A MAC protocol for Reliable Broadcast Communications in Wireless Network-on-Chip

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Context

- Current trends are leading to larger manycores
- Wireless on-chip communication holds promise for the implementation of fast networks for these multiprocessors
- In complement of a wired NoC, wireless provides
  - Low latency
  - Natural broadcast capabilities
  - Flexibility

Motivation

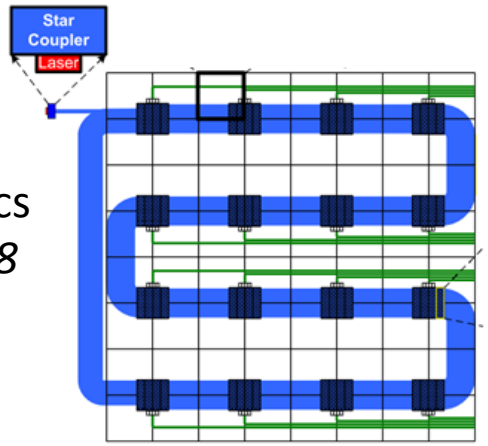
- As the core density increases, more wireless interfaces can be expected on chip
- Need for arbitration strategies (MAC protocols)
  - That provide low latency
  - That support broadcast traffic
  - That are reliable (packets cannot be lost)
  - That scale with number of wireless nodes

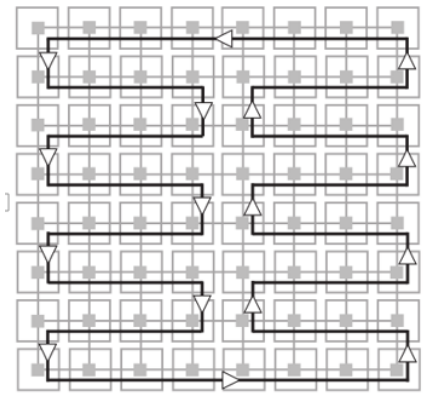
Contribution: **BRS-MAC**

- We propose a BRS-MAC, a protocol based on three pillars: **B**roadcast, **R**eliability, **S**ensing
- We develop analytical models to explore the performance of BRS-MAC
- We compare the obtained performance with that of token passing and a wired mesh

Emerging Interconnect Technologies

Nanophotonics
Vantrease et al, 2008



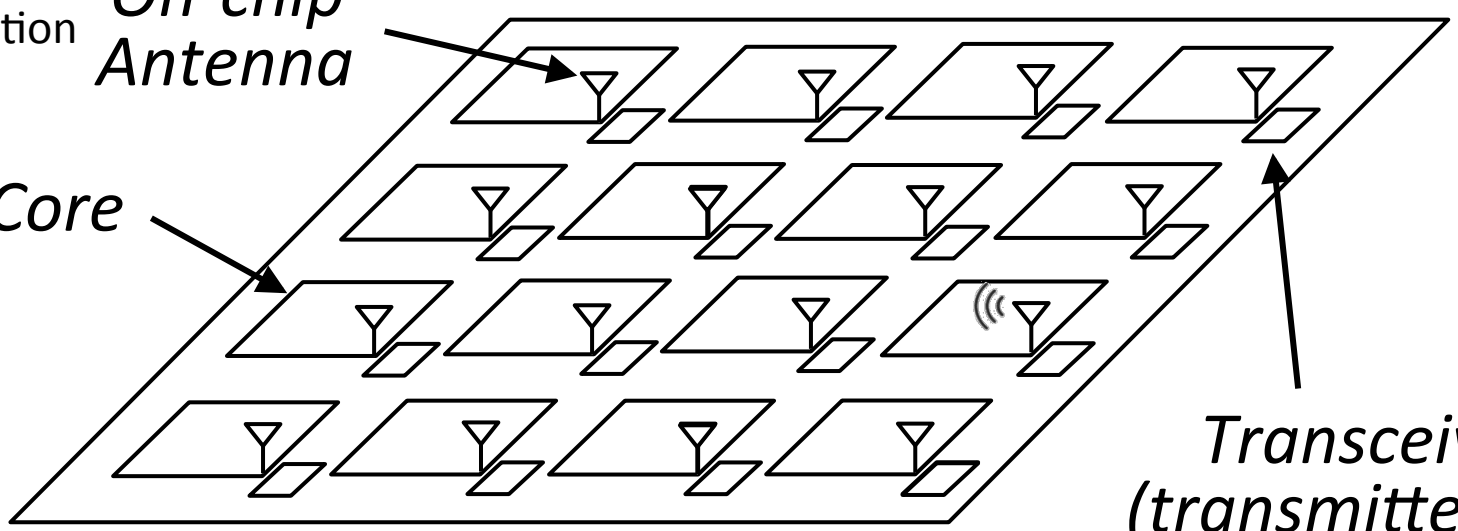


Transmission Line
Interconnects
Oh et al, 2013

Wireless on-chip
Communication

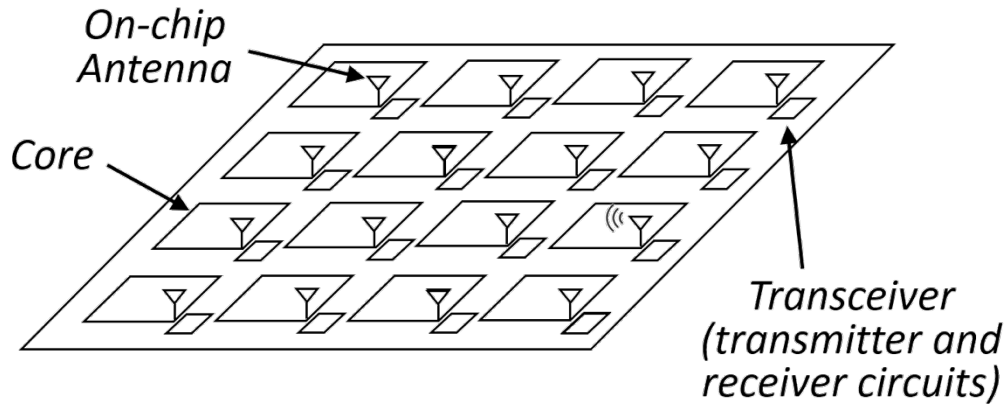
On-chip Antenna

Core



Transceiver (transmitter and receiver circuits)

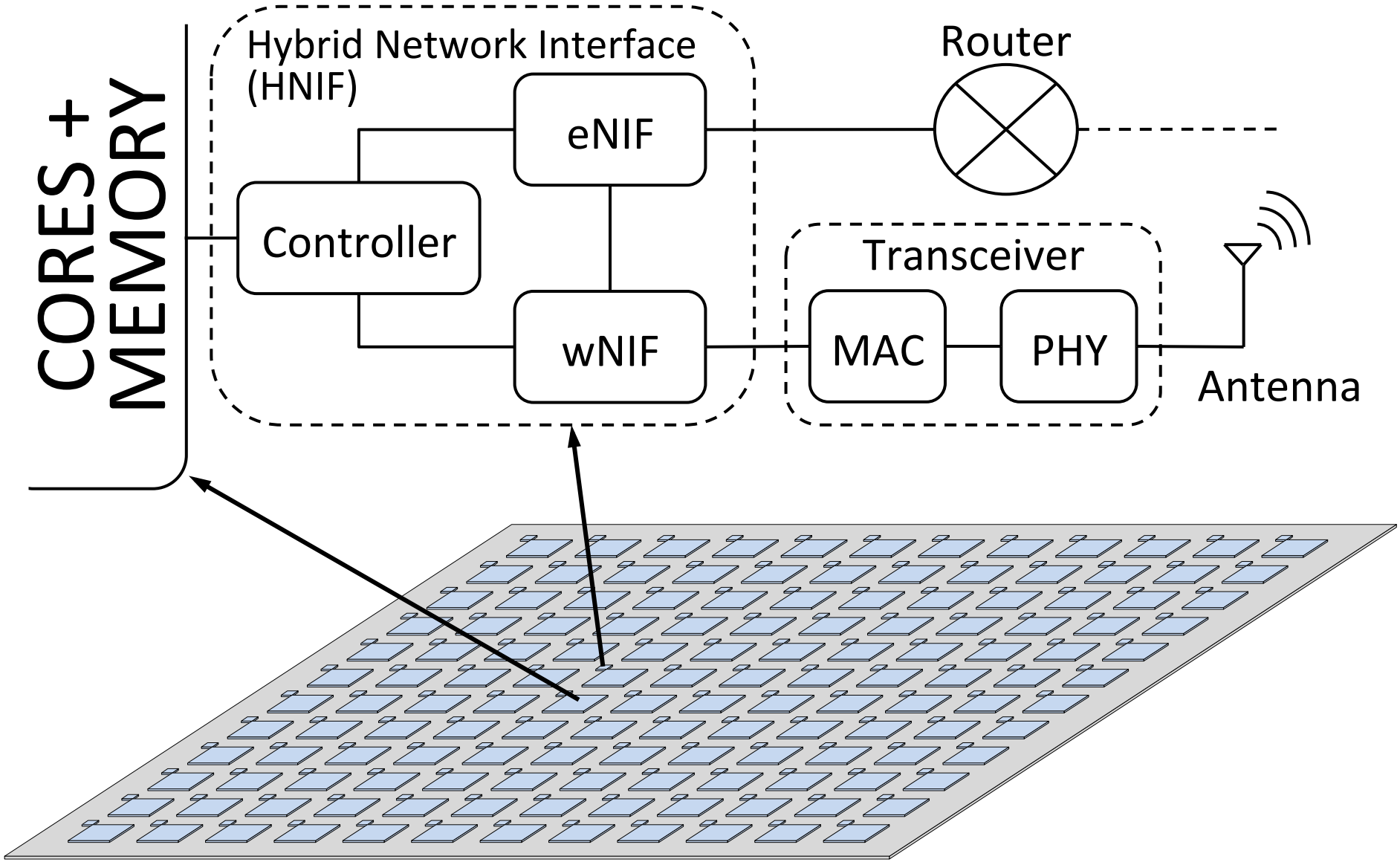
On-chip Wireless Communication



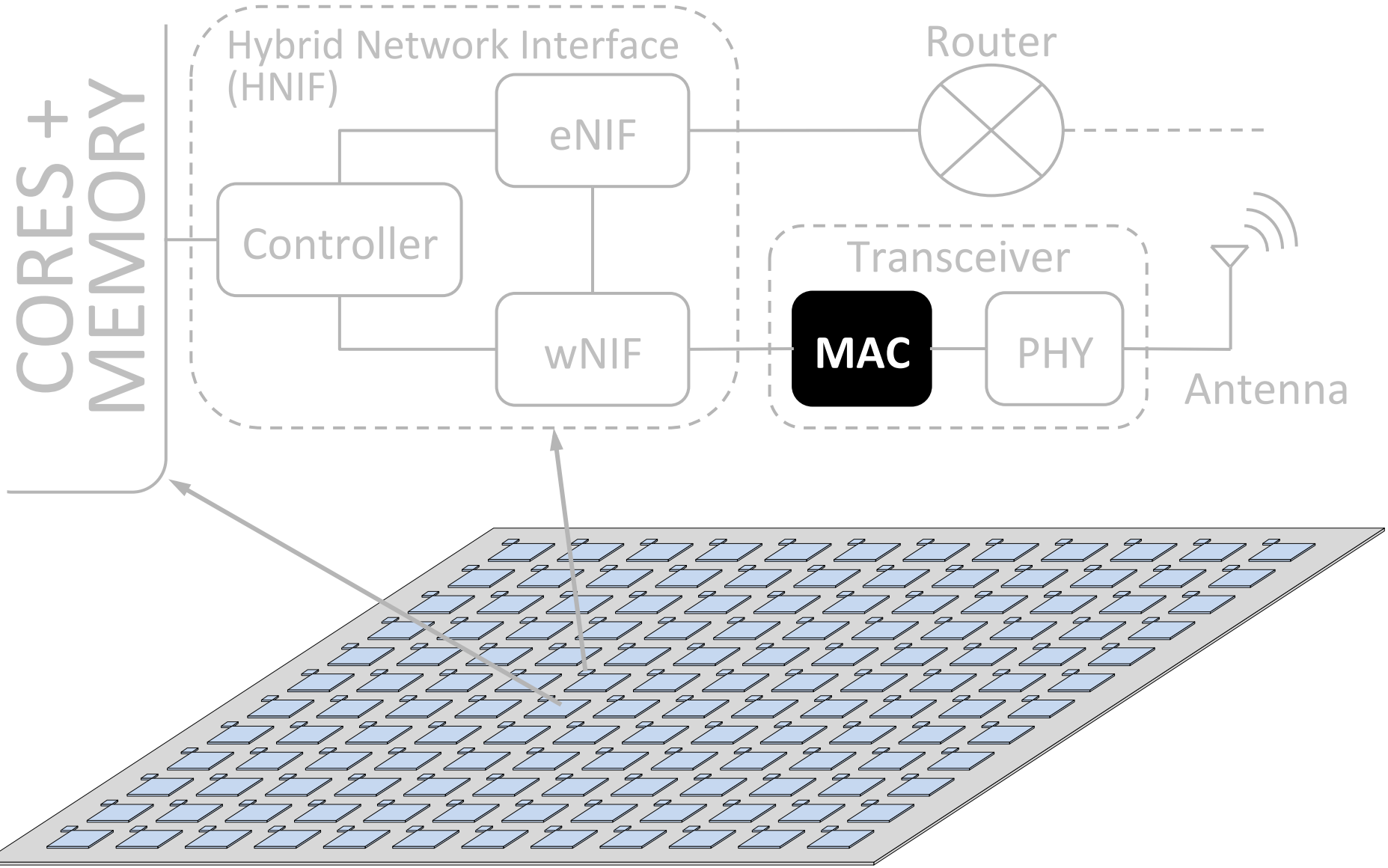
- PROS
  - Inherently broadcast
  - Low latency
  - Simplicity / Flexibility / Non-intrusiveness
- CONS
  - Less energy efficient than TL or photonics
  - Low bandwidth

S. Abadal *et al*, "**Broadcast-Enabled Massive Multicore Architectures: A Wireless RF Approach,**" *IEEE MICRO*, vol. 35, no. 5, pp. 52–61, 2015.

Wired-Wireless Network-on-Chip

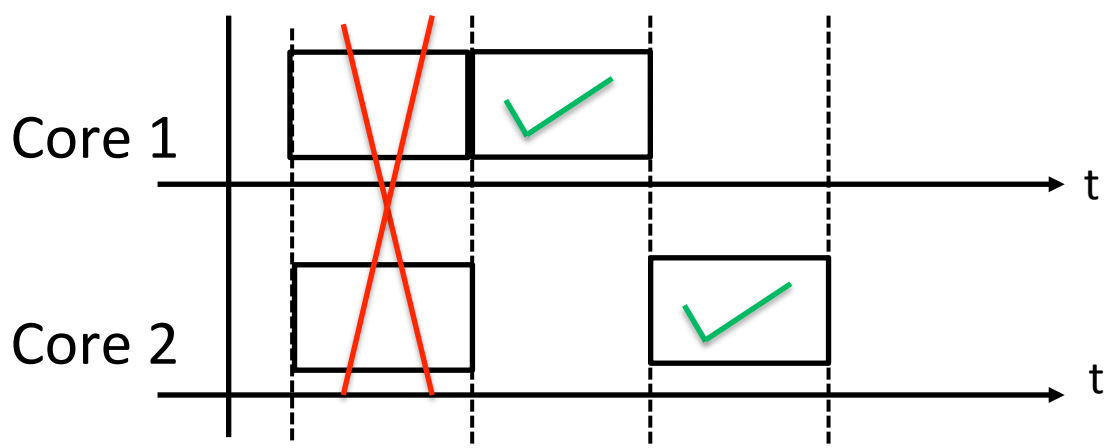


Wired-Wireless Network-on-Chip



Medium Access Control (MAC)

- The MAC layer defines mechanisms to ensure that all nodes can access to a shared medium in a reliable manner
  - Simultaneous accesses to the same channel *collide* and need to retry



MAC Context Analysis

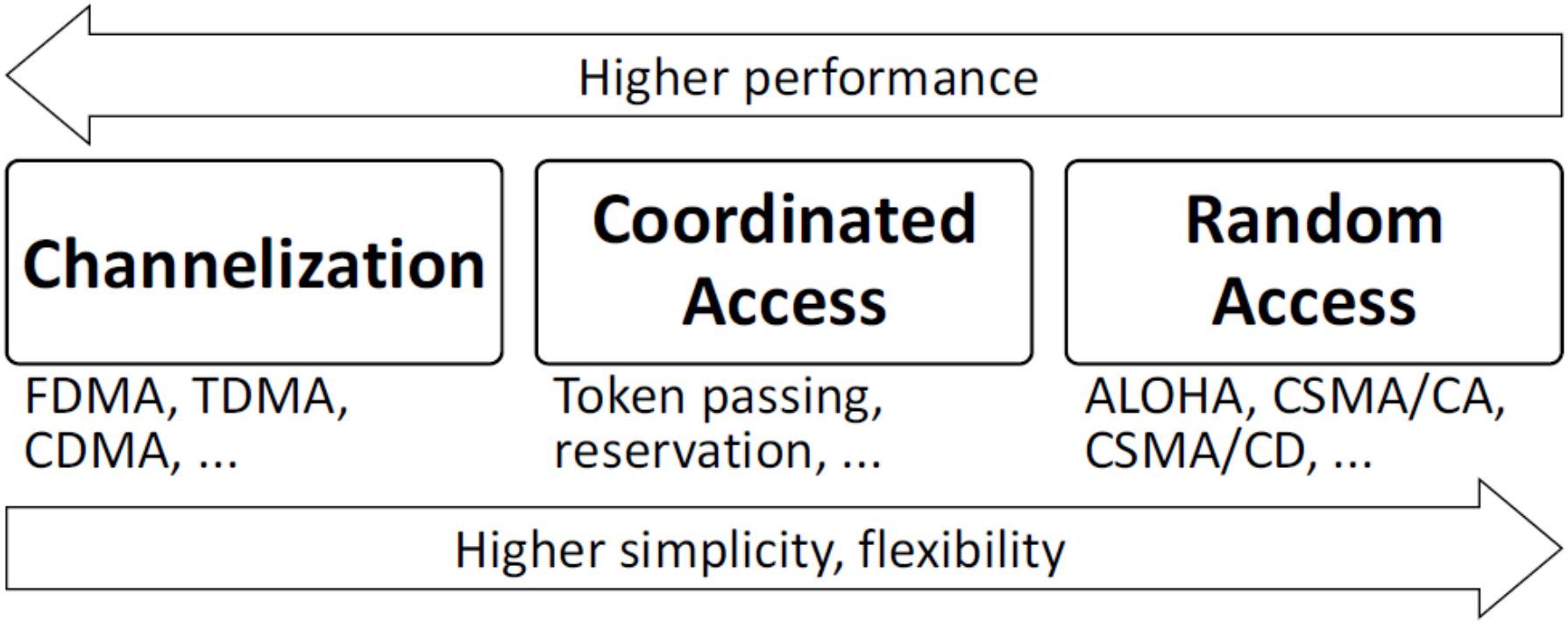
- Chip scenario
  - Physically constrained – need for lightweight MAC
  - Unlike most environments, the chip scenario is *static and known beforehand*
    - "Everyone sees everything"
    - Easy to reach consensus
    - Collisions can be detected
    - **<u>Simpler protocols</u>**

MAC Context Analysis

- Application Requirements
  - Low latency – need for fast solution
  - Reliability – MAC cannot lose packets
  - Scalability – protocol must scale to many cores
- Traffic Characteristics
  - Broadcast is the objective of our WNoC*
  - Variable – flexibility is desirable

*S. Abadal, E. Alarcón, A. Cabellos-Aparicio, and J. Torrellas, "**WiSync: An Architecture for Fast Synchronization through On-Chip Wireless Communication,**" in Proceedings of the ASPLOS '16, April 2016.

MAC in Wireless NoC



MAC in Wireless NoC

- Channelization
  - Low latency, reliability due to multiple channels
  - Inherently rigid, hard to implement broadcast
  - Does not scale ➔ becomes area/power hungry
- Coordinated Access (token passing)
  - High throughput due to the absence of collisions
  - Still somehow rigid
  - Scaling problems ➔ protocol becomes slow
- Random access?

S. Deb, A. Ganguly, P. P. Pande, B. Belzer, and D. Heo, "**Wireless NoC as Interconnection Backbone for Multicore Chips: Promises and Challenges**," *IEEE J. Emerg. Sel. Top. Circuits Syst.*, vol. 2, no. 2, pp. 228–239, 2012.

BRS-MAC protocol

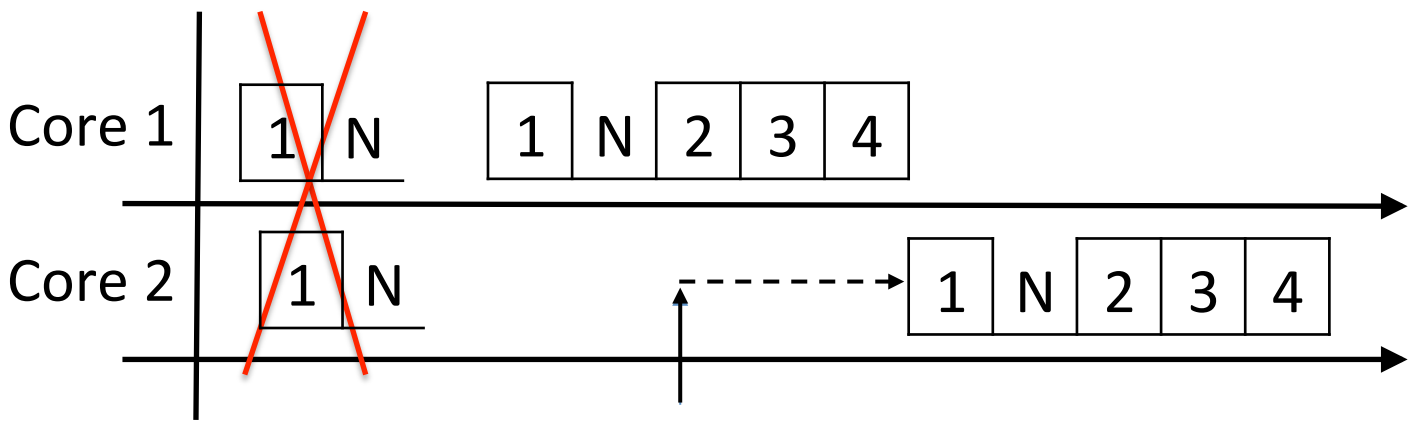
- For all this, we propose BRS-MAC
  - **Broadcast (B):** designed to serve broadcast fast
  - **Reliability (R):** guarantee correct delivery
  - **Sensing (S):** based on carrier sensing and collision detection principles
- Seeks to provide the low latency, scalability, and flexibility desired via random access

BRS-MAC – Basic Assumptions

- Nodes can sense the medium
- In the event of a collision, at least one of the receivers can detect such situation and notify the transmitters
- At least one collision notification will reach all the colliding transmitters

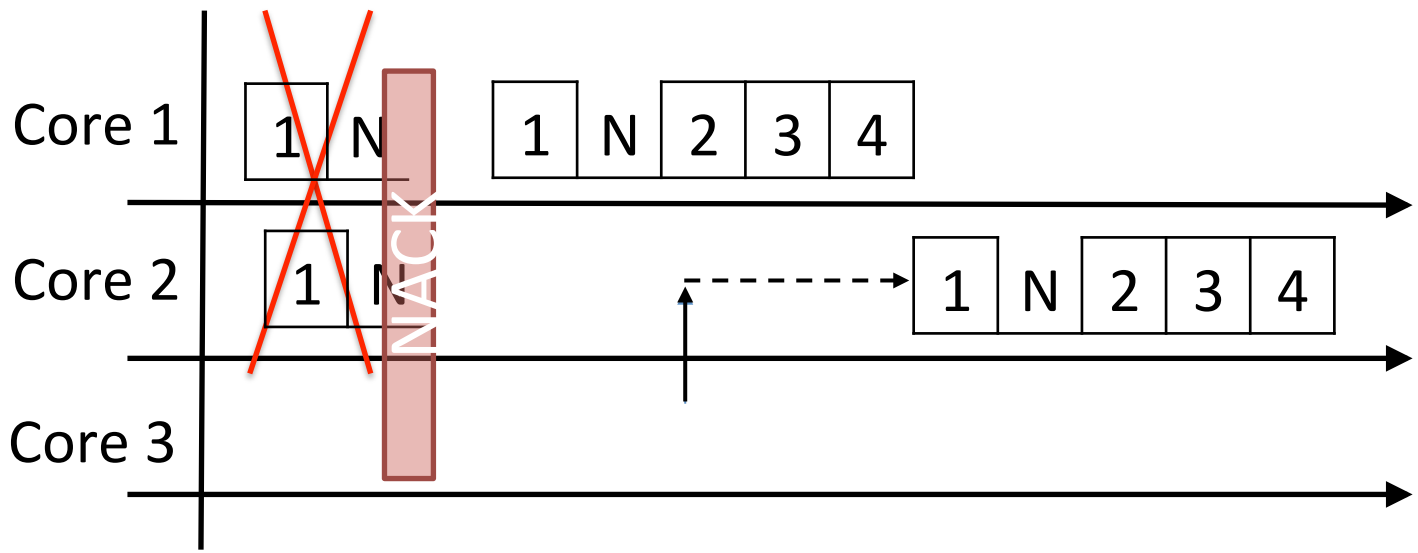
BRS-MAC – Algorithm

- **TX:** Check if the channel is free. If so, transmit a preamble. Then, listen for a Negative ACK:
  - If there is a NACK, there was a collision. Back off (exponential) and retransmit
  - If silence, preamble was OK. Continue with the rest of the transmission (cannot collide)



BRS-MAC – Algorithm

- **RX:** listen for new transmissions. When a preamble is received, check for errors, then
  - If errors, transmit a NACK.
  - If no errors, stay silent.



BRS-MAC – Key Decisions

- There are several key design decisions
  - Collision detection at the RX cannot normally be assumed, but here we have a static scenario
  - Preamble contains the size of packet, receivers can calculate the transmission duration
  - NACK mechanism is chosen because
    - Success will be more probable than collision
    - Only 1 NACK is needed to cancel a colliding tx
    - N-1 ACKs are needed to confirm a successful tx

Analytical Modeling – Outline

L. Kleinrock and F. Tobagi, **"Packet Switching in Radio Channels: Part I--Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics,"** *IEEE Trans. Commun.*, vol. 23, no. 12, pp. 1400–1416, 1975.

Analytical Modeling – Equations

- **Throughput:** $S = E\{U\}/E\{B\}+E\{I\}$
  - U – occupancy of the channel (successful)
  - B + I – time between transmissions (busy+idle)
- **Delay:** $D = N_{re} R + N_c T_{KO} + T_{OK}$
  - N_{re}, N_c – number of retransmissions, collisions
  - R – duration of the backoff periods
  - T_{OK}, T_{KO} – time lost in a collision, delay of successful transmission

Modeling Approaches

- Classical (worst-case)
  - Position of nodes is unknown, they can move
  - Assume a constant propagation time
- Network-on-Chip (exact)
  - Positions are known a priori
  - Propagation time can be calculated exactly
  - Homogeneous deployment is assumed

Analytical Modeling

- Necessary assumptions (Kleinrock *et al*)
  - All arrivals follow Poisson process
  - Traffic uniformly distributed among infinite population (reasonable in manycores)
  - Negligible time to switch between TX and RX
  - Negligible time to sense the channel busy

L. Kleinrock and F. Tobagi, **"Packet Switching in Radio Channels: Part I--Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics,"** *IEEE Trans. Commun.*, vol. 23, no. 12, pp. 1400–1416, 1975.

Closed-form expressions

$$S = e^{-aG} / e^{-aG}(1-b) + b + 2a + 1/G$$

$$S_{e} \approx 1 - G\alpha a / 1 + (2+\alpha)a - (1-b)G\alpha a + 1/G$$

THROUGHPUT

$$N_{c} = a + 1/G/E\{B\} + E\{I\}\ G/S - 1$$

worst-case

$$N_{c,e} = \alpha a + 1/G/E\{B_{e}\} + E\{I\}\ G/S_{e} - 1$$

exact

DELAY

Closed-form expressions

$$S = e\uparrow - \boldsymbol{a}G \,/\, e\uparrow - \boldsymbol{a}G\,(1-b) + b + 2\boldsymbol{a} + 1/G$$

$$S\uparrow e \approx 1 - G\boldsymbol{\alpha a}/1 + (2+\boldsymbol{\alpha})\boldsymbol{a} - (1-b)G\boldsymbol{\alpha a} + 1/G$$

Worst-case propagation time appears in all expressions.

$$N\downarrow c = \boldsymbol{a} + 1/G/E\{B\} + E\{I\}\; G/S - 1$$

$$N\downarrow c\uparrow e = \boldsymbol{\alpha a} + 1/G/E\{B\uparrow e\} + E\{I\}\; G/S\uparrow e - 1$$

Parameter relating average exact propagation with worst-case propagation time

Closed-form expressions

$$S = e\uparrow - aG\,/\,e\uparrow - aG\,(1-\boldsymbol{b}) + \boldsymbol{b} + 2a + 1/G$$

$$S\uparrow e \approx 1 - G\alpha a / 1 + (2+\alpha)a - (1-\boldsymbol{b})G\alpha a + 1/G$$

Length of the preamble and NACK period.

$$N\downarrow c = a + 1/G/E\{B\} + E\{I\}\ G/S - 1$$

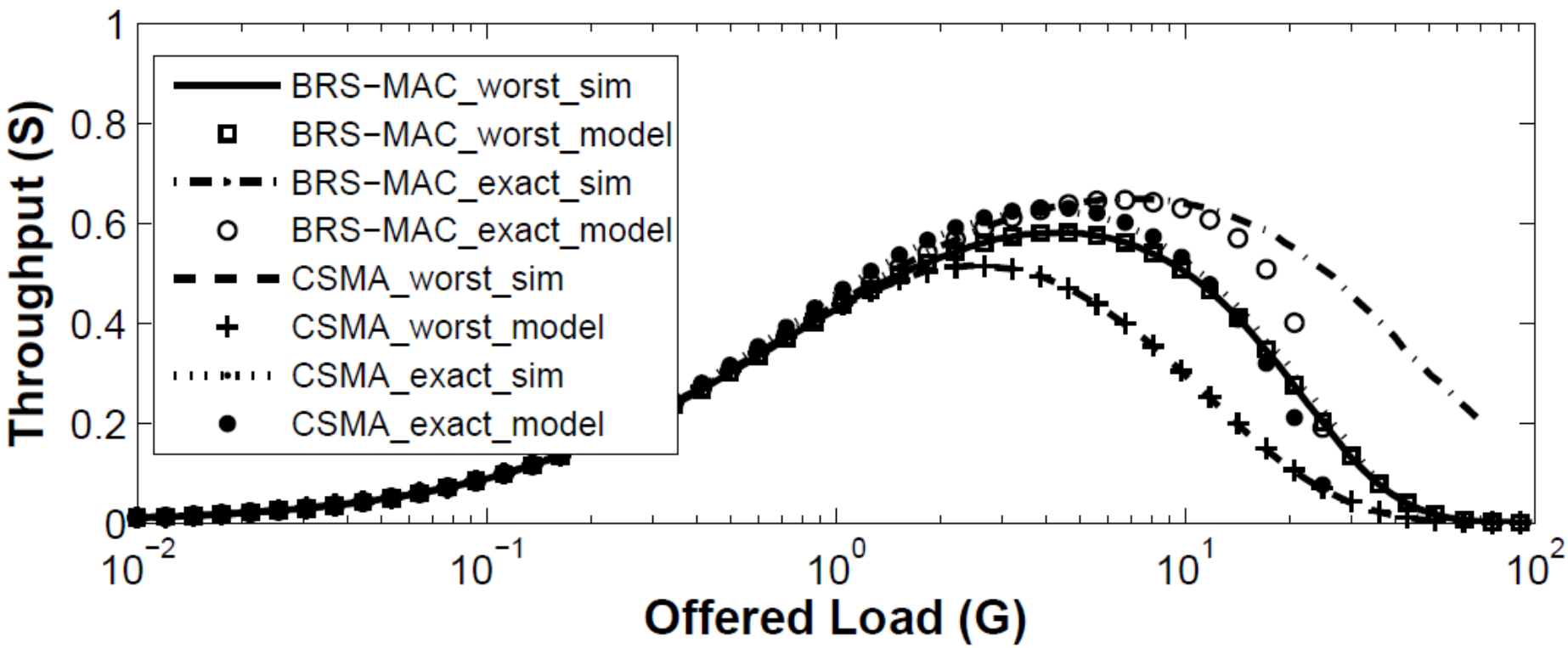
$$N\downarrow c\uparrow e = \alpha a + 1/G/E\{B\uparrow e\} + E\{I\}\ G/S\uparrow e\ - 1$$

Evaluation Environment

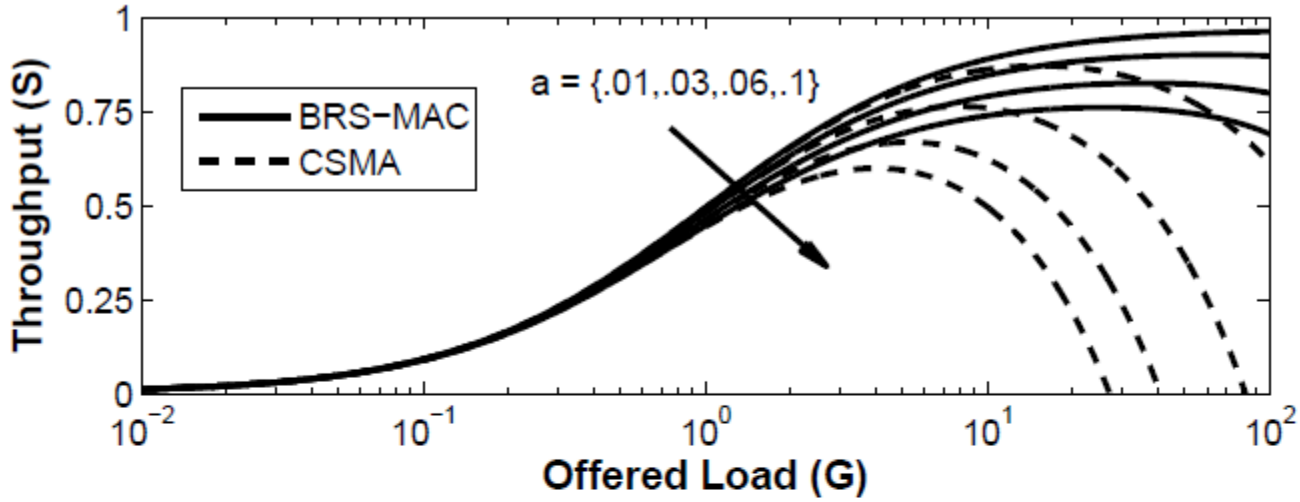
- Implemented BRS-MAC within event-based simulator to validate models
  - Propagation times modeled accurately
  - Overlapping transmissions ➔ collision
- As baseline, we implemented classic CSMA with ideal acknowledging
- Explored impact of *a* and *b* parameters

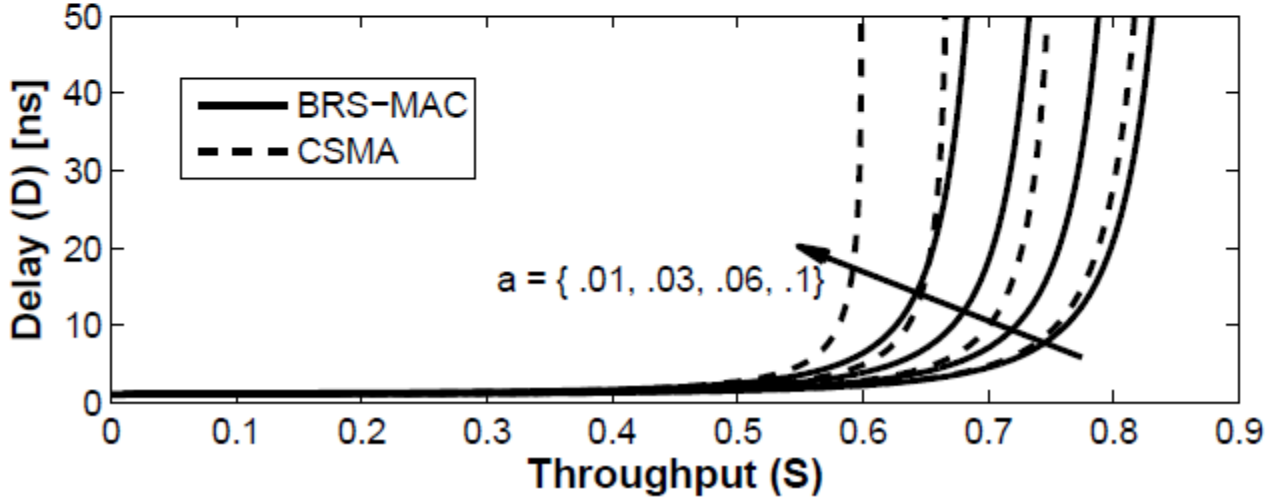
L. Kleinrock and F. Tobagi, **"Packet Switching in Radio Channels: Part I--Carrier Sense Multiple-Access Modes and Their Throughput-Delay Characteristics,"** *IEEE Trans. Commun.*, vol. 23, no. 12, pp. 1400–1416, 1975.

Validation of the model

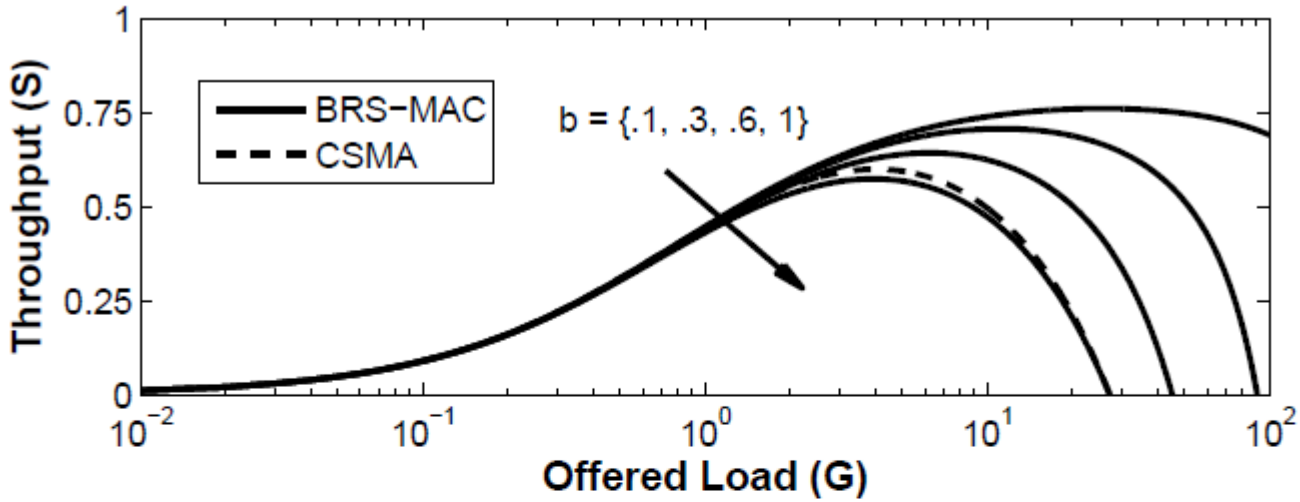


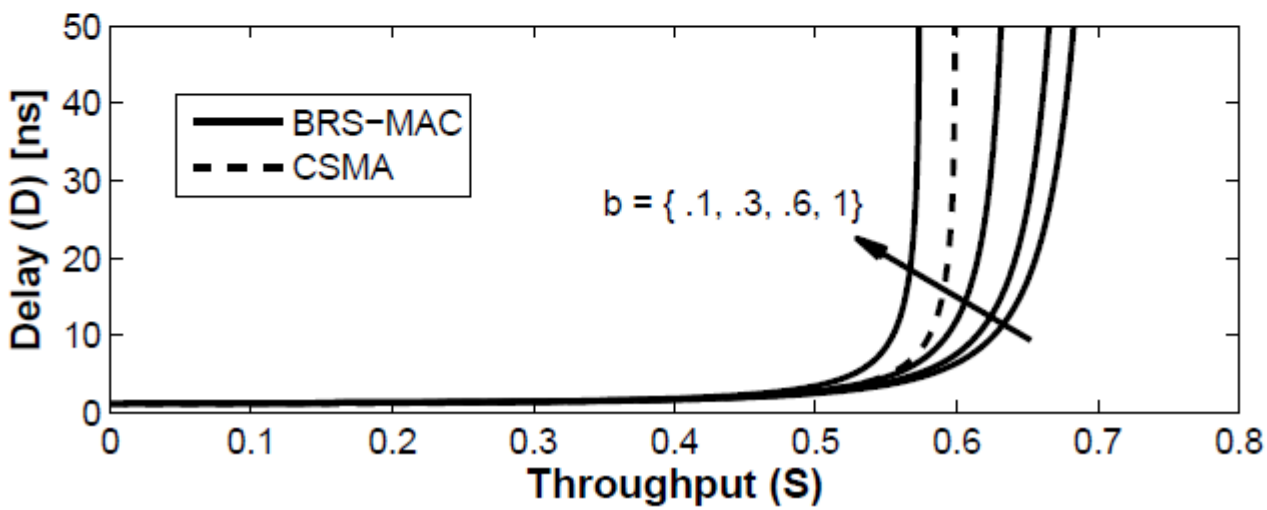
Impact of propagation time





Impact of preamble length





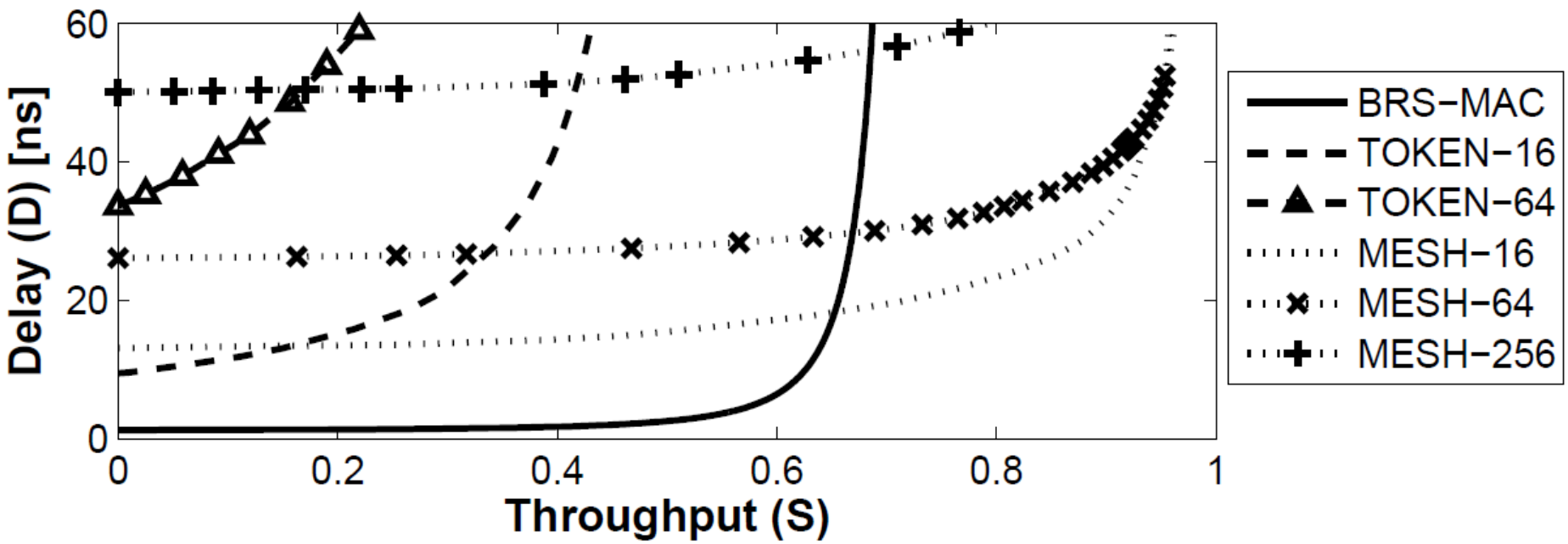
Performance Comparison

- Wireless Token Passing
  - Passing the token takes 1 clock cycle
  - Cannot be overlapped with data transmission
- Aggressive Wired Mesh
  - Each hop takes 2 clock cycles without contention
  - Tree multicast
  - Multiport allocation and multicast crossbar
- Same per-link bandwidth in all cases
- 100% broadcast traffic

Performance Comparison

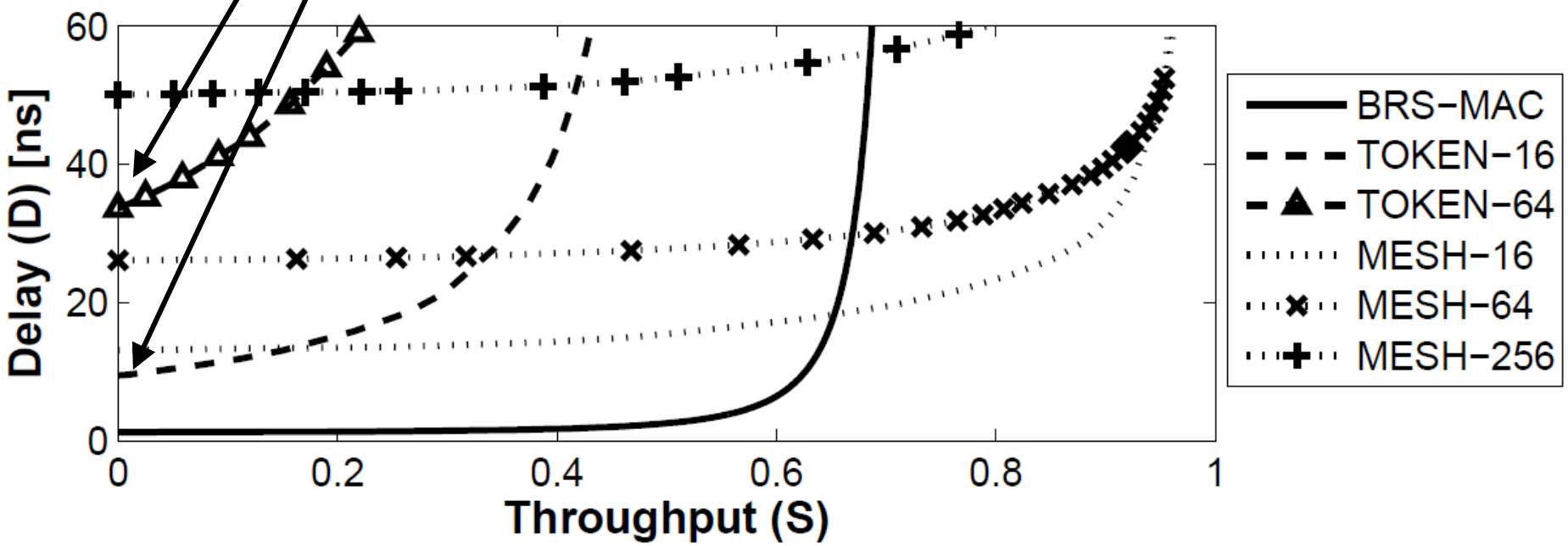
a = 0.1

b = 0.1



Performance Comparison

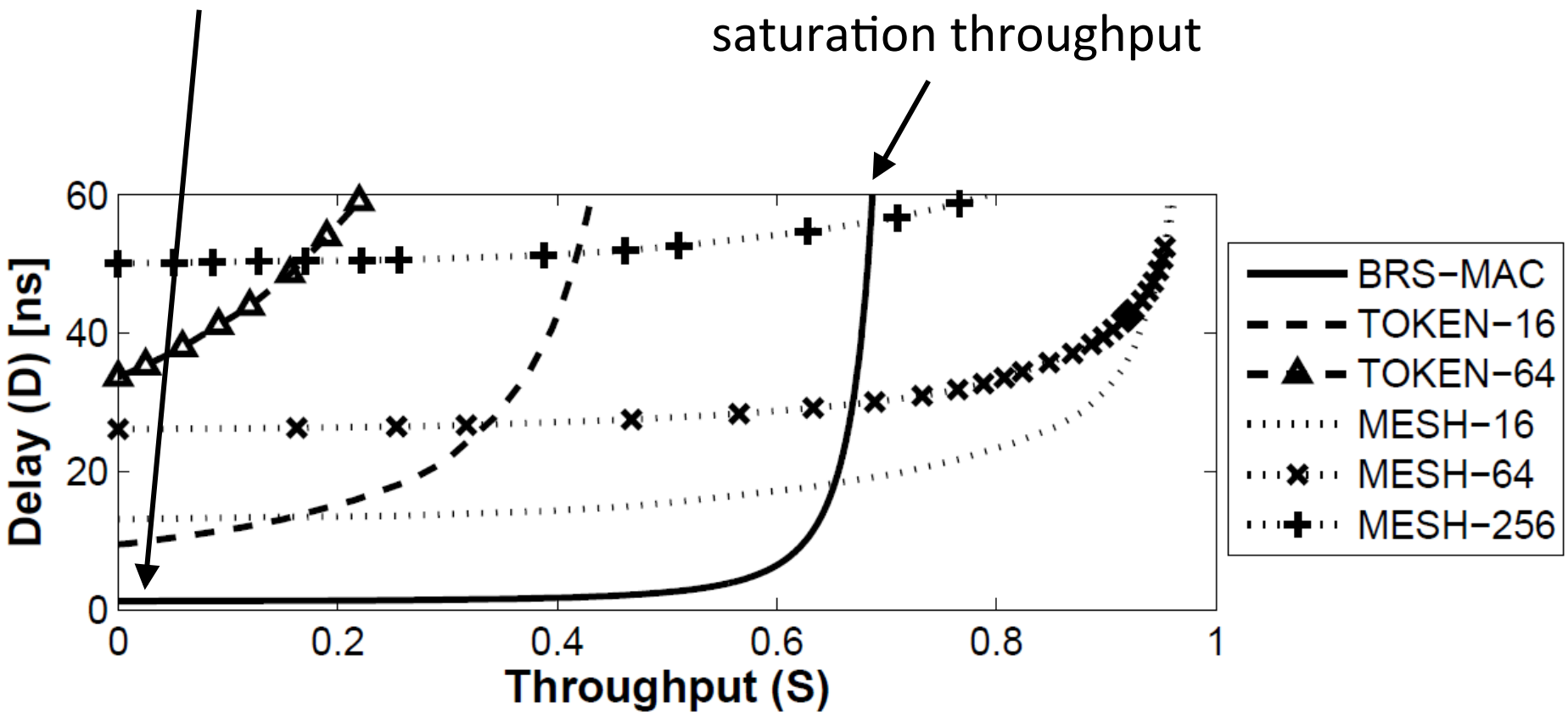
Latency increases with number of nodes due to increasing token round-trip time (TOKEN) or network diameter (MESH)



Performance Comparison

BRS-MAC has the best latency of all options

BRS-MAC has a reasonable saturation throughput



Conclusions

- We presented BRS-MAC, a random access protocol for Wireless Network-on-Chip
- We accurately modeled and explored its performance
- BRS-MAC achieves much lower latency than token passing or mesh networks, with reasonable saturation throughput

The end

Thanks for your attention.

Questions?