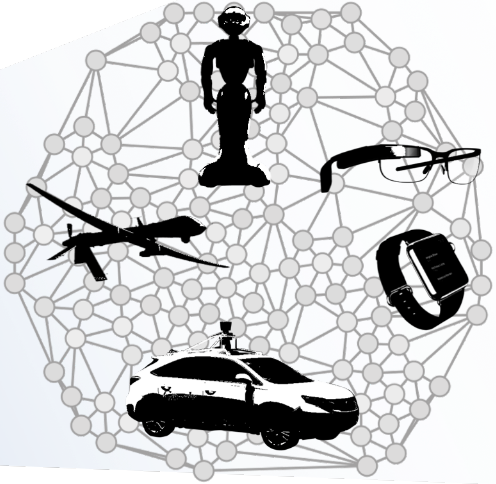
Adaptive Swarm Intelligence (ASI)

80B connected devices in the world by 2025
– IDC

The IoT *boom*



Adaptive Swarm Intelligence (ASI), a *Swarm Intelligence*-inspired paradigm, can boost the AI capabilities of mobile systems by allowing them to operate in *swarm mode* and in *ad-hoc manner*

- → Level of cognition and adaptability that can only emerge synergistically from the swarm but not from individuals
- → Allows swarm individuals to learn from collaborative experience in contrast to traditional *Swarm Intelligence* where individuals follow simple fixed rules

Why Adaptive Swarm Intelligence Now?

- **Three key enablers are becoming available**

1990s onwards

Mobile Computing

Technical Enablers

Small-scale processors

- Low-cost power-efficient SoCs
- Very-large-scale integration

Why Adaptive Swarm Intelligence Now?

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2000s onwards

IoT

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Pervasive Sensing

- Virtually any physical device can be a source of data

Why Adaptive Swarm Intelligence Now?

- **Three key enablers are becoming available**

Near future — **Adaptive Swarm Intelligence**

2000s onwards — IoT

1990s onwards — Mobile Computing

Technical Enablers

Small-scale processors
- Low-cost power-efficient SoCs
- Very-large-scale integration

Pervasive Sensing
- Virtually any physical device can be a source of data

High-Bandwidth Connectivity
- 5G and 802.11p as device-to-device communication enablers

One Paradigm, Multiple Embodiments

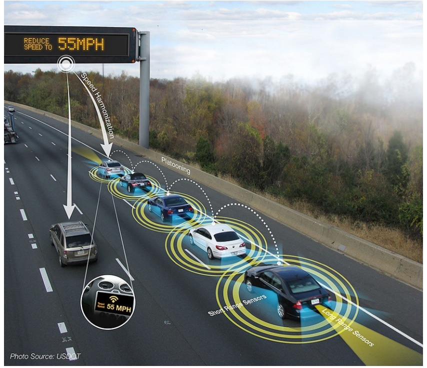
Adaptive Swarm Intelligence

Network Cybersecurity

Detection of DoS attacks via localized node-to-node information exchange

Connected Cars

Real-time driving and navigation via V2V communications



Unmanned Aerial Vehicles

Search-and-rescue operations using “intelligent” swarms of drones

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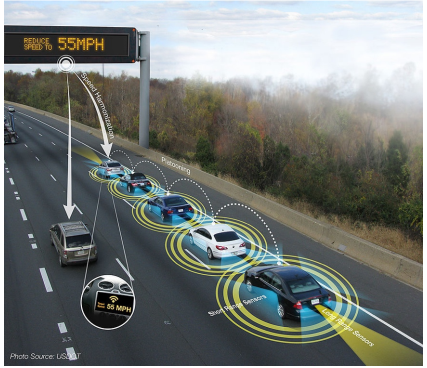


Unmanned Aerial Vehicles

Search-and-rescue operations using "intelligent" swarms of drones

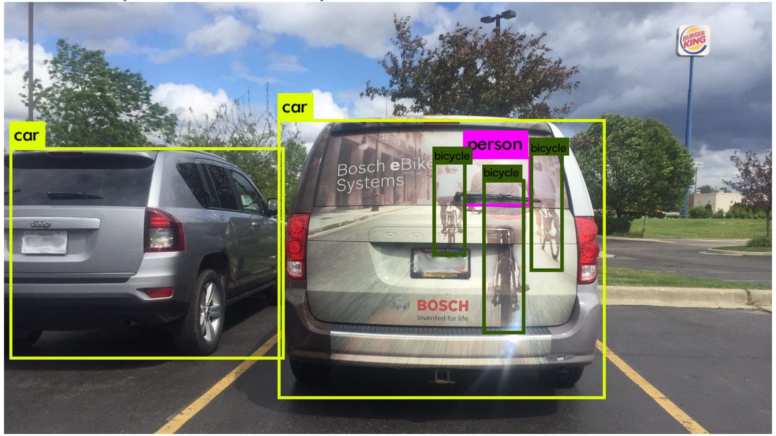
This presentation focuses on
connected and autonomous vehicles

ASI Use Case: Cooperative Sensor Fusion

- Automakers use arrays of sensors to build redundancy into their systems

This Image is Why Self-Driving Cars Come Loaded with Many Types of Sensors

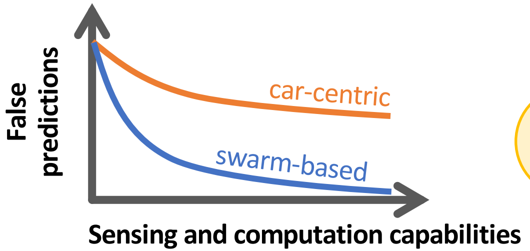
When's a pedestrian not a pedestrian? When it's a decal.

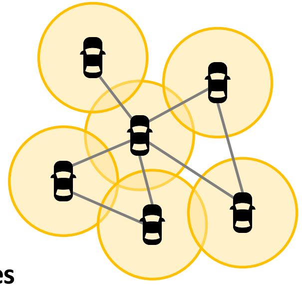


Source: MIT Technology Review

ASI Use Case: Cooperative Sensor Fusion

- Automakers use arrays of sensors to build redundancy into their systems
- We propose a complementary approach: **multi-vehicle (cooperative) sensor fusion**
  - Cars exchange locally-generated maps
  - Each vehicle merges its local map and the received ones in real time





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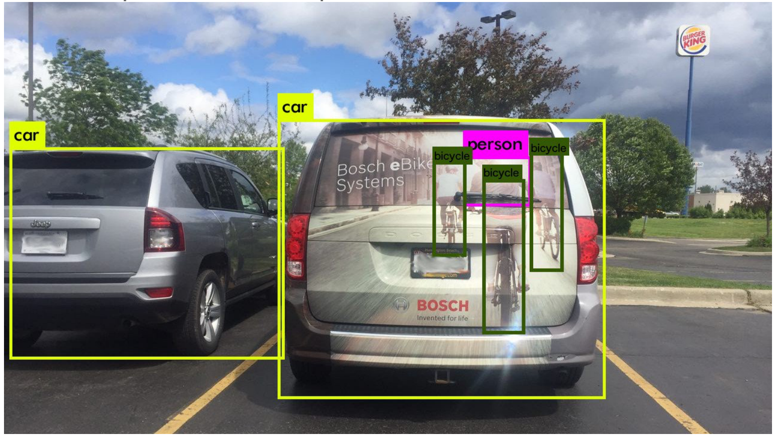

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DARPA’s Domain-Specific System on Chip (DSSoC) Program

Program Manager: Dr. Tom Rondeau

- **Goal:** to develop a heterogeneous system-on-chip (SoC) comprised of many cores that mix general purpose processors, special purpose processors, hardware accelerators, memory, and input/output (I/O) devices to significantly improve performance of applications within a **domain** *

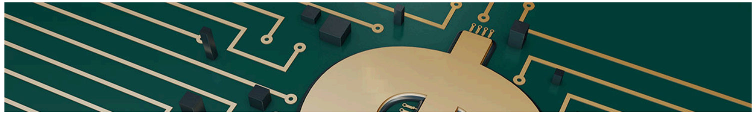
- **A domain is larger than any one application**
  - We target the “super” domain of embedded processors for autonomous/connected cars
  - Within this super domain, we put our attention primarily to **computer vision** and **software radio** applications

24 Jul 2018 | 17:00 GMT

DARPA Picks Its First Set of Winners in Electronics Resurgence Initiative

Teams announced in design, architecture, and materials and integration programs under the $1.5 billion effort to remake U.S. electronics

By **Samuel K. Moore**



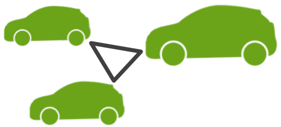
Source: IEEE Spectrum (July 2018)

* *Source: https://www.darpa.mil/program/domain-specific-system-on-chip*

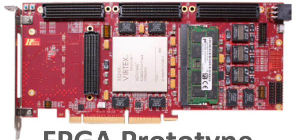
Efficient Programmability Of Cognitive Heterogeneous Systems

"EPOCHS" → our proposed solution for the design challenge presented by the DSSoC program

EPOCHS Reference Application → **Compiler + Scheduler** ⟲ **Ontology & Design Space Exploration**



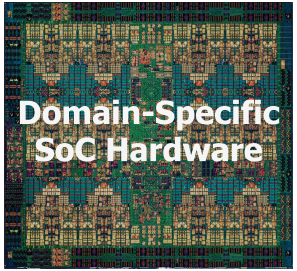
Compiler + Scheduler ↓



FPGA Prototype

Agile Flow

Accelerators + NoC + Memory Architecture → **Implementation** → **Domain-Specific SoC Hardware**



10X – 100X reduction in person-years

↓

FPGA prototype, emulation, optimization, software bring-up

Agile methodology to quickly design and implement an easily programmed domain-specific SoC for real-time cognitive decision engines in connected vehicles

"Super"-Domain: Software-Defined Radio + Computer Vision

Efficient Programmability Of Cognitive Heterogeneous Systems

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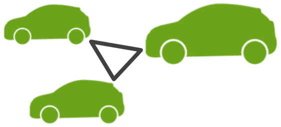
EPOCHS Reference Application



Compiler + Scheduler

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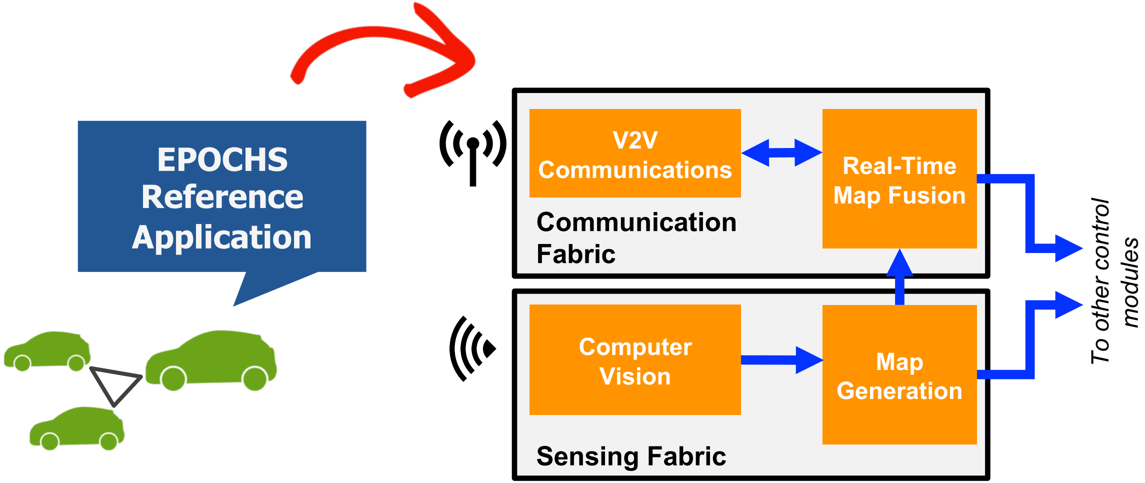
ERA: EPOCHS Reference Application



An ASI Use Case

- **"Cooperative Perception" for connected/autonomous vehicles**
  - Multimodal sensing
  - Local occupancy map generation
  - DSRC-based V2V communication
  - Real-time (global) maps fusion

Contribute!
https://github.com/IBM/era

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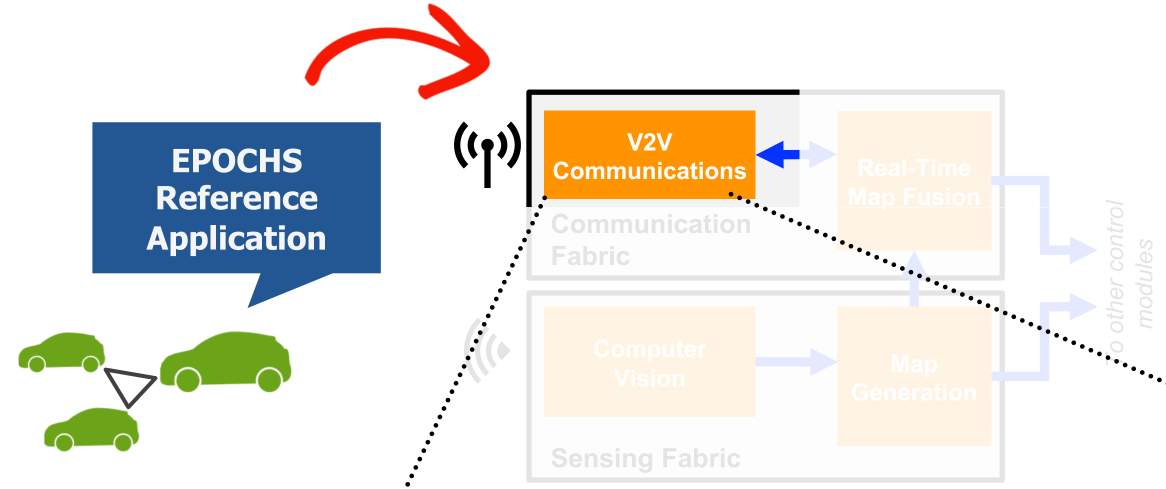
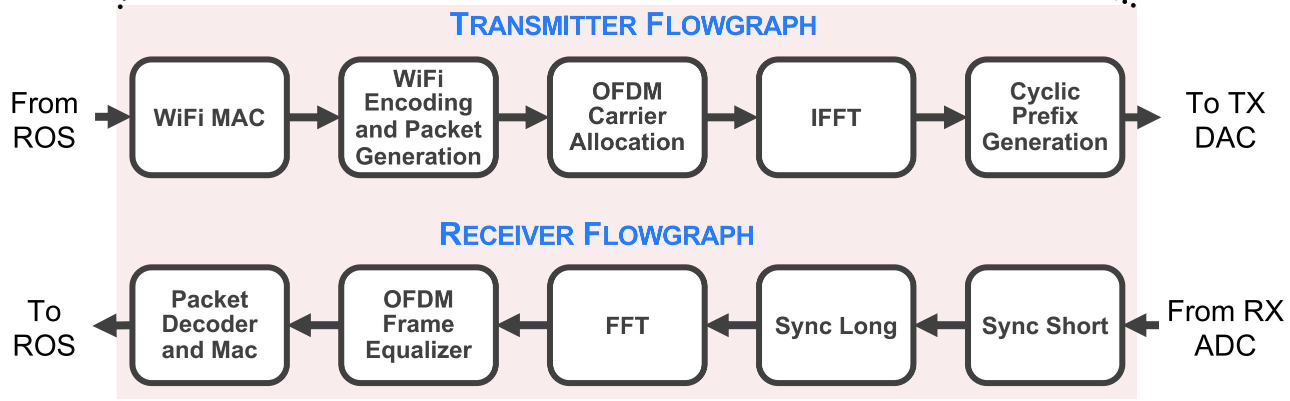
802.11p Transceiver within ERA

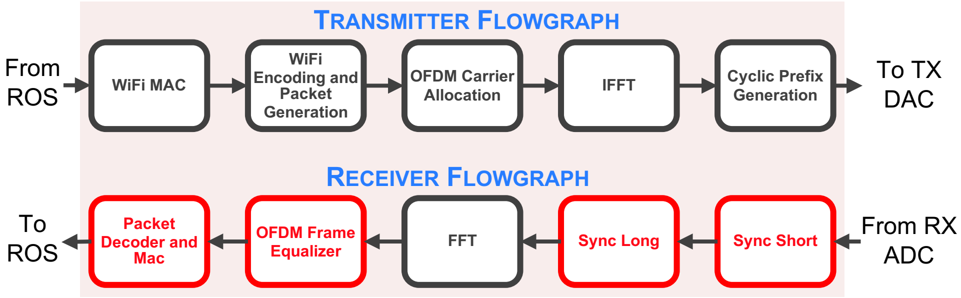


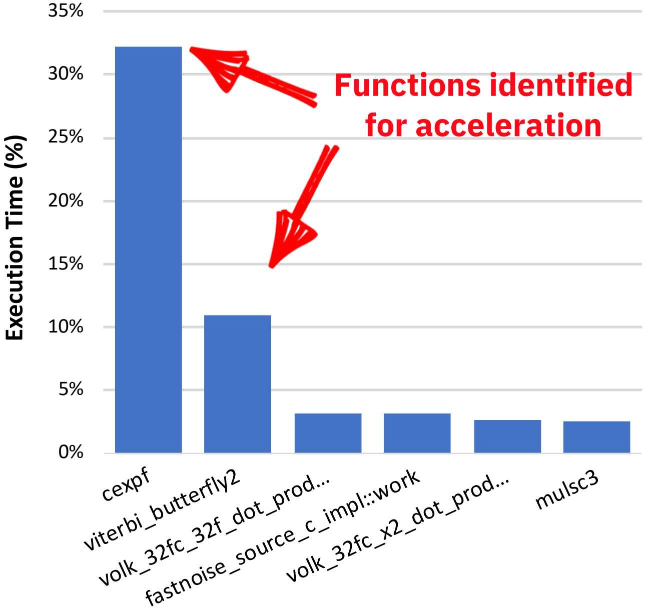
Open-source IEEE 802.11p transceiver implemented in GNU Radio by Bastian Bloessl
https://github.com/bastibl/gr-ieee802-11



Potential Throughput Gains

- RX blocks require **much more processing** than most TX blocks





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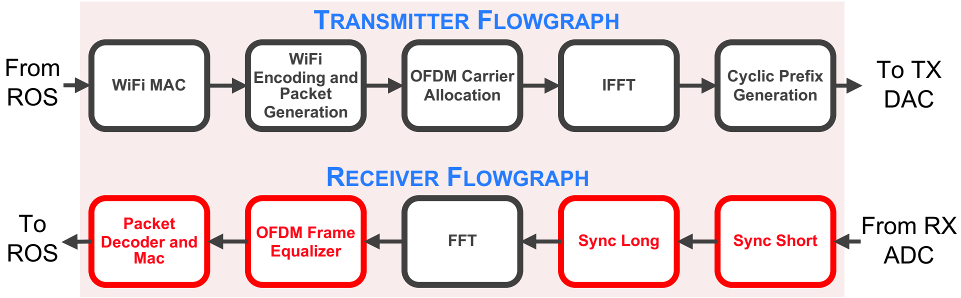
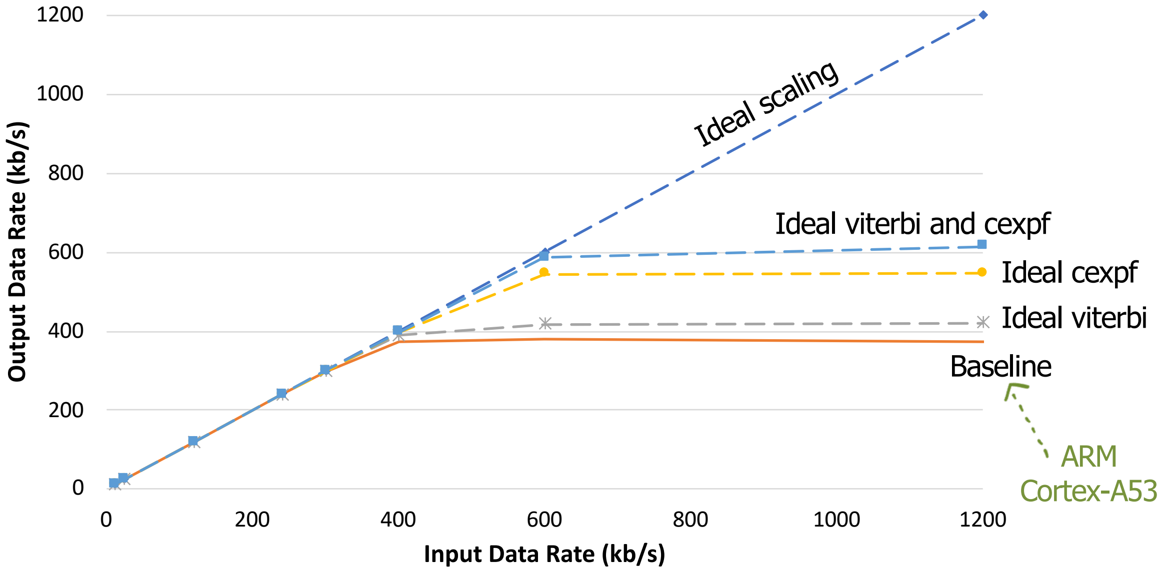
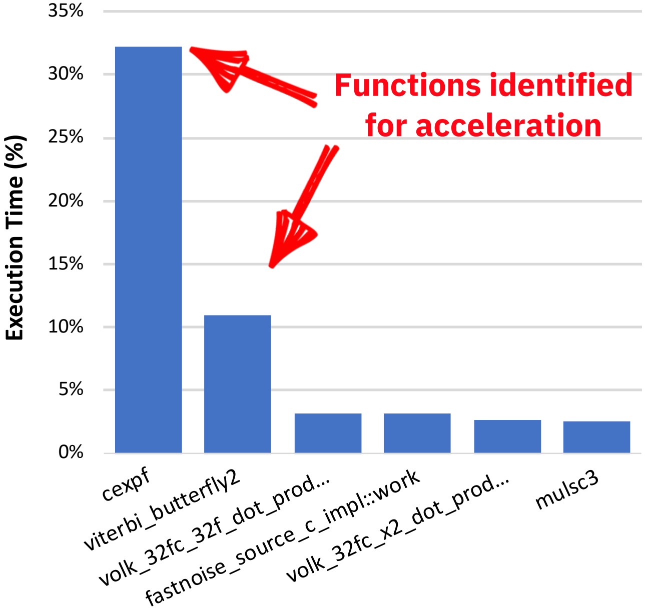
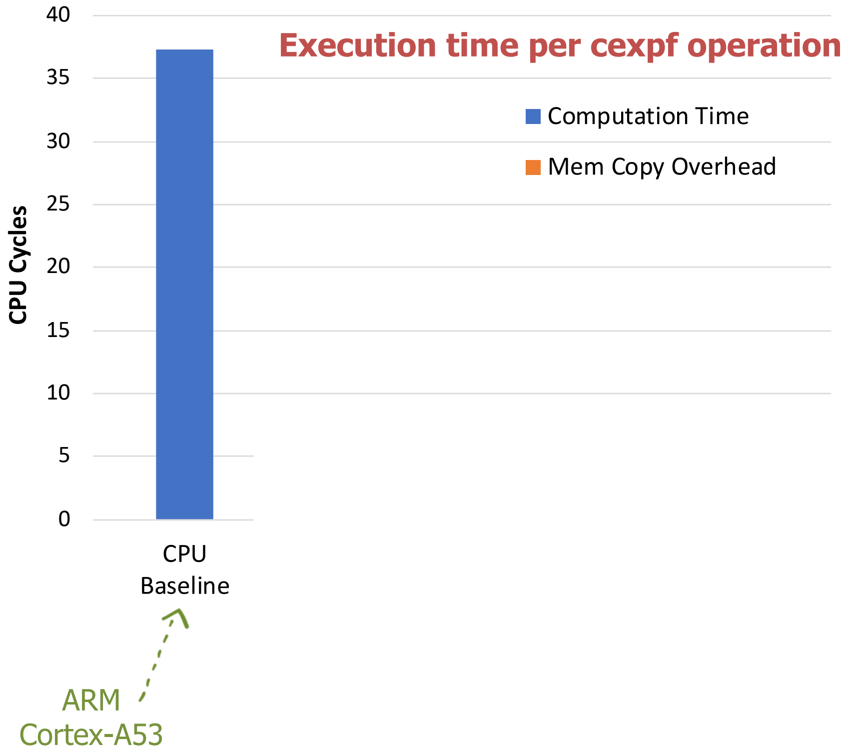


- Maximum performance that can be obtained by accelerating **cexpf** and **viterbi:**





Acceleration Options (for *cexpf*): Preliminary Results



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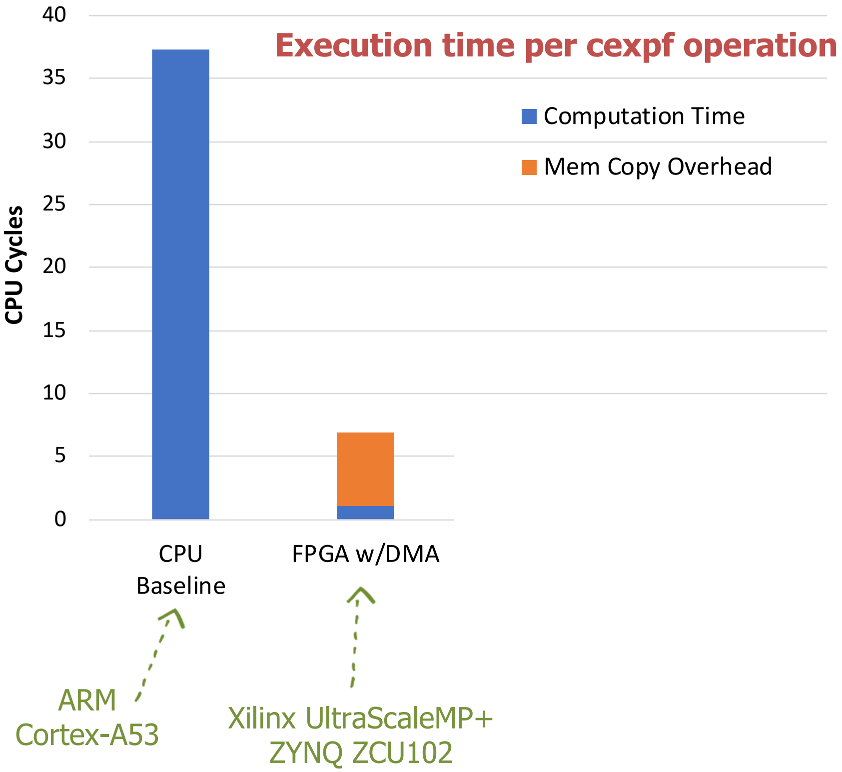
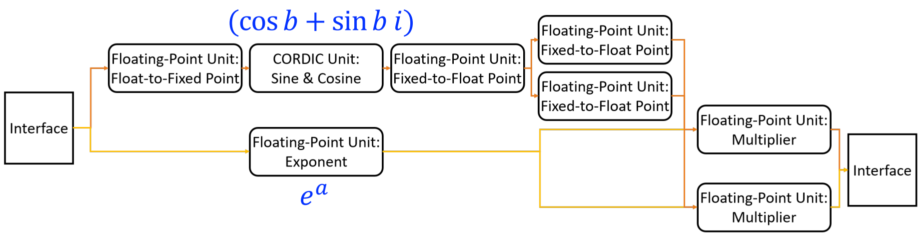


FPGA Implementation
(dual data-path pipeline)



$$e^{a+bi} = e^a * (\cos b + \sin b\ i)$$

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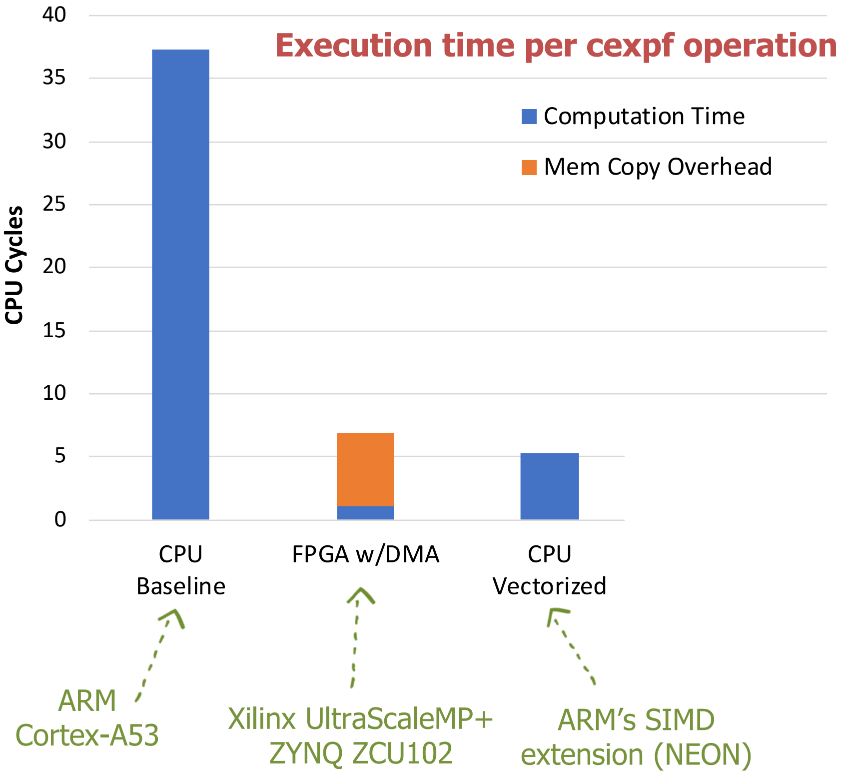

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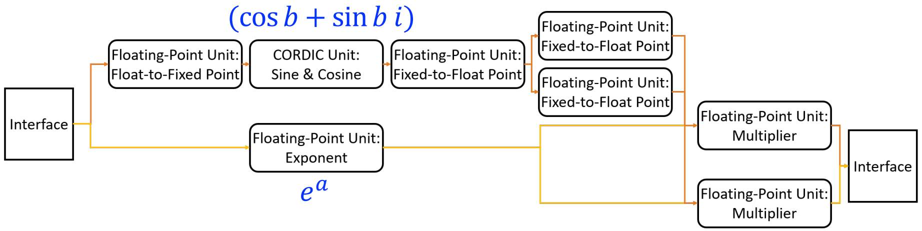

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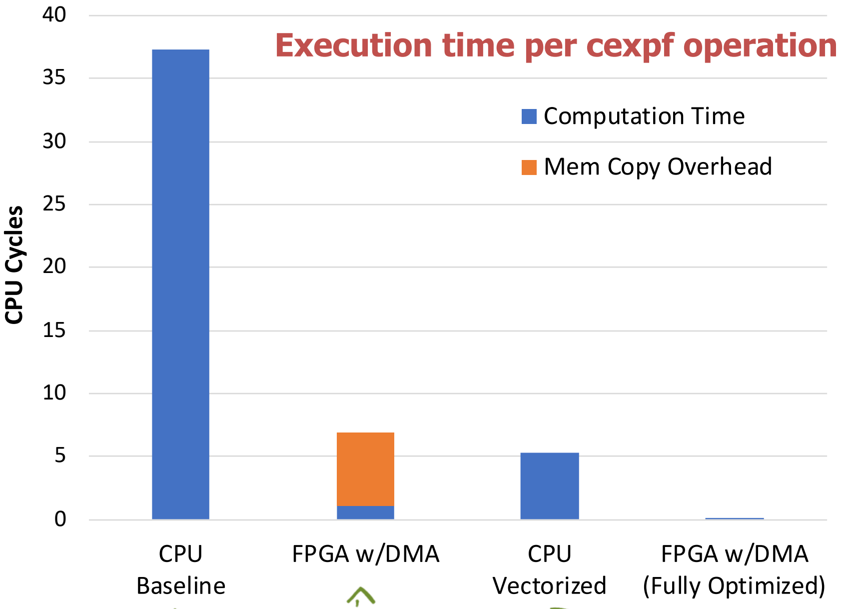
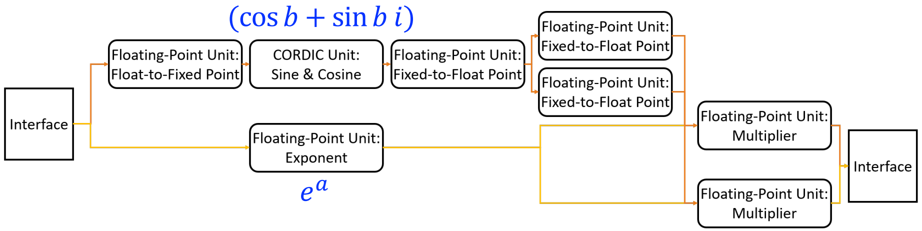


ARM Cortex-A53

Xilinx UltraScaleMP+ ZYNQ ZCU102

ARM's SIMD extension (NEON)

FPGA Implementation
(dual data-path pipeline)

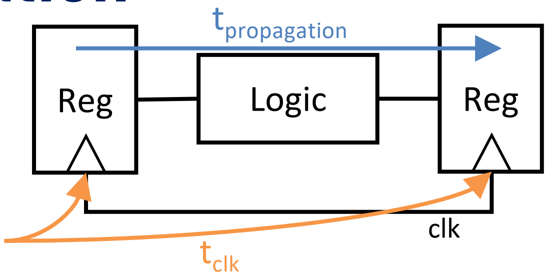


$$e^{a+bi} = e^a * (\cos b + \sin b\ i)$$

Fully-optimized implementation (idealized bound)

- 300 MHz (instead of 100 MHz)
- Four parallel computation engines
- Memory-copy elimination

Path Forward: Fully-Optimized Implementation



- **Frequency Scaling (3✕)**
  - Test implementations run at 100 MHz
  - AXI-bus has been shown to work at least at 300 MHz
  - **Requirement:** Must ensure positive slack time ($t_{propagation} < t_{clk}$)

Path Forward: Fully-Optimized Implementation

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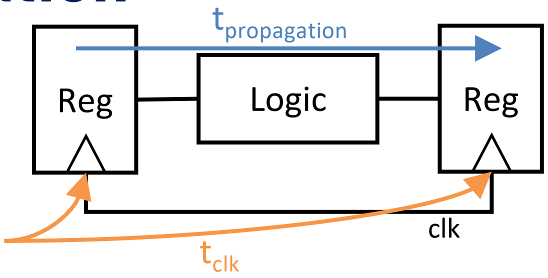
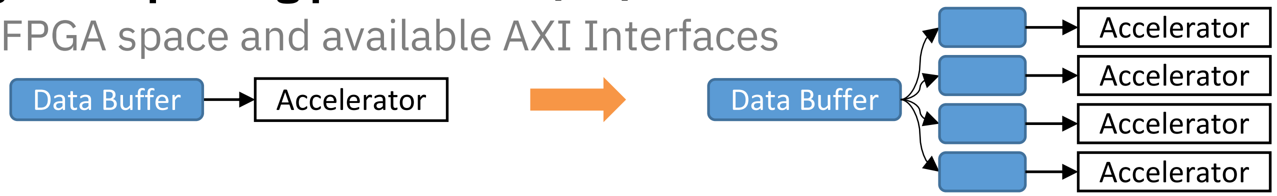


- **Multiple Accelerator Engines exploiting parallelism (4×)**
  - **Requirement:** Enough FPGA space and available AXI Interfaces



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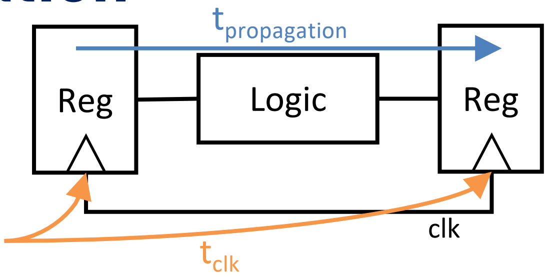

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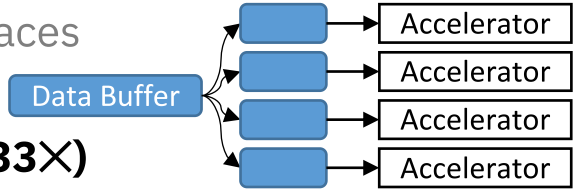
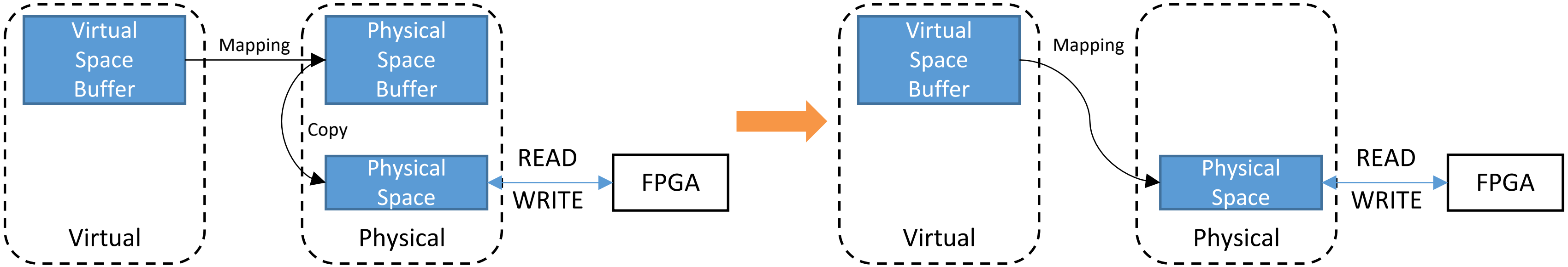
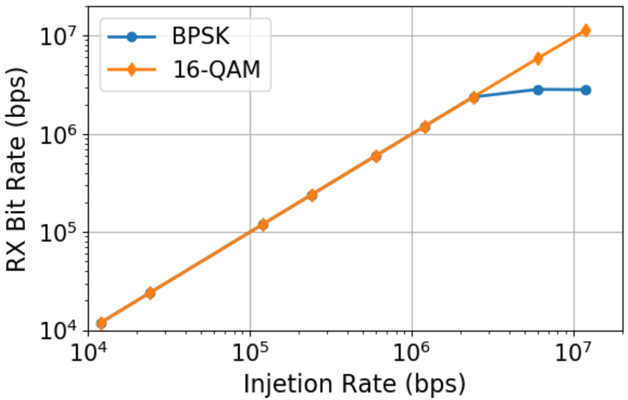
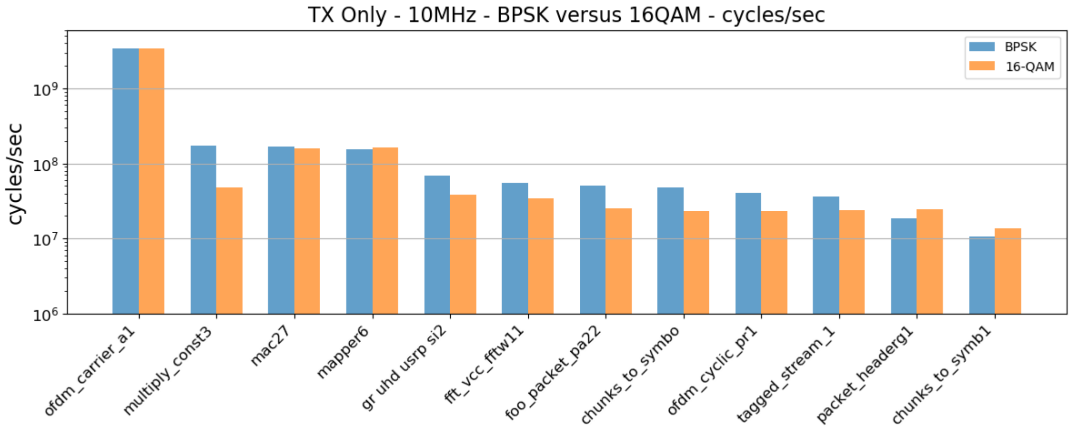


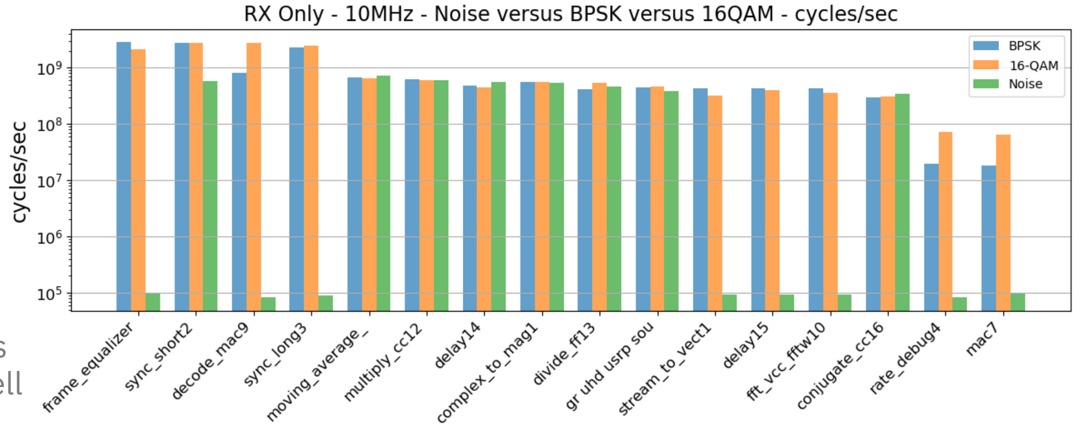
- **Avoiding data movement to physically addressable space (33×)**
  - **Requirement:** Control of *buffers* and *memory mapping*



Over-The-Air Performance Analysis (x86 version)







- BPSK works up to 3 Mbps (rate ½ code)
  - 240 1500-byte packets per second
- 16-QAM works up to 11.4 Mbps (rate ¾ code)
  - 950 1500-byte packets per second
- Rate limited by the 10 MHz RF bandwidth
- Performance analysis at maximum data rate
- Receiver flowgraph processing is a function of whether underlying packets are there
  - When no data present, synchronization dominates
  - When data present, equalization and Viterbi as well

Summary

- The proposed **Adaptive Swarm Intelligence** (ASI) paradigm allows heterogeneous edge devices to engage in collaborative "swarm" computing for **robust real-time operation**
- Use case: cooperative sensor fusion
  - Our proposed "domain" for the **DARPA's DSSoC Program**
  - Local sensing + V2V communications

Do you want to collaborate?

- Contact: ajvega@us.ibm.com
- GitHub: https://github.com/IBM/era

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  - Detailed characterization unveils execution hot spots: *cexpf* and *viterbi*
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Turn ERA into a benchmark platform for **cooperative mobility** with integrated **perception** and **communication** capabilities, for open collaborative development

Do you want to collaborate?

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Thank You!

Photo by Balthazar Korab
Source: http://www.shorpy.com/node/15488

ajvega@us.ibm.com

https://github.com/augustojv

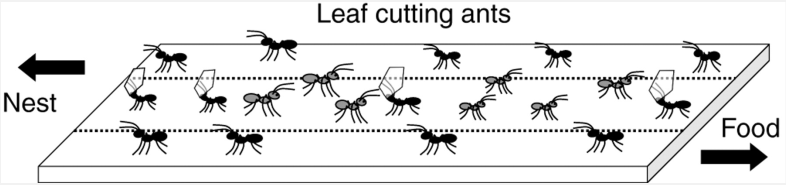
Swarm Intelligence: From Natural to Artificial Systems*

- **Collective behavior of decentralized, self-organized systems**, inspired by nature: ant colonies, bird flocking, animal herding, bacterial growth, fish schooling, etc.
- The swarm exhibits intelligent traits and learning that are impossible at the individual level

Self Organization

Structures appear at the global level from interactions among lower-level components on the basis of purely local information

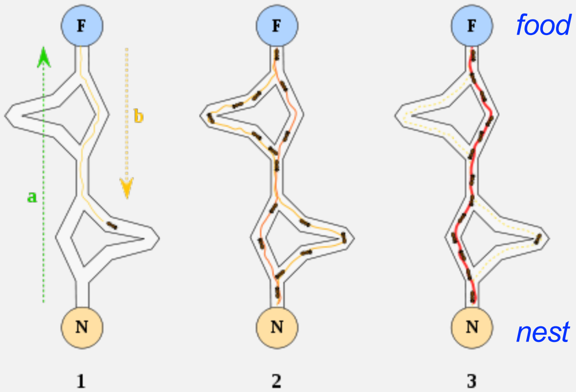
- ✓ **Positive feedback** (recruitment, reinforcement)
- ✓ **Negative feedback** (saturation, competition)
- ✓ **Amplification of fluctuations** (random walks, errors)



Source: http://jeb.biologists.org/content/213/14/2357

Stigmergy

Indirect interaction through environment modifications – e.g. *pheromone* deposition in the case of ants



Source: http://lifeinwireframe.blogspot.com/2010/08/ant-algoithms.html

* E. Bonabeau, M. Dorigo and G. Theraulaz. "Swarm Intelligence: From Natural to Artificial Systems." Oxford University Press, Inc., New York, NY, USA. 1999.

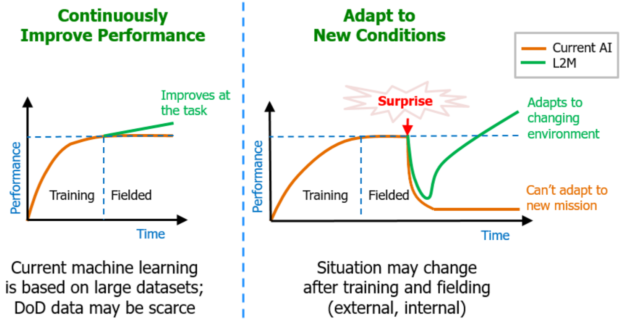
From *Swarm Intelligence* to *Adaptive Swarm Intelligence*

Adaptive Swarm Intelligence (Future)

New AI paradigm that, inspired by swarm intelligence principles, enables a level of cognition that can emerge synergistically from the swarm but not from individual devices only

Natural fit for the IoT where large numbers of devices (*agents*) interact in *ad-hoc* manners

- **Enhanced scalability:** no centralized control structure
- **Inherent robustness:** from the redundancy of the swarm and the crowd-sourced decisions
- **Continuous learning:** agents learn “on the job” with limited new data

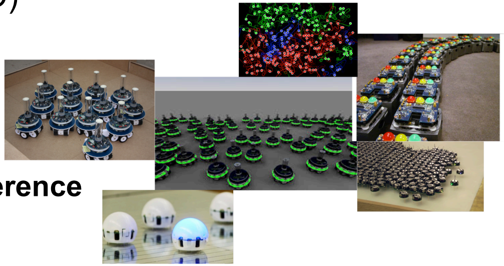


Source: DARPA L2M Program

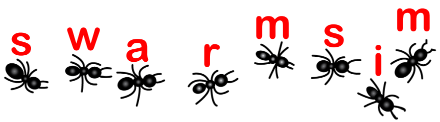
Swarm Intelligence (Today)

A field of research that remains dominated by two algorithms whose early successes inspired much of this field: *ant colony optimization* (ACO) and *particle swarm optimization* (PSO)

- Strong focus on optimization
- Based on simple conditional rules
- **No known focus on knowledge representation or generalized inference**

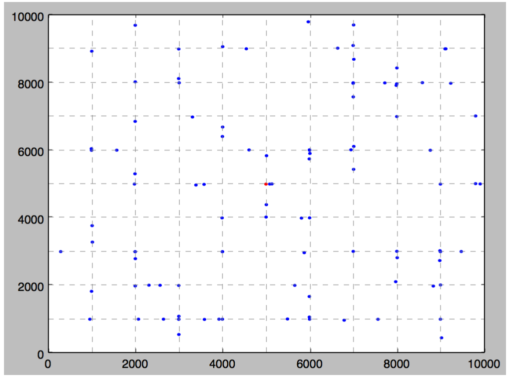


SwarmSim: An ASI Simulation Platform



- Python-based, multi-threaded, object-oriented and fully-parameterizable simulator for ASI scenarios
- Ideal platform to prototype and evaluate *distributed consensus protocol* algorithms

Graphical User Interface



Implements the logic of agents: generation and processing of requests and responses, etc.

Logic
(use case dependent)

Connected cars

Implements the dynamics of agents, message exchanging, and the scenario characteristics

Dynamics and Scenario
(use case agnostic)

`cloud.json`

`car.json`

`sim.json`

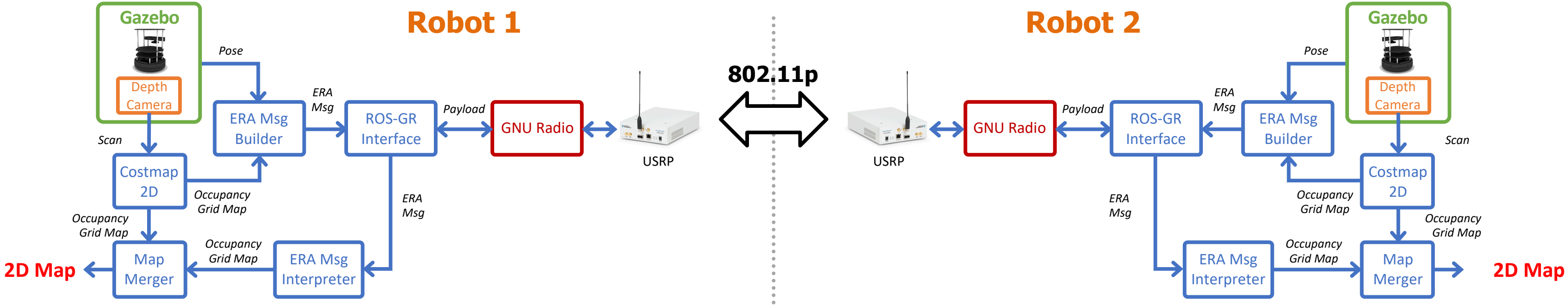
connected cars example

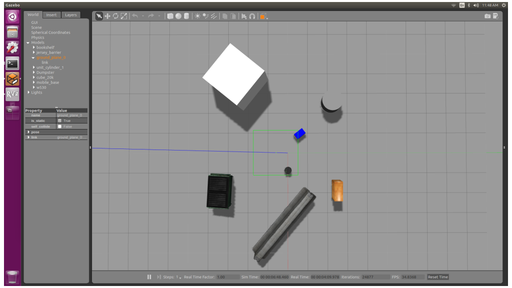
JSON Configuration Files

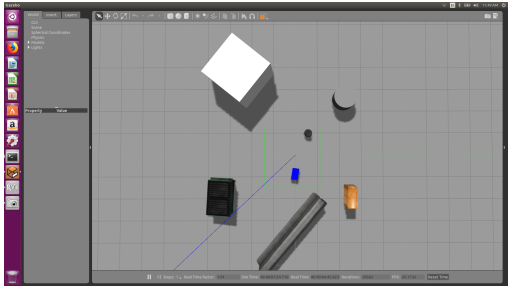
ERA: EPOCHS Reference Application

Current ERA version runs across two computers

– One Gazebo instance simulating one single robot in each computer
– Over-the-air 802.11p communication (10-MHz OFDM with up to 64-QAM modulation)
– More info: https://github.com/IBM/era/wiki/ERA-in-two-computers







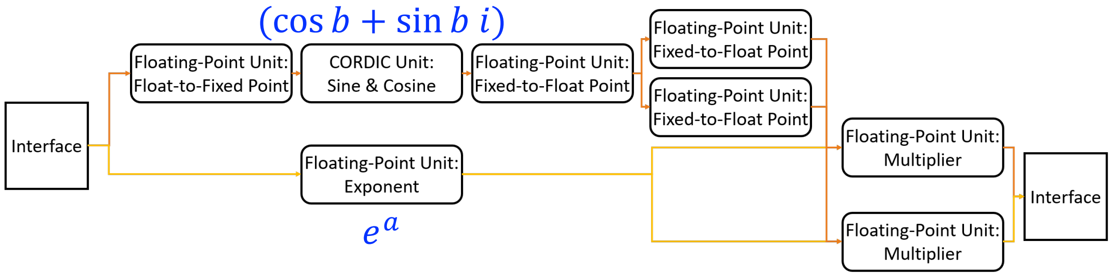
Acceleration Options (for *cexpf*)

- *cexpf* returns the value $e^{a+bi} = e^{a} * (\cos b + \sin b\ i)$
  - sine and cosine are performed using Taylor's series

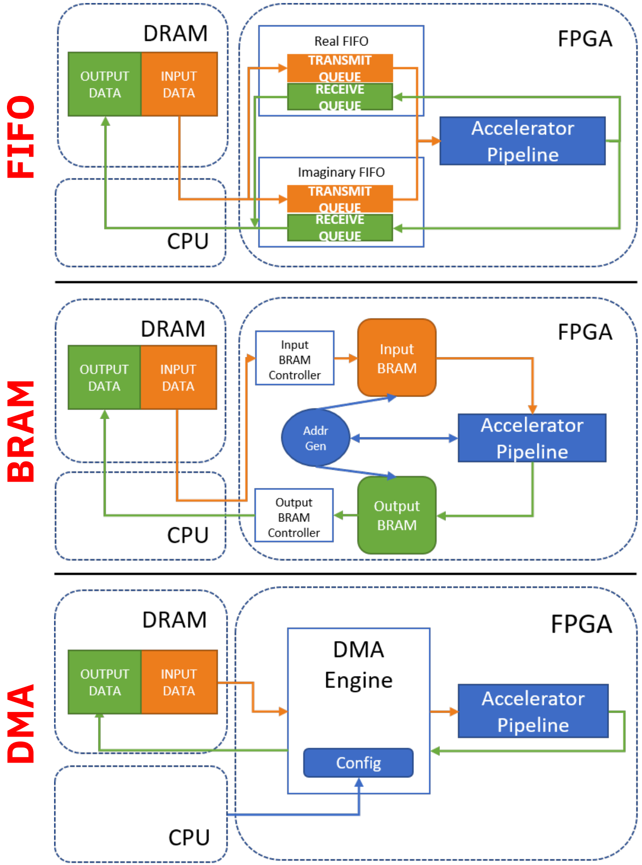
Two acceleration paths considered:

- Vectorization:
  - Using ARM's advanced SIMD extension (NEON)
- FPGA implementation:
  - Basic Xilinx IPs (pre-defined blocks) to implement a *cexpf* computation pipeline

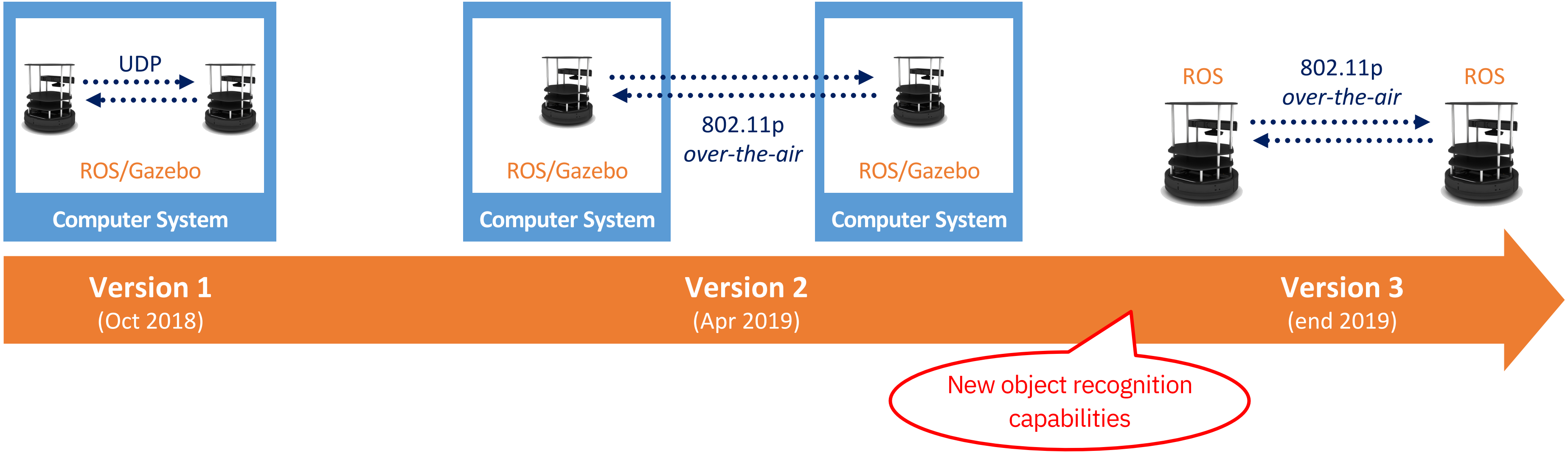
Dual data-path pipeline



Decoupled Data Transfer Options



ERA Roadmap



- ERA will be released in three progressively more complex versions
- Deep learning computer vision capabilities will be added during the next months

GOAL

Turn ERA into a benchmark platform for **cooperative mobility** with integrated **perception** and **communication** capabilities, for open collaborative development

Domain-Agnostic Technical Challenges

A key building block of ASI

- **Real-time distributed consensus (homogeneous swarm)**
  – Develop a method (algorithm) to conduct distributed consensus with real-time constraints
  – Allows the swarm to reach a certain level of consensus (measured by a consensus confidence metric) within a given time deadline

- **Real-time distributed consensus (heterogeneous swarm)**
  – Extend it to heterogeneous swarms (e.g. vehicles using different AI models)
  – Implies the development of an initially simple (domain-specific) data representation protocol to allow the interaction (consensus) between swarm individuals

- **Trustworthiness**
  – Incorporate "trustworthiness" into the consensus protocol
  – Trustworthiness is a feature attributed to individuals within the swarm, and can be learned over time – e.g. some specific car brands may provide more accurate responses than others