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# An Improved Wireless Communication Fabric for Emerging Network-on-Chip Design

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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 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.


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*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, yield and high temperature dissipation issues which affect the reliability of the system [1]. Hence wireless channels in the form of millimeter wave (mm-Wave) for global communication while maintaining the wired network for localized traffic as shown in Fig. 1(a) [2], has been proposed. 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

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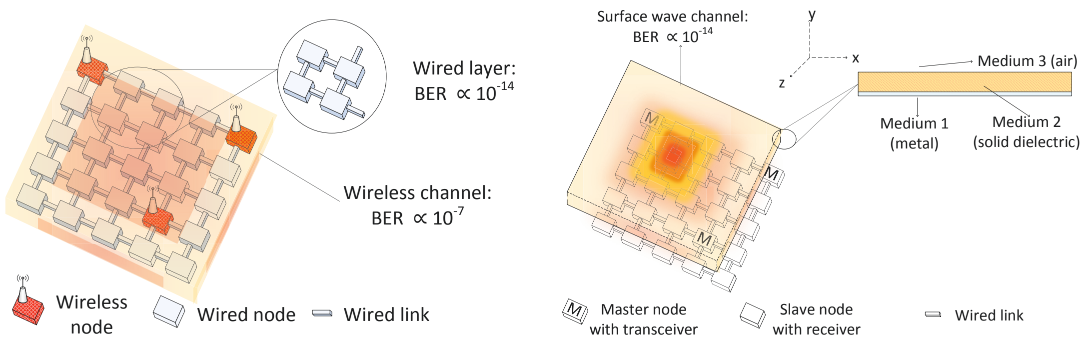



(a) Existing hybrid wired-wireless Network-on-Chip (b) Proposed wireless communication fabric

Figure 1. Wireless communication fabric for WiNoCs. In Fig. 1(b) a dielectric-coated plane surface with a loss tangent *tan* ∇ is used

(BER) of around $10^{-14}$ compared to that of mm-Wave (around $10^{-7}$). 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. 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[3,4]. 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. However, previous contributions on SW have not focused on optimizing the communication fabric to improve the data throughput and reliability of wireless channel[3]. 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[5]) 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. The paper is organized as follows. Section 2 presents an improved wireless communication fabric for WiNoCs. Section 3 evaluates the transmission strength of the proposed wireless communication fabric. Experimental results in Section 4 validates the performance efficiency of the proposed communication fabric. Finally, the main findings are concluded in Section 5.

## 2. 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 Fig. 1(b). 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. The surface reactance, $X_s$ is given by[4]:

$$X_s = 2\pi f \mu_0 \left[ \frac{\epsilon_r - 1}{\epsilon_r} l + \frac{\nabla}{2} \right] \quad (1)$$

$$\nabla = \sqrt{\frac{1}{\pi f \mu_0 \sigma}} \quad (2)$$

It can therefore be deduced from Eq. 1 that, the efficiency of the TM surface wave propagation depends on the

operating frequency, $f$, dielectric constant, $\epsilon_r$, thickness of the dielectric material, $l$, and the skin depth of the metal conductor, $\nabla$ (Eq. 2). Here $\sigma$ is the conductivity of the metal conductor. Hence, our objective is to 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 $f$. The aim is to achieve the maximum transfer signal strength ($S_{21}$) in the surface wave communication medium with a comparable BER to that of the wired layer.
To generate an efficient TM surface wave signal, the following considerations are made for the design of the 2-D waveguide sheet. We use commercially available Taconic $RF - 43$ material[5] 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. 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 (Fig. 2) 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 Fig. 2. 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

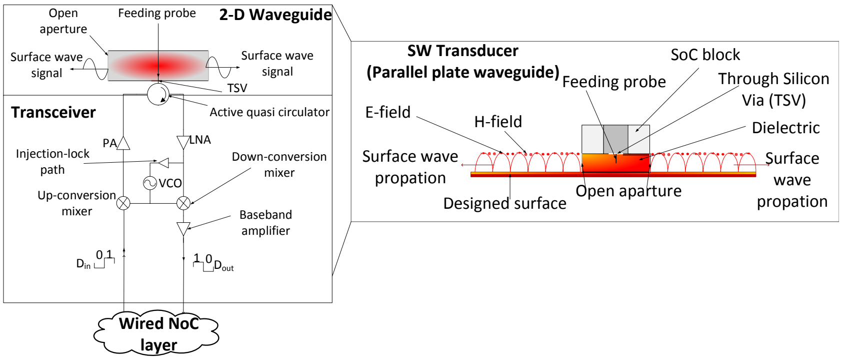
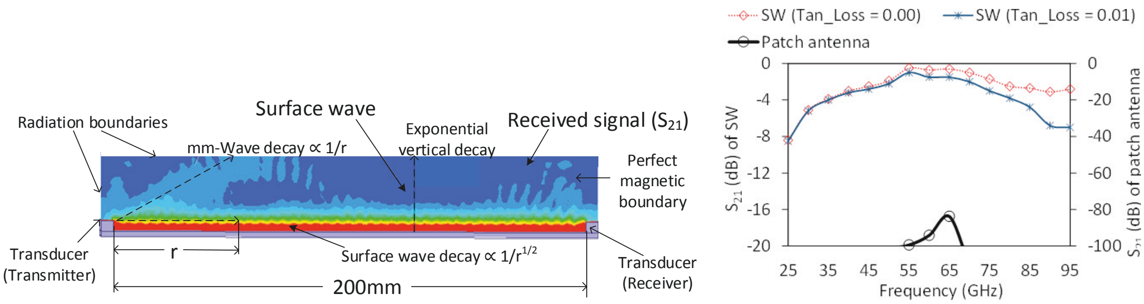



Figure 2. Transceiver and transducer block diagram for generating surface wave for on-chip communication. An inverted quarter-wavelength monopole is stacked over the CMOS-based 2-D waveguide sheet for generating surface wave signals[3]

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. A system-level simulation using Simulink in TSMC 65-nm standard CMOS process performed in[6] have demonstrated that the transceiver is able to achieve a (BER) less than $10^{-14}$ at data rate of at least 16Gb/s within 20mm which is comparable to that of the traditional wired network. Hence we adopt this transceiver design in our implementation[6]. 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.

## 3. Transmission Strength of the Proposed Surface Wave Communication Fabric

To demonstrate the effectiveness of the proposed wireless communication fabric, we have performed simulations in Ansys HFSS[7] with a simulation setup presented in Fig. 3(a). The transducers are placed as far as 200mm (equivalent to 40 free space wavelengths at operating frequency of 60GHz) apart. Moreover, we investigate the effect of adopting an off-the-shelf transducer (patched antenna) on the signal strength of surface wave. As shown in Fig. 3(a), 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 a high signal efficiency. It can be seen that, the reactive surface appears to have a flat $S_{21}$ response




(a) Simulated electric field distribution

(b) $S_{21}$ (dB)

Figure 3. Simulation electric field distribution and $S_{21}$ (dB) over wide-band frequency on the reactive surface with different lossy dielectric materials

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). Fig. 3(b) also 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 which is significantly lower than that of the proposed communication fabric[6].

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.

## 4. Evaluation

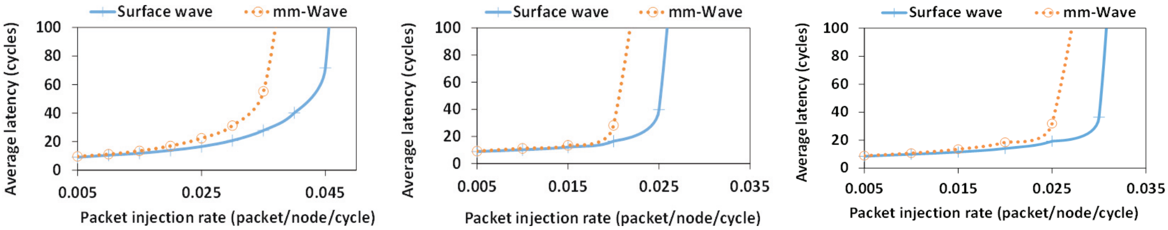
In order to evaluate the performance of the proposed communication fabric, a cycle-accurate simulator is used by extending Noxim simulator, an existing SystemC-based NoC simulator. We adapt the BER and the $S_{21}$ of the communication fabric as the error model. In the simulation, a fixed packet size 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 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. 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[3]:

$$S_{21} = E + 20\lg e^{-\alpha d} \tag{3}$$

where $\alpha$ 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[3] and conducted experiments (see Section 3), $\alpha$ 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.

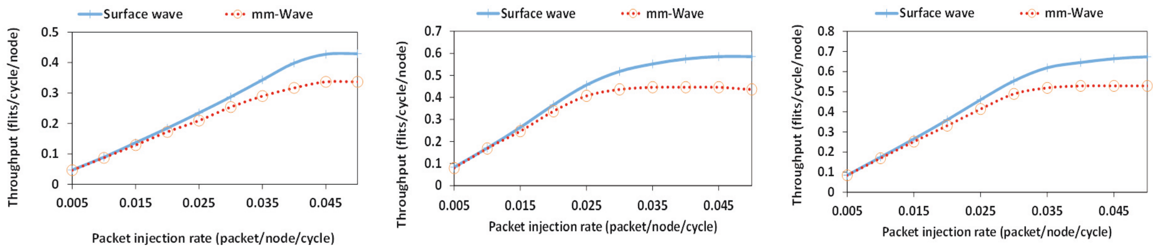
### 4.1. *Performance Under Synthetic Traffic Patterns*

We evaluate the effect of the wireless communication fabric on the average packet latency and data throughput under random and two transpose traffic patterns. Fig. 4 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. Fig. 5 shows




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

Figure 4. Average packet latency under XY routing and different traffic patterns in $6 \times 4$ NoC




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

Figure 5. Network throughput under XY routing and different traffic patterns in $6 \times 4$ NoC

the variation of throughput with traffic load in surface wave and mm-wave WiNoCs under different traffic patterns. Similar to Fig. 4, the improved surface wave communication fabric outperforms mm-Wave in all scenarios. Both communication fabrics have similar throughput at low traffic loads. However, the throughput of mm-Wave saturates at a lower injection load. As can be deduced from Figs. 4 and 5, the maximum sustainable load has a significant effect on the throughput of the communication fabric in the WiNoC. The error rate along the wireless channel in mm-Wave is much higher than both wired and surface wave channel, hence packets in mm-Wave WiNoC experience longer delays compared to surface wave.

Table 4.1 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

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 (%) |
|---|---|---|---|
| $5 \times 5$ | 22.9 | 16.4 | 12.7 |
| $6 \times 6$ | 23 | 8.9 | 13.9 |
| $8 \times 8$ | 18.9 | 6.7 | 14.6 |

routing in $6 \times 4$ WiNoC. 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 $S_{21}$. Therefore, the proposed surface wave communication fabric has more promising power efficiency for long distance communications in WiNoCs compared to traditional mm-Wave.

### *4.2. Performance Under Real Applications*

To further validate the performance benefits of the proposed communication fabric, M5 simulator[8] is used to acquire memory access traces from a full system running PARSEC v2.1 benchmarks[9]. 64 two-wide superscalar out-of-order cores with private 32KB L1 instruction and data caches with a shared 16MB L2 cache are used. Netrace[10] 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 average packet latency improvement of surface wave over mm-Wave in WiNoCs under PARSEC benchmark is presented in Fig. 6. 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.

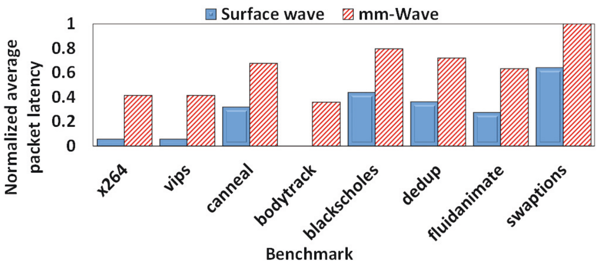



Figure 6. Normalized average packet latency under PARSEC benchmark suite

## 5. 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.

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