On the Design of Reliable Hybrid Wired-Wireless Network-on-Chip Architectures

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***Abstract*—With the ever increase in transistor density over technology scaling, energy and performance aware hybrid wireless Network-on-Chip (WiNoC) has emerged as an alternative solution to the slow conventional wireline NoC design for future System-on-Chip (SoC). However, combining wireless and wireline channels drastically reduces the total reliability of the communication fabric. Besides being lossy, existing feasible wireless solution for WiNoCs, which is in the form of millimeter wave (mm-Wave), relies on free space signal radiation which has high power dissipation with high degradation rate in the signal strength per transmission distance. Alternatively, low power wireless communication fabric in the form of surface wave has been proposed for on-chip communication. With the right design considerations, the reliability and performance benefits of the surface wave channel could be extended. In this paper, we propose a surface wave communication fabric for emerging WiNoCs that is able to match the channel reliability of traditional wireline NoCs. Here, a carefully designed transducer and commercially available thin metal conductor coated with a low cost dielectric material are employed to general surface wave signal to improve the wireless signal transmission gain. Our experimental results demonstrate that, the proposed communication fabric can achieve a 5dB operational bandwidth of about 60GHz around the center frequency (60GHz). By improving the transmission reliability of wireless layer, the proposed communication fabric can improve maximum sustainable load of NoCs by an average of 20.9% and 133.3% compared to existing WiNoCs and wireline NoCs, respectively.**

I. Introduction

Recent efforts to enhance the performance efficiency as well as the technological scalability of the conventional metal based interconnects (wireline) has emanated the research for alternative interconnect fabrics such as optical networks, three dimensional integrated circuits (3-D ICs) and millimeter wave (mm-wave), for emerging System-on-Chip (SoC) design [1], [2]. In optical interconnects a photon needs to be converted back to electrons to be stored in the electronic circuitry. Consequently, optical networks have a high design complexity as well as high power, area, and latency overheads. On the other hand, though 3-D ICs are Complementary Metal Oxide Semiconductor (CMOS) compatible and have shorter vertical links with enhanced scalability, 3D integration is still in its infancy due to alignment, low yield and high temperature dissipation issues in the current technology which lowers the reliability of system [3], [4].

RF interconnect has low area and low power consumption due to its CMOS compatibility. However, RF interconnect relies on long transmission lines for guided data transmission which requires alignment between transmission pairs. Mm-Wave, has emerged as a more feasible solution with promising CMOS components that can scale with transistor technology. However, the on-chip antennas and transceivers have non-negligible area and power overheads. Conventional wireline based NoCs on the other hand, are highly efficient for short distances despite their limitations over long distance. Consequently, hybrid wired-wireless Networks-on-Chip (WiNoCs) have emerged to combine the global performance benefits of mm-Wave as well as the short range low power and area benefits of the wireline communication fabric in NoCs. However the wireless communication fabric is lossy and hence lowers the overall reliability of WiNoCs [5]–[7]. Conventional wires have extremely low bit error rate (BER) of around 10^{-14} compared to that of mm-Wave (around 10^{-7}). Moreover, the E-field decay rate of the mm-Wave can be expressed as:

$$E_{decay} \propto \frac{1}{d} \tag{1}$$

where d is the separation between the transmitting and the receiving nodes. Consequently, the transmit signal loss on the wireless layer is significantly high. Also, 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 [8]. 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 (ECC) [9] and retransmission schemes [5] could be employed. However, these techniques rely on the underlying lossy wireless communication fabric for retransmission of handshake signals, 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.

Wireless communication fabric in the form of surface wave (SW) has been proposed as an emerging wireless communication fabric that is power efficient with improved data throughput for long distance communication [10], [11]. 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 reliability wireless interface [10]. 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 summary, in this paper:

1) We improve the overall reliability of hybrid wired-wireless Networks-on-Chip by combining a thin metal layer coated with low cost dielectric material (Taconic RF-43 [12]) to generate surface wave signals as the reliable wireless communication medium. Additionally, we evaluate the performance of a carefully designed transducer for on-chip wireless communications.
2) We present the design considerations for the realization of the proposed SW fabric 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.
3) We perform cycle-accurate based evaluations of the proposed communication fabric and comparing with emerging WiNoCs as well as conventional reliable wireline communication fabric. Even without any complex error recovery scheme, arbitration or retransmission protocol, the proposed communication fabric can improve the maximum sustainable load of existing WiNoCs and wireline NoCs by an average of 20.9% and 133.3%, respectively, with much lower average packet latency.

II. Related Work

Advances in current integration technology makes it possible to implement a wireless transceiver on a silicon die [13]–[15]. 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 [16]. 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 [7], [17] is the transmission reliability of the wireless channel. As an effort to address this issue, Ganguly et al. [9], [18] 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 codebased 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 [16] to improve the reliability of WiNoCs. However, ECC introduces timing, area and packet overheads which affects the overall transmission efficiency of the WiNoC [5]. Alternatively, Lee et al. [5] adopted an overhearing scheme for WiNoCs. Here a zero-signaling-overhearing-and-retransmission is presented to manage the packet loss along the wireless channel. A checksum-based error-detection and retransmission scheme at the last hop. Vijayakumaran et al. [19] 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 [10]. Previous contributions on SW have focused network architecture and performance with considerations of arbitration, packet routing and efficient handling of multicast packets [10], [20]. 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 the 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.

III. Reliable Wireless NoCs

A. Network Architecture

A promising way to mitigate the communication overhead incurred by the multi-hop channels among remote cores in traditional wireline NoCs is to adopt wireless communication fabric as a supplementary material. Surface wave communication has been recently demonstrated as a feasible on-chip wireless solution with improved long-range communication, low-power and high bandwidth [10], [20]. Here, the wireless communication layer of WiNoCs is replaced with a waveguide medium as the surface wave communication fabric for global communication which generates a NoC architecture as shown in Fig. 1. The 2-D guided wave enhances low power-fast global

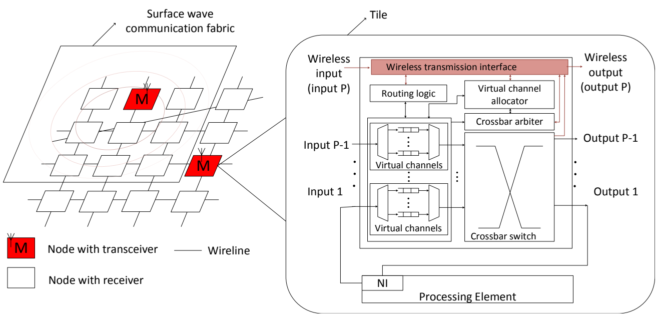


Fig. 1. Hybrid wireline-surface wave NoC architecture

communication which gives reasonably high performance to area ratio with an E-field decay rate of:

$$E_{decay} \propto \frac{1}{\sqrt{(d)}} \quad (2)$$

Compared to traditional mm-Wave-based WiNoCs, 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 adapt to the wireless channels, the routers at the wireless nodes in WiNoCs are equipped with a wireless transmission interface which serves as a bridge between the wireless and the wireline 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 wireline and wireless data for these shared resources.

As an effort 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. However, the overhead of the erroneous packets as well as the retransmission process introduces contention on the wireless and wireless layers, and hence have drastic effects on the performance of the WiNoC. Moreover, buffer spaces contribute significantly to the total power consumption of the NoC [21] and should be used judiciously.

In the following sections we present the design considerations for the proposed reliable wireless communication fabric in the form of surface wave.

B. *Problem Formulation*

The surface reactance X_s for surface wave transmission in the Transverse Magnetic mode *(TM)* is given by:

$$X_s = 2\pi f \mu_0 \left[\frac{\epsilon - 1}{\epsilon} |A| + 0.5\delta \right] \tag{3}$$

Eq. 3 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 (proof and further details are given in Appendix). The skin depth is given by:

$$\delta = \sqrt{\frac{1}{\pi f \mu_0 \sigma}} \tag{4}$$

where σ is the conductivity of the metal conductor. Hence to solve the problem of improving the reliability of the wireless channel of emerging WiNoCs, our objective is to determine the particular design parameters of the TM surface wave communication medium with a positive surface reactance along with a transducer to operate at a frequency f such that:

$$\max_{\forall Tx \rightarrow Rx \in T} (S_{21}) \tag{5}$$

subject to:

$$\psi = BER_w - BER_T \tag{6}$$

where

$$\psi \leq min \tag{7}$$

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 wireline and wireless channels, respectively. The most reliable design has a ψ = 0 and hence the minimum (min in Eq 7) must be as close to zero as possible.

IV. An Improved Wireless Communication Fabric for Emerging Wireless NoC Architectures

Surface wave wireless communication medium can be implemented with a thin lossy dielectric coated perfect conductor plane surrounded by free space. Our aim is to design a communication medium with minimum transmission loss as possible in order to improve the reliability of WiNoCs. Fig. 2 shows the functional blocks of the proposed surface wave communication fabric for WiNoC. Here, a dielectric coated metal layer is employed as a guided medium for surface wave signal propagation. 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 wireline communication layer.

To generate an efficient TM surface wave signal, the following

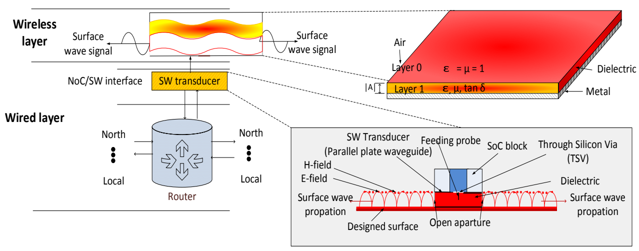


Fig. 2. Interface between the 2-D guided wave channel and the wireline channel

considerations are made for the design of the 2-D waveguide sheet. We use commercially available Taconic $RF-43$ material. Hence, we employ a low loss and cost-effective TacLamplus material which is laser ablatable, non-reinforced microwave substrate that is ideal for very low loss substrate [12] with 0.2mm thickness as the dielectric (Layer 1 in Fig. 2). As shown in Fig. 3 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. To achieve a high surface wave efficiency, a thin substrate is employed. Our goal is to improve

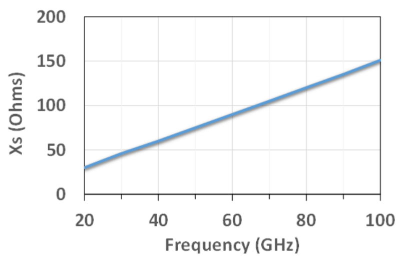


Fig. 3. Variation of surface reactance X_s with frequency

the gain between the transmitted signal and the received signal. Hence, we investigate the design of an efficient transducer that is able to translate between wireline 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. 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 [6].

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 [22]. 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 [23] 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 wireline network. Hence in this paper we adopt the above transceiver [6], [23].

Hence, 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.

V. Evaluation of Proposed Wireless Communication Fabric

To demonstrate the effectiveness of the proposed wireless communication fabric, we have performed simulations in Ansys High Frequency Structured Simulator [24]. Fig. 4 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. We have also implemented a model of mm-Wave for on-chip communication. Here, a zigzag antennas which is considered to be the most efficient antenna for mm-Wave on-chip communication is employed. The zigzag antennas are separated by a distance of only 20mm. As shown in Fig. 4, the electric field distribution is concentrated in Area2 which demonstrates that a high percentage of the transmitted signal is successfully launched into the surface. Across the long distance separation between of 200mm (from Area1 to Area3) 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 a high signal efficiency.

Fig. 5 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 having 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). On the other hand, Fig. 5 also shows that the S_{21} of mm-Wave is around -36dB which is significantly lower than that of the proposed communication fabric. Moreover, though wireline can achieve a high signal strength, transmission frequency high transmission frequency of the wires is inhibited by induced coupling, crosstalk and temperature induced noises [9]. 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). Consequently, when employed as the wireless communication medium for hybrid wired-wireless NoCs, the proposed fabric improves the reliability of the NoC with a BER comparable to that of wireline NoCs. Fig. 6 shows that, for a fixed signal to noise ratio (SNR) of a communication fabric with an attenuation constant α, the improvement in rate of change in transmission gain $G_{a,dB}$ for a receiver node placed at $d^{'}$ from a transmitting node at d which is given by:

$$G_{a,dB} = \frac{-20}{T_{(d'-d),ps}} \left(\log_{10}\left(\frac{d^{'}}{d}\right) + \alpha(d^{'}-d)\log_{10} e \right) \quad (8)$$

of the proposed communication fabric (SW) over mm-Wave increases significantly as the separation between transmitting

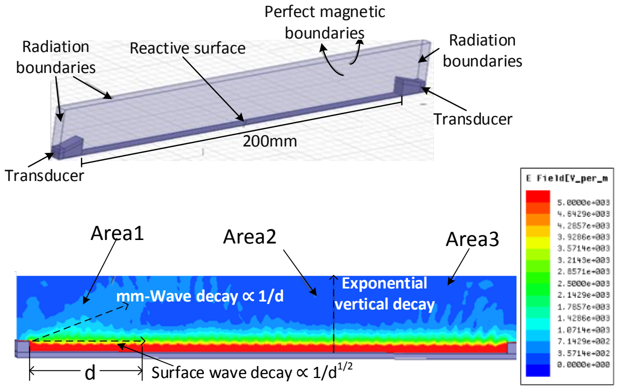


Fig. 4. 2D simulation model for surface wave communication system

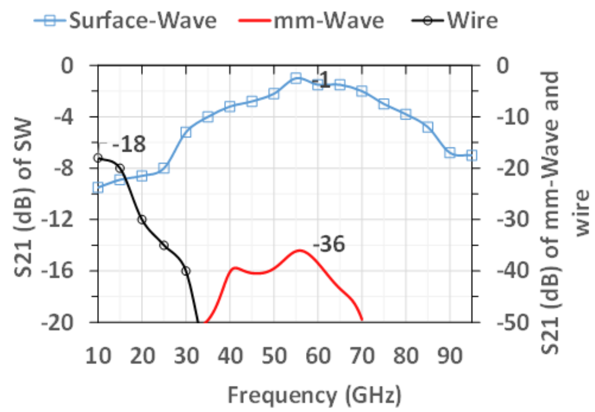


Fig. 5. S_{21} (dB) over wide-band frequency on the reactive surface with different lossy dielectric materials

node and receive node increases. This is because as the distance between the communicating pair increases, the E-field of mm-Wave decays at an exponential rate in free space which lowers the signal strength as shown in Fig. 4. In the wireline channels, there is no need for transceiver circuits to convert wireless signals. Hence at low distances, wireline is more efficient than the wireless communication fabric. However, the delay along the wires have drastic effects which causes significant drop in the rate of transmission gain as the distance to destination node increases. Consequently, the proposed communication fabric provides a feasible performance to distance tradeoff with higher transmission gains and lower delays when combined with wires in hybrid WiNoCs.

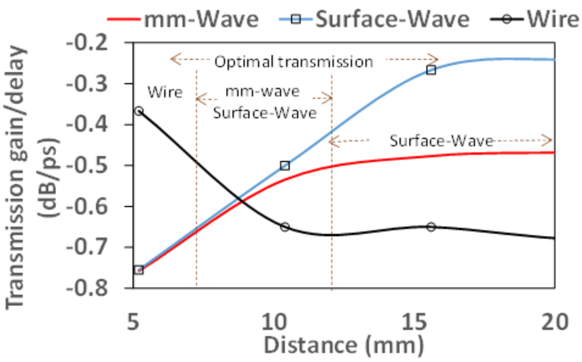


Fig. 6. Variation of ratio of rate of change of transmission gain with distance for different on-chip communication medium

VI. Experimental Results

Cycle-accurate experiments are performed using an extended version of Noxim simulator, an open source SystemC simulator for NoCs. The power of the router is modeled with ORION2.0 NoC power simulator. We adapt the BER and the S_{21} of the communication fabric as the error model. We investigate a wide range of WiNoC configurations with buffer depth of 6 flits and packet size fo 3 flits. Both regular and non-regular mesh topologies are investigated with a setup as summarized in Table I. 5 nodes in the WiNoC, which are evenly distributed in the NoC, are equipped with transceivers. All other nodes have receivers. We consider both deterministic XY routing and adaptive West-first routing algorithms. In both cases, the underlying routing algorithm is employed in the wireline 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 West-first routing technique we employ buffer level selection scheme to avoid creating bottleneck along the wireless channel. In the experiments we compare the effects of the reliability of the proposed surface wave with mm-Wave in WiNoCs and conventional wireline mesh. Note for a given BER, the packet error ratio which dictates the probability of packet retransmission is given by:

$$p_p = 1 - (1 - p_e)^{|P|} \quad (9)$$

where $|P|$ is the packet length in bits and p_e is the bit error probability which is the expectation value of the BER for the communication fabric. Thus, Eq. 9 is modeled and imported into the NoC simulator to assign the probability of retransmission of different communication fabrics at different packet injection rates[1]. FDMA media access control is adopted to give more than one node the right to transmit over the shared wireless medium at a data rate of 256Gbps in one clock cycle over 128 carrier frequencies.

NoC dimensions	6×4, 5×5, 6×6, 8×8, 10×10
NoC virtual channel (VC) number	4
NoC buffer (flit depth)	6
Links and NoC buffer width	128 bits
Transceiver nodes	5
FDMA carrier frequencies per node	128
BER	mm-Wave: 10^{-7}, wire: 10^{-14}, SW: 10^{-13}
Tile dimensions	$3.6 \times 5.2mm^2$
Processing element	Two Pentium class IA-32 cores
cache	Two 256 KB private L2 caches

TABLE I. Simulation Setup

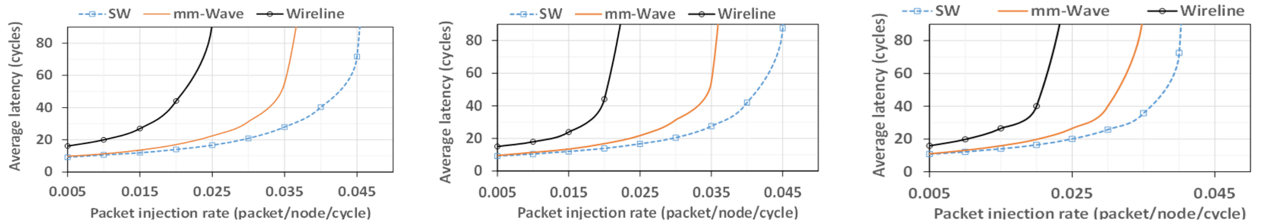
A. *Impact of communication fabric on NoCs*

We treat the hybrid wired-wireless network as a whole and evaluate the effect of the wireless communication fabric on the average packet latency. It can be observed in Fig. 7 that hybrid wired-surface wave NoC (SW) has less average packet delays and can sustain about 29% more traffic load compared to mm-Wave WiNoC under both deterministic and adaptive routing in random traffic pattern. The performance improvement is even more significant (over 100%) when SW is compared to conventional wireline network.

To validate these findings, we have applied two transpose synthetic traffic patterns where source nodes generate packets to specific destination nodes. As shown in Fig. 8, SW outperforms mm-Wave WiNoC in all cases. Though no special wireless channel selection method is employed in deterministic XY routing (Figs. 7(a), 7(c) and 8(a)), the extra traffic load introduced by the high rate of retransmitted erroneous packets causes contention in both the wireline and wireless channels of mm-Wave WiNoCs. On the other hand, though buffer levels are employed for wireless channel selection in west-first adaptive routing (Figs. 7(b), 8(b), and 8(c)) the error rate along the wireless channel in mm-Wave is much higher than surface wave channel, hence packets in mm-Wave WiNoC experience longer delays compared to SW.

We investigate the behavior of WiNoCs under a wide range of regular NoC dimensions with 5 transceiver nodes under random traffic pattern. As shown in Fig. 9(a), SW can sustain about 98% more traffic compared mm-Wave WiNoC when the NoC dimensions is increased to 6×6. This is mainly due to the stronger signal strength with minimum BER of the SW channel over mm-Wave when the distance between remote nodes is increased. Consequently, the number of erroneous packets and retransmissions injected into the network (following Eq. 9) in mm-Wave WiNoC due to the lossy wireless channel increases the network contention even under medium traffic conditions. However, the maximum sustainable load of SW drops to about 25% more efficient compared to mm-Wave WiNoC when the dimension is increased to $10 \times$

[1] An alternative approach is to inject an erroneous packet after millions of cycles as dictated by the BER which is requires extremely large simulation cycles. Experiments conducted with significantly long simulation lengths (which are in order of millions) show that Eq. 9 yields similar results (with shorter but reasonable simulation lengths) as the packet error ratio is a directly proportional to the BER.

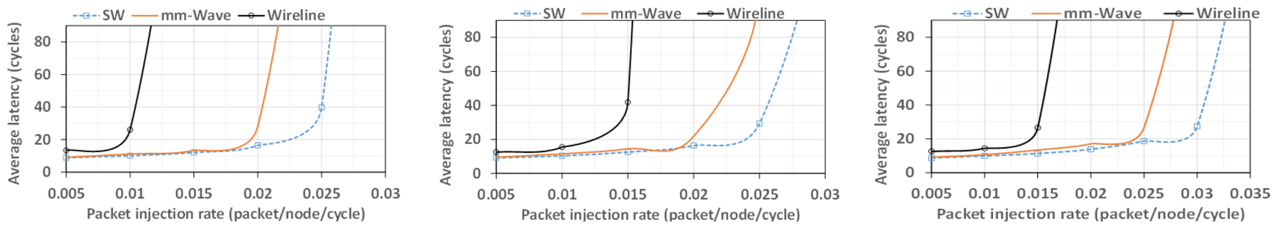


(a) XY routing in 6 × 4 NoC

(b) West-first routing in 6 × 4 NoC

(c) XY routing in 5 × 5 NoC

Fig. 7. Average packet latency under random traffic patterns in 6 × 4 and 5 × 5 NoCs, 6 buffer per port, 4 VCs and 4 transceiver nodes

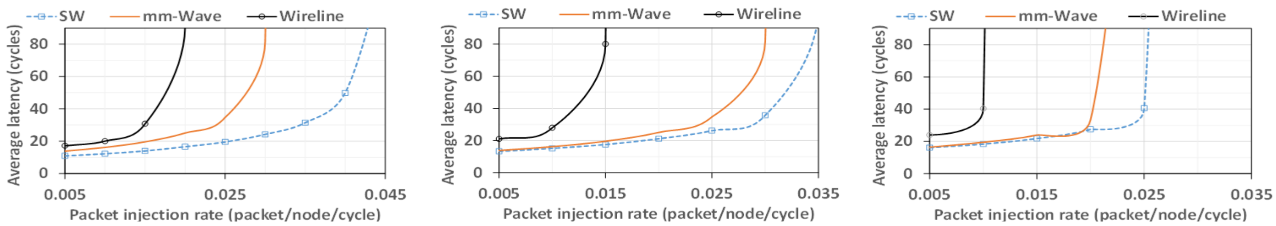


(a) XY routing, Transpose1 traffic

(b) West-first routing, Transpose1 traffic

(c) West-first routing, Transpose2 traffic

Fig. 8. Average packet latency under transpose traffic patterns in 6 × 4 NoC, 6 buffer per port, 4 VCs and 4 transceiver nodes



(a) 6 × 6 NoC

(b) 8 × 8 NoC

(c) 10 × 10 NoC

Fig. 9. Average packet latency under different NoC dimensions, 6 buffer per port, 4 VCs, 4 transceiver nodes, random traffic and west-first routing

10. This is expected as the number of nodes equipped with transceivers is kept constant (5 transceiver nodes) in all cases. As evident in the significantly low saturation rate of traditional wireline NoC (Fig. 9) the contention in the wireline layer have more dominant effect on average packet latency as the number of nodes in the network increases over fixed number of wireless nodes. On the average, SW improves the maximum sustainable load by 27.8% and 133.3% compared to mm-Wave and wireline, respectively, even when a small number of wireless transmitting nodes are used.

B. Power consumption

Both static and dynamic power of the router is calculated in Orion2.0 model for 45nm technology. The wireline links along the x and y dimensions are modeled as 3.6mm and 5.2mm, respectively. For the wireless link power analysis along the surface wave and mm-Wave channels, we exploit the S_{21} signal voltage gain between the transmitter and receivers [20]:

$$S_{21} = E + 20 \lg e^{-\alpha d} \tag{10}$$

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 [20] and conducted experiments (see Section V), 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.

Table II shows the average power consumption of mm-Wave and surface wave in 6 × 4 WiNoCs under different traffic patterns. The figure shows that mm-Wave consumes up to 17% more power compared to the proposed surface wave fabric when employed as the wireless communication channel for WiNoCs. This is because the mm-Wave channel is lossy with high signal loss constant due to free space propagation while the proposed surface wave communication fabric transmits TM signals with high S_{21}.

Therefore, the proposed surface wave communication fabric

Traffic pattern	SW WiNoC (mW)	mm-Wave WiNoC (mW)	Efficiency of SW over mm-Wave (%)
Random	0.00196	0.00219	12
Transpose1	0.00160	0.00187	17
Transpose2	0.00156	0.00174	12

TABLE II. AVERAGE NETWORK POWER CONSUMPTION

has more promising power efficiency for long distance communications in WiNoCs compared to traditional mm-Wave.

C. Realistic Applications

To further validate the performance benefits of the proposed communication fabric, M5 simulator [25] is used to acquire memory access traces from a full system running PARSEC v2.1 benchmarks [26]. In the setup, 64 two-wide superscalar out-of-order cores with private 32KB L1 instruction and data caches as well as a shared 16MB L2 cache are employed. Following the methodology presented in Netrace [27], the memory traces are post-processed to encode the dependencies between transactions. Consequently, the communication dependencies are enforced during the simulation. Memory accesses are interleaved at 4KB page granularity among 4 on-chip memory controllers. A summary of the benchmarks is presented in Table 10. Thus we apply a wide range of benchmarks with varied of granularity and parallelism to study the effects of different wireless communication fabrics on WiNoCs. Fig. 10

Benchmark	Input Set	Cycles	Number of Packets
blackscholes	small	255M	5.2M
blackscholes	medium	133M	7.2M
channeal	medium	140M	8.6M
dedup	medium	146M	2.6M
fluidanimate	small	127M	2.1M
fluidanimate	medium	144M	4.6M
swaptions	large	204M	8.8M
vips	medium	147M	0.9M

TABLE III. SIMULATED PARSEC TRACES

shows the average performance improvement of SW over mm-Wave WiNoC and wireline in terms of average packet latency in realistic traffic traces. In all workloads, SW communication fabric can has lower packet latency compared with other on-chip communication fabrics. Particularly, in high contention workload such as swaptions and channeal with large number of packets simulated over a wide simulation cycle the proposed communication fabric achieves over 60% improvement in the average packet latency compared to the baseline (wireline) NoC.

VII. CONCLUSION

In this paper, a reliable 2-D waveguide communication fabric is proposed to alleviate the performance degradation due to high error rates of the wireless communication channel in hybrid wired-wireless NoCs. The TM characteristics for reliable surface wave signal propagation in the proposed communication fabric is evaluated. As a result, a thin metal layer coated with Taconic RF-43 dielectric material is designed as the 2-D wireless communication medium. A low noise quarter-wave transducer is then proposed as the interface between the SoC blocks and the wireless interface. Experiments conducted in HFSS show that, the proposed transducer has a significantly high bandwidth (45GHz - 60GHz). Finally, the performance effect of introducing the proposed wireless communication fabric in hybrid wired-wireless NoCs is evaluated by cycle-accurate simulations. The experimental results show significant reductions in the average packet delay and power consumption compared to millimeter wave hybrid wired-wireless NoCs with both adaptive and deterministic routing techniques.

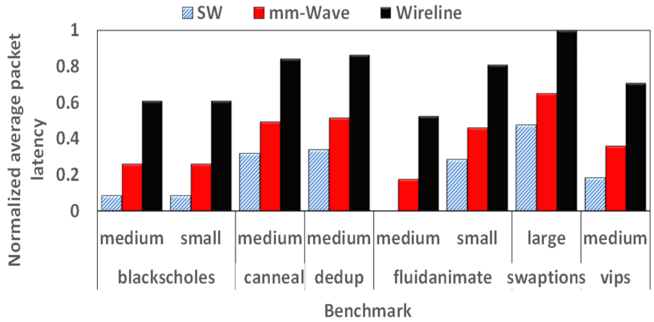


Fig. 10. Normalized average packet latency under PARSEC benchmark suite

VIII. APPENDIX

Lemma 1. *For Transverse Magnetic mode (TM)-surface wave propagation in a 2-D on-chip communication fabric, a dielectric coated conductor with sufficiently high inductive reactance X_s is required.*

Proof: The TM signal independent of the *y* coordinate that propagates along the *x* axis and satisfies the Maxwell equations [28], [29] is evaluated. In free space, *Layer 0* ($\epsilon = \mu = 1$), the following can be derived:

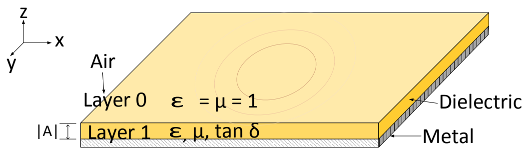


Fig. 11. 2-D waveguide sheet implemented with a dielectric layer (with a loss tangent $tan\ \delta$) placed over a perfectly conducting plane

$$H_y = e^{jk_1(z-|A|)}e^{j(\beta x)} \tag{11}$$

$$E_z = -\frac{Z_0\beta}{k_0\epsilon}e^{jk_1(z-|A|)}e^{j(\beta x)} \tag{12}$$

$$E_x = \frac{Z_0k_1}{k_0\epsilon}e^{jk_1(z-|A|)}e^{j(\beta x)} \tag{13}$$

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, *Layer 1*, the electric and magnetic field components are given by:

$$H_y = \frac{\cos(k_2z)}{\cos(k_2|A|)}e^{j(\beta x)} \tag{14}$$

$$E_z = -\frac{\beta \cos(k_2 z)}{Z_0 k_0 \epsilon \cos(k_2|A|)} e^{j(\beta x)} \tag{15}$$

$$E_x = j\frac{Z_0 k_2 \sin(k_2 z)}{k_0 \epsilon \cos(k_2|A|)} e^{j(\beta x)} \tag{16}$$

where k_1 and k_2 are the transverse waves numbers in Layer 0 and Layer 1, respectively, which can be solved through the Helholtz wave equation [29]:

$$K_1 = \sqrt{k_0^2 - \beta^2} \tag{17}$$

$$K_1 = \sqrt{k_0^2 \epsilon\mu - \beta^2} \tag{18}$$

The surface impedance Z_s of the interface between Layer 0 and Layer 1 is given by:

$$Z_s = -\frac{E_x}{H_y} = -Z_0 \frac{k_1}{k_0}. \tag{19}$$

To enable the field concentration in Layer 0 nearer to the surface of Layer 1 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 X_s needs to be implemented. ■

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