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System Level Modelling and Design of Hypergraph Based Wireless System Area Networks for Multi-Computer Systems

Satyam Arragokula
Assistant Professor
University College of Science
Saifabad, O.U, Hyderabad, Ts
satya.anu11@gmail.com

M. Yesu Ratnam
Assistant Professor
Nizam College
Hyderabad, Ts, India
yesurathnammotamarry@gmail.com

Abstract: **This paper deals with issues pertaining the wireless multicomputer interconnection networks namely topology and Medium Access Control (MAC). It argues that new channel assignment technique based on regular low-dimensional hypergraph networks, the dual radio wireless hypermesh, represents a promising alternative high-performance wireless interconnection network for the future multicomputers to shared communication medium networks and/or ordinary wireless mesh networks, which have been widely used in current wireless networks. The focus of this work is on improving the network throughput while maintaining a relatively low latency of a wireless network system. By means of a Carrier Sense Multiple Access (CSMA) based design of the MAC protocol and based on the desirable features of hypermesh network topology a relatively high performance network has been introduced. Compared to the CSMA shared communication channel model, which is currently the de facto MAC protocol for most of wireless networks, our design is shown to achieve a significant increase in network throughput with less average network latency for large number of communication nodes. System C model of the proposed wireless hypermesh, validated through mathematical models, are then introduced. The analysis has been incorporated in the proper SystemC design methodology which facilitates the integration of communication modelling into the design modelling at the early stages of the system development. Another important application of System C modelling techniques is to perform meaningful comparative studies of different protocols, or new implementations to determine which communication scenario performs better and the ability to modify models to test system sensitivity and tune performance. Effects of different design parameters (e.g., packet sizes, number of nodes) has been carried out throughout this work. The results shows that the proposed structure has outperform the existing shared medium network structure and it can support relatively high number of wireless connected computers than conventional networks.**

Keywords: **MAC, hypermesh, SystemC, Modeling, CSMA, SAN, OFDM, MIMO**

1. INTRODUCTION

The design of modern computing systems is evolving into a more and more complex task. Moreover the increased demand for high performance computing from the military and research centres in industry and academia for the simulation of complex problems makes System Area Networks (SANs) a very interesting research area. System area networks are designed to interconnect high performance computing resources that are located over a short distance, typically in a building with a range of a few meters. Each computer is formed by a processing element, where information is processed, and a switching or communication element, where packets of data are sent or received from other computers. Scientific computing research applications such as fluid dynamics or finite element methods, modelling of nuclear explosions, climate modelling, and others, need a very high level of integration between computation and communication, because they have very rich communication patterns and they produce a huge amount of data, that need to be exchanged between the communication nodes. Others like Google for instance have a very large bandwidth and need to have very high speed access to its databases. So the solution for all these needs is to communicate faster with low latency, and that is the fundamental problem, high bandwidth with low latency. It is impossible or extremely difficult and costly to achieve. The central problem in achieving faster and cheaper communications in large multicomputer networks has proven to be the way in which the processors are connected together (their topology) [1, 2, 3]. There are several network architectures and topologies for implementing a networked computer system. Some of the most important networks are: Fully connected or all-to-all, a Circular Ring, a Star, a Binary tree, Mesh (Torus), Hypermeshes, or even Random networks. Most of the above mentioned interconnections are designed to implement wired networks, which can have more applications in a wireless sensors network.

Current SANs interconnection requires wire connections by means of fibre optics like Myrinet, Gigabit Ethernet, Quadrics, Infiniband and ServerNet. The cost of the hardware rises as the number of computers/workstations increases. As the number of communication nodes increase, so does the switching delay, becoming the bottleneck of the interconnection. This degrades the overall performance.

Connecting a cluster of computers wirelessly by replacing the standard fixed cabling, which creates more compact configurations is an important issue. Cabling technology has reached fundamental limitations in the current technology. The maximum wiring density and the maximum number of pins per chip or per board limits the network scalability [2]. For instance Point to Point (P2P) requires switching elements and that will introduce scaling problems of the networks. The cables are expensive because they need to be controlled and constructed very well. However, a communication node in a wireless environment has the ability to communicate with a large number of other nodes. So, the physical constraints associated with wired connectivity or expensive attenuation equipment (devices that maintain signal strength during transmission) becomes less of an issue in a wireless environment. Disadvantages of wireless network systems are that they are slower than the existing wireless technology, which does not offer the performance of wired network systems.

However, the rapid development of wireless technology and the explosive growth in wireless communication, where fixed cabling is undesirable, has found many applications. An alternative solution is proposed in this work. Namely, the use of wireless technology in the realisation of high performance SANs. To achieve high data rate wirelessly, next generation wireless networks will employ various physical layer techniques, e.g., multiple input multiple output (MIMO) beam forming, directional antenna, etc., to improve the link capacity and reliability. In addition, advanced modulation techniques such as Orthogonal Frequency Division Multiplexing (OFDM) and/or On-Off Keying (OOK) have emerged as a good choice for wide bandwidth to share the electromagnetic spectrum with already deployed systems. These solutions are the most investigated for wide bandwidth communication systems to make maximum use of available bandwidth. It seems reasonable that an attempt to utilise this technology in parallel computing is advised.

This paper evaluates the potential benefits of using hypermesh network topology to design a multi-interface multi-channel wireless SAN. I first carried out the development of a wireless communication link in order to add a missing element of modelling off-chip communications such as wireless links to SystemC. Since, Sys- temC design methodology has been developed for design and implementation of complex systems, in particular for System on Chip (SoC), it has not, to the best of my knowledge, been extended to incorporate, within the same framework, the design of wireless communication system. Wireless communication network system design begins with detailing the channel model, then developing the transmitter and receiver that best compensate for the channel's corrupting behaviour. Then I proceeded to the modelling of a single-channel and multiple-channel network in order to confirm the application of using SystemC design methodology in developing wireless network systems. Based on this work, I designed a mechanism to coordinate multiple radio-interfaces on one node based on the hypermesh channel assignment mechanism described in chapter 8. I then evaluated the network performance for the different network topologies.

2. WIRELESS NETWORK BACKGROUND

I will introduce the background under which the work of this paper is done. A review of wireless data networks will be introduced. I will consider the physical arrangement which is used to interconnect nodes, that is known as the network topology and the process of determining a path between any two nodes over which traffic can pass which is called routing. Next is the switching techniques used in this work, which refers to the transfer method of how data is forwarded from the source to the destination in a network. In addition I will address medium access control protocols for wireless network system. And finally channel assignment strategies and wireless channel models will be reviewed.

Wireless Networks: Wireless networks, also called ad-hoc networks, formed by collections of wireless nodes communicating with one another with no pre-existing infrastructure in place; therefore, they are also called infrastructure less networks. A wireless network is ad-hoc if each node forwards data from other nodes and produces and consumes data of its own. Wireless ad-hoc networks have been the focus of much recent research, and include Mobile Ad-hoc networks (MANETs), Wireless Sensor Networks (WSNs), Wireless Mesh Networks (WMNs), and Vehicular ad-hoc Networks (VANETs).An infrastructure less network can be either a single hop or a multi-hop network which autonomously operates in an ad-hoc mode without a central controller. The term multi-hop refers to the fact that data from the source needs to travel through several other intermediate nodes before it reaches the destination. Ad-hoc networks based on wireless technologies, such as IEEE 802.11 standard, which covers the physical and data link layers and mostly utilize a single radio and a single shared channel. As such, the bandwidth is divided between the nodes trying to communicate. One common problem with such protocols is that the network performance will degrade quickly as the number of nodes increases, due to higher contention/collision. On the other hand, the wireless standards IEEE 802.11a/b/g and IEEE 802.15.4, offer up to 16 non-overlapping frequency channels for simultaneous communication. These multiple channels have been utilized in infrastructure-based networks by assigning different channels to adjacent access points, thereby minimizing interference between access points. However, multi-hop wireless networks have typically used a single channel to avoid the need for co-ordination between adjacent pair of nodes, which is necessary in a multi-channel network. Multiple channels, however, partition the network based on the channel used. This may result in a disconnected network if the nodes communicate only in their assigned channels. To resolve this problem, several multi-channel ad-hoc/mesh network approaches have been proposed in the

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literature. Furthermore, Some research has been done on routing schemes in multichannel networks where the topology discovery and routing are performed with a channel assignment. In addition, they are considered these issues as separate problems thus reducing complexity of the schemes. So et al. have proposed a routing protocol for multi-channel networks that uses a single interface at each node, while our proposed solution works with multiple radio interfaces per node. Raniwala et al. propose routing and interface assignment algorithms for static networks. Similar to our proposal, they also consider the scenario wherein the number of available interfaces is less than the number of available channels. However, their solution is designed specifically for use in those mesh networks where all traffic is directed toward specific gateway nodes.

Routing: The address header of a message carries the information needed by routing hardware inside a switch to determine the right outgoing channel, which brings the data nearer to its destination. The objective of a routing algorithm is to discover efficient paths to obtain high system throughput.

Many deterministic and adaptive routing algorithms have been proposed in the literature. Deterministic routing algorithms always supply the same path between a given source/destination pair. Adaptive routing schemes try to find dynamically alternative paths through the network in the case of overloaded network paths or even broken links. Nevertheless, adaptive routing has not found its way into real hardware yet. Adaptive routing is out of the scope of this work. Since I know the network topology of the whole network, distributed routing algorithms are best fit to regular topologies since it does not relay on central authority. The same routing algorithm can be used in the communicating nodes. With distributed routing, the header of a packet is very compact. It only requires the destination address and a few implementation dependent control bits. In this work I am going to use the hypermesh topology, which can be easily de-composed into orthogonal dimensions. It is possible to use a simple routing algorithm based on a finite-state machine like dimension order routing. This routing algorithm routes packets by crossing dimensions in increasing (or decreasing) order. The routing algorithm supplies an output channel crossing the lowest dimension for which the offset is not null. Dimension-order routing produces deadlock-free routing algorithms [1]. A detailed description of the algorithm can be found in the implementation section.

Switching: The term switching refers to the transfer method of how data is forwarded from the source to the destination in a network. Two main packet switching techniques, as depicted are used in today's networks, store & forward and cut-through switching respectively. The first technique transmits a packet completely across one channel before the transmission across the next channel started. Since the packet may be competing with other messages for access to a channel, a queuing delay may be incurred while waiting for the channel to become available. This mechanism needs an upper bound for the packet size and some buffer space to store one or several packets temporary. This is the common switching technique found in LAN/WANs, because it is easier to implement and the recovery of transmission errors involves only the two participating network stages.

Newer SANs like ServerNet, Myrinet and QsNet use cut-through switching (also referred to as wormhole switching), where the data is immediately forwarded to the next stage as soon as the address header is decoded. In Figure one sees packets transmission over their channel is pipelined, with each phit being transmitted across the next channel as soon as it arrives. A phit is the unit of information that can be

Wireless MAC Protocols: A crucial part of a wireless communication system is the MAC protocol. The MAC protocol is responsible for regulating the usage of the communication medium, and this is done through a channel access mechanism. A channel access mechanism is a way to divide the main resource between nodes, the radio channel, by regulating the use of it [33]. MAC for wireless networks can be categorized into three groups. The fixed assignment set (Channel Partitioning set) divide channel into smaller "pieces" (time slots, frequency) and have schemes like Time Division Multiple Access (TDMA), Code division multiple access (CDMA) and Frequency Division Multiple Access (FDMA). These protocols lack the flexibility in allocating resources and thus have problems with configuration changes. This makes them unsuitable for dynamic and bursty wireless packet data networks.

The random assignment class (Contention based schemes) such as pure Aloha, slotted Aloha, carrier sense multiple access with collision avoidance (CSMA/CA), and non/p/1-persistent CSMA , etc., are very flexible instead and is what is predominantly used in wireless LAN protocols. The demand assignment (Taking turns) with schemes like Token Ring, attempt to combine the nice features of both the above and tightly coordinate shared access to avoid collisions. However, special effort is needed to implement them in the wireless case (E.g. Token Ring needs to know its neighbours).

Channel Model: For the design of wireless systems, where the signal is distorted due to physical phenomena, it is necessary to characterize the channel, using a channel models. Wireless networks are inherently more difficult and computationally expensive to simulate than fixed wired networks. The notion of a fixed link is replaced with an error-prone broadcast channel. Bit errors in wireless networks are orders of magnitudes higher than fixed wired networks and vary with the received Signal- to-Noise-and-Interference Ratio (SINR) or Signal to Noise Ratio (SNR), usually measured in decibel (dB). SNR is actually the ratio of what is wanted (signal) to what is not wanted (noise).

In wireless channels, the state of the channel may change

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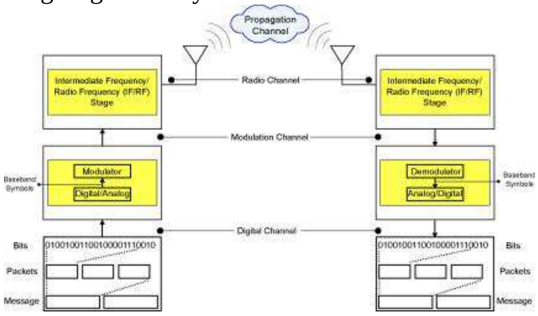
within a very short time span. This random and drastic behaviour of wireless channels turns communication over such channels into a difficult task. In addition, wireless channels may be further affected by the propagation environment encountered. Many different propagation environments have been identified, such as urban, suburban, indoor, underwater or orbital propagation environments, which differ in various ways.

1. The **Transmission Channel**: The transmission channel is the medium between the transmit antenna, and the receive antenna. The signal transmitted consists of the information modulated on top of the carrier frequency.
2. The **radio channel**: consists of the propagation channel and both the transmitter and receiver antennas. As described by the radio channel influences the received signal only by a multiplicative factor, the attenuation (loss of a signal's power) *a(t)*, as given in Figure. Analytically it is useful to distinguish between three different effects that result in an overall attenuation of the transmitted signal.
3. The first effect is called *path loss.* It is a deterministic effect depending only on the distance between the transmitter and the receiver. It is the reduction or loss in signal power as it propagates through space.
   It plays an important role on larger time scales like seconds or minutes, since the distance between transmitter and receiver in most situations does not change significantly on smaller time scales.



Transmitter Receiver

Figure 1: Channel model classification: propagation channel, radio channel, modulation channel, and digital channel

The second effect is called *shadowing.* Shadowing is not deterministic. It is due to obstacles affecting the signal propagation, sometimes called shadow fading. It varies on the same time scale as the path loss and causes fluctuations of the received signal strength at points with the same distance to the transmitter. However, the mean over all these points yields the signal strength given by path loss only.

Interference in Wireless Communications: The wireless signal propagates in space, based on the laws of physics. An electromagnetic Radio Frequency (RF) signal which travels in a medium suffer attenuation (path loss) based on the nature of the medium. In addition, the signal encounters objects and gets reflected, refracted, diffracted, and scattered. The cumulative effect results in the signal getting absorbed, traversing multiple paths and are having its frequency shifted due to the relative motion between the source and receiver (Doppler Effect). Interference phenomena take place at the physical layer of the receiver node, as interfering (undesired) signals disturb the reception of a given desired signal. However, the characteristics of any interfering signal and its disturbance effects are determined by features of the interfering transmission at different layers or domains. Therefore, an interference model can be viewed as the combination of the following components.

4. SYSTEM LEVEL NETWORK MODELLING BACKGROUND

In this chapter, I will briefly describe network simulation methods and the proposed SystemC design methodology to meet my aim to develop digital wireless SAN. And then, I will address the simulation measurement setup of interconnection networks to avoid sources of errors, when estimating network performance. Moreover, the statistical approach for assessing the accuracy of the measurement is presented.

Network Modeling: Network developing environments, or commonly called network simulators, actually propose substantial support for modelling and simulating different protocols (i.e., TCP, routing, and multicast protocols) over wired and wireless networks. Network simulators reproduce the functional behaviour of protocols by managing time information about transmission and simulating packet losses due to congestion or link failure. There are many well accepted network simulators available both commercial OPNET; QualNet and as open source projects OmNet++ ; NS-2 whereby designers can accurately implement protocols, manipulate bytes, packet headers, and implement algorithms that run over large data sets. Libraries with a wide range of communication protocols are generally available and constantly up-dated and, thus, designers can efficiently design, modify, and test various network parameters or configurations, for quickly exploring different network scenarios. However, the main drawback is that network simulation tools describe functionalities without reproducing the interaction between different components within the single node, as in actual systems. This fact limits the reusability of the functional description for the design, validation, and synpaper of the actual system as traditionally happens with hardware description languages.

The SystemC design Methodology: SystemC, which is a design and modelling methodology, has been chosen to develop my models in this work. It represents an emerging standard modelling-platform based on C++ plus a simulation kernel. SystemC builds the bridge between hard- and software

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design. It extends C++ with macros, functions and other constructs to allow a hardware-oriented design. Strictly SystemC is not a language, its a class library that can be used to model systems in a homogeneous environment all the way from requirement capture to system partitioning, cycle accurate modelling and backend implementation.

Transaction-level modelling is an approach to modelling digital systems where details of communication among modules are separated from the details of the implementation of the functional units or of the communication architecture. On the other hand, Behavioural- level modelling is a model of a system at any level of abstraction that includes timing information [12]. The inherent modularity of SystemC allows designers to model and refine the individual elements of a system with varying levels of detail and timing accuracy. It begins with a functional untimed implementation which can be utilized to identify the required elements verifying functional correctness *(behaviour executable model*). However it does not provide sufficient details regarding the final implementation or resulting system performance.

Simulation Measurement: Simulation measurement or in other words simulation setup is an important step that is all too often ignored or skipped. Determining the type, and stopping criteria are the first step toward simulation measurement. The simulation can be set to run for specified fixed period of time or may stop when reaching steady state. Researchers are often interested in the long term average; specifically the cumulative moving average. However, a common pitfall is to claim the simulation results have reached steady state without assuring the degree of convergence.

There are two main sources of errors, when estimating network performance: systematic error and sampling error. Systematic errors are errors introduced by bias in the measurements or simulation itself and for network simulation is generally a result of the initialisation of the simulator. To minimise the effect of systematic errors a suitable warm-up period for a simulation must be chosen. This warm-up period will allow a network to reach its steady state. That is the statistics of the network are stationary and no longer change with time and an accurate estimate of a particular network parameter can be determined [2].

5. WIRELESS CHANNEL MODEL BASED ON SoC DESIGN METHODOLOGY

In this chapter, a new method to model and simulate a wireless communication system based on SoC design methodology will be presented. How well our method correctly exposes the underlying network performance of the system is directly related to the amount of detail in the simulation model. Hence there is a need to develop suitable abstractions that maintain the accuracy of the simulation while keeping the computational resource requirements low. The integration of communication modelling into the design modelling has been shown by modelling a noisy communication channel in SystemC. The channel supports different modulation techniques such as, Amplitude-shift keying, Phase-shift keying, Quadrature amplitude modulation. It supports the setting of different Signal to noise ratio and different types of interference for Point-to-Point and Point-to-Multipoint platforms based on SystemC design methodology.

The design complexity of digital communication systems has risen significantly in recent years [11]. This trend is likely to continue, as devices continue to incorporate an ever-growing number of components in order to support new functionalities whilst providing inter-operability with the large plethora of standards and protocols from previous and present state of the art systems.

Channel Model: According to the mathematical model shown in Figure 2.4 in Chapter 2 the transmitted signal is influenced by three effects: interference signal, attenuation and noise, which have been discussed in Chapter 2. For a digital communication system the question arises, how these signal distortions translate into noticeable service degradations of running applications. Moreover, how to use the channel model presented in Chapter 2 to predict the performance of my communication system at the system level. For example this knowledge is crucial in order to design and parametrise simulation models of wireless channels at the system level. And also applying this knowledge in designing of communication protocols.

Noise Generation Process: The performance of any communication system is effected by noise and interference from other sources, which play a crucial role in communication systems. In practise noise and interference represent the number of errors occurring in the system. The simplest model of the digital noise is just to consider the impulsive noise, in which the individual bits or packets are modified with a given probability. The other type of error is lost bits, which is only happen, if the system is out of synchronisation. However it is assumed that, there is no model of a Phase-Locked Loop (PLL) in the system, and it is assumed to be PLL locked. So as consequence, I will not going to model the second type of error at this stage, which will be left as an exercise for future work. Here the model is done in conventional way and, I assumed a memory-less system, which implies the Markov property. Therefore the exponential distribution is good fit for the model. Though other distributions such as Pareto distribution can be easily coded as well. Here for simplicity I used the exponential distribution, but it is not accurate to model real world systems. And it gives the inter-arrival times for errors. Then by solving the Probability Density Function (PDF) of the exponential distribution for t, which represents the inter-arrival time of errors. And therefore, a random experiment is performed to determine the position, where errors are injected in the bit stream.

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6. RTL-LEVEL MODELING OF AN 8B/10B ENCODER-DECODER

This chapter presents an RTL-level model of an 8B/10B encoder/decoder block in SystemC. The use of 8B/10B coding is an important technique in the construction of high performance serial interfaces. These are particularly suitable for alleviating the I/O bottleneck of state of the art systems (which are pinout, rather than bandwidth limited). Moreover, to optimise the use of the transmission medium encoding may be chosen to conserve bandwidth or to minimise errors.

Serial transmission technology is increasingly used for the transmission of digital data. State of the art communication networks make use of serial links for transferring data. This is in part due to the reduction in pinout and cost; but most importantly because it is inherently immune to skew, which plagues high speed parallel interfaces. To improve the performance in serial data transmission systems, block coding is used to ensure sufficient data transitions occur for clock recovery and also to help guard against errors. In the early 80's the 8B/10B block coding technique was introduced by Albert X. Widmer and Peter A. Fransazek of IBM Corporation. Although dated, the technique continues to be employed in state of the art technologies, such as HyperTransport, IEEE1394b, SATA, DVB, and many others.

This chapter describes the construction of an RTL model of an 8B/10B encoder in SystemC. Although other HDL models have been used, a SystemC model is desirable as it integrates into the SystemC design methodology, which provides a consistent framework for the design and modeling of complex systems at numerous levels of abstraction. This is particularly important for the design of SoC systems, where it is necessary to determine the system performance before a prototype is constructed, in order to evaluate the merit of different implementations.

7. NETWORK PERFORMANCE EVALUATION BASED ON SoC DESIGN METHODOLOGY

This chapter presents an original development methodology for the use of SystemC to model an executable model of a wireless network system. SystemC methodology allows the model to be reconfigurable for extensive early architectural analysis and easy re-mapping to new wireless standards and applications at numerous levels of abstraction. On the other hand network protocols have many complex concurrent and distributed characteristics, thus it is very difficult to be analysed theoretically. One of the most promising solutions to this problem is system-level modelling and simulation, which have been covered in this work. Performance results for the simulations as well as development effort are presented thus showing how this methodology is well suited to the modelling of a wireless network systems. Moreover the experiences of using SystemC design methodology to analyse the performance properties of wireless network has been presented.

With the advent of digital communication systems, more and more components to support new functionalities is being integrated in a single package. This trend is likely to continue, as devices continue to incorporate an ever growing number of components to provide inter-operability with the large plethora of standards and protocols from previous and the present state of the art. It is an important issue to verify the interaction and the integration of communication modelling into the design modelling before actually realising a system in terms of hardware and software components. Waiting until silicon is available to validate system interactions and find bugs would be a costly and time consuming.

8. DUAL-RADIOS HYPERMESH NETWORK BASED ON CSMA PROTOCOL

Recently, multi-radio mesh technology in wireless networks has been put under extensive research. This is because of its potential to overcome the inherent wireless multi-hop throughput, scalability and latency problems caused by the half-duplex nature of the IEEE 802.11. This chapter introduces a design and modelling of different elements on a distinct type of multicomputer networks, the dual-radio wireless hypermesh, based on SystemC methodology.

The hepermesh is a well-known topology that belongs to the hypergraph family of networks. Hypermeshes have been proposed as potential alternatives to the graph networks for the future System Area Networks. In this work, I consider a two dimensional dual-radio wireless hypermesh network, where each router node is equipped with two radio interfaces and two non-overlapping channels are available for each node. I address the problem of assigning channels to communication links in the network with the objective of keeping overall network latency low and provide a relatively high throughput.

The simulations and analysis have shown that my design achieves a significant increase in network throughput with less average network latency for large number of communication nodes, compared with the CSMA shared channel model, which is currently the de facto MAC protocol for most wireless networks. My simulations have been validated analytically to show the accuracy of the developed model. In addition, simulation results have shown that the wireless hypermesh outperforms shared medium wireless networks under the constant total bandwidth argument, especially in large networks.

The increasing demand for high performance computing from the military and research centres in industry and academia for the simulation of complex problems makes SANs a very interesting research area. SANs are Hardware/Software systems designed to perform specific applications in which network communications are essential. For this reason, their processing functionality is strictly connected with communication functionality. Typically, the processing part is implemented through CPU, memory, and application-specific components; the communication part is implemented through HW components (e.g., network interface and wired or wireless links) and SW components (e.g., the protocol stack). The design of SANs is the context of this paper. It requires the capability of modelling and simulating both their behaviour/architecture and the complex communication environment in which SANs operate.

9. CONCLUSION

In this paper I modelled and evaluated the performance of wireless networks using SystemC design methodology. SystemC was chosen as it provides a homogeneous platform for the design and modelling of complex systems. Furthermore, as systems become more tightly integrated, the ability to evaluate the system performance at early stages of a design becomes increasingly important. This is facilitated by the system level network modelling techniques in particular SystemC design methodology, and by following an IP-based design. Single interface, single channel and multi-interface multi-channel nodes have been considered in my work. In order to deal with the fundamental limitations of single frequency wireless networks, I proposed a multi-channel solution that leverages more than one radio-interface on each node. With this approach, one node can potentially simultaneously communicate with two neighbours at the same time.

The first part of this paper has presented a first step towards the integration of communication modelling into the design modelling at the early stages of the system development. This part demonstrates a simple and computationally efficient way to model a noisy communication channel within a system level. The simple noisy digital channel can be used to model the whole communication system interactions. The model is developed at a high level of abstraction which allows for fast simulation and early estimation, which are necessary for successful system development using the SoC design methodology. To my knowledge and to date of our published work, this was the first time that the modelling of wireless communication system was undertaken in SystemC and incorporated into a uniform design methodology, suitable for developing new technologies following the SoC design methodology.

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About the Authors:

Satyam Arragokula working as an Assistant Professor in University College Of Science, Saifabad, Hyderabad, he completed M.Tech CSE from Osmania University, Hyderabad and Completed MSCIS from Osmania University, Hyderabad.

M. Yesu Ratnam working as an Assistant Professor in Nizam College, he completed M.Tech from JNTU Hyderabad and completed MCA from Osmania University Hyderabad