# BeiHang Short Course, Part 5: Pandora "Smart" IP Generators

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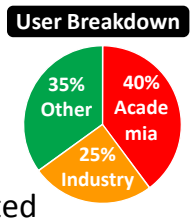
## CONNECT NoC IP Generator

http://users.ece.cmu.edu/~mpapamic/connect/

- Highly-parameterized "push-button" framework
- Multiple interfaces for configuring the desired NoC
- Bundled output
  - synthesizable Verilog RTL
  - documentations
  - testbenches and scripts
- Public web-based release in March 2012
  - actively used by researchers
  - 4500+ unique visitors, 1200+ NoCs generated



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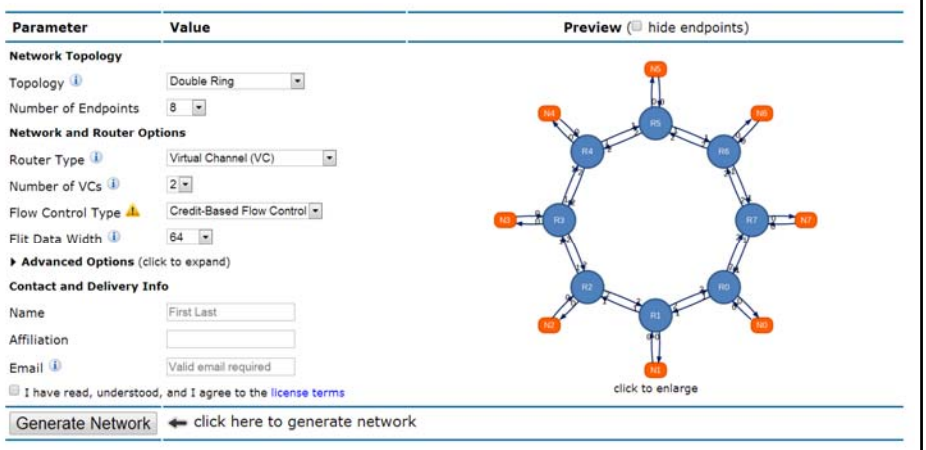






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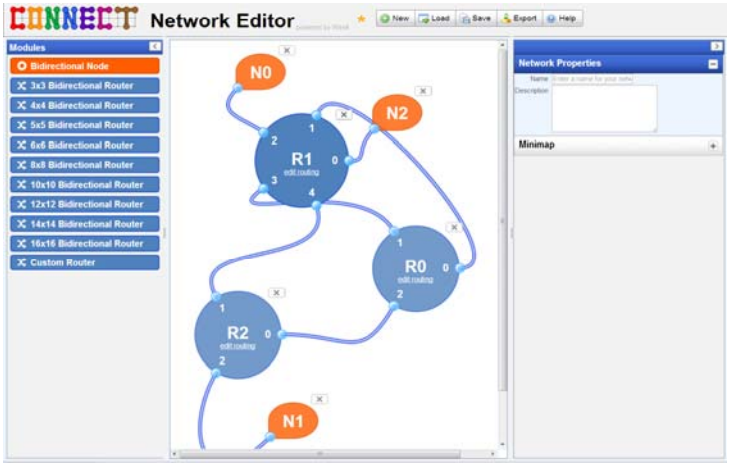


# Generator as IP

- Powerful? **Very!**
- Easy to use? **Not Really . . . . .**
  - low-level cryptic domain-specific parameters
  - complexity of integrating, using, tuning and validating an instantiated IP within an enclosing context
- If you went to CONNECT for an NoC right now
  - which configuration would you ask for first?
  - if not good enough, how to get a better one . . . . .
  - do you know what good enough is . . . . .





# Rethink the IP Paradigm

- Generator is the "21st-centry" IP
- Why limit to structural view of design
- Why not offer also . . . .
  - pre-knowledge about outcome & tradeoff of parameter combinations
  - IP-specific "meaningful" parameterizations,

    that is, ask **how fast?** instead of **how many?**
  - any **X** where IP authors can do better than IP users

**Shift burdens from IP users to IP authors**

**⇒ make knowledge and expertise reusable**

# Outline

- CONNECT Demo and Motivation
- Pandora Smart-IP Paradigm
- Applying Pandora to CONNECT
- Conclude





# IP Ecosystem and Roles

**IP Users**

**Application Developers**

Assemble, configure and integrate multiple IPs to build larger chips

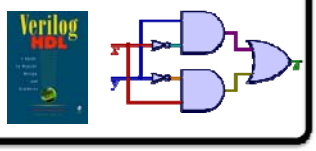
**IP Authors**

**Domain Experts**

Know the underlying **algorithms and theory** specific to the domain

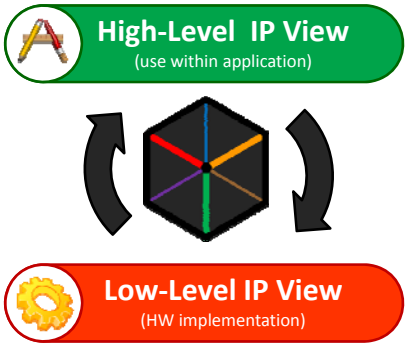
**Hardware Experts**

Can build HW based on a set of specs or SW implementation



# Pandora Smart-IPs

- IP enriched with domain/HW expert knowledge to simplify IP use (integration, tuning, validation)
- Bridge the gap between
  - high-level app **goals+req's**
  - low-level IP-specific knowledge: **algo+HW**
- May save work for the IP author in the long term








# Pandora Key Principles

1. Embodying Domain-Expert Knowledge
2. Raising the Level of Abstraction
3. Instrumentation and Introspection
4. Providing Supporting Collaterals

# IP know thyself

1 - Embody Knowledge | 2 | 3 | 4

- Carry quantitative and qualitative meta-data

⇒ **facilitates faster, informed design space navigation**

- Generic HW implementation characteristics
  - how IP parameters affect impl. characteristics

    e.g., area, frequency, power/energy, memory size)
- Domain-specific metrics and properties
  - how IP parameters affect higher-level domain metrics

    e.g., for NoC IP: saturation bandwidth, idle latency
  - can also include high-level properties

    e.g., for NoC IP: ordering guarantees



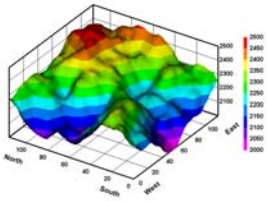


# Varying Form and Precision

1 - Embody Knowledge | 2 | 3 | 4

**HW Characterization Libs**

**Design Space Mapping**



**Designer Knowledge**

**Analytical formulas**

# Don't ask what I don't know

1 | 2 - Raise Level of Abstraction | 3 | 4

- Today's IP generators are richly parameterized
  - needed for efficiency and design space coverage
  - BUT too many low-level parameters ⇒ **complexity**
- Pandora goal-oriented parameterization
  - in terms of application-level design goals
  - meaningful and intuitive to the non-expert end-user
- Coordinated changes of multiple **low-level param's** to achieve user **high-level design goals**
  - well-known points, heuristic driven, feedback-search
  - leverage embedded characterization data





# Speaking the Right Language

1 | 2 - Raise Level of Abstraction | 3 | 4

- What is "high-level"?
  - depending on user objectives and levels of expertise
  - varying forms and levels of abstraction

## Configuration interfaces

Pick points in the design space, e.g.,

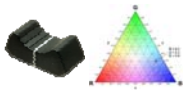

**Set of good configurations or personalities**

**Objective & Constraint-Driven Queries**

## Tuning Interfaces

Move within the design space, e.g.,


**Tuning knobs**



**Fuzzy trade-off selectors**

# Do you know what your IP is doing?

1 | 2 | 3 - Instrumentation & Introspection | 4

- Instrumentations
  - tap into design for monitoring validation purposes
  - monitor, collect and analyze info about IP's operation

- Introspection
  - process low-level data to reach high-level conclusions
  - diagnose & fix performance or correctness issues





# Built-in and Context-Appropriate

1 | 2 | 3 - Instrumentation & Introspection | 4

- Created by the IP author with design familiarity
  ⇒ easy to use, no guess work by IP user
- Feedback interpreted with IP author knowledge
  ⇒ natural & meaningful to IP user
  e.g., protocol checker and deadlock detector
  **Greatly facilitate debug and validate**
- Synthesizable?
  - monitor deployed or under-test designs
  - minimal speed overhead, full fidelity
  - capture rare or hard-to-reproduce behaviors

# Providing "Full Service"

1 | 2 | 3 | 4 -Supporting Collaterals

- Elementary supporting material
  e.g., testbenches, documentation, etc.
- Scripts and interfaces, e.g.,
  - for configuring the IP, or
  - processing output logs

**Minimizes barrier-to-entry for IP user**





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# Generic HW Characterization

1 - Embody Knowledge | 2 | 3 | 4

- HW resource usage (e.g., slices, BRAM, LUTRAM) & frequency
- At the network level, router level and subcomponents

## Sample characterization targeting FPGAs

| Flit Width | | 32 bits | | | | | | | | 128 bits | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Num. VCs | | 2 VCs | | | | 4 VCs | | | | 2 VCs | | | | 4 VCs | | | |
| Buf. Depth | | 4 | 8 | 16 | 32 | 4 | 8 | 16 | 32 | 4 | 8 | 16 | 32 | 4 | 8 | 16 | 32 |
| 2 In/Out | LUTs | 242 | 292 | 340 | 485 | 373 | 427 | 564 | 952 | 562 | 612 | 659 | 936 | 693 | 739 | 1020 | 1861 |
| Ports | MHz | 306 | 284 | 247 | 218 | 260 | 240 | 217 | 195 | 306 | 283 | 245 | 221 | 260 | 232 | 219 | 193 |
| 4 In/Out | LUTs | 688 | 813 | 893 | 1236 | 938 | 1137 | 1454 | 2408 | 1424 | 1550 | 1629 | 2230 | 1672 | 1872 | 2460 | 4310 |
| Ports | MHz | 180 | 183 | 154 | 143 | 169 | 167 | 147 | 139 | 180 | 183 | 154 | 143 | 166 | 165 | 147 | 139 |
| 6 In/Out | LUTs | 1893 | 2005 | 2161 | 2812 | 2000 | 2351 | 2861 | 4399 | 3705 | 3839 | 4018 | 4987 | 4055 | 4442 | 5364 | 8439 |
| Ports | MHz | 150 | 142 | 130 | 126 | 122 | 123 | 115 | 109 | 149 | 140 | 127 | 122 | 122 | 124 | 117 | 110 |
| 8 In/Out | LUTs | 3012 | 3171 | 3439 | 4149 | 3767 | 3953 | 4849 | 6565 | 5368 | 5544 | 5780 | 7035 | 6134 | 6322 | 7753 | 11280 |
| Ports | MHz | 117 | 114 | 103 | 101 | 107 | 102 | 103 | 95 | 117 | 114 | 102 | 101 | 107 | 102 | 103 | 94 |

E.g., across different router choices

| | Xilinx LX240T | | Xilinx LX760 | |
|---|---|---|---|---|
| Network | %LUTs | MHz | %LUTs | MHz |
| Ring64 | 30% | 175 | 9% | 200 |
| DoubleRing16 | 9% | 139 | 3% | 158 |
| DoubleRing32 | 11% | 146 | 4% | 169 |
| FatTree16 | 12% | 117 | 4% | 143 |
| Mesh16 | 15% | 101 | 5% | 113 |
| Torus16 | 25% | 91 | 8% | 100 |
| HighRadix8 | 20% | 73 | 5% | 76 |
| HighRadix16 | 28% | 67 | 9% | 75 |

E.g., across different topology choices

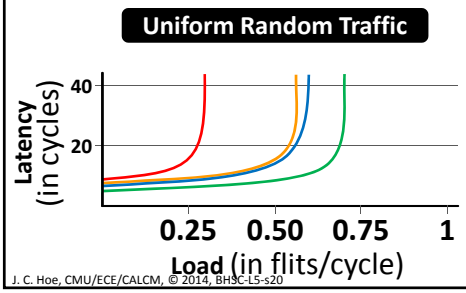


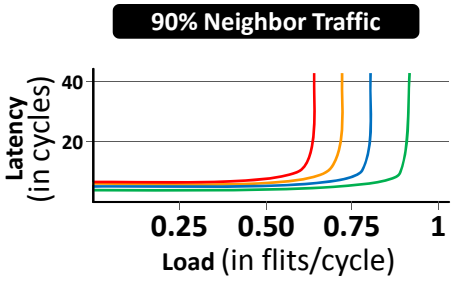


# Domain-specific characterization

1 - Embody Knowledge | 2 | 3 | 4

- Network performance metrics, e.g., load-latency across various NoCs and traffic patterns
- Capture Network properties qualitative criteria and heuristics, e.g., traffic isolation, QoS properties, buffer size based on packet size

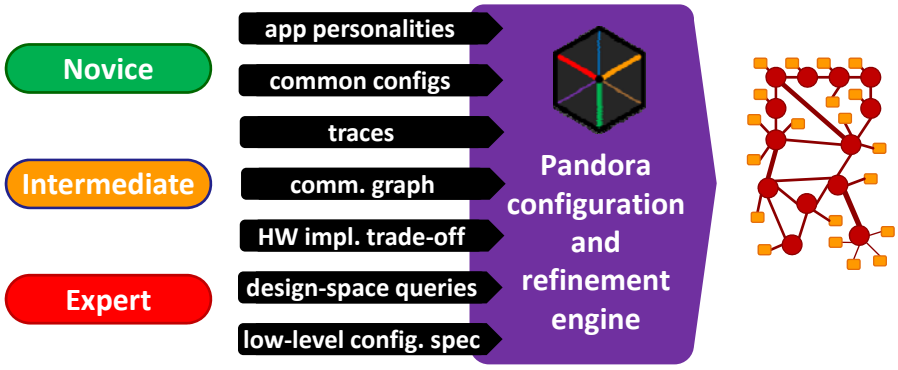


# Interface at Multiple Expertise Levels

1 | 2 - Raise Level of Abstraction | 3 | 4

**User Expertise** | **User Input** | **Resulting NoC**








# Novice / Intermediate / Expert

1 | 2 - Raise Level of Abstraction | 3 | 4

- Pick NoC based on quantitative input, e.g.,
  - weighted graph representing communication pattern
  - traffic traces from application runs
- Pick NoC based on qualitative input, e.g.,
  - "mostly neighbor request-response traffic, 3 hot spots, need traffic isolation"
- Design space query on objectives & constraints, e.g.,
  - "lowest area NoC @ 800MHz & has bisection bandwidth of 8 Gbps"

These examples don't help me if my IP is not NoC :(

# Runtime Monitoring and Analysis

1 | 2 | 3 - Instrumentation & Introspection | 4

- Monitoring of events & gathering of statistics
  - e.g., link utilization, allocation conflicts, average load per endpoint/router/port, avg. buffer occupancy, how frequently high-priority traffic blocked low-priority traffic
- Capturing sequence of events
  - e.g., protocol transitions triggered by flow control messages or transient temporal network behavior

Built into the NoC and tailored to specific instance





# Runtime Monitoring and Analysis

1 | 2 | 3 - Instrumentation & Introspection | 4

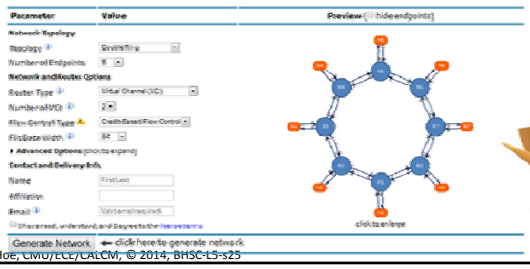
- Dynamically detect configuration & usage issues
  - e.g., invalid routing configuration, packets making U-turns, allocation errors, improper implementation of flow control
- Diagnostic tools that capture domain-specific effects
  - e.g., deadlock, livelock or starvation detection
  - offline post-processing for more sophisticated analysis, e.g., detect suboptimal endpoint mapping on NoC

Aid debugging, provide feedback, and guide tuning

# "Generator as IP" to "IP as a Service"

1 | 2 | 3 | 4 -Supporting Collaterals

- Packaging and releasing the IP as a service
  - only need internet and browser to use CONNECT
  - no worry about equipment, environment and tools setup
  - transparent updates and fixes
  - usage statistics, crowd-sourcing









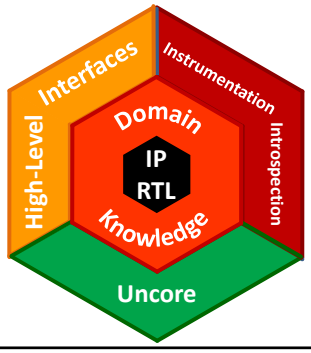
# Recap the Last Hour

1 **Embodying Domain Knowledge**
Design space characterization w.r.t. HW cost + domain metrics

2 **Raise the Level of Abstraction**
High-Level Interfaces tailored to domain, meaningful to IP user

3 **Instrumentation and Introspection**
Monitor, collect and analyze info about IP operation

4 **Providing Supporting Collaterals**
Supporting material, toolset, release strategies



# What else could we do?

- Standard interfacing schema for composing IPs
- Can composed Smart-IPs cross-tune amongst themselves?
- Frameworks for building Smart-IPs: expressing structural and meta-knowledge/expertise
- What else to encapsulate?





CALCM

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