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Pulse Interspersing in Static Multipath Chip Environments for Impulse Radio Communications

Albert Mestres[a], Sergi Abadal[a], Ignacio Llatser[a], Eduard Alarcón[a], Heekwan Lee[b], Albert Cabellos-Aparicio[a]

[a] *NaNoNetworking Center in Catalonia (N3Cat); Universitat Politècnica de Catalunya, Barcelona, Spain; E-mail: {amestres,acabello}@ac.upc.edu, eduard.alarcon@upc.edu*
[b] *Samsung Advanced Institute of Technology (SAIT); South Korea; E-mail: heekwan.lee@samsung.com*

Abstract

Communications are becoming the bottleneck in the performance of Chip Multiprocessor (CMP). To address this issue, the use of wireless communications within a chip has been proposed, since they offer a low latency among nodes and high reconfigurability. The chip scenario has the particularity that is static, and the multipath can be known *a priori*. Within this context, we propose in this paper a simple yet very efficient modulation technique, based on Impulse Radio - On–Off-Keying (IR-OOK), which significantly optimizes the performance in Wireless Network-on-Chip (WNoC) as well as off-chip scenarios. This technique is based on interspersing information pulses among the reflected pulses in order to reduce the time between pulses, thus increasing the data rate. We prove that the final data rate can be considerably increased without increasing the hardware complexity of the transceiver.

Keywords: Multiprocessor interconnection, Chip interconnection, Wireless communications, Impulse Radio, Multipath, Data Rate

1. Introduction

Throughout the decades, technology advancements have allowed the integration of more transistors on the same chip and resulted in a very high performance increase and cost decrease per transistor. However, the energy consumption currently grows faster than the performance of a single processor, due to the small dimensions of the transistors and the interconnections. To address this issue, parallel architectures have been introduced in microprocessor architecture design. Parallelization is achieved by interconnecting several independent processors forming a Chip Multiprocessor (CMP). The main performance bottleneck in these systems is currently defined by the intra-chip communication requirements set by coherency or synchronization, among other common and necessary operations in parallel computing.

In this context, the Network-on-Chip (NoC) paradigm was proposed to increase the performance of CMP systems by providing scalable and efficient inter-core communication through wireline routed interconnections [1]. This approach arose as opposed to the traditional bus-based architectures, which scale poorly in terms of delay and energy efficiency due to its time division multiplexing nature when the number of cores is increased. However, as the technology downscaling allows the integration of more cores in the same chip, the communication demands also increase. Initial wired NoC solutions pose several challenges in terms of hardware optimization; there is an intrinsic trade off among delay, power requirements, and chip area utilization, also referred to as area overhead [2].

To address these difficulties, the use of Wireless Network-on-Chip (WNoC) has been proposed [3, 4]. Wireless interconnections offer a low latency interconnection among on-chip antennas. The approach of integrating at least one antenna per core becomes interesting in order to offer direct transmissions among all cores. However, the size of metallic on-chip antennas might render this approach unfeasible, as the core sizes continue to shrink. Within this context, the Graphene Wireless Network-on-Chip (GWNoC) solution has been introduced [5] as a particular implementation of a WNoC. The employment of small-scale wireless communication is enabled by means of graphene antennas [6, 7, 8]. Graphene antennas just a few micrometers in size, i.e. two orders of magnitude below the dimensions of future metallic on-chip antennas, could provide inter-core communication in the Terahertz (0.1-10 THz) band. These characteristics will both enable size compatibility with each processor core and offer enough bandwidth in massively parallel multiprocessors [5].

A critical aspect when considering the WNoC paradigm is the design of efficient modulation techniques suited for this particular scenario. Indeed, the WNoC scenario presents strong requirements as well as uniqueness when compared to more traditional wireless environments. First, the WNoC environment is completely static and known *a priori*. Second, the modulation must offer high data-rates while keeping the energy consumption low. Third, given that the scenario is confined, the propagation of the waves includes strong multipath components. Finally, the associated transceiver must be co-integrated with the cores (area overhead) and therefore complexity should be low.

Given the above-mentioned requirements, Ultra Wide-Band (UWB) transmission techniques [9] are a good candidate for the WNoC scenario. UWB offers high-bandwidth communications for short-range and very low energy level using a large portion of the radio spectrum [9]. In the context of UWB techniques, Impulse Radio (IR) [10] encodes the information by means of pulses, which have a short duration in time and occupy a large bandwidth. Among the different modulation schemes proposed, On–Off-Keying (OOK) is the simplest one, imposing very low requirements to the transceiver and at the same time offering high data-rate transmissions. OOK uses one pulse to transmit '1' and silence to transmit '0'. The IR paradigm in general and the OOK in particular are known to be resistant to multipath, due to the time resolution used [10, 11] –which avoids the narrow-band fading. In IR this is achieved by separating the pulses in such a way the reflected pulses do not interfere with the subsequent pulses.

However, IR-OOK –as is– is not taking advantage of the opportunities and uniqueness offered by the WNoC scenario and typically not present in traditional wireless environments. First, given the ultra-high frequency, the duration of the pulses is much lower than the delay of the different multipath components. And second, given that the scenario is static and known *a priori*, the multipath components are *deterministic*.

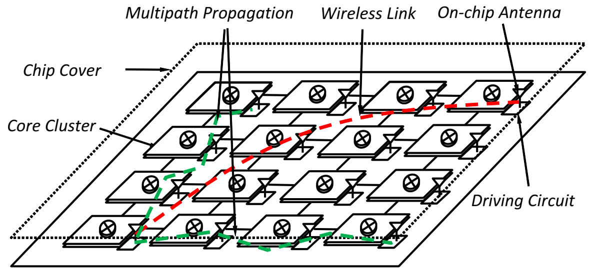

Figure 1: Network-on-chip scenario, in which the multipath is caused by reflections in the chip cover.

In this paper we propose a simple yet very efficient modulation technique, based on IR-OOK, that significantly optimizes the performance in WNoC as well as off-chip scenarios. We show that this novel modulation offers significant advantages in terms of data-rate while keeping its simplicity and low energy requirements.

2. System and propagation model

Figure 1 shows a schematic representation of the environment assumed in the paper. We consider a point-to-point communication between two components in a known and deterministic environment, as an example, two antennas communicating in a Network-on-Chip or in an off-chip scenario. In both cases, we assume that there is a dominant path (such as Line-of-Sight) and that the electromagnetic waves propagate through the medium (chip package or air). Given that the system is static and deterministic, both components have this *a priori* knowledge. We consider as out of the scope of this paper the exact procedure used to obtain this knowledge. Finally, we assume that the pulse duration is smaller than the delay among the multipath copies. In the following sections, we review the communication scheme and the propagation model assumed in this paper.

2.1. Impulse-Radio On-Off-Keying definition

The IR-OOK transmission scheme is based on the transmission of one pulse to transmit the bit '1' and silence to transmit the bit '0'. The mathematical representation of the IR-OOK technique is as follows:

$$u(t) = \sum_{\forall k} u[k] s(t - kT_s) \quad (1)$$

where $u[k]$ is the k-th binary signal transmitted and $s(t)$ is the pulse. We define T_s as the separation between pulses, which determines the data rate and the speed at which the transmitter and the receiver have to work. We define $T_{b'}$ as the duration of the transmitted pulse, which is a design parameter and depends on the total bandwidth used; and T_b as the duration of the pulse in reception, which may have been distorted during the propagation (see next subsection).

2.2. Propagation model

The propagation takes place in a close and static environment. Consequently, the propagation is deterministic and can be described using the well-known ultra-wideband propagation model. We consider the classic transmission scheme, in which the transmitter modulates the signal, which is radiated by the antenna. The radiated signal propagates in free space, and may be reflected in different surfaces found within the device. The different copies of the signal reach the receiving antenna, wherein they are converted into an electric signal and it is processed in order to obtain the information.

The signal after the receiving antenna is conformed by the multiple distorted copies of the transmitted signal. It can be analytically expressed – assuming that both characteristic transmit and receive antenna impedances are equal– as [12]:

$$r(t) = \sum_{\forall p} \mathbf{h}'_{rx,p}(t) * \mathbf{h}'_{ch,p}(t) * \mathbf{h}_{tx,p}(t) * \frac{\mathrm{d}}{\mathrm{d}t}(u(t)) \quad (2)$$

where p stands for each possible path and $u(t)$ is the transmitted signal (1). $\mathbf{h}_{tx,p}$ and $\mathbf{h}_{rx,p}$ are vectors representing the transfer functions of the antennas at the direction defined by path p, and $\mathbf{h}_{ch}$ is a matrix representing the transfer functions of the channel at the path p.

In simple environments, the determination of each path can be done analytically by considering the reflections of each path in the surrounding materials, to obtain the channel transfer function. However, in more complex environments, the use of other techniques, such as the ray tracing [13] or computational electromagnetics software, may be necessary. Moreover, during the propagation, the signal is attenuated and distorted due to the free space path loss and the reflections and delayed due to the propagation time. The behavior of reflections depends on the material and on the roughness of the surface. The roughness of the materials used in an electronic device in the frequency range of interest is negligible [14]; thus, producing specular reflections.

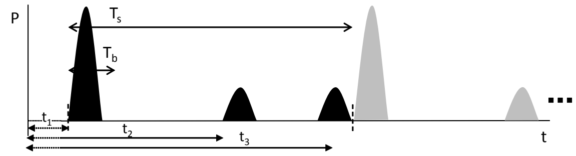

Figure 2: Example of a received signal. The data rate $(1/T_S)$ in traditional schemes depends on the delay difference between the first and the last multipath component.

2.3. Received signal and data rate

The received signal depends on the pulse shape, the number of multipath components and the distortion caused during the propagation. Figure 2 shows the received signal assuming the propagation environment sketched in Figure 1, in which only two reflected components are received. We assume that the rest of multipath components will be negligible. The maximum data rate achieved in traditional incoherent IR-OOK schemes depends on the position of the last multipath received [15], and determines the inter-symbolic time T_S. Consequently, the later the last reflected pulse arrives, the lower is the data rate. Incoherent receivers are simpler than coherent receivers and they are able to work at much higher frequencies, since they only use the energy received in a predefined integration period [16].

3. Proposed transmission scheme for NoC and off-chip environments

In this section, we introduce a novel transmission technique to increase the maximum data rate in static multipath environments. We assume that the delay between multipath components is higher than the pulse duration. This makes sense if we use small antennas (see Introduction) which radiates in ultra-high frequencies, i.e. at the Thz band. When using this frequency band, the duration of the pulses is shorter than the delay difference in the multiple paths. We also assume that the multipath is completely deterministic, by taking advantage of the known and static scenario, as discussed in Section 2.

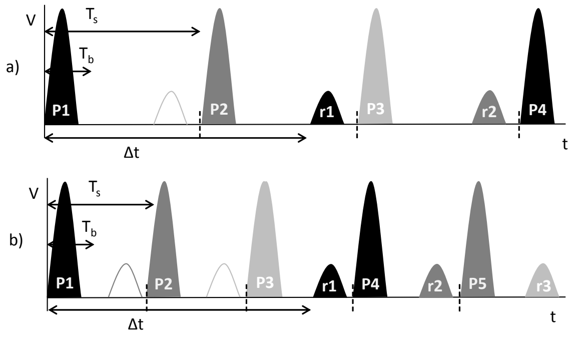

Figure 3: Application of the transmission scheme in an example signal, with two received pulses. a) $N = 1$, one pulse is placed between the strongest pulse (P) and the reflected pulse (r). b) $N = 2$, two pulses are placed between the strongest pulse and the reflected pulse (white pulses represent reflections of previous pulses).

The objective is to overcome the limitation of traditional IR-OOK systems, in which the data rate is limited by the last multipath component. In scenarios in which the reflected pulses are largely delayed in comparison of the pulse duration, the data rate is dramatically reduced. Such reduction in the data rate is mainly due to the fraction of time in which nothing is transmitted, since it is necessary to wait for the reflected pulse.

In order to increase the data rate, we propose an alternative technique consisting of interleaving information pulses among the reflected pulse. The receiver will receive and decode the first pulse, which is the strongest, and will ignore the other pulses. This scheme cannot be applied when the multipath is not static and cannot be completely characterized. The characterization of the multipath can either be precalculated in the design of the chip or measured in the initialization of the wireless link. In this scheme, the achievable data rate does not depend directly on the position of the last multipath component, but on the number of pulses that can be placed between the first and reflected pulses. Note that the proposed algorithm is independent of the pulse shape, the pulse energy and the propagation channel, since it only consider the pulse duration in the receiver T_b and the delay of the multipath components.

Figure 3 shows a representation of this scheme, considering one reflected pulse. In Figure 3 a), the data rate is effectively doubled, and in Figure 3 b), the achievable data rate is multiplied by three. The maximum number of information pulses that can be placed between the original and reflected pulses depends on the delay distribution of this pulses.

In the simplest case, in which only one reflected pulse is considered, the number of interleaved pulses N and the separation among pulses T_S can be analytically calculated. If we define Δt as the delay between pulses, the maximum number of pulses that can be placed in between is:

$$N_{max} = \left\lfloor \frac{T_b + \Delta t}{2Tb} \right\rfloor - 1 \quad (3)$$

in which the factor 2 in the denominator accounts for the time slots of direct and the reflected pulses.

Figure 3 a) shows a case where $N = 1$ and figure 3 b) shows a case where $N = 2$. The separation among pulses T_S is:

$$T_S = \frac{T_b + \Delta t}{N} \quad (4)$$

When an arbitrary multipath profile, N_{max} and T_S cannot be analytically calculated. The following algorithm describes a procedure to find the minimum T_S by using the position and the duration of all multipath components.

input : T_b: duration of the received pulse
input : MPC : multipath information
output: T_S: separation between pulses

```
1  T_S = 2 T_b;
2  found = false;
3  while not found do
4      txBits = 0;
5      t = 0;
6      timeVect = emptyTimeVector;
7      while t < T_Sim do
8          insert(timeVect,t,MPC);
9          if ifCollision(timeVect) then
10             T_S = (t + T_b)/txBits;
11             break;
12         else
13             txBits++;
14             t += T_S;
15         end
16     end
17     found = true; // T_S found
18 end
```

Algorithm 1: Pulse separation determination

The idea of the algorithm is the following: it starts with the lower possible T_S (line 1) and it checks if it provokes a collision (lines 3-18). This verification is done by checking for a sufficient number of transmitted pulses (lines 7-16) if the transmission of a new pulse (line 8) collides with the multipath components of previous pulses (line 9).

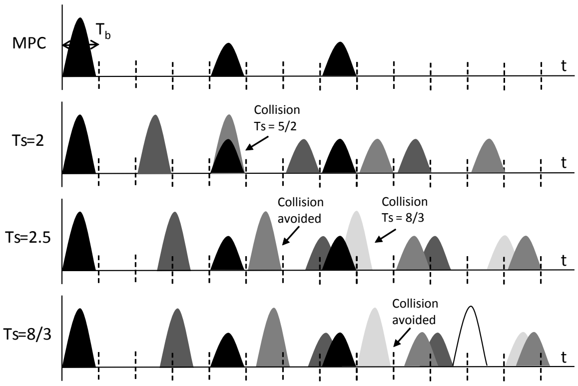

Figure 4: Different steps during the execution of the algorithm. MPC is the multipath information (smaller pulses represent reflections). The other lines represent the different steps of the algorithm.

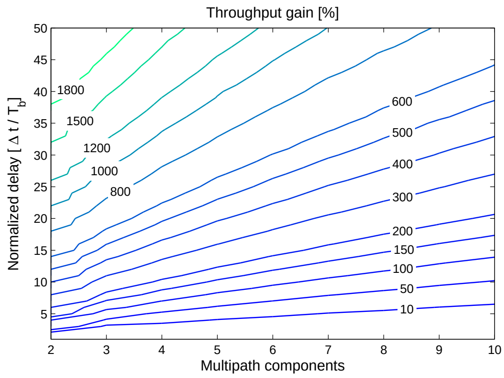

Figure 5: Average increase of the data rate (in %) as a function of the number of non negligible reflected pulses and the normalized delay of the last multipath component, calculated by averaging random configurations of the multipath.

When a collision is detected (lines 9-11), the new T_S to check is calculated to place the pulse which has collided right after the reflected pulse in which it has collided (line 10). A collision is detected when the new transmitted pulses overlap any multipath component of previously transmitted pulses. This procedure is repeated until a valid T_S is found (line 3). Figure 4 shows an example of the application of the algorithm in a simple case where two multipath copies are received after $4T_b$ and $7T_b$. It needs three iterations until it finds that the optimal T_S is 8/3.

4. Numerical Results

The objective of this section is to numerically evaluate the improvement in the data rate in different propagation environments, which determines the position of the multipath components and consequently the performance of the algorithm. The received signal would be obtained with (2) in the specific environment.

In this section, in order to present general results, we generalize the environment by only considering the duration of the received pulse and the delay of the different multipath components. In a real scenario, T_b would be between 1 ps and 0.1 ps, according to the antenna bandwidth and the distortion in this scenarios. The maximum time delay between reflected pulses depends on the specific chip dimensions, we have chosen between a range between $1T_b$ and $30T_b$ to consider different scenarios and to show the tendency as this delay increases.

In the simplest case, when only reflected pulse is considered, the separation between pulses tends to be $2T_b$. Consequently, the achieved data rate tends to be independent of the multipath propagation and it only depends on the pulse width.

When there are more non negligible reflected pulses, the achievable data rate depends on the exact distribution of the reflected pulses. To evaluate this technique, we have calculated the average gain in the maximum data rate for a different number of reflected pulses and different delay distributions in the multipath components. This gain is defined as the increase of the data rate using the pulse interspersing technique with respect to the traditional IR approach [15]. Figure 5 shows this average gain, calculated by averaging the T_S obtained with algorithm 1, considering between 1 and 10 reflected pulses randomly distributed between T_b and certain maximum time delay between T_b and $30T_b$. The graphic shows that an important gain in the data rate can be obtained, especially when the number of non-negligible pulses is small and the delay among pulses is high, where gains higher than 10 can be obtained.

5. Conclusions

Wireless communications have been recently proposed to communicate in the chip scale. A critical aspect when considering chip communications is the design of efficient transmission techniques suited for the particular application. It must offer a high data rate, whereas the complexity must be low. Moreover, the scenario is completely static and known *a priori*, which makes possible to fully characterize the multipath propagation.

In this paper, we have proposed a transmission scheme for point-to-point Impulse Radio (IR)-On–Off-Keying (OOK). This technique consists of interspersing information pulses among reflected pulses in order to increase the data rate. We described the procedure to find the maximum data rate and we showed the average increase of it in different scenarios. We conclude that the data rate can be considerably increased for this particular application, and in similar applications in which the multipath is completely deterministic.

Acknowledgment

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