FPGA-based accelerator for stochastic SI1I2 epidemic model

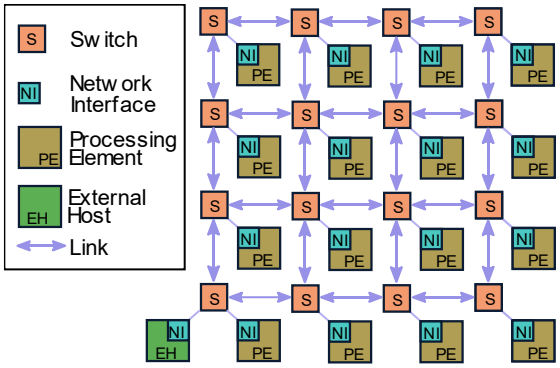
1 GOAL

This hardware design preresent an FPGA-accelerator based on a packet-switched network-on-chip (NoC) architecture to accelerate stochastic epidemic projection of SI1I2S model. The design is easily scalable to support large network sizes, only limited by the resource availability of the target.

2 SIMULATION STEPS

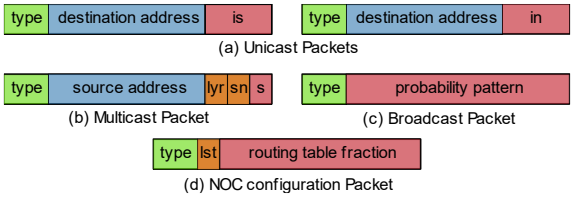
- The host computer executes the following steps for the proposed NoC-based SI1I2S model simulation:
- Inject the NoC configuration broadcast packets to configure the routing tables .
- Inject the broadcast packets to configure infection and recovery probabilities pi[0], pi[1],pr[0],pr[1] in the listed order.
- Inject the unicast packets to configure the number of neighbors and the initial status to each node
- Receive packets from the NoC and monitor the network status. Once status packets are received from all nodes, increment the discrete time step and log the number of infected and susceptible nodes.

3 HARDWARE ARCHITECTURE



The proposed NoC-based platform follows mesh topology with each processing element (PE) along with its network interface (NI) representing node in the contact network. Nodes are interconnected with the help of switches and bi-directional physical links.The NoC configuration and inter-node communication are supported via packet switching. The bottom left switch acts as the communication interface with external world, through which configuration packets are sent as well as the network status is monitored. An external host (EH) such as a server computer configures the NoC for the target network and monitors the network status as time progresses. By analyzing the packets received from the network, the host can determine the specific nodes that are infected, their infection type and nodes that have recovered, and the overall spreading pattern of the process.

3.1 PACKET FORMAT



The NoC manages configuration as well as inter-node communication using the different packet formats. It supports unicast, multicast and broadcast packet transmissions based on the packet.

Unicast packets are used for configuring parameters specific to individual nodes at the beginning of the simulation (at zero epoch or at t = 0) by an external host. The target node address (X and Y coordinates of the node) is stored in the destination address field and the configuration data are carried in the input number (in) and initial status (is) fields, which stand for node's number of inputs and initial infection status, respectively.

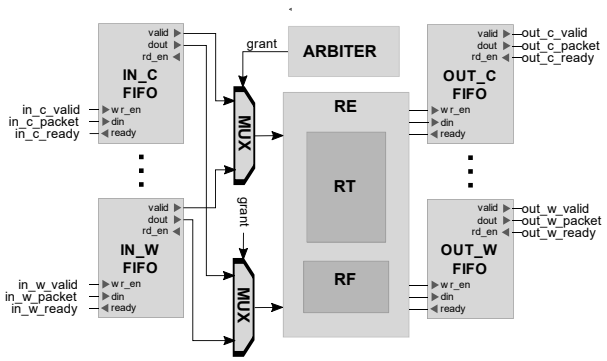
Multicast packets are used for inter-node communication, where each node updates all its neighbors with its status after each epoch (each discrete time in simulation). Rather than sending the same packet to each of its neighbors, each node injects a single packet to the NoC and the unique router design duplicates the packets close to the target nodes. Since the layers have distinct topologies, each layer status is sent in separate packets with the address of the injecting node in the source address field, the layer index (0-1) in the layer (lyr) field and the infection status (infected/susceptible) in the status (s) field. Each multicast packet carries a sequence number (sn) field, which differentiates the discrete simulation time.

In every iteration step neighbors of an infected node are infected with a certain probability - probability of infection (pi), while already infected nodes recover with a certain probability - probability of recovery (pr). The probabilities are distinct for each layer and are carried in probability patttern (pp) field of the corresponding configuration packet which initializes the shift registers used in the network interface. Pr and pi parameters are shared between all nodes in the network, those packets are broadcasted across the network at the beginning of the simulation.

NoC configuration packets are special broadcast packets that configure the routing tables RTs inside the switches. Each packet configures a portion of an RT and multiple packets are required to configure the entire network.

3.2 SWITCH

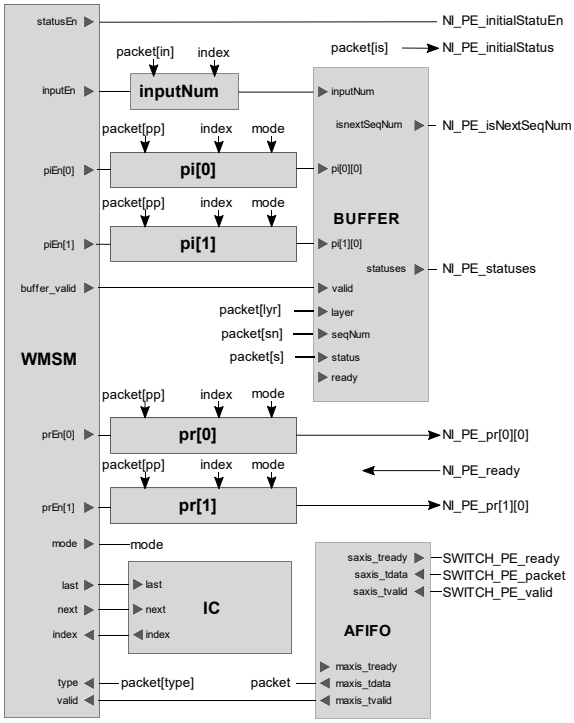
The switch follows store and forward architecture with output and input FIFOs at each interface (from 4 neighboring switches and the node). An arbiter chooses one of the input FIFOs for packet transmission following a round-robin scheme. The signal from the arbiter drives the output of a multiplexer which selects the appropriate FIFO output for packet transmission. The selected packet is forwarded to the routing engine (RE). The RE logic first checks for the packet type. Unicast packet routing is managed by a routing function (RF) and multicast packet routing is managed by a routing table (RT). The RF logic implements the traditional dimension-ordered XY routing by comparing the destination address embedded in the packet with the switch's address.



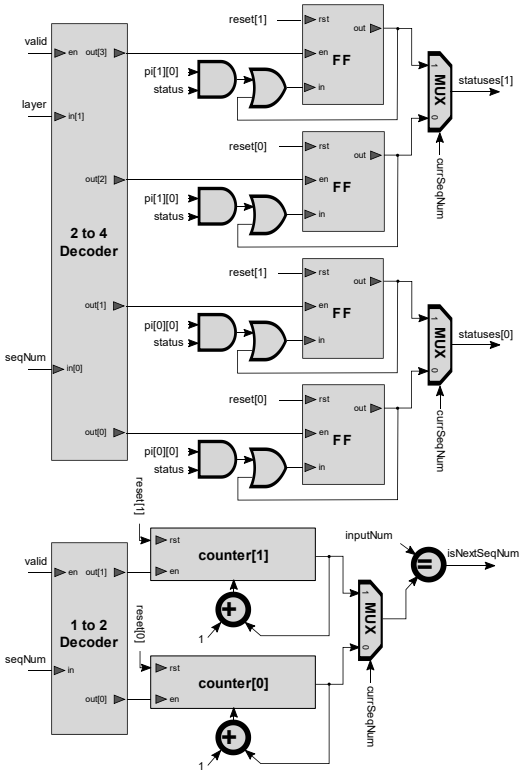
Each entry in the RT used for multicast routing is 10 bits wide, with 5 bits for each layer and the its depth is same as the overall network size. The source address embedded in the multicast packets serves as the RT entry number and the ly} field selects the half of the entry corresponding to the specified layer. The obtained bits determine the directions in which a packet originating from the corresponding address will be forwarded. The broadcast could be to one or more of the neighboring switches as well as the to the node interfaced with the switch. By appropriately configuring the RTs, packets from any node can be broadcasted to any given subset of nodes within the network. Output of the RE determines the output FIFO(s) to which the previously selected packet is sent. The control signals are passed back to the input FIFOs to acknowledge successful packet transfer.

3.3 NETWORK INTERFACE

The NI interfaces follow AXI4-Stream protocol. AXI4-Stream Asynchronous FIFOs are located at input and output of NI to cope with differing clock domains between the switches and PE. The working mode state machine (WMSM) manages the operating mode of a node, which may be either in one of configuration states or in a running state. When the node undertakes configuration, WMSM routes the configuration packets received from the switch interface to appropriate destination registers.



The contents of the unicast packet specifying the number of neighbors of the node is stored in the inputNum register. The intended infection and recovery probabilities is achieved using PRBS generators, which constitute linear feedback shift registers (LFSRs) composed of 100 flip-flops with the last stage feeding back to the first stage. The input number and probability patterns are generated offline through a software application and traversed to the nodes through multiple packets as discussed before. To reassemble the data, these registers were separated into blocks, where each block is addressed through its corresponding ind ex. The Index Counter (IC) logic specifies the index of a block to which the incoming configuration data segments are written. Upon arrival of the unicast packet carrying the node's initial status, it is transferred to the PE and operating mode is switched to the running state.



When status packets are received, they are initially stored in a buffer. Although it is possible to provide a separate entry for each status, this approach would require a memory which size is a linear function of the NOC size. For large networks this could cause scalability issues. For a node at Susceptible (S) state having multiple infected neighbors, transmission of the infection from any one neighbor is enough for the node to switch state. One can relate the set of edges, connecting the receiving node to its adjacent neighbors, to a single input channel output of which is the output of an OR gate with the edges being the inputs. This frees the competition among the neighbors and allows to transform the parallel process of transmitting infection into sequential process. However, the two-layer model infers the competition among the constituent layers. Thus, there would be two channels, one for each layer, and in case the infections are present in both layers, infection is transmitted by one of the layers, chosen uniformly at random at the PE. Whenever packet stemming from neighbor node arrives, the s field of the packet is first ANDed with the LSB of pi of the corresponding layer which is determined according to the lyr field. The result is then ORed with the

current accumulated channel status of the layer and stored into the designated flip-flop as the new accumulated channel status.

The fact that the probabilities of infection pis does not depend on time allows to accumulate out-of-order statuses in the same manner as the statuses within the current sequence number currSeqNum. Thus, there would be two pairs of flip-flops altogether, one pair devoted for each sequence number. Each pair maintains its own counter which counts the number of status that have already arrived. When the counter corresponding to the currSeqNum reaches the value of the inputNum, the statuses are sent to the PE and currSeqNum is incremented to switch to the next pair.

Thus, instead of maintaining 4*NS (NETWORK SIZE) memory, the size of the buffer is reduced to 4 bits.

3.4 PE

Each PE runs the SI1I2S state-machine. The initial infection status is received from the NI during the configuration stage. Once the NI receives status from all the neighbors for a discrete time, it transfers the accumulated channel statuses to the PE. If the PE is in susceptible state and the infection is present in one of the layer channel, the infection corresponding to that layer is transmitted. If both layers imply infection, priority among the layers is allocated based on the output of the ring counter. As mentioned before, since the arrival of packets depends on various factors within network, the grant of priority to a layer is almost random but with the equal distribution among the layers to avoid unfair domination of particular layer. If the PE is in one of the Infected (I1 /I2) states, it checks the LSB of the corresponding pr. If the PRBS output is high, the state is switched to S and the status of the neighbors play no role in this state transition.

In all cases, the new state of PE is conveyed to the NI output block module from where it is sent to all it's neighbors using multicast packet type. The state is sent in two packets, one for each layer, due to the fact that different layer packets are routed differently. Moreover, the infection from the infected node is transferred exclusively to the neighbors in the layer corresponding to that infection. For instance, the node in I1 state first sends packet carrying index 0 in lyr field and infection status 1 in s field, and then sends second packet with index 1 in lyr field and infection status 0 in s field.