Channel Modeling for Wireless Networks-on-Chips

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ABSTRACT

Designing and implementing wireless networks on chips (WiNoCs) presents numerous engineering challenges, in the areas of computer architecture, multiple access, wireless propagation, physical layer communications processing, and device design and fabrication. In this article we provide a survey on WiNoC propagation and the issues involved with WiNoC channel modeling. We address both attenuation and dispersion, and illustrate the dramatic differences between the miniature WiNoC case and more familiar terrestrial wireless channels. Remaining channel modeling research is outlined.

INTRODUCTION

Wireless networks on chips, or WiNoCs, represent a new area of research in wireless communications — wireless communications at *very* small scales. In a sense, this application might be considered yet another step in the continual evolution of cellular communication systems where "cell" sizes shrink: in the literature, we have seen the terminology progress from cells and macrocells to microcells, then picocells, and most recently femtocells, whose range is on the order of 10 m. For communication networks on integrated circuit (IC) chips with dimensions on the order of 1 cm — three orders of magnitude smaller than femtocells — we enter the realm of "attocells."[1] We can also think of this form of wireless communication as *plesio*communication, communication between entities that are near, in contrast to the familiar *tele*communications between entities that are far apart.

The driving motivation behind the use of wireless communications in the IC environment is higher aggregate data rates among the growing numbers of processing cores that must intercommunicate, with the aim to supplement wired communication, not fully supplant it. A second key motivation is power reduction, and a third is latency reduction. These motivations are with respect to present-day exclusively wired communication lines, which are nearing their capacity as circuit dimensions get smaller. Smaller circuits and larger numbers of cores mean quadratic growth in pairwise connections between these cores (i.e., for N cores, the number of pairwise connections is twice the binomial coefficient $2C(N; 2) = N \times (N - 1)$). Smaller wires also mean larger resistance, requiring larger transmission power to reach a given distance. Wired communications between cores that are relatively far apart on the IC must also traverse multiple hops, incurring greater latency than a single long wireless hop. Wireless communications also offers broadcast/multicast capabilities that are not as easily accomplished with wired lines.

Wireless plesiocommunication in WiNoCs does present significant challenges in multiple areas. This includes the chip multiprocessor architecture and multiple access (MA) scheme design for large numbers of cores, physical layer (PHY) link design areas such as modulation and detection and wireless channel modeling, and the fundamental area of actual device fabrication for the PHY components such as mixers, amplifiers, filters, and antennas. These research challenges are addressed in [1], along with some of our initial WiNoC design results. This article addresses the fundamental PHY area of modeling the wireless channel for attocell WiNoCs.

Although several papers have been published in the past few years on WiNoCs, very little attention has been paid to the wireless channel itself. As we discuss subsequently, the two most important features of the channel that must be modeled are the attenuation (or path loss) and dispersion, used here in the sense of channel variation with frequency. We first briefly review results from the most notable papers before our discussion of the channel's characteristics and models for them.

In [2], the authors cite numerically computed results from a full-wave electromagnetics software package for attenuation vs. distance when dipole antennas are embedded within either one of two different dielectrics, silicon or polyimide. The attenuation with distance was linear in dB on a log-distance scale. It is not made explicitly clear in [2] what carrier frequency is used, but the discussion mentions 300–500 GHz. It is interesting that the simulated attenuation results show a path loss exponent of approximately two — the exact same as the value for free-space — in both dielectrics, although silicon has a 35 dB larger bulk attenuation than polyimide. That is, both have the same attenuation-vs.-distance slope (path loss exponent), but the intercept of

[1] *Future systems may even reach smaller dimensions (i.e., zeptocells of range 10 mm, yoctocells of range 10 nm, etc.).*

silicon is 35 dB larger. The physical model in [2] was also very simple, with air above the dielectric layer and silicon below, and nothing but pure dielectric between the antennas.

Reference [3] also proposes a model for attenuation that is quite simple: that of a two-ray model in air. The two-ray model is well known in terrestrial (tele)communications, where the physical description is that of two propagation paths, one direct (line-of-sight, LOS) path, and one ground reflection. The model in [3] assumes the WiNoC is contained atop the IC in a "vacuumed-out" chamber — a potential fabrication complication. The discussion in [3] refers to carrier frequencies on the order of 500 GHz to 750 THz. Note that the upper limit is in the infrared range.

One of the few papers reporting experimental work and providing actual channel characteristics is [4], with results in the 10–110 GHz range. The authors observed surface wave guiding for dipole antennas printed on silicon, with air above. Path loss exponents were approximately 1.5, with delay spreads up to 160 ps for a 30 mm link in this specific design.

The two-ray model is actually a dispersive channel. We address this in more detail subsequently, but the two-ray dispersion is only appreciable at shorter ranges, since at longer ranges, the reflection angle approaches zero and path length difference between the two rays decreases. Although additional work has followed [2–4], to our knowledge no comprehensive WiNoC channel models have been reported.

The remainder of this article is organized as follows. We outline the major considerations and challenges with WiNoC channel modeling. We discuss the modeling of attenuation or path loss, and the modeling of dispersion, typically addressed via estimation of channel impulse responses (CIRs). Finally, we provide additional remarks and comments on areas for future work, and then conclude the article.

WiNoC Channel Modeling Overview

We state first that except for the simplest (largely unrealistic) geometries, it is not possible to accurately model the WiNoC channel without precise specification of the physical landscape. The landscape is the physical structure of the region of space in the WiNoC through which electromagnetic waves will propagate. Hence, precise channel description requires specification of all dimensions and electrical properties (conductivity σ, permittivity ε_r, and permeability μ_r) of all objects in the environment. The WiNoC landscape could be quite complex, which means that truly accurate models for the channel are infeasible without detailed numerical computations (i.e., the non-uniformity of the landscape will greatly complicate CIR estimation). For example, the landscape may include multiple dielectric (and/or conducting) layers, "steps" and "plateaus," irregular geometric shapes due to fabrication imperfections, and so on. An example landscape is shown in Fig. 1. Figure1c shows the global IC landscape consisting of 16 clusters of multiple cores each, and Fig. 1a shows a close-up view of one such cluster. These are intended to be a conceptual illustration to show potential landscape complexity, not necessarily a final WiNoC structure. Figure 1b shows an actual electron microscope image we have taken of a "cut-open" Pentium 4® processor, illustrating six layers of progressively more dense metallization.

There is a vast amount of work on modeling wireless channels for more conventional settings such as cellular radio, terrestrial point-to-point communications, broadcast radio, and indoor wireless local area network. [5]. This body of knowledge, both theoretical and empirical, will of course be of use in the WiNoC setting, but some conditions will be distinct, and "classical rules" may be inapplicable. One example of this is the far field assumption: depending on frequency band, transmitter and receiver antennas in such small spaces may not be in each other's far field region. Established rules can easily be used to determine the far field minimum distance [6]. If the far field condition is violated, radiating and reactive near fields must be taken into account. This not only complicates the analysis of channel characteristics, but if multiple transmitters (Tx) or receivers (Rx) are close, there will be mutual coupling that reduces efficiency, since some energy intended for transmission/reception is stored in resonances. Thus — at least for conventional antenna design techniques — link design will be far simpler, and the antennas far more efficient, if we can employ frequencies and antennas that guarantee far field conditions. This translates to large frequencies and very small antenna dimensions.

As an example, assume our minimum expected range is r = 1 mm and that transmit and receive antennas are identical. For antennas smaller than one wavelength, the most stringent condition on the far field distance is $10D_A$, with D_A the largest dimension of the antenna. With the value of D_A less than wavelength λ, this translates to a minimum frequency of 3 THz; if minimum range drops to 0.1 mm, we obtain $f_{\min}$ = 30 THz. (Note that these values are for a vacuum. Wavelengths in dielectrics are shorter than those in a vacuum by a factor of $\sqrt{\varepsilon_r}$, and propagation velocity is similarly reduced, so for propagation through a dielectric, these frequencies get reduced by this factor.) The above analysis applies if we choose to use, for example, conventional quarter-wave monopoles as our antennas for r = 1 mm. If such high frequencies are unattainable for other WiNoC system reasons (e.g., lack of PHY devices), initial WiNoCs may have to contend with electrically small and inefficient antennas and near field effects, in which case channel modeling becomes complicated, and best conducted with complex full-wave electromagnetic solutions such as finite-difference time-domain (FDTD) modeling. Traditionally, antennas are often excluded from many channel models, or incorporated via their far field patterns, but for accuracy in the tens to hundreds of gigahertz, or terahertz frequency ranges, we will need to incorporate detailed antenna characteristics as well.

Next we list some basic WiNoC channel characteristics:

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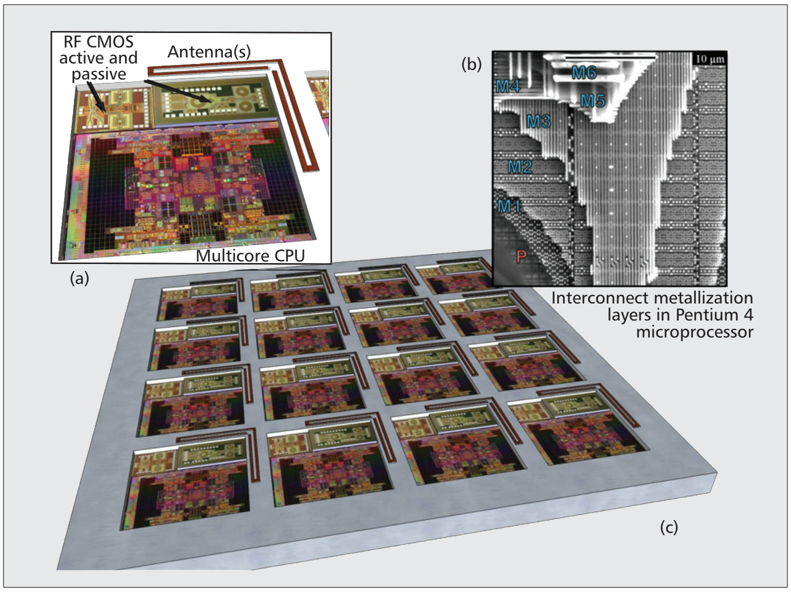

Figure 1. *Conceptual illustration of possible WiNoC landscape: a) close up view of one cluster of cores along with RF transceiver components and antenna; b) actual electron microscope image showing multiple metallization layers used for interconnections in a single-core Pentium 4® microprocessor by Intel (scale bar is 10 mm); c) global layout of 16-cluster IC design.*

1) All WiNoC links will be non-mobile, and assuming no substantial material property changes over short durations, the media involved will have constant properties; hence, each individual Tx-Rx channel will be *time-invariant*. As a consequence of this, a complete channel characterization is a set of CIRs $\{h_i(\tau)\}_{i=1}^{K}$, where index i ranges from 1 to K, the total number of Tx-Rx links (e.g., $K = N \times (N - 1)$), and τ is delay. Equivalently, we can characterize the K channels via their frequency responses, the Fourier transforms of the CIRs $\{H_i(f)\}_{i=1}^{K}$, also known as channel transfer functions (CTFs). If material properties do change significantly over time (e.g., due to thermal variations), this will have to be incorporated into the channel characteristics, typically via upper and lower bounds on the affected parameters.

2) Direct Tx-Rx link distances will be less than $d\sqrt{2}$, where d is the length of the (longest) rectangular IC side. For example we may have d = 20 mm, so $d_{max} \cong$ 28 mm or less to allow for boundaries and placement of Tx/Rx away from IC edges. Reflected or multipath components (MPCs) will traverse longer distances; specific distances will depend on the landscape, frequency, and material parameters.

3) The actual channel will be three-dimensional (3D), but the height h should be typically small compared to d (e.g., we might have $h < d/10$ or even $h < d/100$).

4) Any dielectric material through which the signal propagates (e.g., silicon, polyimide) will be lossier than air, but perhaps not by much. Material-dependent phenomena such as absorption and resonance may need to be accounted for. These are strong functions of frequency. Larger losses imply larger required transmit signal powers, but for delay dispersion, larger losses mean weaker multipath components, and weaker multipath components will improve bit error ratio (BER) performance.

5) Metal surfaces (mostly, or perhaps only, planar) will likely be present in the landscape. Given this, we may be able to bound some channel characteristics by use of work done on parallel-plate guides or reverberation chambers [7]. Care must be used to ensure that assumptions applied in such structures do indeed pertain to the significantly smaller WiNoC. We address this in the section on dispersion.

Path Loss Modeling

As noted, for conventional terrestrial radio systems, even at millimeter-wave frequencies and higher, we have a vast amount of literature from which to draw for modeling attenuation. In most systems where transmission is at ranges of meters or more in the lower troposphere, the vast majority of the received signal energy comes from electromagnetic waves that travel through air. The air is usually approximated as nearly ideal, that is, lossless, linear, time-invariant, nondispersive, isotropic, and homogeneous. Obstacles in the terrestrial environment create loss, anisotropies, inhomogeneities, and multipath-induced (but often not material-induced) dispersion; yet in non-mobile conditions, we still have linearity and time invariance. The WiNoC landscape will also yield loss, anisotropies, and inhomogeneities, and depending on frequency, bandwidth, and material, we may also have to consider material dispersion characteristics (i.e., frequency-dependent material polarization).

For conventional terrestrial cases, simple free-space and two-ray path loss models are sometimes used to obtain rough estimates. More generally, recent empirical models take the "log-distance" form; for example, path loss L in dB at distance d is given by $L(d) = A + 10n\log_{10}(d/d_0) + X$ where A is the path loss in dB at a reference distance d_0, $d > d_0$ is the link distance, n is the dimensionless propagation path loss exponent, and X quantifies path loss variation about the linear fit (e.g., in nearly all conventional terrestrial models, X is a zero mean Gaussian random variable in dB with a standard deviation σ_X). The reference distance d_0 is generally chosen for convenience, within the far field of antennas. A value of n = 3 or 4 is common in cellular settings when no LOS path exists; free-space pertains for n = 2. For WiNoCs, d_0 could be on the order of 1 mm or less. Some example WiNoC models of this form are the numerically computed models for the relatively simple structure in [2]: from plots in [2] we have estimated n = 1.98, and for polyimide, A = 44.6 dB, and for silicon, A = 79.6 dB, and d_0 = 1 cm. The applicable distance range is 0.5 mm to 5 cm (so here, d0 can be less than d), and the model did not use any variable X since the computations were for a single path.

The two-ray model [5] for path loss vs. distance d shows a path loss exponent of n = 2 for distances less than the so-called breakpoint distance $d_b \cong 2\pi h_T h_R/\lambda$, with h_T and h_R the transmitter and receiver antenna heights, respectively. For distances greater than this breakpoint the path loss exponent n = 4. At distances less than

d_b — where the "lobed" structure of the sinusoidally shaped path loss function pertains — dispersion occurs. Assumptions required for use of this model are that link distance $d \gg h_T, h_R$, "ground" conductivity is good, and antenna gains for direct and reflected components are approximately the same. Figure 2 shows plots of the two-ray model path loss for some example WiNoC conditions. As this model is well known, the forms of the curves here are not novel, but the model inputs are very atypical: $h_T = h_R$ takes values 0.001 mm, 0.01 mm, or 0.1 mm, distance ranges from 0.01 mm to 1 cm, and frequencies are 750 THz, 100 THz, 10 THz, and < 1 THz. Figure 2 also assumes the material is a vacuum (~air). The shapes of the curves would be similar for propagation through low-loss dielectrics, but would increase at a greater slope if the dielectric is very lossy.

Also note that for the inhomogeneous and anisotropic WiNoC landscape, even an empirical log-distance model would likely be dependent on orientation and location within the WiNoC. In other words, *several* models of the log-distance form might be needed in practice to characterize the spatial variation of path loss across the landscape. Alternatively, a "global" WiNoC model with a constant intercept value (A) and path loss exponent (n) might suffice, with the variation with location captured by several values of X (deterministic or random). Whatever the path loss model form, an accurate model is vital to specification of key WiNoC parameters such as transmitter power. Note that maximum path loss, while sufficient to estimate the maximum value of transmit power needed, is not sufficient for an adaptive WiNoC where Tx and Rx locations change dynamically.

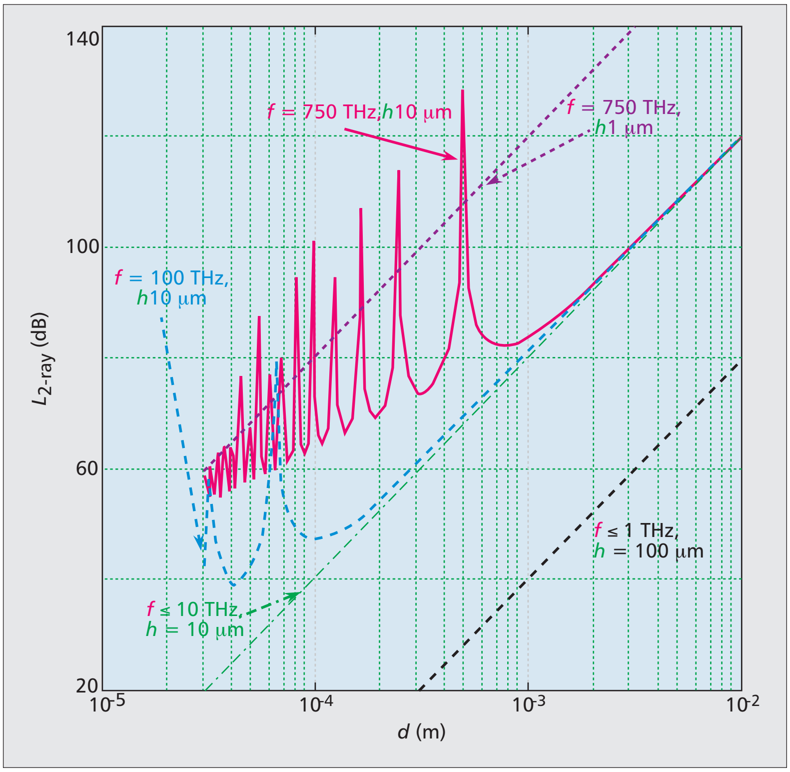

Figure 2. *Example two-ray path loss model attenuations (dB) vs. distance for several WINoC conditions.*

Dispersion Modeling

Dispersion can be viewed as the more "detailed" description of the CIR: path loss by itself tacitly employs an ideal CIR, $h(t) = \alpha\delta(\tau - \tau_0)$, with channel gain a a real positive constant given by $a = 10^{-L_{dB}/20}$, and τ_0 a real positive constant representing the propagation delay. In complex environments where the propagation involves reflections, absorption, and possibly scattering and diffraction, the CIR can be approximated by a sum of attenuated and delayed impulses (i.e., $h(\tau) = \sum_{k=0}^{L-1} \alpha_k e^{j\phi} \delta[\tau - \tau_k]$), where L is the number of MPCs, and α_k and τ_k denote the amplitude and delay of the kth MPC, respectively. Parameter ϕ_k is the aggregate phase shift of the kth MPC due to any interactions (reflections, diffractions, etc.) with obstacles the field encounters between Tx and Rx. This CIR is in complex baseband form.

The Dirac deltas denote *discrete* impulses, and these mean that the channel produces component-specific attenuations, phase shifts, and delays for any signal sent through it. The discrete approximation is very good for signal bandwidths up to tens of megahertz or more, and is even used for some ultrawideband models for bandwidths on the order of 500 MHz to a few gigahertz [8]. For wide enough signal bandwidths, though, the attenuation factors (α's) will be frequency-dependent, although this dependence may be moderate. In addition, the Dirac deltas may no longer be applicable over signal-band frequency ranges, and may need to be replaced by pulse shape functions of non-zero duration. That is, the kth MPC at delay τ_k is represented using $g_k(\tau - \tau_k)$ instead of $\delta(\tau - \tau_k)$, where the pulse shape $g_k(\tau)$ accounts for the frequency dependence over the signal bandwidth. This pulse shape can also account for antenna effects if needed. Developing approximations for $g(\tau)$ functions is not trivial, but first-order approximations may be possible for some cases, such as propagation through a homogenous and isotropic lossy dielectric of known properties, with all conducting materials in the landscape modeled as very good conductors. The determination of when the $g(\tau)$ functions must be used instead of the Dirac deltas is dependent on bandwidth and the material properties.

As with path loss, the CIR will be "distance and location specific" within the WiNoC. For assessing effects on a digital communication signal, though, the "longest" CIR may be sufficient to specify as a limiting case. The definition of "longest" is not necessarily obvious, since MPCs at very large delay values may be very weak (small α_k) and inconsequential to communication system performance. For the time-invariant case, statistical measures such as the root-mean square delay spread (RMS-DS), while common for mobile terrestrial channels, may not be optimal here. The use of the "longest" CIR provides us with the maximum amount of delay dispersion imposed on any communication signal. This in turn allows us to estimate the degradation caused by this dispersion. If the performance degradation (again in BER) is significant

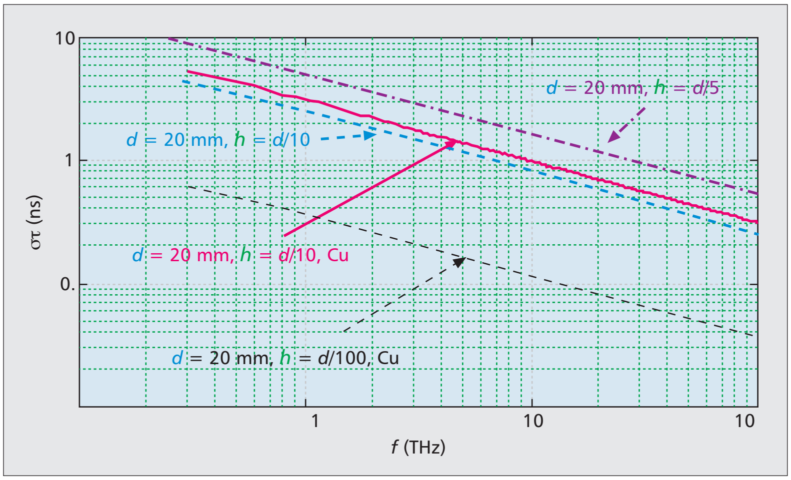

Figure 3. *Example RMS-DS (ns) vs. frequency (THz) for "micro" reverberation chambers.*

enough, we might have to apply remedies via signal processing such as equalization and/or multiple access redesign (e.g., reducing channel bandwidth) and/or physical link redesign (e.g., adding some spatial suppression — directive antennas — to suppress MPCs). Note that at present, sophisticated signal processing is impractical — slow and power hungry — at bit rates of tens of gigabits per second and larger that WiNoCs will require. The WiNoC directive antenna design is also an open research problem.

As another idealized but informative approximation, we consider the WiNoC to lie within a micro-reverberation chamber, or a box with conducting walls. For the reverberation chamber, analyses have derived the RMS-DS, denoted σ_τ. This is given in terms of several quality (or Q) factors by [7], where $\sigma_\tau = 1/(2\pi f S_Q)$, with S_Q the sum of reciprocals of the various Q-factors. These Q-factors take into account the presence of any electromagnetically absorptive material, chamber apertures, conductive wall properties, and antenna sizes. The aperture Q is only pertinent if there are large openings in the chamber walls; hence, for our "closed-box" estimates we need only use the wall and antenna factors [9], given by $Q_{wall} = 3V/(2\mu_r \delta S)$, and $Q_{antenna} = 16\pi^2 V/(m\lambda^3)$, where V is cavity volume ($d \times d \times h$), S is surface area ($2d^2 + 4hd$), $\mu_r = \mu_w/\mu_0$ is the relative wall permeability, with μ_w the actual wall permeability and μ_0 the permeability of free space, m is the antenna impedance mismatch factor (=1 for a perfect impedance match), and δ is the skin depth, given by

$$\delta = 1/\sqrt{\pi f \mu_w \sigma_w},$$

with σ_ω the wall conductivity. For non-ferric materials we can assume $\mu_\omega = \mu_0$. For an air-filled cavity, we show in Fig. 3 an example plot of the delay spread in nanoseconds vs. frequency from 300 GHz to 100 THz, for copper and aluminum conductors, and for $d = 20$ mm and several values of h. As noted in [7], the functional form of the plots are approximately $\sigma_\tau \sim 1/\sqrt{f}$.

For cavities filled with dielectric (lossy), the delay spreads will be smaller, since the propagating waves get attenuated with each path from wall to wall within the chamber (i.e., we add $Q^{-1}{}_{absorber} > 0$ to S_Q). Thus the results in Fig. 3 can be viewed as upper bounds for this model.

The largest RMS-DS occurs at the lowest frequency, and for the largest cavity size ($h = d/5$). This delay spread value is approximately 5 ns, but this chamber height is likely unrealistically large. If we assume that the $h = d/100$ case is representative, the maximum RMS-DS is 0.6 ns at $f = 300$ GHz. A convention in communication systems is to declare a channel *non*-dispersive if the RMS-DS is less than one-tenth of a symbol duration [10]; in general, the larger the RMS-DS, the lower the distortion-free data rate. The 0.6 ns delay spread implies a minimum symbol duration of $T_s = 6$ ns, and this would then correspond to a maximum symbol rate $R_s = 1/T_s \cong$ 167 Msymbols/s (167 Mb/s if binary modulation).

This is an extremely low (i.e., uncompetitive) data rate for WiNoCs, but note that the reverberation chamber analysis is a worst case one in terms of delay spread. As noted, the delay spreads would be substantially smaller if a lossy dielectric were within the cavity instead of air, and as frequency increases, delay spread also decreases; for example, if we used $f = 40$ THz, the maximum RMS-DS would drop by an order of magnitude, yielding a data rate of 1.67 Gsymbol/s by our previous rules. Note also that the very low error probabilities required of WiNoCs ($\sim 10^{-14}$ for wired links [2]) would likely require even smaller values of dispersion unless some higher-layer error correction could be applied. Sophisticated forward error correction coding and decoding could dramatically reduce error probability, but this would be at the expense of throughput and latency, plus circuit area and power, and like equalization, error correction at rates of multiple gigabits per second is not trivial with present-day devices.

Although the reverberation chamber analysis is clearly quite pessimistic, the degree of pessimism in the result is difficult to quantify precisely without more sophisticated analysis and landscape specification. As another idealized example, if we assume $d = 20$ mm and $h = d/10$, the two-ray model yields a maximum delay spread of approximately 2 ps, corresponding to a maximum symbol rate on the order of 50 Gsymbols/s — very competitive for WiNoCs. These two examples illustrate the enormous range of possible WiNoC delay spreads, which depend on the environment.

Additional Considerations and Future Work

In addition to propagation path loss and dispersion, WiNoCs will also have to contend with other challenges related to the channel. This includes the following.

Noise: In addition to typical thermal noise and other well-characterized noise sources such as shot noise, at terahertz frequencies we may also have to contend with other noise sources such as molecular absorption noise [11] (related to material polarization).

Interference: Since device design and fabrication remains a challenge for frequencies at millimeter waves and larger, filters will initially be simple, and hence will not have sharp rolloff outside their passband; this will induce adjacent channel interference. This can be only partially alleviated via careful multiple access design, that is, frequency-division multiplexing (FDM) which spatially and/or temporally separates adjacent channel signals. Outside system interference may also occur, for example, if multiple WiNoCs are in close proximity on the same circuit board. If the WiNoCs are enclosed in metallic casings, such interference should be minimal, but this may not be desirable for thermal reasons.

Antennas: We first note that entire papers can (and surely will) be written on the topic of antennas for WiNoCs, so we cannot address this in detail here (see references within [1] for direction to additional sources). The ideal WiNoC antenna would be electrically small but efficient, easy to fabricate, easy to impedance match to other radio frequency devices and transmission lines, and capable of directionality if needed. These desires are often in conflict, so compromises will be made. Some hope may lie in novel materials such as carbon nanotubes, graphene, and metamaterials.

Several areas for future work have already been mentioned. This includes development of realistic WiNoC landscapes, to which realistic channel modeling can be directed. This can be in the form of simplified techniques such as high-frequency methods (e.g., ray tracing) for terahertz frequencies, but in general may require full-wave electromagnetic modeling (e.g., finite difference time domain). Treatment of optical propagation by quantum methods may also need consideration. The variety of WiNoC landscapes that may be employed should also be defined so that some general channel model rules or guidelines might be defined. These guidelines would not necessarily serve to replace full-wave solutions for each design, but could expedite the design process via good (and fast) estimates of path loss and dispersion. To these results must be added any variations caused by thermal effects. This leads into so-called multi-physics analyses that address multiple physical phenomena simultaneously (here, electromagnetic fields and material property variation due to thermal effects).

The ultimate validation of any models is by measurements, and these will initially be done using simplified prototypes. The design of other WiNoC transceiver components will follow a similar process from simulations to prototyping, as all aspects of WiNoCs will need thorough testing prior to any mass deployments. As work on WiNoCs progresses, we will see further definition of physical dimensions and landscape as well as specification of actual materials, selection of WiNoC frequency bands, and reports on detailed channel models.

Conclusion

In this article, we present an introduction to the intriguing and important research area of modeling the wireless channel for attocell wireless networks on chips, or WiNoCs. The use of WiNoCs to supplement wired connections is expected to grow as communication throughputs for multicore processors grow, and more cores are packed onto each circuit. After highlighting the sparse literature, we provide an overview of WiNoC channel characteristics, contrasting them with more familiar terrestrial settings. Obtaining far field conditions may not always be easy, and terahertz or optical frequencies may be needed. Identifying path loss and dispersion as two crucial channel characteristics to quantify, we provide example computations for popular models, indicate their limitations, and describe consequences for the NoC wireless links and devices. Although the common two-ray model may serve as a reasonable approximation in some cases, it must be used with care. Similarly, the reverberation chamber model is overly pessimistic in estimating dispersion, but can approximate extreme cases if multiple "large" conducting surfaces exist in the WiNoC. Additional channel-related areas of study include characterization of noise sources and antenna design.

As work on WiNoCs progresses, we will see further definition of physical dimensions and landscape as well as specification of actual materials, selection of WiNoC frequency bands, and reports on detailed channel models.

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