Performance Comparison of Selected Wired and Wireless Networks on Chip Architectures

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Abstract—**In this paper we compare performance intra-core communications in network on chips. We consider two alternative architectures, wired and wireless. The wired on is based on a common bus (ring) with all the cores attached to it. We compare it to the mesh (point-to-point) architecture based on THz wireless links operating in $0.1 - 0.54$ frequency band. Using reference latencies of inter-core communications in modern CPUs we perform an applicability assessment of considered schemes. As performance metrics of interest we consider both delay and capacity. Our results indicate that the latter architecture outperforms the former by a singificant margin. The proposed system can be realized implementing directional antennas at all cores and ensuring that cores are placed on a chip such that there is no interference between them.**

I. Introduction

Over the last few years we haven't witnessed any drastic increase in central processing units' (CPU) performance. There are multiple reason behind that including reaching already extremely high operational frequencies and no qualitative progress in manufacturing process. The future improvements in processors' performance are mainly associated with multi-core concept, where a single CPU features multiple processing elements operating in parallel when solving complicated tasks. While such systems are already available on the market for around ten years there have been no notable progress after that aside from increase in operating frequency.

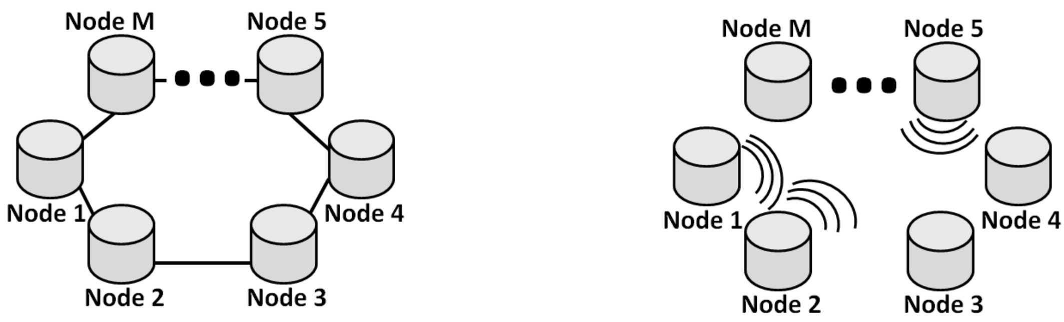
In order to effectively utilise multi-core processors one needs to implement an efficient exchange of date between processing elements. Today the usual way of supporting such a communication is through shared access to cache on CPU. The need for caching of instruction and data comes from extremely high delays associated with exchange of data between random access memory based on dynamic random access memory (DRAM). Caching predicted data and instructions using fast static RAM (SRAM) allows for significant improvement in processing performance.

Networks on chip (NoC) is a modern concept targeted on implementing a number of computational elements on a single chip. One of the critical problems in such systems is connectivity between nodes. Taking into account modern requirement on information exchange of information between processing elements the latency is usually upper bounded by just few nanosecods. To address this issue a number of routing scheme have been proposed in the past including mesh-based, i.e. point-to-point links between any two cores and common bus, i.e. a ring with all the nodes attached to it. The former solution does not scale well with the number of cores while the former could be considered as a potential candidate for future NoCs.

Realizing the challenges of wired communications in NoCs researchers introduced the concept of wireless NoCs (WNoC). According to this concept, wired links are replaced by wireless ones. This approach has a number of advantages including the lack of multilane buses and inherent multicasitng and broadcasting properties. At the same time, the requirements of inter-core communications bring their own challenges including very small bit error rate, very limited delays, efficient channel access mechanisms and guarantees on delivery of data without the use of comprehensive reactive and/or proactive error correction mechanisms.

Compared to most academic studies addressing general questions of wireless network on chip design we will study the abovementioned practical limitation of modern processors proposing a wireless solution for exchange of data between individual cores. We consider two extreme architectures for exchange of data between cores on a chip. The first one is based on NoC concept with a shared bus (ring) connecting all the cores. The second one is WNoC with all the cores equipped with transicenvers capable of establishing direct point-to-point links. Our proposal is based on the usage of a special parts of THz spectrum called transparency windows. In particular, we will show that operating in one of these windows ($0.1 - 0.54$THz) one could achieve extremely high throughput and low bit error rate at the distance of up to few centimeters even when simple modulations schemes like on-off shift keying (OOK) is used. These rates are comparable with those provided by QPI and HyperTransport v3.1 and could be further extended up until the theoretical bound of few Tbps when more complex modulations are used.

The rest of the paper is organized as follows. In Section II we briefly review the relevant studies in WNoC design and given an overview of modern processor architectures. The considered architectures are introduced in Section III. Further, in Section IV we assess the performance of wireless THz channel operatring in $0.1 - 0.54$THz band. Numerical



(a) Wired NoC topology (b) Wireless NoC topology

Fig. 1. Considered NoC architectures

comparison of proposed architectures is performed in Section V. Fnally, conclusions are drawn in the last section.

II. Related Work

Various bottlenecks of modern processor architectures have been a topic of ongoing research for more than a decade. One of the major problems envisioned in the beginning of 2000s is the information exchange between multiple processors performing joint tasks. The research community responded to this issue with a Networks-on-Chip (NoC) concept where a number of processors are connected to each other using wires. Since that different topologies, including mesh, grid, and small-world have been studied to alleviate the problem, see [10], [11] for detailed outlook of various proposals.

In particular, grid topology is characterised by unacceptable delays and non-efficient memory usage as the traffic should go through a number of intermediate nodes. While the mesh topology being more suitable one in term of latency, it suffers from power dissipation of long distance wired links [9]. Moreover, the implementation complexity increases exponentially with the number of connected processors. A compromise between these two topologies is a small-world configuration, where there are only few long distance links while most connections are short ones. Unfortunately, such a complicated hierarchical design requires additional hardware and results in increasing complexity of operation system task scheduler. To efficiently utilise the proposed topology scheduler has to be aware of latency variations between different inter-processor links and select only neighbouring processors for joint tasks.

The issues highlighted above have recently led to the concept of Wireless Networks-on-Chips (WNoC). In [35] the authors proposed to replace the long-distance links in small-world topology by wireless interfaces suggesting to use a part of the spectrum 5 — 750GHz. Since then, there were a number of proposals to use different sets of frequencies. Despite being applicable to inter-processors links, neither Ultra-WideBand (UWB) [36], nor even mm-waves technology [11] is capable of handling inter-core traffic inside a modern CPU. Both proposals starve from capacity and communication distance at the air interface providing 1Gbps at 1mm and 16Gbps at 20mm, respectively, which is not sufficient for modern and future processors.

To address the question of capacity at the air interfaces, the use of THz range has been recently proposed for inter-core communication [12]. Originally suggested for Internet-of-Thins [13] and nano-scale networks, the THz frequency channel has shown much higher capacity, comparing to molecular-based solutions [14]. Also, compared to smaller frequencies it has been shown to provide significantly higher rates for the $0.1-10$THz band: several Tbps at the distance of few millimetres [1]. Further, it has been shown that utilising the so-called ”transparency windows” one can extend the communication range to several centimetres holding similar value of capacity [6].

For completeness we have to mention the proposals advocating photonic NoC design. While such systems will not starve from power dissipation issue of wired connections and can operate at extremely high rates they still require physical interconnections between communicating nodes. The question whether physical waveguides will be required for THz systems is still open. Nevertheless, any kind of wiring between communicating nodes may prevent from efficient scaling of WNoCs from few dozens to several hundreds of nodes even when small-world topologies are be used. Finally, it is important to mention that for both THz and photonic approaches one of the major question nowadays is development of efficient trancievers and antennas, see e.g. [9]. Challenges of massive WNoCs are discussed in [16] while channel modeling methodologies for THz and sub-THz bands are discussed in [15].

III. Proposed architectures

In this work we compare wired and wireless NoC arcitectures. For wired architecture we study ring topology while for wireless one we consider a full mesh (point-to-point) model. In network on chip the topology of the network is known in advance. In this case two different ways of interconnecting nodes are possible. First one is to connect all nodes to the single ring bus (see Fig. 1(a) for details). This topology is simple and reliable and also proven in networking. However, delay in this system is high as the message must go through up to the half of nodes to reach the destination. There are two principally ways to decrease delay in this system. According to the first one we add additional links between nodes. However, this approach adds additional complexity due to the need for routing. The second approach is to use wireless links between nodes, as shown in Fig. 1(b). The resulting system is a single hop wireless network, where the communications delay equals to the time to transmit a packet over the air interface [24]. Despite the fact, MAC layer protocol for wireless system might add a considerable power consupsion [17], [19], [20] and delay [18], [21], we rely on the THz channel characteristics being sufficient for handling this issue.

The wireless architecture brings additional challenges to the system. First of all, due to the space constraints miniaturized antennas must be used. The second issue is possible interference between nodes. Finally, reliability of communication wireless channel is of special interest for NoC design. If the bit error rate is not negligibly small we might need protocols providing delivery guarantees. These protocols have been deeply studies so far, e.g. see [22], [23] for absolutely reliable communication, [25] for semi-reliable communication, while unreliable channels are studied in [33]. Moreover, collisions may occur during the message transmission, so some additional error control must be included. Standard solutions like distributed coordination function in IEEE 802.11 [26], [27] are not suitable due to their low efficiency. Cross-layer optimization [34] could be good alternative in this case. A separate problem in this architecture is traffic modeling [28], [29], [30], [31] which is a topic of ongoing research in WNoCs.

For simplicity reasons, the congestion effect in wireless system, that might occur in an overloaded scenario [32], has not been addressed in this work.

IV. THz CHANNEL PERFORMANCE

In this section we evaluate the capabilities of THz wireless channels. We start with the short review of the propagation model used to compute channel characteristics and proceed with channel characteristics including SNR and Shannon capacity. In order to achieve communications over sensible distances we advocate the use of the so-called transparency windows. Finally, we assess the bit error rate (BER) performance of on-off shift keying (OOK) modulation schemes showing that at the distances in question it is negligibly small.

A. THz channel model

Following [1], the link budget for THz channel is

$$P_{Rx} = P_{Tx} - L_A(f,d) - L_P(f,d), \tag{1}$$

where P_{Tx} is the p.s.d. of the transmitted signal, P_{Rx} is the p.s.d. of received signal, $L_P(f,d)$ is free-space propagation loss, $L_A(f,d)$ is the p.s.d. of the molecular absorption loss. The unknown components are shown to be

$$L_A(f,d) = \frac{1}{\tau(f,d)}, \tag{2}$$

where f is the operating frequency while $\tau(f,d)$ is the transmittance of the medium at the separation distance d that can be found using the Beer-Lambert law $\tau(f,d) = e^{-K(f)d}$, where $K(f)$ is overall absorption coefficient.

The free-space propagation loss is [9]

$$L_P(f,d) = \left(\frac{4\pi f d}{v}\right)^2, \tag{3}$$

where v is the speed-of-light in the medium of interest, d is the separation distance between the transmitter and the receiver, f is the frequency of interest.

In addition to the molecular absorption loss and path-loss, the received signal is also affected by the molecular absorption noise as molecules convert a part of the absorbed energy into kinetic energy. A part of this energy is re-emitted in the channel, effectively creating the so-called molecular absorption noise. The p.s.d. $P_N(f)$ of molecular absorption noise can be written as

$$P_N(f,d) = k_B B[N_M(f,d) + N_A(f)], \tag{4}$$

where k_B is the Boltzmann constant, B is the bandwidth of a channel, $N_M(f,d) = T[1 - \tau(f,d)]$ is the equivalent molecular noise temperature, $N_A(f)$ is the temperature of other sources of noise at the frequency f.

The molecular noise brings a number of special features to the channel behavior. First of all, the thermal noise when using graphene-based nano-antennas is currently not known, but expectedly very low [2], [3] due to special features of graphene, implying that noise is mostly due to molecular absorption noise created in response to absorption of EM waves by molecules in the channel. This implies that the noise exists in the channel only when energy is emitted by the transmitter. We call it a self-induced noise. This is a very special phenomenon that has never been observed in macro-networks.

In addition to the molecular noise affecting the received signal there is the effect of noise relaxation making the THz channels even more specific. The noise relaxation is a process of a gradual decrease of the noise after the pulse transmission. The molecular noise relaxation time $T_R(f,d)$ is defined as the amount of time required for excited molecules to reduce their amplitudes below 10%. It is a complex function of many parameters and depends on the state of matter. According to [4], [5], the relaxation time T_R is at least 1ps. In [6] we proposed to model its effect using using exponential function in the form

$$R(f,t,d) = R_{f,A}(d)e^{-\gamma t}, \tag{5}$$

where $R_{f,A}(d)$ is the noise amplitude at the end of pulse transmission at the distance d, γ is the rate of molecular relaxation that can be estimated using the molecular relaxation time T_R. The time-domain representation of the received energy at a separation distance d is

$$P(f,t,d) = [S(f,t,d) + N(f,t,d)]R(f,t,d). \tag{6}$$

B. Frequency selection

Fig. 2 shows the overall loss in the range $0.1-3$THz at different separation distances from the transmitter. The absorption loss manifests itself in short peaks at different frequencies while the propagation loss results in non-linear increase as frequencies get higher. On important observation is that there are spans of frequencies where the absorption loss is almost non-existent. Since the transmittance of the medium, defining the absorption loss, is also the major factor affecting the molecular noise, the latter is close to non-existent at these frequencies as well.

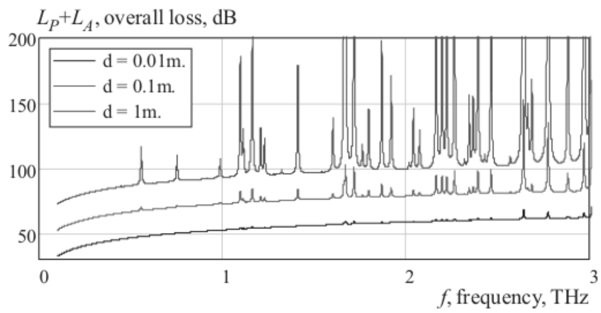


Fig. 2. The molecular absorption and path loss

The absorption feature of the THz channels prevents us from using the arbitrary frequencies in $0.1-10$THz range and requires the wise choice of the spectrum. It has been recently proposed in [6] to use the so-called transparency windows existing in this band. In these windows the transmittance of the considered medium, $\tau(f,d)$, is higher than 98%. Operating in these transparency windows both the molecular absorption and noise level are as small as feasible. The bandwidth of the transparency depends on the molecular noise and thus may decrease with the distance. Out of those window described in [6] we use $0.1-0.54$THz window. The reason is that its bandwidth is relatively high, 440GHz, potentially allowing to achieve extremely high communication rates while these frequencies are still close to the beginning of the THz range making implementation of antennas simpler [9].

C. Channel capacity and SNR

The capacity, $C(d)$, is estimated using the Shannon formula

$$\int_{B(d)} \log_2 \left(1+\frac{P(f)}{L_P(f,d)L_A(f,d)N_M(f,d)}\right) df, \quad (7)$$

where C is the channel capacity, Δf is the channel bandwidth, $P(f_i)$ is the emitted power of the signal at f_i, $L_P(f_i,d)$ is the free-space propagation loss, N_0 is the molecular noise power per one Hz.

The capacity for $0.1-0.54$Thz transparency window for different emitted powers of a signal is shown in Fig. 3. The nominal power for graphene-based transmitters depends on numerous factors [7]. In most studies it is considered safe to use the values around 0.1aJ per symbol, [1], [6]. It is important to note that the value of energy per symbol dictates both SNR and capacity of the channel. In what follows we will always presume 0.1aJ. It is important to note that for our calculations the standard environment has been assumed ($T=296$K, $p=760$mmHg, 1.8% of vapor molecules). However, the temperature of around a working processor can be significantly higher than $T=296K$ implying that the data shown in Fig. 3 provide the lower bound on the achievable capacity. Observing the data one may notice that capacities on the order of few Tbps are theoretically possible at distances up to few centimeters.

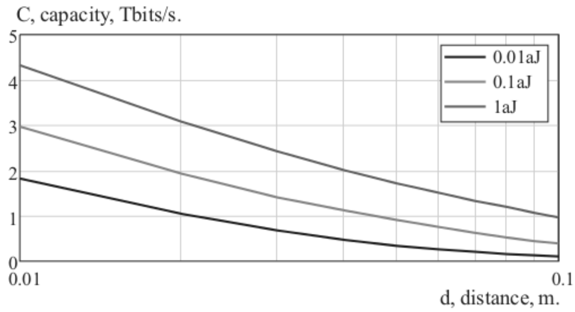


Fig. 3. Channel capacity for few values of emitted power

The factor determining the achievable communication range is the signal-to-noise ratio (SNR). Fig. 4 shows SNR of the $0.1-0.54$ channel as a function of the distance d for $P_{Tx}=0.1$aJ. As one may observe, at the distance 3cm SNR is around 4 (exact value is 4.376). Taking into account simplicity of the OOK modulation scheme reception with small bit error rate (BER) might still be possible at distances up to 3cm.

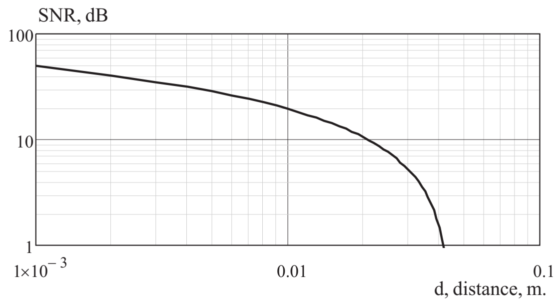
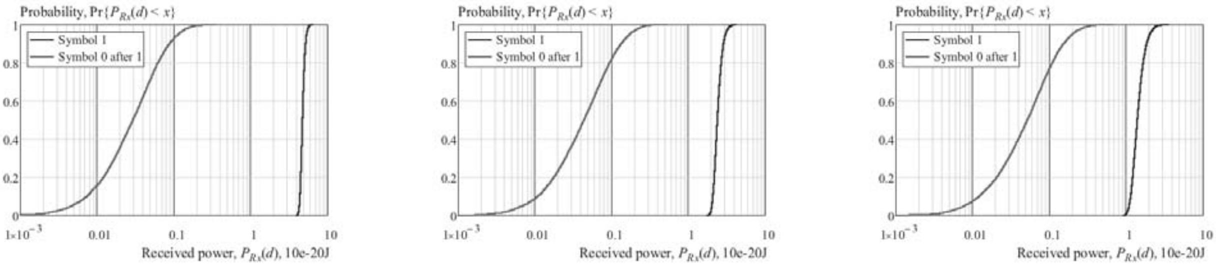


Fig. 4. SNR for $P(f)=0.1$aJ

D. Throughput and BER

In our study we will assume a simple modulation scheme called ON/OFF keying (OOK). In this scheme 1 is represented using a pulse of energy while no energy in the channel denotes transmission of 0. There are several constraints prohibiting the use of more complex modulations including the complexity of recievers/transmitters and antennas, emitted power constraints etc. The use of OOK for communication in THz band was firstly proposed in [7] and then used in a number of studies, e.g. [6], [8].



(a) $d = 0.025$ (b) $d = 0.03$ (c) $d = 0.035$

Fig. 5. CDF and conditional CDF of received power for 1 and 10, respectively

Shannon channel capacity specify potential upper bound for information rate over a channel. Similarly, SNR allows for get basic ideas of how good a channel is. Given a certain modulation we are interested in parameters like channel throughput and bit error rate. For OOK the former is immediately given by $T = 1/\Delta$, where Δ is the symbol duration. The whole symbol duration for the first window is computed to be 3.16ps leading to $T = 0.31$Tbps.

In order to compute BER we need to specify pulse detection scheme. Here, following [6], [8] we assume power-based detection system where one differentiates between reception of 1 or 0 based on the following rule

$$Pr\left\{\int_0^{\Delta t}([S(t,d)+N(t,d)]R(t,d))^2 dt < P_T(d)\right\}, \quad (8)$$

where $P_T(d)$ is the power detection threshold, $S(t,d)$ is the pulse at the distance d, $N(t,d)$ is the noise at the distance d, $R(t,d)$ is the relaxation noise.

The presence of relaxation noise in the channel introduces intersymbol interference (ISI). This ISI is only present in the channel when we transmit 0 immediately after transmitting 1. Further we assume no source coding implying that 1 and 0 are generated with equal probabilities. Following the framework we employed in [6], we translate the signal and noise models to the time domain and then estimate the unconditional probability of receiving 1 incorrectly, p_1, and conditional probability of receiving 0 incorrectly given that the previous symbol is 1, p_{10}. Then these two probabilities are combined (p_{10} with weight 0.5) to get BER. Note that this approach limits the memory of ISI to one previous symbol. However, for realistic values of relaxation constant and symbol duration of 3.16ps the memory of the transmission process becomes negligible for values greater than 2. In other words, in the sequences of 100 type the presence of 1 in the first place does not affect the the reception of 0 at the third place.

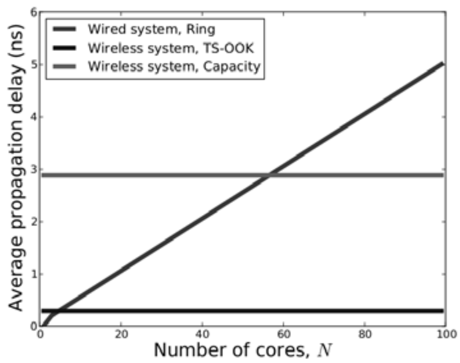
For OOK modulation with intersymbol interference between 1 and 0 and with no intersymbol the critical task is to determine the power detection threshold, $P_T(d)$ resulting in the best possible BER. We note that the authors in [6] studied low SNR regime highlighting that with given the optimal choice of the power detection threshold and intersymbol spacing in OOK BER can be less than $10e-4$ for SNR values around 1. In our context, BER of $10e-4$ is still extremely high. Furthermore, the intersymbol interval introduces additional delays translating in lower capacity values. Thus, we assume no spacing between symbols here. The cumulative distributions functions of the received power for symbol 1 and symbol 0 following 1 is shown in Fig. 5. These illustrations have been obtained using numerical simulations. As one may observe when the communication distance increases from 0.025m to 0.035m CDF of the received power for symbol 0 gets closer to that of 1. We note that even for simple OOK scheme with relation noise getting analytical results is a non-trivial task. Using computer simulation we determined that the optimal value of the power detection threshold, $P_T(d)$, is $0.85e-20$ for $d = 0.03$m and $P_{Tx} = 0.1$aJ. This results in BER smaller than $10e-6$. Note that without an accurate analytical model it is impossible to say what is the actual value of BER is for $d = 0.03$m. However, running $10e6$ simulations with $P_T(d)$ we observed no symbol errors. Increasing the communication distance further to $d = 0.035$ while keeping the same emitted power results in BER $10e-4$ corresponding to the optimal $P_T(0.35)$ around $0.7e-20$J. Thus, it is safe to assume that using 0.1aJ the maximum distance resulting in negligible BER is upper bounded by 0.03m.

V. Comparison of Architectures

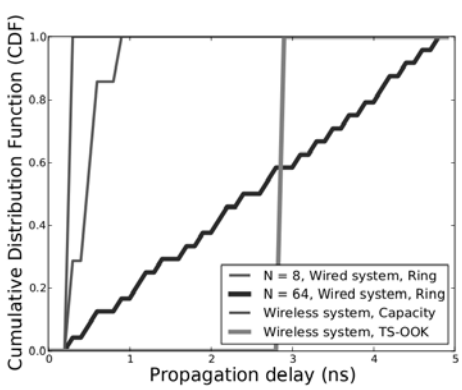
When the number of active nodes in a network-on-chip grows, the data exchange between nodes becomes one of the most taught challenges. In this section, we compare the two discussed architectures of networks-on-chip – ring and wireless mesh – focusing on the end-to-end communication delays, as the major metric related to the computation systems.

We propose a simple technique to roughly estimate the propagation delay, assuming that each of the messages is transmitted through the link exclusively without a way to get collided with another message. Admitting that this technique is not fully accurate due to effects of collisions not being taken into account, we still consider the proposed method to give a reasonable prediction, regarding the system performance.

We start with the analysis of the wired system by calculating the propagation delay in hops, H, depending on the number of nodes in the system. There are two options for H, depending on if number of cores, N, is odd or even:



(a) Average versus number of nodes



(b) Cumulative distribution function

Fig. 6. Multiple bacteria scenario: the effect of distance between the nanomachines

$$H_{odd} = \frac{1+1+2+2+...+k+k+(k+1)}{2k+1} = \frac{k(k+1)+(k+1)}{2k+1} = \frac{(k+1)^2}{2k+1}, \quad (9)$$

where $k = (N-1)/2$.

Thus, the closed-form equation for H_{odd} is given by

$$H_{odd} = \frac{N+1}{4}, \quad (10)$$

where N is the number of nodes in the network.

Similarly, we obtain H_{even} as

$$H_{even} = \frac{N^2}{4(N-1)} \quad (11)$$

To get the actual delay in seconds, one has to multiply H with the value of the propagation delay via a single hop, defined as δ.

$$D_{ring} = \begin{cases} \frac{\delta(N+1)}{4}, N \text{ is odd} \\ \frac{N^2\delta}{4(N-1)}, N \text{ is even.} \end{cases} \quad (12)$$

Regarding the wireless mesh architecture we recall that with the communication range discussed in the previous section, all the nodes are technically capable to hear each other. Thus, the propagation delay in the wireless mesh system is constant and can be estimated as

$$D_{mesh} = 8T_s(L_{data} + L_{addr}), \quad (13)$$

where L_{data} is equal to 64 bytes, L_{addr} is estimated as 8 bytes, while T_s states for the symbol duration. Based on the results, given in the previous section, we define the two possible values for the symbol duration as

$$T_s^{Cap} = \frac{1}{C}, T_s^{TS-OOK} = \frac{1}{T}, \quad (14)$$

where T_s^{Cap} is the minimum symbol duration (following the Shannon's capacity limit), while T_s^{TS-OOK} is almost the symbol duration for constructive modulation and coding scheme, namely On/Off Keying (TS-OOK [7]), C is the theoretical channel capacity, and T is the throughput for TS-OOK.

In the following part we numerically compare the propagation delay for all three considered scenarios – ring, wireless mesh capacity, wireless mesh TS-OOK – in terms of both average and estimation of cumulative distribution function.

The Fig. 6(a) presents the comparison of the average values. As can be seen from this plot, the wireless mesh system starts being more efficient in terms of delay from 64 nodes with simple TS-OOK modulation, and already from 4 nodes for the capacity case. Regarding the cdfs, presented in Fig. 6(b), we also note, that even in case of similar averages (64 and 4 nodes for Capacity and TS-OOK, respectively), the propagation delay in the wireless mesh topology is much more stable, which gives a significant benefit for higher level hardware, such as load balancer and cache controllers, as well as software-based task schedulers and virtual memory managers.

VI. Conclusions

Network-on-chip is a promising architecture for the next generation computation systems that, in principal, can scale up to infinite number of nodes. However, the communication between the high number of nodes via wired links can be challenging. To mitigate this issue, the wireless network-on-chip has been recently proposed. In case of full connectivity between all the nodes, the propagation delay in WNoC should drop significantly, comparing to the wired solutions.

At the same time, a set of research challenges has to be solved to enable wireless connectivity between hundreds and thousands of nodes in prospective wireless networks-on-chips, starting primary with design of transceivers and more efficient modulation and coding schemes.

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