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An Improved Wireless Communication Fabric for Performance Aware Network-on-Chip Architectures

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Abstract: Existing wireless communication interface has free space signal radiation which drastically reduces the received signal strength and hence reduces the throughput efficiency of Hybrid Wired-Wireless Network-on-Chip (WiNoC). This paper addresses the issue of throughput degradation by replacing the wireless layer of WiNoCs with a novel Complementary Metal Oxide Semiconductor (CMOS) based waveguide communication fabric that is able compete with the reliability of traditional wired NoCs. A combination of a novel transducer and a commercially available thin metal conductor coated with a low cost Taconic Taclamplus dielectric material is presented to generate surface wave signals with high signal integrity. Our experimental results demonstrate that, the proposed communication fabric can achieve a 5dB operational bandwidth of about 60GHz around the center frequency (60GHz). Compared to existing WiNoCs, the proposed communication fabric has a performance improvement of 13.8% and 10.7% in terms of throughput and average packet delay, respectively. Specifically, under realistic traffic patterns, the average packet latency can be reduced by 30% when the mm-Wave is replaced by the proposed communication fabric.

Keywords: Wireless Network-on-Chip, Communication Fabric, Surface wave, Performance Evaluation, Throughput, Reliability

1. INTRODUCTION

The projected issues of high latency and high power consumption of conventional on-chip networks for multi-core design can be addressed by alternative wireline technologies such as three dimensional integrated circuits (3-D ICs) design. However, although 3D ICs have shorter wire links between the stacked layers, they suffer from alignment issues along with low yield and high temperature dissipation which affect the reliability of the implemented components [1, 2, 3, 4, 5, 6]. Hence wireless channels in the form of millimeter wave (mm-Wave) for global communication while maintaining the wired network for localized traffic has been proposed [7, 8, 9, 10, 11]. While the resulting Hybrid Wired-Wireless Network-on-Chip (WiNoC) architecture has high performance benefits over traditional wired NoCs, the wireless layer has a poor reliability. This is due to the three-dimensional free space signal radiation in the lossy wireless communication fabric which lowers the overall reliability of the system. Consequently, traditional wires have extremely low bit error rate (BER) of around 10^{-14} compared to that of mm-Wave (around 10^{-7}) as shown in Figure 1.

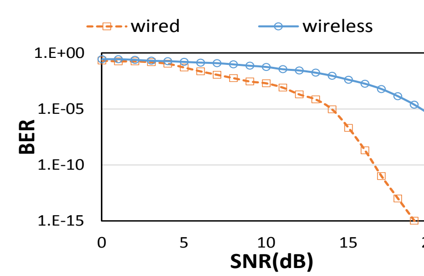

Figure 1. Variation of BER with signal-to-noise (SNR) for conventional wireless NoC and wired NoC

Moreover, the radiation patterns of the antenna for existing wireless NoCs is limited by a distance of up to 23mm with significantly high power dissipation and losses due to free space propagation. In NoCs, a single message loss can have drastic effects on the performance of the multi-core system. To improve the reliability of existing WiNoCs, Error-control-coding [12] and retransmission schemes [7] could be employed. However, these techniques rely on the underlying lossy wireless communication fabric for retransmission of handshake signals,

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erroneous and non-erroneous packets. Therefore, the throughput of WiNoCs is reduced due to the extra timing overhead and retransmitted packets in the network. Hence, novel wireless communication fabrics that offer high data bandwidth as well as improved reliability with BER similar to the wired communication fabric are required to provide a good trade-off for WiNoCs. We replace the wireless communication layer of WiNoCs with a reliable surface wave communication fabric for global communication. The hybrid wired-surface wave network-on-chip architecture employs a 2-D guided wave for low power-fast global communication to give reasonably high performance to area ratio. Compared to traditional hybrid wired-mm-Wave NoCs, the hybrid wired-SW NoC architecture has significantly reduced power consumption due to the propagation of wireless signal in a 2-D guided medium. 2-D guided wave in the form of surface wave (SW) interconnect is an emerging wireless communication fabric that is power efficient and has a highly reliable data throughput for long distance communication [13, 14].

The surface wave propagates in a specially designed sheet, which is an inhomogeneous plane that supports electromagnetic transmission. The signal generated in the 2-D sheet traverses in all directions providing a natural fan-out feature for supporting realistic on-chip applications such as cache coherency where multicast is dominant. Moreover, a transceiver similar to that of traditional RF or millimeter wave design can be employed for surface wave propagation. However, previous contributions on SW have not focused on optimizing the communication fabric to improve the data throughput and reliability of wireless channel [13]. In this paper, we propose a highly reliable SW communication fabric along with an efficient transducer interface that is able to match the signal integrity of short range wired NoCs. By employing a novel CMOS based 2-D waveguide communication fabric implemented with a thin metal layer coated with low cost dielectric material (Taconic RF-43 [15]), the proposed SW fabric serves as an alternative communication fabric for the wireless layer of WiNoCs. Evaluated results show that a wide-band 5 dB operational bandwidth of about 40GHz to 60GHz can be achieved around 60GHz operational frequency. The paper is organized as follows. Section 2 motivates the paper by discussing related work. Section 3 discusses emerging wireless NoC architectures. Section 4 formulates the problem of implementing an improved wireless communication fabric for NoC architectures. Section 5 presents an improved wireless communication fabric for WiNoCs. Section 6 evaluates the transmission strength of the proposed wireless communication fabric. Experimental results in Section 7 validate the performance efficiency of the proposed communication fabric. Finally, the main findings are concluded in Section 8.

2. Related Work

Advances in current integration technology make it possible to implement a wireless transceiver on a silicon die [16, 17, 18]. Hence, several work have been presented in literature to exploit the energy and performance efficiency of long ranged wireless links in the form of mm-wave over the traditional wire-based NoCs [19, 20, 21, 22, 23, 8]. To improve the throughput and power efficiency of both localized and global data transmission hybrid wired-wireless NoCs have already proposed. One of the key problems with WiNoCs identified in [11, 24] is the transmission reliability of the wireless channel. As an effort to address this issue, Ganguly et al. [12, 25] proposed an error control coding for WiNoCs. By implementing a joint crosstalk triple error correction and simultaneous quadruple error detection codes in the wire line links and Hamming code-based product codes in the wireless links with Carbon Nanotube (CNT) antennas, it was demonstrated that, the reliability of the wireless channel could be improved. Similarly, ECC has been adapted in [19] to improve the reliability of WiNoCs.

However, ECC introduces timing, area and packet overheads which affects the overall transmission efficiency of the WiNoC [7]. Alternatively, Lee et al. [7] adopted an overhearing scheme for WiNoCs. Here a zero-signaling-overhearing-and-retransmission is presented to manage the packet loss along the wireless channel. Vijayakumaran et al. [26] presented an improved filter design to enhance the performance as well as reduce the error probability of incurred by synchronization delays in CDMA based WiNoCs. However, these techniques rely on the underlying lossy wireless communication fabric for retransmission of handshake signals, erroneous and non-erroneous packets. Surface wave interconnect is an emerging wireless communication fabric that has been demonstrated to be power efficient and with high data throughput for on-chip communication [27]. Previous contributions on SW have focused network architecture and performance with considerations of arbitration, packet routing and efficient handling of multicast packets [13, 27]. However, optimizing the communication fabric to improve reliability wireless interface which is a major issue in WiNoCs have not received much attention. We propose a highly reliable SW communication fabric along with an efficient transducer interface that is able to match the signal integrity of short range wired NoCs. In this paper, we propose a reliable 2-D communication fabric to alleviate these problems. Our aim is to optimize the emerging 2-D communication fabrics to achieve stronger wireless transmission signal in order to reliability of the wireless interface.

3. Emerging Hybrid Wired-Wireless Architectures for NoCs (WiNoCs)

The projected issues of high latency and high power consumption of conventional on-chip networks for multi-core design can be addressed by inserting express wireless channels for global communication while maintaining the wired network for localized traffic as shown in Figure 2. Recently, hybrid mm-Wave (Figure 2) and hybrid hierarchical/multi-level mm-Wave NoC architectures have been proposed for WiNoCs [7, 10, 11]. While both WiNoC architectures have high performance benefits over traditional wired NoCs, the wireless layer has a poor reliability.

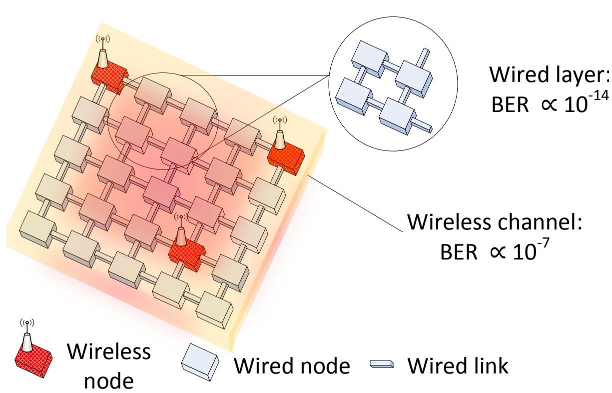


Figure 2. Existing hybrid wired-wireless Network-on-Chip Architecture

The E-field decay rate of the mm-Wave can be expressed as:

$$E_{decay} \propto \frac{1}{src-dst} \quad (1)$$

where *src* and *dst* represents the location of the transmitting and the receiving nodes, respectively. Consequently, the transmit signal loss on the wireless layer is significantly high with reduced BER. We replace the wireless communication layer of WiNoCs with a reliable surface wave communication fabric for global communication (see Figure 3).

The hybrid wired-surface wave network-on-chip architecture employs a 2-D guided wave for low power-fast global communication to give reasonably high performance to area ratio with an E-field decay rate of:

$$E_{decay} \propto \frac{1}{\sqrt{src-dst}} \quad (2)$$

Compared to traditional hybrid wired-mm-Wave NoCs, the hybrid wired-SW NoC architecture has significantly reduced power consumption due to the propagation of wireless signal in a 2-D guided medium. To improve the reliability of existing WiNoCs, the router micro-architecture of the nodes equipped with wireless transmission and receiving capabilities have a slightly different implementation from that of the wired communication layer. As shown is Figure 4 the routers at the wireless nodes in WiNoCs are equipped with a wireless

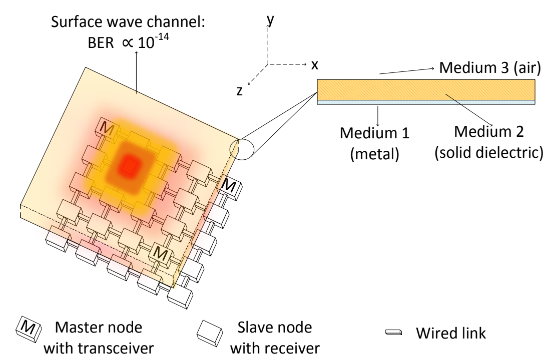


Figure 3. Proposed wireless communication fabric: a dielectric-coated plane surface with a loss tangent tan Δ is used

transmission interface which serves as a bridge between the wireless and the wired communication layers. The wireless transmission interface, responsible for transmitting and receiving wireless signals, works closely with the routing logic, virtual channel allocator, arbiter and crossbar switch for efficient wireless signal transmission. Hence, an unreliable wireless communication fabric with numerous erroneous signal transmissions will increase the competition among the wired and wireless data for these shared resources.

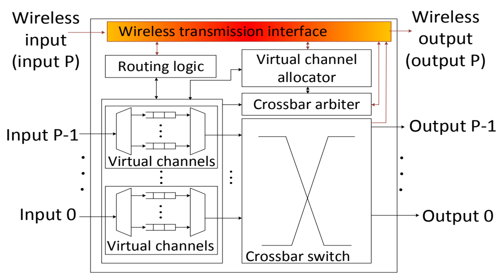


Figure 4. Hybrid wired-wireless router architecture for wireless NoCs

To increase the reliability of such networks, the wireless transmission interface can be equipped with a retransmission buffer and a suitable error encoding and decoding scheme as shown in Figure 5 [23]. However, the overhead of the erroneous packets as well as the retransmission process introduce contention on the wireless and wireless layers, and hence have drastic effects on the performance of the WiNoC.

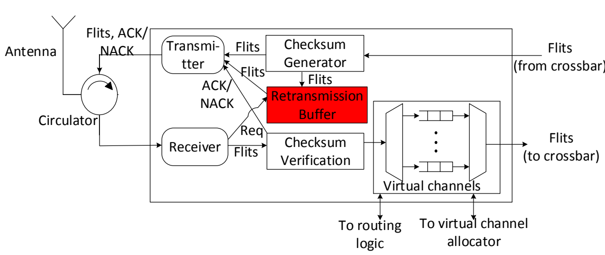


Figure 5. Wireless transmission interface for mm-Wave WiNoC [23]

Moreover, buffer spaces contribute significantly to the total power consumption of the NoC [28] and should be used judiciously. In the proposed surface wave communication fabric for WiNoC, a dielectric coated metal layer is employed as a guided medium for surface wave signal propagation. The router micro-architecture has a similar design as presented in Figure 4. With the right design consideration, the transducer and wireless medium could be designed to transmit with minimum communication loss and achieve a transmission reliability similar to the wired communication layer. Consequently, the retransmission buffer in Figure 5 can be avoided or adopted for more novel performance improvement techniques. In the following sections we present the design considerations for the proposed reliable wireless communication fabric in the form of surface wave.

4. Problem Formulation

To understand the problem of designing a reliable alternative CMOS based 2-D waveguide communication fabric for existing WiNoCs as well as the relationship between the choice of waveguide material and signal strength, we characterize the field components of surface wave transmission in the Transverse Magnetic mode (TM). A thin lossy dielectric coated perfect conductor placed in the x-y plane and surrounded by free space, as shown in Figure 3, is investigated. The TM signal independent of the y coordinate that propagates along the x axis and satisfies the Maxwell equations [29, 30] is evaluated. In free space, Medium 3 (ε = μ = 1), the following can be derived:

$$H_y = e^{jk1(z-|A|)}e^{j(\beta x)} \tag{3}$$

$$E_z = -\frac{Z_0\beta}{k_0\varepsilon}e^{jk1(z-|A|)}e^{j(\beta x)} \tag{4}$$

$$E_x = \frac{Z_0 k_1}{k_0\varepsilon}e^{jk1(z-|A|)}e^{j(\beta x)} \tag{5}$$

where k_0 and Z_0 are the number of waves and the impedance of free space, respectively. β is the propagation constant. Inside the dielectric layer, Medium 2, the electric and magnetic field components are given by:

$$H_y = \frac{\cos(k_2 z)}{\cos(k_2|A|)}e^{j(\beta x)} \tag{6}$$

$$E_z = -\frac{\beta\cos(k_2 z)}{Z_0 k_0\varepsilon\cos(k_2|A|)}e^{j(\beta x)} \tag{7}$$

$$E_x = j\frac{Z_0 k_2\sin(k_2 z)}{k_0\varepsilon\cos(k_2|A|)}e^{j(\beta x)} \tag{8}$$

where k_1 and k_2 are the transverse waves numbers in Medium 3 and Medium 2, respectively, which can be solved through the Helholtz wave equation [30]:

$$k_1 = \sqrt{{k_0}^2 - \beta^2} \tag{9}$$

$$k_1 = \sqrt{{k_0}^2\varepsilon\mu - \beta^2} \tag{10}$$

The surface impedance Z_s of the interface between Medium 3 and Medium 2 is given by:

$$Z_s = -\frac{E_x}{H_y} = -Z_0\frac{k_1}{k_1} \tag{11}$$

To enable the field concentration in Medium 3 nearer to the surface of Medium 2 for TM-surface wave propagation, Z_s must be inductive. Thus the imaginary part of k_1 should be positive. Therefore to design a 2-D waveguide fabric for on-chip communication, a dielectric coated conductor with sufficiently high inductive reactance needs to be implemented. The surface reactance, X_s is given by [31]:

$$X_s = 2\pi f \mu_0 \left[\frac{\varepsilon-1}{\varepsilon}|A| + 0.5\delta\right] \tag{12}$$

Equation 12 confirms that the realization of TM mode for 2-D wave propagation for communication is related to the operating frequency, f, dielectric constant, ε, thickness of the dielectric material, |A|, and the skin depth of the metal conductor, δ. The skin depth is given by:

$$\delta = \sqrt{\frac{1}{\pi f \mu_0 \sigma}} \tag{13}$$

where σ is the conductivity of the metal conductor. Hence, the problem of designing a reliable surface wave communication fabric for the wireless layer of WiNoCs can be formulated as follows:

Objective: Determine the particular design parameters of the TM surface wave communication medium with a positive surface reactance X_s along with a transducer to operate at a frequency *f* such that:

$$\max_{\forall Tx \to Rx \in \mathrm{T}}(S_{21}) \tag{14}$$

subject to:

$$\Psi = BER_w - BER_T, where\ \Psi\ \leq min \tag{15}$$

where S_{21} represents the signal strength transferred from the transducer *Tx* to the receiver *Rx* and *T* is the set of transducers with transmitters and/or receivers, respectively. BER_w and BER_T are the bit error rates of the wired and wireless channels, respectively. The most reliable design has a ψ = 0 and hence the minimum (min in Equation 15) must be as close to zero as possible.

5. IMPROVED WIRELESS COMMUNICATION FABRIC FOR NOCS

In order to solve the issue of throughput degradation due to the increased error rates in existing WiNoCs, we replace the wireless channel with a reliable 2-D communication fabric which radiates signals in the form of surface waves as shown in Figure 3. Transverse Magnetic mode (TM) surface wave can be supported by a dielectric-coated metal surface. To enable the field concentration in Medium 2 nearer to the surface of Medium 1 for TM-surface wave propagation, a positive surface reactance is required. We use commercially available Taconic RF-43 material [15] with 0.2mm thickness as the dielectric. The Taconic material employed is low loss cost-effective TacLamplus material which is laser ablatable, non-reinforced microwave substrate that is ideal for very low loss substrate. For the same frequency, f, it can be deduced from Equation 12 that X_s will increase with |A|. Therefore, more wave will stay on the surface and in effect increase the efficiency. However, for TM surface propagation, X_s has an upper bound constraint: it cannot be too high, otherwise the wave will propagate into the dielectric, rather than on the surface. Consequently X_s should around j200 Ω to j250 Ω. By introducing the 0.25mm thick Taconic material, we can achieve a surface reactance X_s of 30Ω to 150Ω over the wide frequency range of 20GHz to 100GHz for TM mode surface wave. Our goal is to improve the gain between the transmitted signal and the received signal. Hence, we investigate the design of an efficient transducer (Figure 6) that is able to translate between wired and wireless signals at the preferred operating frequency (60GHz in this paper). The designed transducer consists of a parallel waveguide fed by a quarter-wavelength monopole through an open aperture. The transducer is coupled to a transceiver circuit which is responsible for modulation, signal transmission and receiving capabilities. For a reliable transmission, a low power consumption transceiver circuit which has a wide bandwidth with high data throughput must be considered. Hence, we adopt the low-power non-coherent on-off keying (OOK) modulator for our implementation. Embedded in the transmitter design is an up-conversion mixer and a power amplifier (PA) while the receiver is equipped with a low noise amplifier (LNA), a baseband amplifier and a down-conversion mixer as shown in Figure 6. A single injection-lock voltage-controlled oscillator (VCO) is used for both the transmitter and the receiver to reduce the area overhead and power consumption. More details on the implementation of the transceiver module along with the circuitry can be found in [10].

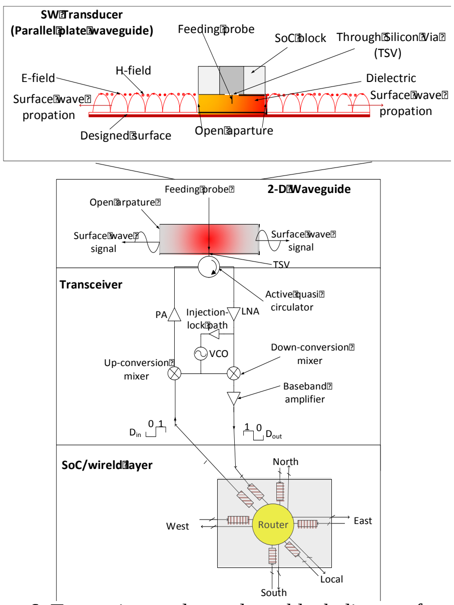


Figure 6. Transceiver and transducer block diagram for generating surface wave for on-chip communication

At the nodes equipped with both wireless transmission and receiving capabilities, a CMOS-based circulator is employed as a communication bridge between the transmitter, receiver and the 2-D waveguide medium, to enable the use of a single wave feeder at the nodes [32]. It should be noted the some nodes in the WiNoCs do not have transmitting capabilities and hence are only equipped with the receiver circuits. A system level simulation using Simulink and in TSMC 65-nm standard CMOS process performed in [33] have demonstrated that the total power consumption of the adapted OOK transceiver is 36.7mW. Moreover, the transceiver is able to achieve a (BER) less than 10^{-14} and at data rate of at least 16Gb/s for the designed communication range of 20mm which is comparable to that of the traditional wired network. Hence we adopt this transceiver design in our implementation [33, 10]. Therefore, the challenge is to demonstrate that the receive signal power at the destination node is similar to the transmit signal power at the source node over the proposed wireless communication fabric, which is demonstrated in the next section.

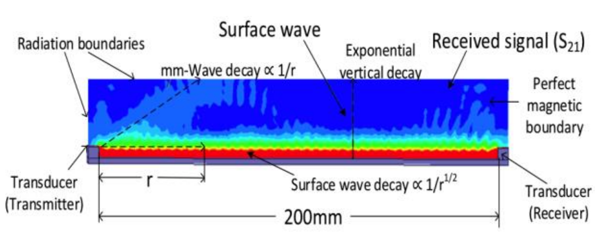


Figure 7. Simulated electric field distribution

6. TRANSMISSION STRENGTH OF THE PROPOSED SURFACEWAVE COMMUNICATION FABRIC

To demonstrate the effectiveness of the proposed wireless communication fabric, we have performed simulations in Ansys High Frequency Structured Simulator [34]. Figure 7 shows the HFSS simulation setup. The transducers are placed as far as 200mm (equivalent to 40 free space wavelengths at operating frequency of 60GHz) apart to investigate the signal integrity and the possible performance benefits of the proposed 2D waveguide over existing on-chip wireless NoCs. Moreover, we investigate the effect of adopting an off-the-shelf transducer (patched antenna) on the signal strength of surface wave. As shown in Figure 7 the electric field distribution is concentrated on the designed surface which demonstrates that a high percentage of the transmitted signal is successfully launched into the communication fabric. Across the long distance separation of 200mm between the transducer and transceiver, a near constant electric field distribution is achieved. Also the electric field decays exponentially away from the implemented surface, indicating that surface wave is successfully launched and received with high signal efficiency.

Figure 8 shows the S_{21} (dB) over wide-band frequency on the reactive surface with different lossy dielectric materials. It can be seen that, the reactive surface appears to have a flat response over a wide frequency range and has a 3 dB bandwidth of almost 45GHz (from 30GHz to 75GHz with Tan Loss = 0.01), and a 5dB bandwidth of almost 60GHz (from 30GHz to 87GHz with Tan Loss = 0.01). Figure 9 demonstrates that surface wave signal generated with an off-the-shelf transducer (eg. patch antenna) results in a much lower S_{21} (around -84dB) at the operating frequency (64GHz). Moreover, the S_{21} of the zigzag antenna which is commonly used in mm-Wave WiNoCs is around -36dB (see Figure 8) which is significantly lower than that of the proposed communication fabric [19]. Therefore, the proposed communication fabric is able to successfully excite and transmit high frequency-high bandwidth surface wave signals with high reliability ($S_{21}$of 0 to -2dB) of the NoC with a BER comparable to that of wired NoCs.

7. Evaluation

In order to evaluate the performance of the proposed communication fabric, a cycle-accurate simulator is used by extending Noxim simulator, an existing SystemC-based NoC simulator. We adapt the BER and the S_{21} of the communication fabric as the error model. In the simulation, a fixed packet size of 3 flits and buffer depth of 6 flits are used. Both regular and non-regular mesh topologies are investigated. 5 evenly distributed nodes in the WiNoC have both transmitting and receiving capabilities while all other nodes have only receivers. We consider deterministic XY routing algorithm. The underlying routing algorithm is employed in the wired layer until a wireless node with a transceiver is encountered. Packets are then sent to the destination node via the single-hop wireless channel. In the experiments we compare the performance efficiency of the proposed communication fabric with mm-Wave in WiNoCs.

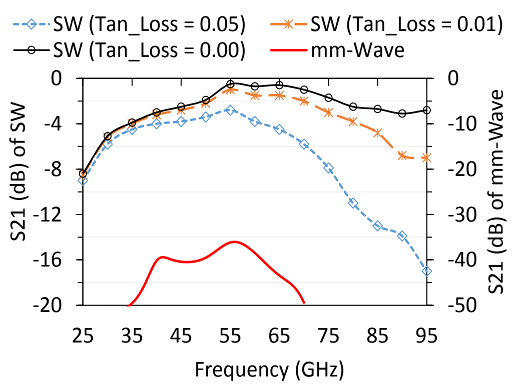


Figure 8. S_{21} (dB) over wide-band frequency on the reactive surface

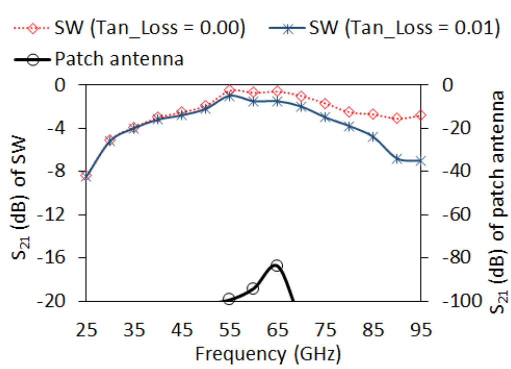


Figure 9. S21 (dB) over wide-band frequency on the reactive surface with different transducer designs

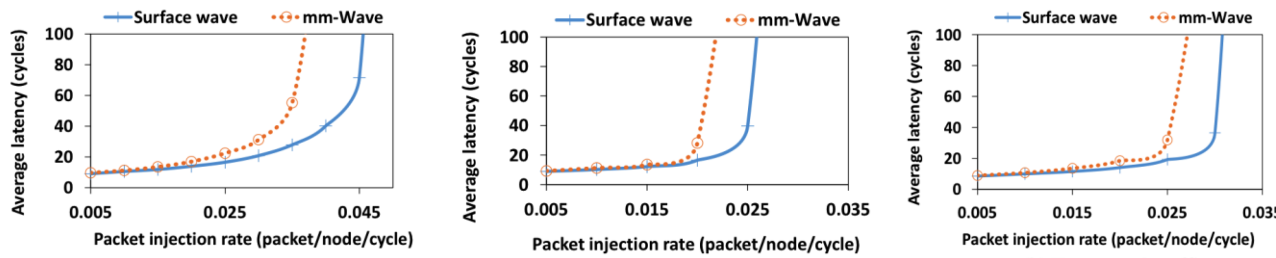
Both static and dynamic power of the router are calculated in Orion2.0 model for 45nm technology. The wired links along the x and y dimensions are modeled as 3.6mm and 5.2mm, respectively. For the power analysis along the surface wave and mm-Wave channels, we exploit the S_{21} signal voltage gain between the transmitters and receivers [13]:

$$S_{21} = E + 20 \log e^{\alpha d} \tag{16}$$

where α is the attenuation constant of the wireless communication fabric, d is the separation between the transmitting and receiving nodes and E is the loss constant due to the transducer. Based on extracted values from a Matlab fitting tool [13] and conducted experiments (see Section 3), α is calculated as 6.33 and E values of -23:8 and -1 are calculated for mm-Wave and surface wave, respectively. These values have been imported in to the simulator for power estimation.

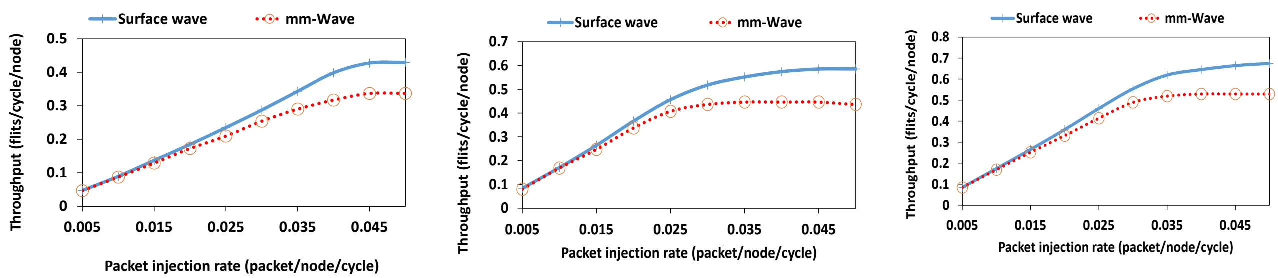
A. Performance Under Synthetic Traffic Patterns

Random traffic mimics high internode communication density due to the even distribution of communication among nodes. Hence, we evaluate the effect of the wireless communication fabric on the average packet latency and data throughput under random traffic patterns. Moreover, we have applied two transpose synthetic traffic patterns where source nodes generate packets to specific destination nodes. Figure 10 shows that, the proposed hybrid wired surface wave NoC has less average packet delays and can sustain about 29% more traffic load compared to mm-Wave WiNoC under deterministic XY routing in both random and transpose traffic patterns. This is due to the extra traffic load introduced by the high rate of retransmitted erroneous packets which causes contention in mm-Wave WiNoCs. Figure 11 shows the variation of throughput with traffic load in surface wave and mm-wave WiNoCs under different traffic patterns. Similar to Figure 10, the improved surface wave communication fabric outperforms mm-Wave in all scenarios. Both communication fabrics have similar throughput at low



(a) Random traffic (b) Transpose1 traffic (b) Transpose2 traffic

Figure 10. Average packet latency under XY routing and different traffic patterns in 6 x 4 NoC



(a) Random traffic (b) Transpose1 traffic (b) Transpose2 traffic

Figure 11. Network throughput under XY routing and different traffic patterns in 6 x 4 NoC

traffic loads. However, the throughput of mm-Wave saturates at a lower injection load. As can be deduced from Figures 10 and 11, the maximum sustainable load has a significant effect on the throughput of the communication fabric in the WiNoC. The error rate along the wireless experience longer delays compared to surface wave.

Table 1 shows the average performance improvement of surface wave over mm-Wave WiNoC in terms of saturation load, average packet latency and throughput of various NoC configurations under random traffic pattern with west-first adaptive routing and random selection method. In general, surface wave improves the maximum sustainable load, average packet latency and throughput by an average of 20.9%, 10.7% and 13.8% compared to mm-Wave. The power consumption of surface wave is compared with that of mm-Wave under different traffic patterns and XY routing in 6 x 4 WiNoC.

Table 1. Improvement of surface wave over mm-wave WiNoC averaged over different virtual channels (2, 4 and 6) and buffer sizes (4, 6, 8, 10, 18).

Network Dimensions	Saturation load (%)	Latency (%)	Throughput (%)
5x5	22.9	16.4	12.7
6x6	23	8.9	13.9
8x8	18.9	6,7	14.6

Compared to surface wave, mm-Wave consumes around 12%, 17% and 12% more power in random, transpose1 and transpose2 traffic patterns, respectively. This is because the wireless channel in mm-Wave WiNoC is lossy with high signal loss constant due to free space propagation while the proposed surface wave communication fabric transmits signals with high S21. Therefore, the proposed surface wave communication fabric has more promising power efficiency for long distance communications in WiNoCs compared to traditional mm-Wave.

B. Performance Under Real Applications

To further validate the performance benefits of the proposed communication fabric, M5 simulator [35] is used to acquire memory access traces from a full system running PARSEC v2.1 benchmarks [36]. 64 two-wide superscalar out-of-order cores with private 32KB L1 instruction and data caches with a shared 16MB L2 cache are used. Netrace18 is used to retrieve the memory traces which are post-processed based on the dependencies between transactions. Memory accesses are interleaved at 4KB page granularity among 4 on-chip memory controllers. The normalized average packet latency improvement of surface wave over mm-Wave in WiNoCs under PARSEC benchmark is presented in Figure 12. The proposed surface wave communication fabric has lower packet latency compared with mm-Wave on-chip communication fabrics in all cases. Specifically, the performance improvements of surface wave over mm-Wave is over 30% in high contention workload such as swaptions and channeal.

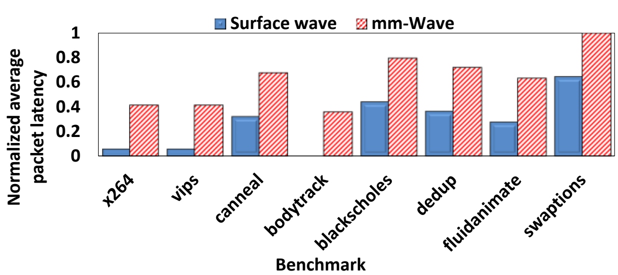


Figure 12. Network throughput under XY routing and different traffic patterns in 6 x 4 NoC

Conclusions

This paper proposes an improved wireless communication fabric for WiNoCs as a solution to the throughput and reliability degradation of the wireless channel. A quarter-wave transducer and a commercially available thin metal conductor coated with a low cost Taconic Taclamplus dielectric material are designed as the wireless communication fabric which generates reliable surface wave signals. HFSS and cycle-accurate evaluations show that, a high bandwidth of up to 60GHz can be achieved with significant improvements in average packet latency, throughput and power consumption compared to existing WiNoCs. Future work includes an efficient technique to improve transmission signal strength of the wireless channels in existing hybrid wired-wireless NoCs by a novel dynamic cooperative management system.

References

[1] M. O. Agyeman, A. Ahmadinia, and A. Shahrabi, “Heterogeneous 3d network-on-chip architectures: area and power aware design techniques,” *Journal of Circuits, Systems and Computers*, vol. 22, no. 4, p. 1350016, 2013.

[2] “Tour guide to 3d-ic design tools and services,” http://-www.gsaglobal.org/eda/docs/, 2015, accessed: 06/2012.

[3] M. O. Agyeman and A. Ahmadinia, “Optimising heterogeneous 3d networks-on-chip,” in *PARELEC*, 2011, pp. 25–30.

[4] Y. H. H. L. X. L. Ying Wang, Lei Zhang, “Economizing TSV Resources in 3D Network-on-Chip Design,” *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, 2014.

[5] M. O. Agyeman, A. Ahmadinia, and A. Shahrabi, “Low power heterogeneous 3d networks-on-chip architectures,” in *International Conference on High Performance Computing and Simulation (HPCS)*, 2011, pp. 533 –538.

[6] M. Agyeman and A. Ahmadinia, “An adaptive router architecture for heterogeneous 3d networks-on-chip,” in *NORCHIP, 2011*, 2011, pp. 1 –4.

[7] S. Lee, S. Tam, I. Pefkianakis, S. Lu, M. F. Chang, C. Guo, G. Reinman, C. Peng, M. Naik, L. Zhang, and J. Cong, “A scalable micro wireless interconnect structure for cmps,” in *Annual International Conference on Mobile Computing and Networking MOBICOM*, 2009, pp. 217–228.

[8] M. Yuan, W. Fu, T. Chen, and M. Wu, “An exploration on quantity and layout of wireless nodes for hybrid wireless network-on-chip,” in *High Performance Computing and Communications, Intl Symp on Cyberspace Safety and Security, IEEE Intl Conf on Embedded Software and Syst (HPCC,CSS,ICESS)*, 2014, pp. 100–107.

[9] S. Gade, H. Mondal, and S. Deb, “A hardware and thermal analysis of dvfs in a multi-core system with hybrid wnoc architecture,” in *International Conference on VLSI Design (VLSID)*, 2015, pp. 117–122.

[10] X. Yu, S. Sah, S. Deb, P. Pande, B. Belzer, and D. Heo, “A wideband body-enabled millimeter-wave transceiver for wireless network-on-chip,” in *International Midwest Symposium on Circuits and Systems (MWSCAS)*, 2011, pp. 1–4.

[11] C. Xiao, Z. Huang, and D. Li, “A tutorial for key problems in the design of hybrid hierarchical noc architectures with wireless/rf,” *Smart CR*, no. 6, pp. 425–436, 2013.

[12] A. Ganguly, P. Pande, B. Belzer, and A. Nojeh, “A unified error control coding scheme to enhance the reliability of a hybrid wireless network-on-chip,” in *IEEE International Symposium on Defect and Fault Tolerance in VLSI and Nanotechnology Systems (DFT)*, 2011, pp. 277–285.

[13] A. Karkar, R. Al-Dujaily, A. Yakovlev, K. Tong, and T. S. T. Mak, "Surface wave communication system for on-chip and off-chip interconnects," in *Fifth International Workshop on Network on Chip Architectures (NoCArc)*, 2012, pp. 11–16.

[14] A. Noda and H. Shinoda, "Selective wireless power transmission through high-q flat waveguide-ring resonator on 2-d waveguide sheet," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 8, pp. 2158–2167, 2011.

[15] "Taconic rf-41, rf-43, rf-45 datasheet," http://-www.taconic-add.com/pdf/rf43.pdf, 2015, accessed: 02/2015.

[16] P.-J. Guo and H. R. Chuang, "A 60-ghz millimeter-wave cmos rfic-on-chip meander-line planar inverted-f antenna for wpan applications," in *IEEE Antennas and Propagation Society International Symposium (AP-S)*, 2008, pp. 1–4.

[17] J. Lin, H.-T. Wu, Y. Su, L. Gao, A. Sugavanam, J. Brewer, and K. O, "Communication using antennas fabricated in silicon integrated circuits," *IEEE Journal of Solid-State Circuits*, vol. 42, no. 8, pp. 1678–1687, 2007.

[18] J. Lin, L. Gao, A. Sugavanam, X. Guo, R. Li, J. Brewer, and K. O, "Integrated antennas on silicon substrates for communication over free space," *IEEE Electron Device Letters*, vol. 25, no. 4, pp. 196–198, 2004.

[19] S. Deb, A. Ganguly, P. Pande, B. Belzer, and D. Heo, "Wireless noc as interconnection backbone for multicore chips: Promises and challenges," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 2, no. 2, pp. 228–239, 2012.

[20] K. Chang, S. Deb, A. Ganguly, X. Yu, S. P. Sah, P. P. Pande, B. Belzer, and D. Heo, "Performance evaluation and design trade-offs for wireless network-on-chip architectures," *J. Emerg. Technol. Comput. Syst.*, vol. 8, no. 3, pp. 23:1–23:25, 2012.

[21] J. Branch, X. Guo, L. Gao, A. Sugavanam, J.-J. Lin, and K. O, "Wireless communication in a flip-chip package using integrated antennas on silicon substrates," *IEEE Electron Device Letters*, vol. 26, no. 2, pp. 115–117, Feb 2005.

[22] M.-C. Chang, V. Roychowdhury, L. Zhang, H. Shin, and Y. Qian, "Rf/wireless interconnect for inter- and intra-chip communications," *Proceedings of the IEEE*, vol. 89, no. 4, pp. 456–466, 2001.

[23] S. Yin, Y. Hu, Z. Zhang, L. Liu, and S. Wei, "Hybrid Wired/Wireless On-Chip Network Design for Application-Specific SoC," *IEICE Transactions on Electronics*, pp. 495–505, 2012.

[24] A. Hajimiri, "mm-wave silicon ics: Challenges and opportunities," in *IEEE Custom Integrated Circuits Conference (CICC)*, 2007, pp. 741–747.

[25] A. Ganguly, P. P. Pande, B. Belzer, and A. Nojeh, *Sustainable and Reliable On-Chip Wireless Communication Infrastructure for Massive Multi-core Systems*. Springer, 2013.

[26] V. Vijayakumaran, M. P. Yuvaraj, N. Mansoor, N. Nerurkar, A. Ganguly, and A. Kwasinski, "Cdma enabled wireless network-on-chip," *J. Emerg. Technol. Comput. Syst.*, vol. 10, no. 4, pp. 28:1–28:20, 2014.

[27] A. Karkar, N. Dahir, R. Al-Dujaily, K. Tong, T. S. T. Mak, and A. Yakovlev, "Hybrid wire-surface wave architecture for one-to-many communication in networks-on-chip," in *Design, AutomationTest in Europe Conference Exhibition (DATE)*, 2014, pp. 1–4.

[28] J. Hu and R. Marculescu, "Application-specific buffer space allocation for networks-on-chip router design," in *IEEE/ACM International conference on Computer-aided design*, ser. ICCAD, 2004, pp. 354–361.

[29] O. Balosso, J. Sokoloff, and S. Bolioli, "Brief overview about surface wave theory and applications," in *International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM)*, 2012, pp. 1–7.

[30] R. Ling, J. Scholler, and P. Y. Ufimtsev, "The propagation and excitation of surface waves in an absorbing layer - abstract," *Journal of Electromagnetic Waves and Applications*, vol. 12, no. 7, pp. 883–884, 1998.

[31] J. Turner, M. Jessup, and K.-F. Tong, "A novel technique enabling the realisation of 60 ghz body area networks," in *Ninth International Conference on Wearable and Implantable Body Sensor Networks (BSN)*, 2012, pp. 58–62.

[32] R. Bahri, A. Abdipour, and G. Moradi, "Analysis and design of new active quasi circulator and circulators," *Progress In Electromagnetics Research*, vol. 96, pp. 377–395, 2009.

[33] X. Yu, S. P. Sah, B. Belzer, and D. Heo, "Performance evaluation and receiver front-end design for on-chip millimeter-wave wireless interconnect," in *International Green Computing Conference*, 2010, pp. 555–560.

[34] M. Ravenstahl and M. Kopp, "Application brief: Ansys hfss for ecad, ansys," 2013.

[35] N. Binkert, R. Dreslinski, L. Hsu, K. Lim, A. Saidi, and S. Reinhardt, "The m5 simulator: Modeling networked systems," *IEEE Micro*, vol. 26, no. 4, pp. 52–60, 2006.

[36] C. Bienia, S. Kumar, J. P. Singh, and K. Li, "The parsec benchmark suite: Characterization and architectural implications," in *Parallel Architectures and Compilation Techniques*, 2008, pp. 72–81

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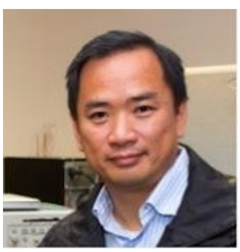

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