An Energy Aware Transmission Control in Wireless Network-on-Chip

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Abstract: - In wireless Network-on-Chip (WiNoC), radio frequency (RF) transceivers account for a significant power consumption, particularly its transmitter, out of its total communication energy. In current WiNoC architectures, high transmission power consumption with constant maximum power suffers from significant energy and load imbalance among RF modules which leads to hotspot formation, thus affecting the reliability requirement of the network system. This paper proposes an energy-aware packet transmission control mechanism, in which, based on transmission energy consumption and predefined energy threshold, packets are routed to adjacent transmitter for communication with receiver radio hub, aiming an optimized energy distribution in the network system. Our proposed strategy achieves a total system energy reduction by about 15% for WiNoC upper sub layer network energy saving with less significant impact on total system energy with limited performance degradation.

Key-Words: WiNoC; energy aware mechanism; RF transmitter; energy threshold; energy saving; energy imbalance

1 Introduction

It is predicted that the rapid advancement in multi-core System-on-Chip (SoC) has driven the number of processing cores to manifold increase on a single die over the next few years. The Network-on-Chip (NoC) emerged as the communication backbone integrating high density processing cores is one of the best candidates to replace bus-interconnects system on a single die.

However, as the number of cores in the network size increases, the scalability limitations of conventional planar metal interconnect NoC such as high latency and power consumption become significant. To mitigate this problem, a few emerging NoC derivatives have been introduced such as 3D-NoC, nanophotonic communication and RF-based interconnect or also known as wireless network-on-chip (WiNoC). RF interconnects replace metal wires in traditional wire-based NoC.

RF communication links offer a mid range to far range communication solution for a large network platform. The main objectives of introducing WiNoC are to transmit data with high bandwidth and low latency for middle and long range communication between far apart processing cores. The biggest advantage of using on-chip RF links is its compatibility with the traditional CMOS process. Due to the introduction of on-chip transceiver and antenna, silicon area and power consumption overheads also emerge.

In terms of energy consumption in WiNoC, the major contribution of WiNoC power consumption is due to the radio transmitter front-end connected to the antenna. In realizing the proposed energy management control, we consider the implementation on homogeneous multicore system with application specific integrated circuit design. The importance of energy aware scheme in WiNoC platform are discussed as follow:

1) Firstly, computation and communication loads vary over time depending on extrinsic factors such as power saving mode specification and online data streaming that require extra run-time computation and communication efforts.

2) Secondly, intrinsic parameter that affects computational and communication loads such as application specific algorithm. Data transmission and execution on different processors for a long period of time drives load imbalance and hotspot formation at the upper layer network of WiNoC platform.

3) Packet error rates at receiver terminal in WiNoC platform is not trivial to overcome for on-chip wireless communication. Thus, existing WiNoC architectures employ constant maximum transmitting power between communicating radio hubs irrespective of physical location of the cores. Significant signal-to-noise ratio effect may be observed when the maximum transmission power is utilized for communication in order to optimize bit error rate. However, this leads to thermal hotspot formation radiated by high switching activity transceivers.

For all the above reasons, we believe dynamic energy management on NoC cores offers improvement in energy consumption while satisfying system throughput constraint. In this paper, we propose a novel mechanism for managing energy dissipation of transmitters in WiNoC architectures. The idea of applying our proposed technique is that, when a thermal hotspot occurs at a radio hub, a request block of its transmitter migrates the packets to the nearest radio hub via a physical link for communication with destination radio hub. The wire link utilizes less energy than the RF link for a certain number of hops where we discuss the practical measurement in Section 3. Because our scheme employs single hop packet migration pattern, we believe the energy aware mechanism is significant as well as achieving load balancing objective at the upper layer network of WiNoC platform.

Our proposed strategy achieves an average total system energy reduction of about 15% for second layer WiNoC energy saving with less significant impact on total system energy when verified using SPLASH-2 and PARSEC benchmarks. The major contributions of this article are:

- To perform a sub layer transmitter-based energy management mechanism in WiNoC platform.
- To present a proposed design that supports the mechanism implementation on two WiNoC platforms, namelys McWiNoC and iWise architectures.
- To evaluate the efficiency of the proposed design using SPLASH-2 and PARSEC benchmarks to observe the energy saving and performance impacts in the WiNoC architectures.

The rest of this article is organized as follows: Section 2 provides an overview of related works in WiNoC dynamic energy management. Section 3 discusses the background theory on energy management from transmitter perspective. Our proposed core design is detailed out in Section 4. The efficiency of the proposed method and its performance impact are reported in Section 5. Finally, Section 6 delivers some conclusion remarks.

2 Related Works

NoCs has emerged as the future of multicore interconnects solution. Traditional NoCs use multi-hop packet switched communication which introduces significant latency as the network size grows larger, hence becomes the bottleneck in wire based NoC communication system. To deal with this issue, several emerging technologies have been introduced such as 3D, optical and wireless NoC architectures [1]. In the case of wireless NoCs, several works propose radio frequency (RF) transceivers replacing electrical links as a communication medium [2][3]. On-chip antenna designs that operate in high frequency at deep submicron level have been proposed in support of the transceivers design [4][5]. Hybrid architecture that combines electrical wire link with RF link as communication paradigm has also been proposed [6]. Cluster-based WiNoC architecture connects each transceiver to a group of neighbouring processing cores [6][7]. Guidelines on designing on-chip wireless communication in sub-terahertz frequencies under performance requirements have been explored. The work proposed an architecture applying *small world* property that integrates conventional NoC platform with different topologies via radio hubs [8].

Traditional transmitters in WiNoC use fixed transmitting power regardless of the physical location of the receiver. Maximum transmission power is utilized to meet the reliability requirement of maximum bit error rate constraint. The design drives power amplifier (PA) [9] to configure real output power for communication with destination radio hub.

Our scheme imitates task migration strategy introduced in traditional mesh topology NoC, but being implemented in the context of on-chip RF communication. In traditional 2D NoC [10][11], task migration involves dynamic task rescheduling and remapping of originally assigned core-task execution to available cores within the cluster partition. Our energy aware scheme is different with its traditional counterpart due to its data type handling. In WiNoC, the data does not need to be rescheduled because of large bandwidth capacity the transceivers can transmit.

In the context of WiNoC, dynamic energy management requires specific controller and implementation policy in semiconductor ambience. The main problem is that, although communication energy at RF layer consumes about 20% - 30% of the total WiNoC energy, if a particular RF transmitter propagates data for a long period when other transmitters are less utilized, imbalanced energy density distribution may take place, causing hotspot formation in the particular fraction of area.

For this reason, this paper presents an energy aware scheme that applies a mechanism which dynamically reroutes the transmitting packets based on normalized energy constraint. We implemented our design on two WiNoC architectures; McWiNoC[7] and iWise[3]. These architectures employ cluster-based WiNoC architectures.

3 Backgrounds

In this section, we present a background study on determining energy dissipation at wireless level of WiNoC. As the energy quantity increases continuously at runtime, our proposed energy aware formulation is also presented to quantify energy consumption of upper subnet hierarchy in any WiNoC architectures. For a hybrid wired/wireless architecture, the energy dissipation of a wireless link, $E_{totupperlink}$ is given by

$$E_{totupperlink} = \sum_{i=1}^{m} \left(E_{pkt,uppernet} + E_{transceiver} \right) \quad (1)$$

where $E_{pkt,uppernet}$ and $E_{transceiver}$ are the energy dissipations of the packet traversing in the upper hierarchy components and transceiver circuits for the i-th frequency for a number of frequency channels in the link represented by m. To determine packet energy dissipations at wireless link, $E_{pkt,uppernet}$, it is defined by

$$E_{pkt,intrasubnet} = N_{uppernet}\, E_{uppernet}\, h_{uppernet} \quad (2)$$

where $N_{uppernet}$ is the total number of packets routed between two communicating wireless subnets, $E_{uppernet}$ is the energy dissipated by a packet that traverses between the subnets via single hop wireless link. Whereas $h_{uppernet}$ denotes the average number of hops for each packet in the upper level network. Most existing WiNoC platforms employ maximum constant transmitting power hence maximum transmission energy is dissipated, $E_{transmission}$. Considering this case, we define percentage of energy threshold, $E_{threshold}$ as

$$E_{threshold} = E_{transmission}\, N_{cycle,window}\, P_{threshold} \quad (3)$$

beyond which the next incoming packets are transmitted via upper hierarchy wired link. Based on Eq. (3), $E_{transmission}$ is measured for a defined period of simulation time, $N_{cycle,window}$. The percentage of energy threshold which is the limiting factor for wireless transmission at a particular radio hub is denoted as $P_{threshold}$.

Considering N cycles running 64 bits packet transmission at radio hub level, if the total energy dissipation at upper hierarchy energy at runtime (denoted by $P_{threshold}$) exceeds $E_{threshold}$, the next predefined, k incoming packets are routed to adjacent radio hub via a second layer wired link. The packet energy dissipation for the new route, $E_{newupperlink}$ is expressed as

$$E_{newupperlink} = E_{newupperlink,pkt} + E_{newupperlink,wired} + E_{transceiver} \quad (4)$$

where $E_{newupperlink,pkt}$ is energy dissipated for packets at upper network layer and $E_{newupperlink,wired}$ is energy dissipated via wired capacitance when packets are routed to adjacent radio transmitter for communication with destination radio hub. This can be formulated as

$$E_{newupperlink,pkt} = N_{newupperlink,wired}\, E_{newupperlink,wired}\, h_{newupperlink,wired} \quad (5)$$

Based on DSENT and SPICE simulations for 32nm technology, one hop electrical link consumes 0.68

pJ/bit as compared to 1.4 pJ/bit for its RF link counterpart. A 2 electrical link hop dissipates 1.36 pJ/bit, which is 0.4 pJ less energy than a single RF link communication hopping. We assume wire length implementation of the upper layer WiNoC platform is double the wire length of the connecting sub layer cores. For an example, we consider McWiNoC with 16 radio hubs architecture which its wire power consumption depends on wire lengths. If a Silicon die size of 20x20 mm platform is implemented, the distance between two consecutive hubs, derived from the following formula is 5mm:

$$L_{wire} = \frac{\sqrt{\text{die size}}}{\sqrt{\text{no. hubs}}} \qquad (6)$$

Meanwhile, for a traditional mesh NoC with 64 cores, using Eq. (6), the distance between two consecutive cores is 2.5mm.

4 Adaptive Energy Aware Control

In realizing the proposed energy management control, we consider the implementation on homogeneous multicore system with application specific integrated circuit design.

In this section, we present a scheme that dynamically reconfigures the transmission energy dissipation at the upper layer network of WiNoC architectures. In the first subsection, the architectural design of the strategy is discussed. Illustration of the proposed design and its algorithm is detailed out in the following subsection. The core architecture design of our energy aware implementation and the access control mechanism are shown in the last two subsections.

4.1 Architecture

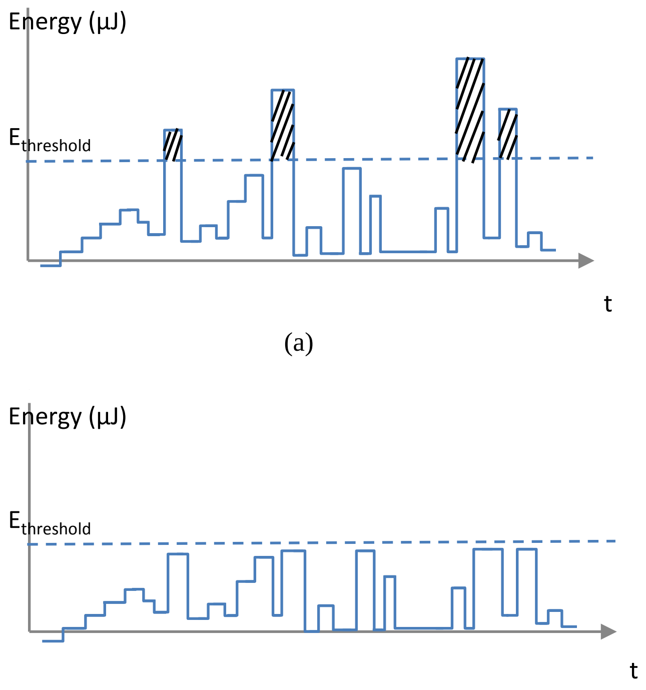
The main idea in the proposed architecture is to introduce energy aware mechanism to the transmitter at the upper layer network of WiNoC architectures. Equipped with good energy detection at the transmitter module, the architecture is assumed to be able to provide accurate statistical energy dissipation information to the adaptive energy management scheme.

The core architecture of the distributed self-calibration approach is the adaptive packet relocator. The module features a dynamic packet relocation scheme that senses the transmitted packets energy dissipation inside the transmitter buffer across a finite window cycle and adapts the system's most suitable energy aware decision. The energy aware scheme routes incoming packets to adjacent radio hub via either wire overhead introduced at the upper layer network or regular wireless transmission when necessary.

Our distributed mechanism introduces a dynamic packet relocation module based on predefined energy threshold and packet energy dissipation at the transmitter buffer. Based on the radio hub address information, the <*src,adj*> table entry drives the packets to the associated radio hub for communication with destination radio hub.

4.2 Adaptive Mechanism

Fig. 1 shows the transmitting energy implementing the energy aware module. Fig. 1(a) shows the discrete packet energy dissipation graph of a transmitter at the upper layer network of WiNoC for a certain period, *t*. The energy pattern changes variably across the cyclic period depending on the switching activity triggered by transmitted packets buffered at the terminal.



(a)

(b)

Figure 1 Transmitter buffer energy distribution
(a) without energy aware strategy
(b) implementing an energy aware strategy

As the distributed energy aware mechanism is implemented, a balanced energy distribution can be achieved throughout the WiNoC platform as shown in Fig. 1(b). Fig. 2 illustrates a finite state machine implementing the energy manager.

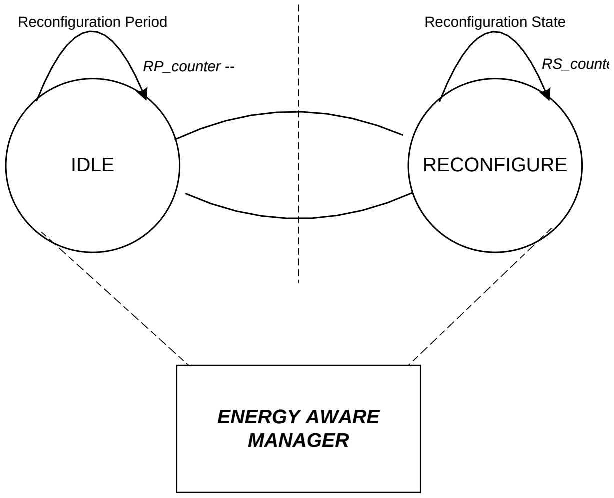


Figure 2 Finite state machine implementing the proposed energy aware method.

Distributed power manager adopts two modes of operation: Reconfiguration period (RP): During this period, each WiNoC transmitter collects the periodic energy dissipation for packets transmitted via wireless link. As soon as the adaptive module notifies excessive packet energy dissipation beyond an energy threshold, it activates an energy aware mechanism that transmits incoming packets via overhead wire link, entering Reconfiguration State (RS). Based on the energy management strategy, next incoming packets are directed to the closest radio hub via a look-up table in each radio hub until the original transmitter energy value decrements below the allowable quantity. The packets are piggybacked on the adjacent radio hub for communication with destination radio hub based on the packet header information.

The management strategy can be formalized as in Algorithm 1. The algorithm can be described as follows. A source radio hub, *i* transmits packets to a destination radio hub, *j* via antenna of the source transmitter.

Each transmitter, *T* consists of a dedicated module, *PC[T]* that counts the number of packets stored in and out of the internal FIFO buffer of transmitter across the predefined reconfiguration period, RP. The period RP varies up to maximum 1000 cycles so that the energy dissipation activity of a particular transmitter is efficiently regulated. This also means, for any specific RP, 1000 packets is the highest allowable volume for temporary packet buffering at the transmitter while regulating the energy aware mechanism. *PC[T]* is decremented each time *j* receives a packet from *i*.

Algorithm 1 Proposed energy aware control mechanism

Require: *PC*, *energy_threshold*

```
PC ← k
if energy_current > energy_threshold then
    if en_token = 1 then
        for (i = k; i > 0; i--)
        {
            SendCmdRelocate($T,T_{adj}$)
            PC ← k – 1
        }
    else
        BufferPacket(T)
    end if
else
    SendCmdTransmitWireless(T,R)
end if
```

We assume there is a good energy detection module attached to each radio hub, providing accurate packet transmission energy information. The mechanism senses and computes the energy of incoming packets in the radio transmitter FIFO buffer before the end of period *PC[T]*.

Signal *energy_current* determines run-time energy consumption within the period *PC[T]*. When RP ends and no excessive energy consumption as limited by *energy_threshold* is reported at transmitter radio hub T_{src}, signal *energy_current* is not asserted. The manager assumes the buffer energy consumption of the pair $<T_{src},T_{dst}>$ is optimized. Hence, the packets are transmitted in normal operation via wireless link.

The algorithm is activated as soon as the signal *energy_current* is asserted due to over consumption of packet transmitted energy. If the total computed energy of transmitted packets is greater than the energy threshold denoted by *energy_threshold*, radio transmitter *T* forward the next incoming packets to T_{adj} through an overhead wire link. The *energy_threshold* value is predetermined before the execution of RP to guarantee reliability.

An internal updown counter, *k* inside the adaptive manager counts the number of cycles which packets are routed to T_{adj} via wired link when the energy aware mechanism is activated for optimized energy distribution all over the WiNoC platform. *k* is initially configured to a user defined value and is decremented each cycle when triggered.

The functions SendCmdRelocate(T,T_{adj}) and SendCmdTransmitWireless(T,R) drive the adaptive manager to sense and adapt transmission of packets either via wire or wireless link, depending on the underlying control network access status.

From an architectural viewpoint, Fig. 3 shows a block diagram of the radio transmitter T_{src} and T_{adj}.

The chain of bubbles labeled as CSw represents the control network used by T_{src} for sending transmitted packets to radio transmitter T_{adj}. In the next subsections, the main elements of our proposed architecture, which are the adaptive energy module and network control, will be presented in detail.

4.3 Adaptive Packet Relocator

The adaptive packet relocator consists of a mechanism that regulates the transmission energy from source *T* to destination *R* as well as a lookup table consisting of pair $<T_{src},T_{adj}>$ employed for energy management strategy as shown in Fig. 4. During the period RP, packets are received by transmitter module for wireless communication via an 8-bit input TX_PKT_i after the serializer module. If the accumulated energy of the transmitter buffer that stores the packets is less than the energy threshold, the packets are transmitted via an 8-bit TX_ANTENNA output port. However, if the energy is equal or greater than the normalized threshold, TX_WIRE is used to route packets to T_{adj} for communication with destination radio hub.

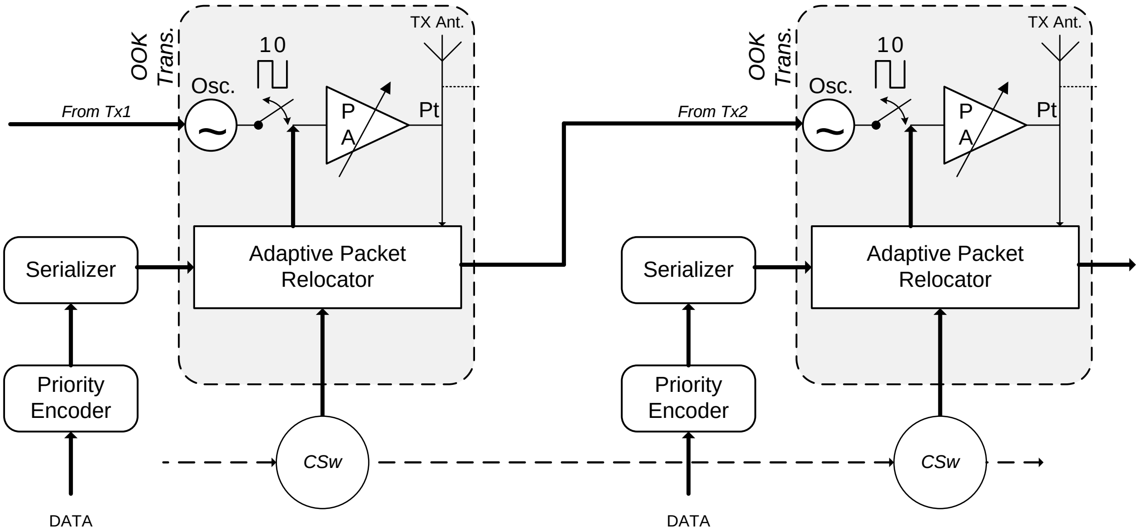


Figure 3 Block diagram of the architecture implementing the proposed WiNoC scheme

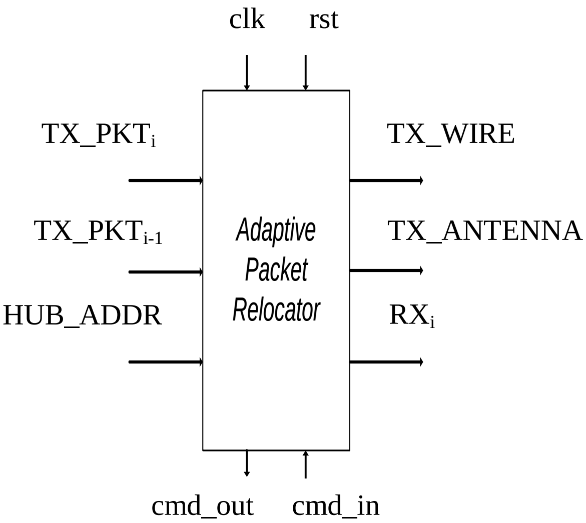


Figure 4 Proposed adaptive packet relocator module

As soon as the energy aware mechanism is activated, packets from T_{src} are received by input TX_PKT_{i-1} of T_{adj}. Based on the destination field of the received packets, T_{adj} broadcasts the data via its antenna, TX_ANTENNA output port. If the transmitted packet is destined for T_{adj}, RX_i output port passes down the packet to IP core for computational process. The commands cmd_in and cmd_out are used by the module to obtain the proprietary control in administering its energy aware mechanism.

4.4 Access Control Mechanism

The control network allows radio transmitters to notify other transmitters in the platform about the opportunity of routing its packet via an overhead wire. The network access does not interfere with actual WiNoC data transmission. In order to minimize the cost of the control network and given that there are no stringent performance requirements due to the fact that the control messages are dispatched once every RP received flits, we consider a ring based topology for connecting the radio hubs

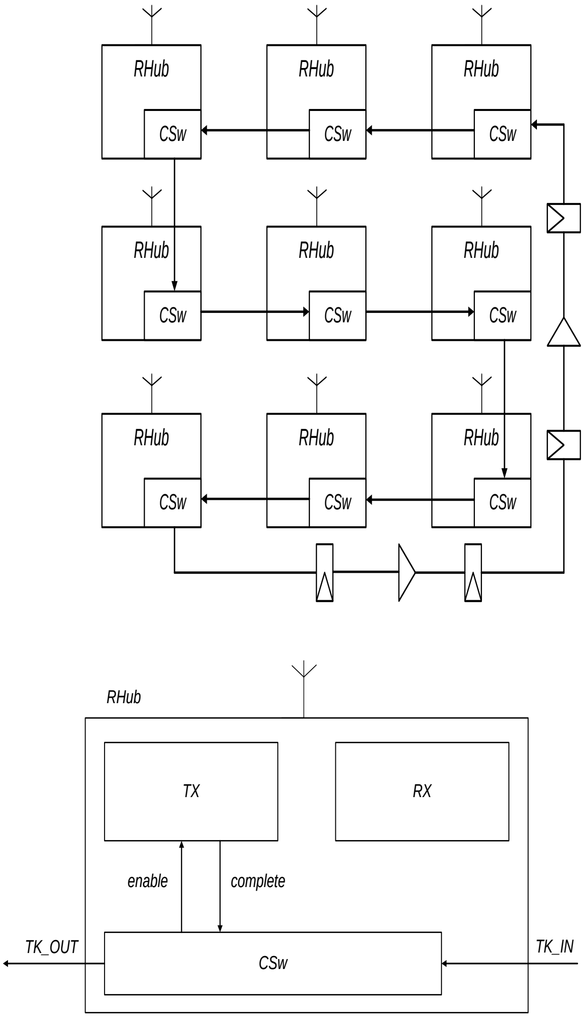


Figure 5 Access control module: A proposed floorplan for 3 x 3 radio hubs.

as shown in Fig. 5.

The control switch (CSw) receives commands from the radio transmitter. A command is a 1-tuple packet protocol. A 1-bit signal *enable* is the command used to notify a transmitter about its status to access the control network, either granted or denied (via signal cmd_in). Signal *complete* is an output command that updates the current transmitter status to the respective CSw (via signal cmd_out). CSw stores the commands into an internal FIFO buffer. A token circulates among the CSws enabling the CSw holding the token to forward the command to the output port cmd_out. The CSw that does not hold the token, simply forwards the command received in its input port cmd_in to its output port cmd_out. The token is released and forwarded to the next CSw through the output port TK_OUT when the internal FIFO buffer of the transmitter is empty.

5 Experiments, Results and Discussion

5.1 Experimental Setups

We implement the proposed technique in an extended version of Noxim[10] supporting wireless communications. It has been applied on two well-known WiNoC architectures: McWiNoC[7] and iWise[3]. We apply transmission power with a single transmitting power and vary the number of radio hubs to prove scalability of the proposed design. We implement a 4 radio hub network size and followed by 8 radio hubs. The proposed design has been modeled in VHDL and synthesized using Synopsys Design Compiler and mapped on 28 nm CMOS standard cell-library from TSMC operating at 1 GHz.

We compare the level of energy saving and performance improvement by applying the design on McWiNoC[7] and iWise[3] architectures.

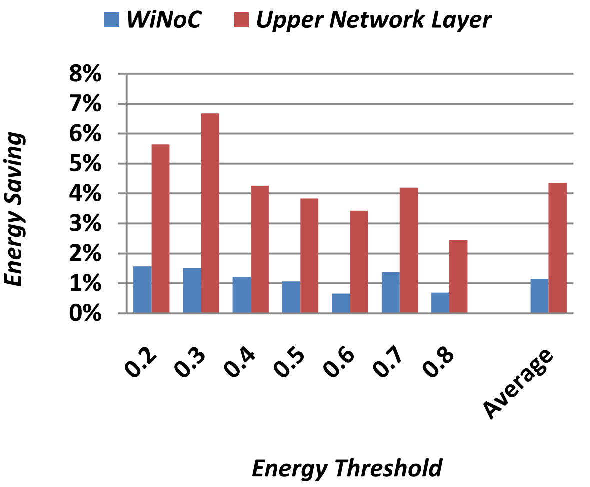


Figure 6 Total energy saving and upper network layer energy saving for McWiNoc-16 architecture.

Benchmarking has been done with SPLASH-2 and PARSEC application files. The transmitter power is set to 794 µW (-1 dBm) which corresponds to 1.4 pJ/bit. The attenuation map has been obtained from the Ansoft HFSS (High Frequency Structural Simulator)[16] modeled with zigzag antenna.

Energy threshold is a normalized unit for packets energy stored temporarily in the transmitter buffer for communication with destination radio hub. For every packet that is transmitted, the energy value is normalized based on a maximum 1000 packet size in the buffer. For example, value 0.5 on the horizontal axis of Fig. 6 is the energy limitation at a transmitter buffer if its switching energy

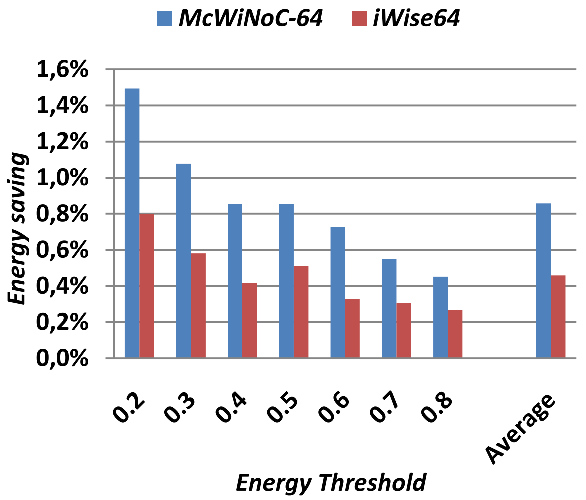


Figure 7 Total energy saving (McWiNoC-64 versus iWiSe64 architectures)

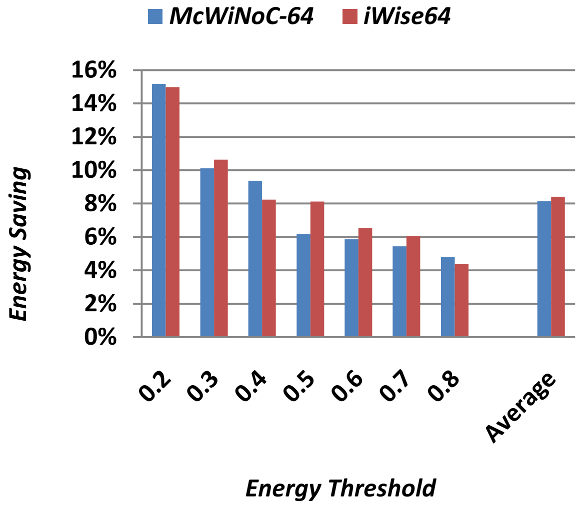


Figure 8 Upper layer network energy saving (McWiNoC-64 versus iWiSe64 architectures)

consumption reaches 50% out of maximum energy. The energy saving is achieved when packets are routed to adjacent radio hub via wire link instead of its RF link.

The energy saving analysis has been carried out in two types discussed as follow. Firstly, energy saving in the whole WiNoC platform which consists of a hybrid under layer traditional NoC link and RF nodes denoted as total energy saving. Second perspective is the energy saving at the upper network layer of WiNoC that contains RF transceivers and our proposed scheme. The latency analysis stated in the following experiments defines the number of extra cycles needed when executing our proposed scheme as opposed to the baseline iWise and McWiNoC architectures without the energy aware scheme.

5.2 Experimental Results

In terms of energy saving and latency, our experimental results are compared with the baseline architectures of McWiNoC and iWise64 that utilize constant power for communication with all radio hubs on their platforms. A low threshold value increases system's responsiveness towards energy management strategy. Due to the stringent energy limitation at transmitter module, the energy saving of WiNoC platform decreases as the energy threshold increases. Fig. 6 shows the experimental results conducted on McWinoC-16 architecture which consists of 4 radio hubs.

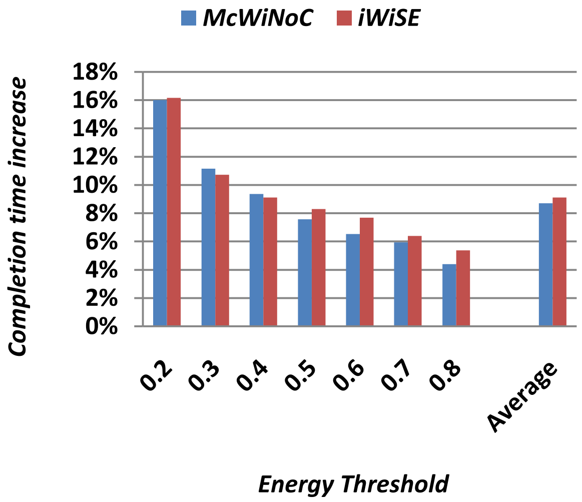


Figure 9 Packets delay (McWiNoC-64 versus iWiSe64 architectures)

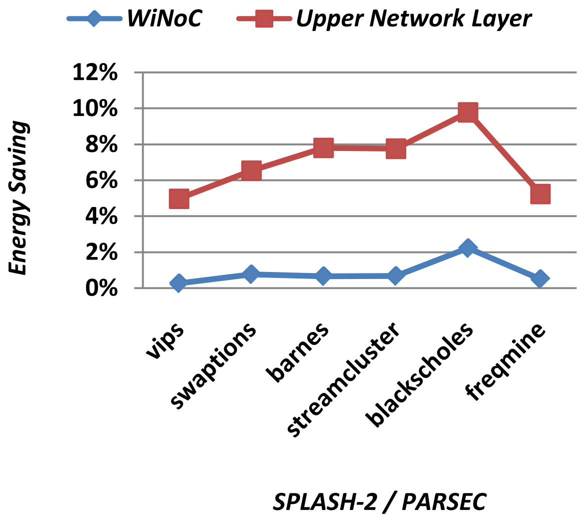


Figure 10 Total network energy saving and upper network layer energy saving for McWiNoC-64 architecture, implementing $E_{threshold} = 0.5$

Reconfiguration Period is set to 1000 clock cycles. More than 5% energy saving is observed for $E_{threshold}$ of 0.2 due to high response activity between the energy manager and transceivers. However, the energy saving proportionally decreases with the increase of $E_{threshold}$. On average, the total system energy saving is about 1% and the upper network layer reaches about 4.5% energy saving.

Similar trend is observed when we implemented the design on McWiNoC-64 and iWise-64 architectures with 8 radio hubs each (Fig. 7). As the network size is increased, the platform has longer reconfiguration paths to achieve energy saving. It can be observed, on average, the implementation of the proposed design on McWiNoC results in more than 0.8% in total energy saving. On the other hand, around 0.45% energy saving reduction is observed for iWise-64 between $E_{threshold}$ 0.2 and 0.8. Small total energy saving on the platform is due to the additional routing links introduced to transmit packets when the threshold is reached, suppressing more wire link burden than its wireless link counterparts.

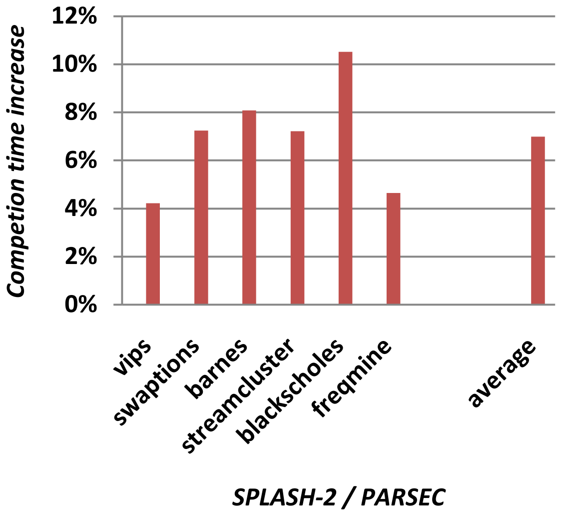


Figure 11 Packet delay on McWiNoC-64 architecture, implementing $E_{threshold} = 0.5$

Even though the number of radio hubs in iWise and McWiNoC is identical, the frequency of intra cluster radio hub communication for iWise is four times more than the frequency of inter cluster communication for McWiNoC due to the nature of iWise architectural design. Hence, an effective and responsive energy management becomes less efficient as energy threshold value is increased. In the second layer network, transceivers in both architectures save 8% of transmission energy in average energy threshold. In McWiNoC-64 with 256 cores, RF layer energy saving is higher than in McWiNoC-16 that consists of 64 cores. Fig. 8 represents the upper layer network energy saving.

As the platform enters the reconfiguration phase, wireless data transmission is switched to wire transmission to adjacent radio hub for communication with destination radio hub, causing performance degradation.

Fig. 9 shows the effect of varying energy threshold on communication latency. As shown in the figure, the latency is inversely proportional to $E_{threshold}$. A high threshold value results in lesser energy saving with lower performance impact. Conversely, a low energy threshold value makes the system more responsive in terms of its adaptation to the optimal energy saving. A high threshold magnitude maintains the status for a long time as compared to its low counterparts because more packets are able to transmit before the energy management mechanism is triggered. This reflects the level of stringent energy requirement assigned to transceivers. However, overall, both architectures suffer about 8% performance degradation. From the experiment, we observe that 0.5 gives an optimized $E_{threshold}$ value (near 8%) since the performance degradation difference is minimum on both McWiNoC architectures (64 and 256 cores). Our scheme introduces high delay because the transceivers that migrate packets have no mechanism to keep track of the adjacent radio hub status.

The analysis has been carried out considering a reconfiguration state of 10 clock cycles. We take for an example, the measurement of energy saving and latency when we set $E_{threshold}$ value to 0.5 on McWiNoC-64 architecture, verified with SPLASH-2 and PARSEC benchmarks (Fig. 10 and Fig. 11). Although the results refer to the application of the proposed technique to McWiNoC, the same conclusions are valid for the remaining architectures.

6 Conclusion

We have proposed an energy aware management scheme for reducing the radio hub layer energy consumption in WiNoC architectures by about 8%. The scheme is able to limit, at runtime, the buffer energy consumption at transmitters during on-chip radio communications. Based on normalized energy threshold, we have proposed a mechanism for on-line reconfiguration of transmitter distributing energy throughout the WiNoC platform for a certain period. Regular data transmission operation takes place as soon as a certain energy reduction in the transmitters is reached. The proposed energy manager dynamically regulates transmission energy of a source radio hub by performing the mechanism. The proposed technique can be generally applied to any WiNoC architecture. In assessing the energy saving and performance, we verified our design on two WiNoC architectures, namely McWiNoC and iWise with SPLASH-2 and PARSEC benchmark files. Based on our experimental results, it has been shown that the technique is effective in achieving total communication and upper layer network energy saving (about 1% and 8% respectively) with limited impact on performance.

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