A Control and Management Network for Wireless ATM Systems

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Abstract

This paper describes the design of a control and management network (orderwire) for a mobile wireless Asynchronous Transfer Mode (ATM) network. This mobile wireless ATM network is part of the Rapidly Deployable Radio Network (RDRN). The orderwire system consists of a packet radio network which overlays the mobile wireless ATM network, each network element in this network uses Global Positioning System (GPS) information to control a beamforming antenna subsystem which provides for spatial reuse. This paper also proposes a novel Virtual Network Configuration (VNC) algorithm for predictive network configuration. A mobile ATM Private Network-Network Interface (PNNI) based on VNC is also discussed. Finally, as a prelude to the system implementation, results of a Maisie simulation of the orderwire system are discussed.

1: Introduction

Research involving mobile wireless ATM is advancing rapidly. One of the earliest proposals for a wireless ATM architecture is described in [1]. In this paper, various alternatives for a wireless Media Access Channel (MAC) are discussed and a MAC frame is proposed. The MAC contains sequence numbers, service type, and a Time of Expiry (TOE) scheduling policy as a means for improving real-time data traffic handling. A related work which considers changes to Q.2931 [2] to support mobility is proposed in [3]. A MAC protocol for wireless ATM is examined in [4] with a focus on Code Division Multiple Access (CDMA) in which ATM cells are not preserved allowing a more efficient form of packetization over the wireless network links. The ATM cells are reconstructed from the wireless packetization method after being received by the destination. The Rapidly Deployable Radio Network Project (RDRN) architecture described in this paper maintains standard ATM cells through the wireless links. Research work on wireless ATM LANs have been described in [5] and [6]. The mobile wireless ATM RDRN differs from these LANs because the RDRN uses point-to-point radio communication over much longer distances. The system described in [7] and [8] consists of Portable Base Stations (PBS) and mobile users. PBSs are base stations which perform ATM cell switching and are connected via Virtual Path Trees which are preconfigured ATM Virtual Paths (VP). These trees can change based on the topology as described in the *Virtual Trees Routing Protocol* [9]. However, ATM cells are forwarded along the Virtual Path Tree rather than switched, which differs from the ATM standard. An alternative mobile wireless ATM system is presented in this paper which consists of a mobile PNNI architecture based on a general purpose predictive mechanism known as Virtual Network Configuration that allows seamless rapid handoff.

The objective of the Rapidly Deployable Radio Network (RDRN) effort is to create an ATM-based wireless communication system that will be adaptive at both the link and network levels to allow for rapid deployment and response to a changing environment. The objective of the architecture is to use adaptive point-to-point topology to gain the advantages of ATM for wireless networks. A prototype of this system has been implemented and will be demonstrated over a wide area network. The system adapts to its environment and can automatically arrange itself into a high capacity, fault tolerant, and reliable network. The RDRN architecture is composed of two overlaid networks:

- a low bandwidth, low power omni-directional network for location dissemination, switch coordination, and management which is the orderwire network described in this paper,
- a "cellular-like" system for multiple end-user access to the switch using directional antennas for spatial reuse, and and a high capacity, highly directional, multiple beam network for switch-to-switch communication.

The network currently consists of two types of nodes, Edge Nodes (EN) and Remote Nodes (RN) as shown in Figure 1. ENs where designed to reside on the edge of a wired network and provide access to the wireless network; however, EN also has wireless links. The EN components include Edge Switches (ES) and optionally an ATM switch, radio handling the ATM-based communications, packet radio for the low speed orderwire running a protocol based on X.25 (AX.25), GPS receiver, and a processor. Host nodes or remote nodes (RN) consist of the above, but do not contain an ATM switch. The ENs and RNs also include a phased array steerable antenna. The RDRN uses position information from the GPS for steering antenna beams toward nearby nodes and nulls toward interferers, thus establishing the high capacity links as illustrated in Figure 2. Figure 2 highlights an ES (center

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of figure) with its omni-directional transmit and receive orderwire antenna and an omni-directional receive and directional transmit ATM-based links. Note that two RNs share the same 45^o beam from the ES and that four distinct frequencies are in use to avoid interference. The decision involving which beams to establish and which frequencies to use is made by the topology algorithm which is discussed in a later section.

The ES has the capability of switching ATM cells among connected RNs or passing the cells on to an ATM switch to wire-based nodes. Note that the differences between an ES and RN are that the ES performs switching and has the capability of higher speed radio links with other Edge Switches as well as connections to wired ATM networks.

The orderwire network uses a low power, omni-directional channel, operating at 19200 bps, for signaling and communicating node locations to other network elements. The orderwire aids link establishment between the ESs and between the RNs and ESs, tracking remote nodes and determining link quality. The orderwire operates over packet radios and is part of the Network Control Protocol (NCP)[1]. An example of the user data and orderwire network topology is shown in Figure 3. In this figure, an ES serves as a link between a wired and wireless network, while the remaining ESs act as wireless switches. The protocol stack for this network is shown in Figure 4.

The focus of this paper is on the NCP and in particular on the orderwire network and protocols. This includes protocol layer configuration, link quality, hand-off, and host/switch assignment along with information provided by the GPS system such as position and time. The details of the user data network will be covered in this paper only in terms of services required from, and interactions with, the NCP.

Section 2: provides a more detailed description of the RDRN system, with a focus on the requirements and interaction of each protocol layer with the NCP. Operation of the NCP is described in Section 3:. A new concept known as Virtual Network Configuration (VNC) is explained in Section 4: along with an example application of a Mobile Private Network-Network Interface (PNNI) enhanced with VNC. The development and implementation of the NCP is described along with initial timing results in Section 5:. In Section 6:, an analysis of NCP indicates the performance of NCP as the system is scaled up. Finally, emulation results are presented in Section 7:.

2: Wireless ATM-Based Network Configuration Requirements

This section provides a brief overview of the high speed protocol architecture for the RDRN wireless ATM network [10]. The purpose is to introduce the RDRN network and more importantly to identify the requirements that each layer will have for the network configuration protocol.

2.1: Physical Layer

The physical layer includes all hardware components and the wireless connections. This includes the high speed radios, orderwire packet radios, ATM switch, antennas, and additional processor for configuration and setup. This layer provides a raw pipe for the data link layer described in the next section. Directional beams from a single antenna are used to obtain spatial reuse and Time Division Multiple Access (TDMA) is used to provide access to multiple RNs within a beam. The physical layer details can be found in [11]. The NCP sets up the physical layer wireless connections.

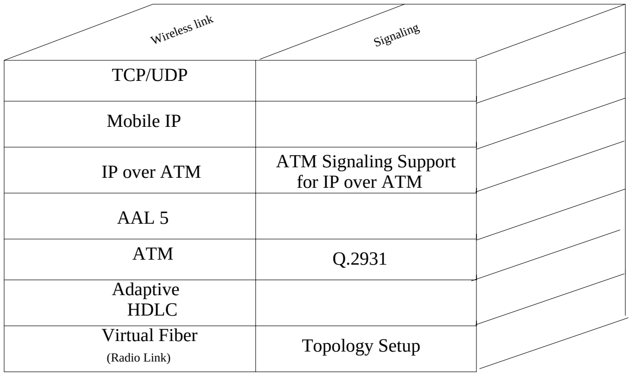

Figure 4. Wireless ATM Protocol Stack.

2.2: Link Layer

In this architecture ATM will be carried end-to-end. However, at the edge between the wired (high-speed) network and wireless links, multiple ATM cells will be combined into an HDLC-like frame. These frames comprise the Adaptive HDLC (AHDLC) protocol. The wireless data link layer is adaptive to provide an appropriate trade-off between data rate and reliability in order to support the various services. For example, we may want to drop voice packets, which are time sensitive, but retry data packets. The edge interface unit makes this decision based on knowledge of the requirements of each traffic stream, possibly based on virtual circuit number.

For some types of traffic, error correction may be achieved using retransmission. Here, delay is increased for this class of traffic to prevent cell losses. It is well known that even a few cell losses can have a significant impact on the performance of TCP/IP (Transmission Control Protocol/Internet Protocol), while TCP/IP can cope with variable delays [12]. The Adaptive High Level Data Link Control (AHDLC) protocol can change in response to traffic requirements. ATM end-to-end provides the following benefits:

1. Moderate cut-through, e.g. an IP segment may contain 8192 bytes or about 170 cells, while one ATM HDLC-like frame will contain on the order of 3-20 cells
2. ATM is a standard protocol.
3. ATM can incorporate standardized Quality of Service (QoS) parameters which could be based on the virtual circuit identifier.

The link layer must also maintain cell order; this will be critical during hand-off of an RN from one ES to another. Details of the Adaptive HDLC protocol and frame structures can be found in [10] and [11] .

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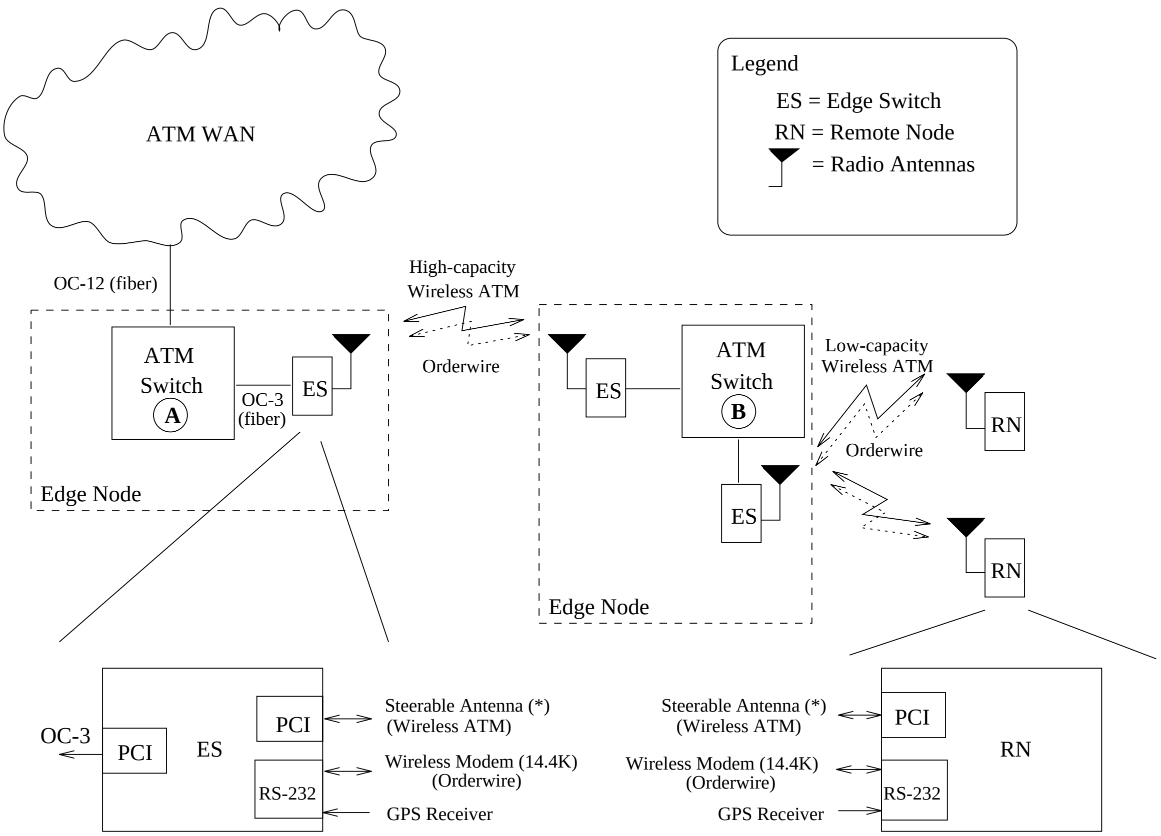
[1] The Simple Network Management Protocol (SNMP) Management Information Base (MIB) for the NCP operation as well as live data from the running prototype RDRN system can be retrieved from http://www.ittc.ukans.edu/∼sbush/rdrn/ncp.html.



(*) Low Speed: 2Mbps, High Speed (planned): 10Mbps

Figure 1. RDRN High-level Architecture.

2.3: ATM Layer

The protocol on the Edge Switch (ES) will remove ATM cells from the AHDLC frames and switch them to the proper port. It will also pack ATM cells into an Adaptive HDLC frame to send to the radio. The ATM Device Driver API and Adaptive Driver are detailed in [10]. Note that standard ATM call setup signaling is used and no AAL is precluded from use.

2.4: Network Layer

This section of the architecture is concerned with the Internet Protocol and how it relates to ATM and mobility. This layer provides a well known and widely used network layer, whose primary purpose is to provide routing between subnetworks and service for the Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) transport layers. The relation between IP and ATM is still an open issue. *Classical IP and ARP over ATM* [13] (CLIP) is an initial standard solution. However, it has several weak points such as requiring a router to connect Logical IP Subnetworks (LIS) even when they are directly connected at the ATM level, and requiring an ATM Address Resolution Protocol (ARP) server to provide address resolution for a single LIS. The *Non-Broadcast Multiple Access (NBMA) Next Hop Resolution Protocol* (NHRP)[14] provides a better solution but it is still in draft form. The RDRN architecture has implemented CLIP and supports both PVCs and SVCs via ATMARP.

3: Network Control Protocol Overview

An initial implementation of the RDRN Network Control Protocol (NCP) for the prototype system is presented next. The physical layer of the high speed radio connection has a corresponding layer in the NCP, as shown in Table 1. The following is a description and ordering of events for the establishment of the wireless connections.

3.1: Physical Layer of the Network Control Protocol

At the physical level we will be using the orderwire to exchange position, time and link quality information and to setup the wireless connections. The process of setting up the wireless connections involves setting up links between ESs and between ESs and RNs.

The network will have one master ES, which will run the topology configuration algorithm [15] and distribute the resulting topology information to all the connected ESs over point-to-point orderwire packet radio links. In the current prototype the point-to-point link layer for the orderwire uses AX.25 [16]. The master ES is initially the first active ES, and any ES has the capability of playing the role of the master.

The first ES to become active initially broadcasts its callsign and start-up-time in a **MYCALL** packet, and listens for responses from any other ESs. In this prototype system, the packet radio callsign is assigned by the FCC and identifies the radio operator. Since it is the first active ES,

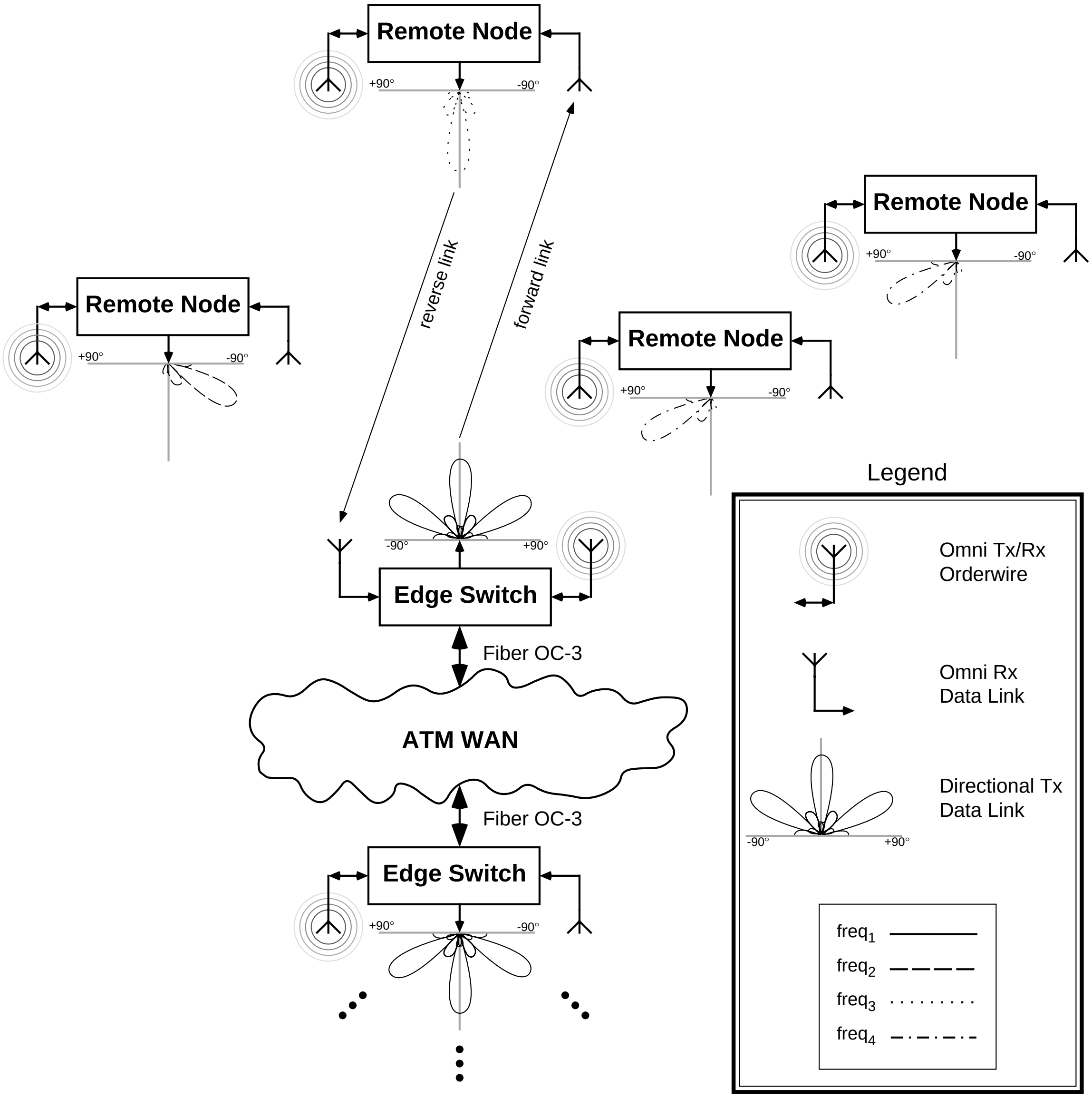


Figure 2. RDRN Component Overview.

Protocol Layer	Packet Types	Packet Contents
Physical Layer	MYCALL	Callsign, Start-Up-Time
	NEWSWITCH	*empty packet*
	SWITCHPOS	GPS Time, GPS Position
	TOPOLOGY	Callsigns and Positions of each node
	USER_POS	Callsign, GPS Time, GPS Position
	HANDOFF	Frequency, Time Slot, ES GPS Position

Table 1. Network Control Protocol Packets.

there would be no responses in a given time period, say T. At the end of T seconds, the ES rebroadcasts its **MYCALL** packet and waits another T seconds. At the end of 2T seconds, if there are still no responses from other ESs, the ES assumes that it is the first ES active and takes on the role of the master. If the first two or more ESs start up within T seconds of each other, at the end of the interval T, the ESs compare the start-up times in all the received **MYCALL** packets and the ES with the oldest start-up time becomes the master. In this system, accurate time stamps are provided by the GPS.

Each successive ES that becomes active initially broadcasts its callsign in a **MYCALL** packet. The master on receipt of a **MYCALL** packet extracts the callsign of the source, establishes a point-to-point link to the new ES and sends it a **NEWSWITCH** packet. The new ES on re-

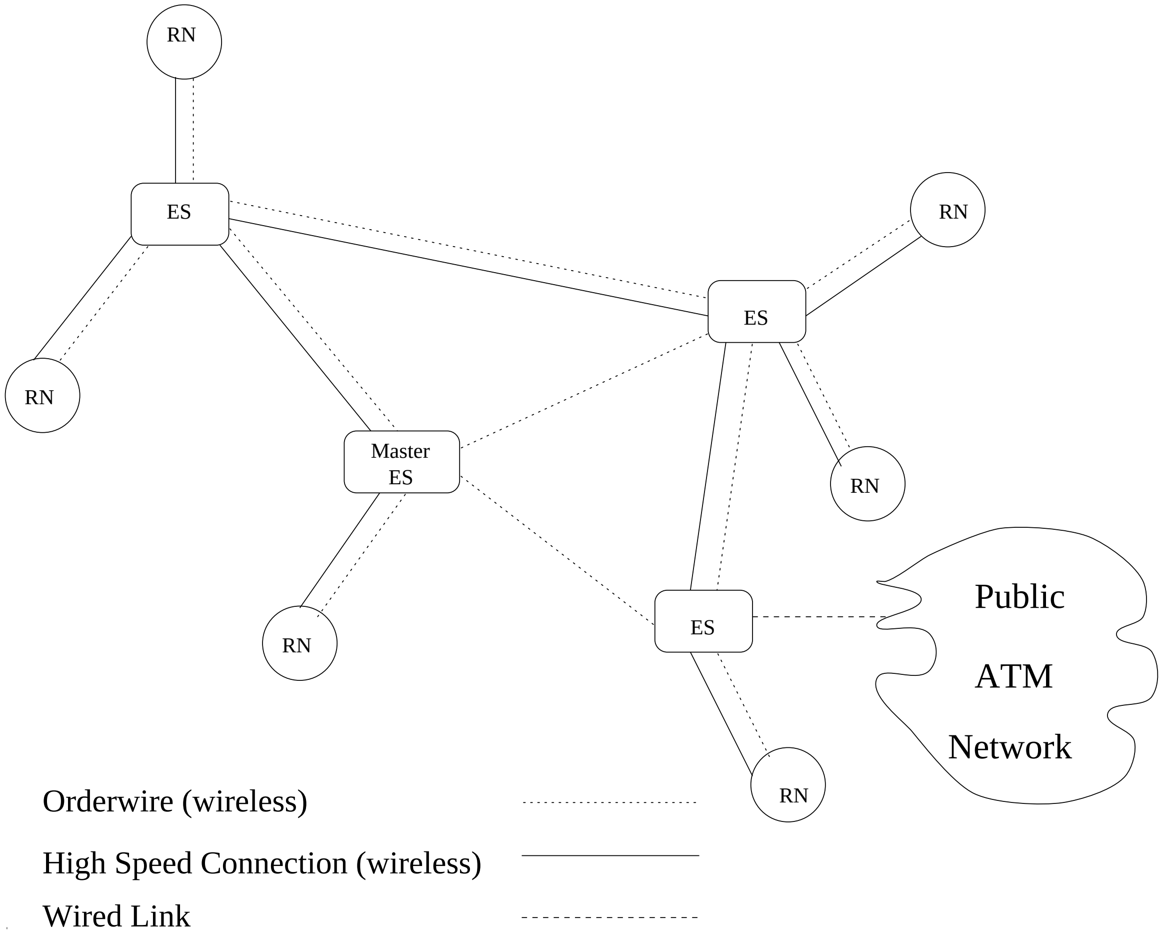


Figure 3. Example Orderwire Topology.

ceipt of the **NEWSWITCH** packet over a point-to-point orderwire link, obtains its position from its GPS receiver and sends its position to the master as a **SWITCHPOS** packet over the point-to-point orderwire link. On receipt of a **SWITCHPOS** packet, the master records the position of the new ES in its switch position table, which is a table of ES positions, and runs the topology configuration algorithm [15] to determine the best possible interconnection of all the ESs. The master then distributes the resulting information to all the ESs in the form of a **TOPOLOGY** packet over the point-to-point orderwire links. Each ES then uses this information to setup the inter-ES links as specified by the topology algorithm. The master also distributes a copy of its switch position table to all the ESs over the point-to-point orderwire links, which they can use in configuring RNs as discussed below. This sequence of operations is illustrated in Figure 5 and Figure 6. Also, the ES then uses the callsign information in the switch position table to setup any additional point-to-point orderwire packet radio links corresponding to the inter ES links required to exchange any link quality information. Thus this scheme results in a point-to-point star network of orderwire links with the master at the center of the star and also point-to-point orderwire links between those ESs that have a corresponding inter ES link, as shown in Figure 3.

In the event of failure of the master node which can be detected by listening for the AX-25 messages generated on node failure, the remaining ESs exchange **MYCALL** packets, elect a new master node, and the network of ESs is reconfigured using the topology configuration algorithm [15].

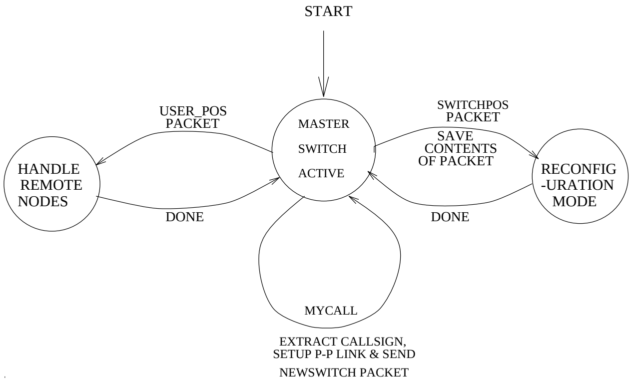


Figure 5. State Diagram for Master EN.

Each RN that becomes active obtains its position from its GPS receiver and broadcasts its position as a **USER_POS** packet over the orderwire network. This packet is received by all the nearby ESs. Each candidate

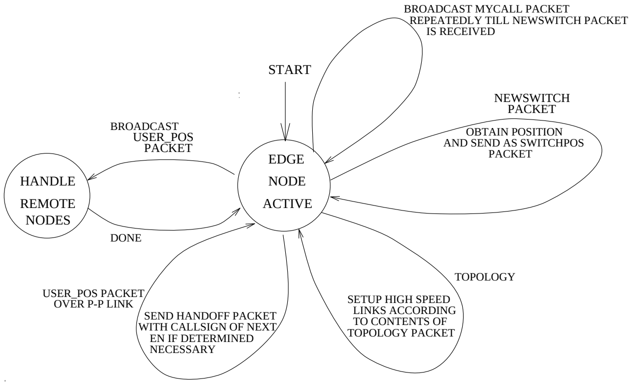


Figure 6. State Diagram for EN not serving as Master.

ES then computes the distance between the RN and all the candidate ESs which is possible since each ES has the positions of all the other ESs from the switch position table. An initial guess at the best ES to handle the RN is the closest ES. This ES then feeds the new RN's position information along with the positions of all its other connected RNs to a beamforming algorithm that returns the steering angles for each of the beams on the ES so that all the RNs can be configured. If the beamforming algorithm determines that a beam and TDMA time slot are available to support the new RN, the ES steers its beams so that all its connected RNs and the new RN are configured. It also records the new RN's position in its user position table which contains positions of connected RNs, establishes a point-to-point orderwire link to the new RN and sends it a **HANDOFF** packet with link setup information indicating that the RN is connected to it. If the new RN cannot be accommodated, the ES sends it a **HANDOFF** packet with the callsign of the next closest ES, to which the RN sends another **USER_POS** packet over a point-to-point orderwire link. This ES then uses the beamform algorithm to determine if it can handle the RN. Figure 7 shows the states of operation and transitions between the states for a RN.

This scheme uses feedback from the beamforming algorithm together with the distance information to configure the RN. It should be noted that the underlying AX.25 protocol [16] provides error free transmissions over point-to-point orderwire links. Also the point-to-point orderwire link can be established from either end and the handshake mechanism for setting up such a link is handled by AX.25. If the RN does not receive a **HANDOFF** packet within a given time it uses a retry mechanism to ensure successful broadcast of its **USER_POS** packet.

A point-to-point orderwire link is retained as long as a RN is connected to a particular ES and a corresponding high-speed link exists between them to enable exchange of link quality information. The link can be torn down when the mobile RN migrates to another ES in case of a hand-off. Thus at the end of this network configuration process, three overlaid networks are setup, namely, an orderwire network, an RN to ES network and an inter-ES network. The orderwire network has links between the master ES and every other active ES in a star configuration, links between ESs connected by inter-ES links as well as links between RNs and the ESs to which they are connected, as shown in Figure 3. Raw pipes for the user data links between RNs and appropriate ESs as well as for the user data links between ESs are also set up.

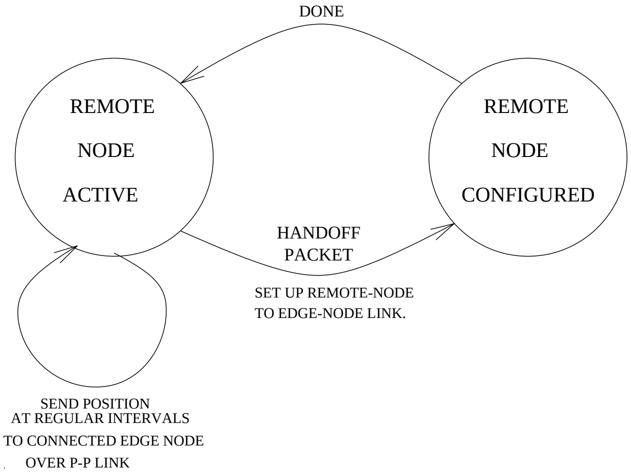


Figure 7. State Diagram for RN.

3.2: ATM Network Configuration Layer

This section briefly describes how ATM VCs are setup by the NCP. As the orderwire network determines the topology of all nodes in the wireless segment (e.g., RNs, ESs) in our architecture, and establishes link connectivity among adjacent nodes, setup is still required of the actual ATM circuits on which wireless ATM are carried on the user data overlay network. This is accomplished by providing standard ATM signaling capabilities to RNs and ESs and using Classical IP over ATM [13] to associate ATM VCs to IP addresses. The Classical IP over ATM implementation provided works for PVCs and SVCs (using ATMARP). Since an ES may connect to multiple RNs (wireless connections) or ATM switches (wired connections), it can be thought of as a software-based ATM switch. In this sense, an ES features ATM PNNI signaling while an RN features ATM UNI signaling. By default, an RN creates one wireless-ATM protocol stack and establishes an ATM VC signaling channel on such a stack; however, the stack is initially in an inactive state (i.e., non-operational mode) since there is no link connectivity to another node established yet. Likewise, an ES creates a predefined number of wireless-ATM protocol stacks – acting like ports in an ATM switch – and establishes ATM VC signaling channels on all configured stacks which are also initialized as inactive. Wireless-ATM protocol stacks are controlled by a daemon, called the adaptation manager, which acts on behalf of the orderwire network. The adaptation manager daemon not only controls the stacks by setting their state to either active or inactive (default), but also may modify configuration parameters of the stacks to provide dynamic adaptation to link conditions. Two possible scenarios illustrate the interactions between the orderwire network and the wireless-ATM network. In the first scenario the orderwire detects link connectivity between an adjacent pair of nodes (e.g., RN-ES or ES-ES). In this case, the orderwire network requests an inactive stack from the adaptation manager daemon at each end and associates them with a designated address. Upon establishment of link connectivity, a requested wireless stack has its state set to active and is ready to operate. Note that since the signaling channels are preconfigured on the stacks in question, users on the wireless establish end-to-end connections exactly as if they were connected in a wired ATM network. The other scenario occurs when the orderwire network detects a broken connection, at the link level, between two connected nodes. This case is typical of an RN moving away from the connectivity range of an ES. The orderwire network thus contacts the adaptation manager daemon at each end to set the wireless stacks in question to inactive. Since a wireless stack is never destroyed, it can be reused in a future request from the orderwire to establish connectivity to another pair of nodes.

4: Virtual Network Configuration for a Rapidly Deployable Network

In order to make RDRN truly rapidly deployable, configuration at all layers has to be a dynamic and continuous process. Configuration can be a function of such factors as load, distance, capacity and permissible topology, all of which are constantly changing in a mobile environment. A Time Warp [17] based algorithm is used to anticipate configuration changes and speed the reconfiguration process.

4.1: Virtual Network Configuration Algorithm

The Virtual Network Configuration (VNC) algorithm is an application of a more general mechanism called Time Warp Emulation (TWE). Time Warp Emulation is a modification of Time Warp [17]. The motivation behind TWE is to allow the actual components of a real-time system to work ahead in time in order to predict future behavior and adjust themselves when that behavior does not match reality. This is accomplished by realizing that there are now two types of *false* messages, those which arrive in the past relative to the process's Local Virtual Time (LVT) and those messages which have been generated which are timestamped with the current real time, but whose values exceed some tolerance from the component's current value.

The basic Time Warp mechanism is modified by adding a verification query phase. This phase occurs when real time matches the receive time of a message in the output queue of a process. In this phase, the physical device being emulated in time is queried and the results compared with the value of the message. A value exceeding a prespecified tolerance will cause a rollback of the process.

4.2: Virtual Network Configuration Overview

The Virtual Network Configuration (VNC) algorithm can be explained by an example. A remote node's direction, velocity, bandwidth used, number of connections, past history and other factors can be used to approximate a new configuration sometime into the future. All actual configuration processes can begin to work ahead in time to where the remote node is expected to be at some point in the future. If the prediction is incorrect, but not far off, only some processing will have to be rolled back in time. For example, the beamsteering process results may have to be adjusted, but the topology and many higher level requirements will still be correct. Working ahead and rolling back to adjust for error with reality is an on-going process, which depends on the tradeoff between allowable risk and amount of processing time allowed into the future. As a specific example, consider the effects of hand-off on TCP performance as described in [12]. In this work, throughputs were measured for hand-off under various conditions and determined to degrade badly.

4.3: Virtual Network Configuration Implementation

The effort required to enhance the network configuration algorithm to include Virtual Network Configuration is minimal. Three new fields are added to each existing message in Table 1: antimessage toggle, send time, and receive time. Physical processes include beamforming, topology acquisition, table updates, and all processing required for configuration. Each physical process is assigned a tolerance. When the value of a real message exceeds the tolerance of a predicted message stored in the send queue, the process is rolled back.

Also, an additional packet type was created for updating an approximation of the Global Virtual Time (GVT). Because the system is composed of asynchronously executing logical processes, each working ahead as quickly as possible with its own local notion of time, it is necessary to calculate the time of the system as a whole. This system-wide time is the GVT. The difference between GVT and current time is the amount of lookahead, Λ. Although GVT $\geq t$ where t is real time, Λ is required because it is used to control the efficiency and accuracy of the system. Since the network configuration system uses a master node as described in the physical layer setup, this is a natural centralized location for a centralized GVT update method. RNs transmit their LVT to the master, the master calculates an approximate GVT and returns the result.

An estimate of the additional load on the orderwire packet radios using VNC is shown in Figure 8. It is assumed that virtual messages are 65 bits longer than real messages and there is one virtual message for each real message. The figure shows the prototype 19,200 bps orderwire link capacity as a function of the number of RNs, the position update rate of each RN, and the hand-off rate. The capability of the orderwire to support these rates without VNC is discussed later in detail and is shown in Figure 13. Comparing Figures 8 and 13, it is apparent that the VNC slightly more than doubles the orderwire load. However enough capacity remains to support users with a reasonable position update rate and handoff rate with this relatively low 19,200 bps orderwire bandwidth.

4.4: Seamless Mobile ATM Routing

This section discusses an incorporation of Virtual Network Configuration (VNC) and the Network Control Protocol (NCP) as described in the previous sections into the Private Network-Network Interface (PNNI) [18] to facilitate seamless ATM hand-off. An attempt is made to minimize the changes to the evolving PNNI standard. Figure 9 shows a high level view of the PNNI Architecture. Terminology used in the PNNI Specification. In this version of mobile PNNI, the standard PNNI route determination, topology database, and topology exchange would reside within the NCP. The NCP stack with VNC is shown in Figure 10.

The enabling mechanism is the fact that VNC will cause the NCP to create a topology which will exist after a hand-off occurs at a time prior to the hand-off. This will cause PNNI to perform its standard action of updating its topol-

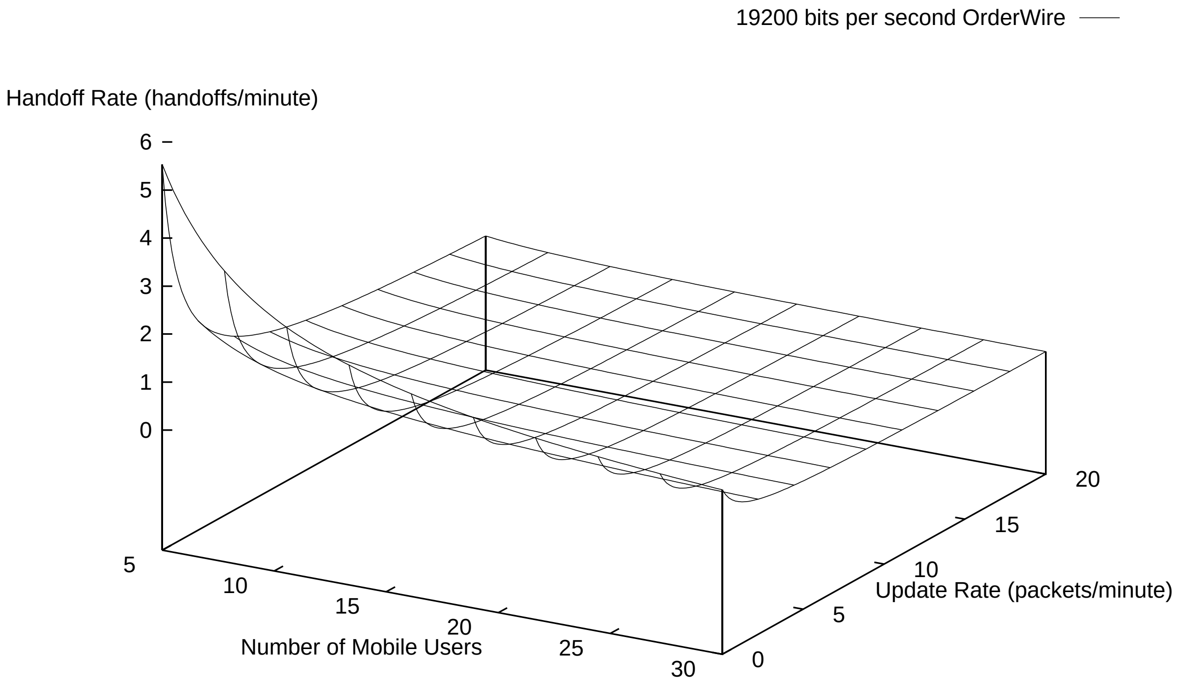


Figure 8. Orderwire Traffic Analysis **with** Virtual Network Configuration.

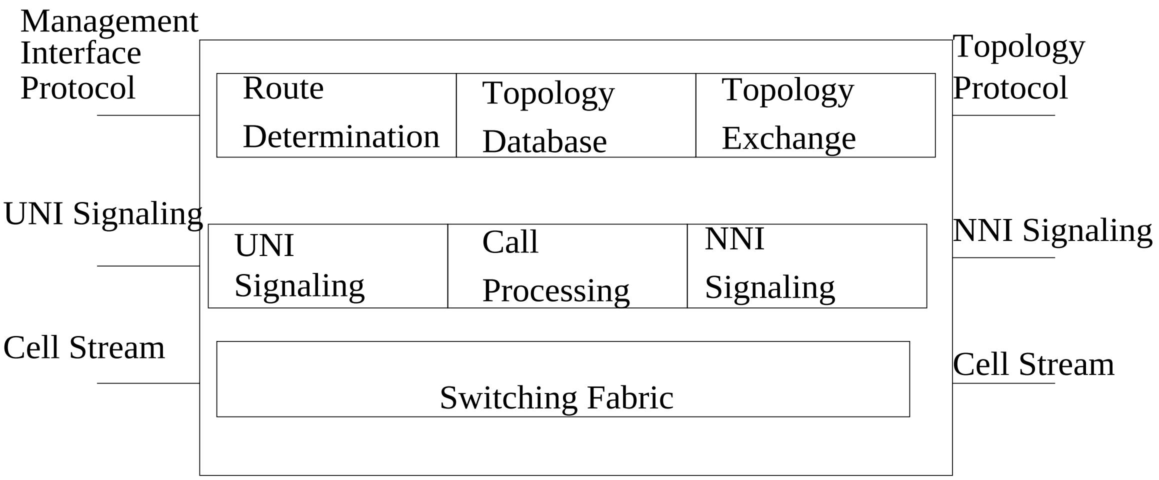


Figure 9. PNNI Architecture Reference Model.

ogy information immediately before the hand-off occurs. Note that this is localized within a single Peer Group (PG).

The second enabling mechanism is a change to the PNNI signaling protocol. In mobile PNNI, standard PNNI signaling is allowed to dynamically modify logical links when triggered by a topology change. This is similar to a **CALL ABORT** message except that the ensuing **RELEASE** messages will be contained within the scope of the Peer Group (PG). This new message will be called a **SCOPED CALL ABORT** message.

When the topology changes due to an end system hand-off, a check is made to determine which end system (RN) has changed logical nodes (LN). An attempt is made to establish the same incoming VCs at the new LN as were at the original LN and connections are established from the new LN to the original border LNs of the Peer Group. This allows the RN to continue transmitting with the same VCI as the hand-off occurs. The connections from the original LNs to the border LNs are released after the hand-off occurs. If the new LN is already using a VCI that was used at

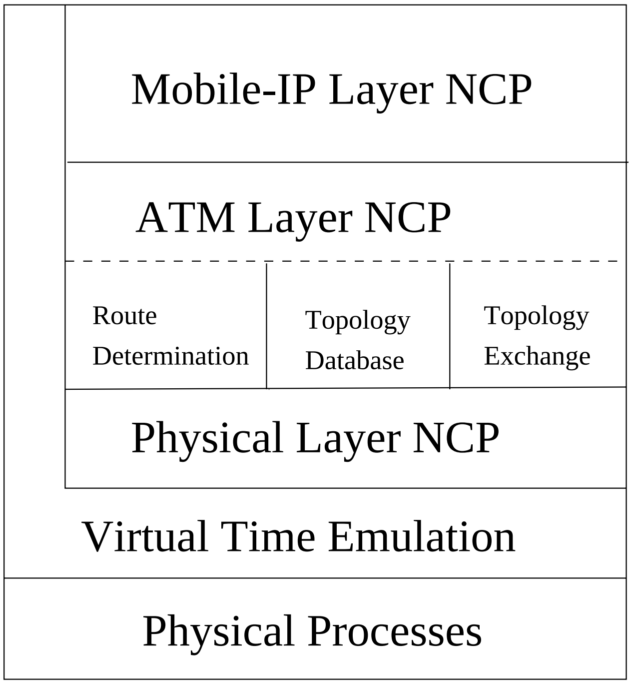


Figure 10. Virtual Network Configuration Stack.

the original LN, the **HANDOFF** packet will contain the replacement VCIs to be used by the end system (RN). There are now two branches of a logical link tree established with the border LN as the root. After the hand-off takes place the old branch is removed by the new **SCOPED CALL ABORT** message.

Note that link changes are localized to a single Peer Group. The fact that changes can be localized to a Peer Group greatly reduces the impact on the network and implies that the mobile network should have many levels in its PNNI hierarchy. In order to maintain cell order the new path within the Peer Group is chosen so as to be equal to or longer than the original path based on implementation dependent metrics.

Consider the network shown in Figure 11. Peer Groups are enclosed in circles and the blackened nodes represent the lowest level Peer Group Leader for each Peer Group. End system A.1.2.X is about to hand-off from A.1.1 to A.2.2. The smallest scope which encompasses the old and new LN is the LN A.

A.3.1 is the outgoing border node for LN A. A **CALL SETUP** uses normal PNNI operations to setup a logical link from A.3.1 to A.2.2. After A.1.2.X hands off, a **SCOPED CALL ABORT** message releases the logical link from A.3.1 to A.1.1.

5: Development and Implementation

The initial physical layer network control protocol design was done using Maisie [19], a C-based parallel programming language. It facilitates creation of entities which execute in parallel and the ability to easily send and receive messages between entities. A Maisie emulation of the entire network was developed which uses the actual NCP code. This helped build confidence that the design of the Network Control Protocol was correct.

Event	Time (ms)
USER_POS	677
NEWSWITCH	439
HANDOFF	473
MYCALL	492
SWITCHPOS	679
TOPOLOGY	664

Table 2. Network Control Protocol Timing Results.

The network control protocol code was initially tested with only the two packet radios available. Since at least three packet radios are necessary for a complete RN-ES-RN orderwire connection, the next step involved emulating the packet radios via TCP/IP over Ethernet, and completing the development of the code. The packet radio emulation also allowed testing of various configurations that helped determine if the network control protocol was scalable.

The physical layer of the Network Control Protocol is a single-unit consumable resource system. There can be no deadlock since there are no cycles. All message interactions take place with a master switch, except for the initial **MYCALL** packet broadcast.

The GPS system was also emulated to provide the appearance of mobility so that hand-offs of a host from one ES to another could be tested. The GPS emulation is also an important component of the Virtual Network Configuration Algorithm. The actual orderwire code is used in these emulations.

5.1: Timing Results

This section summarizes the results of initial timing experiments that were undertaken to examine the performance of the orderwire system. The experiments involved determining the time required to transmit and process each of the packet types listed in Table 1 using the real packet radios. These times represent the time to packetize, transmit, receive, and depacketize each packet at the Network Control Protocol process. Figure 12 illustrates the physical configuration used for the experiments involving the real packet radios. The results are presented in Table 2. Most of the overhead occurs during the initial system configuration which occurs only once as long as ESs remain stationary. With regard to a handoff, the 473 millisecond time to transmit and process the handoff packet is on the same order of time as that required to compute the beam angles and steer the beams. The following sections provide an analysis and discuss the impact of scaling up the system on the configuration time.

5.2: Bandwidth required for the Orderwire Network

The traffic over the orderwire was analyzed to determine a relation between the maximum update rate and the number of RNs. The protocol used for contention resolution on the broadcast channel is the Aloha Protocol which is known to have a maximum efficiency close to 18%. Given the bandwidth of the orderwire channel, size of an orderwire packet and this value for the efficiency, we compute and plot the value for the maximum update rate (in packets per minute) for a given number of RNs. The plot of Figure 13 shows the variation in update rate for between 5 and 30 RNs. This study gives us an upper limit on the number

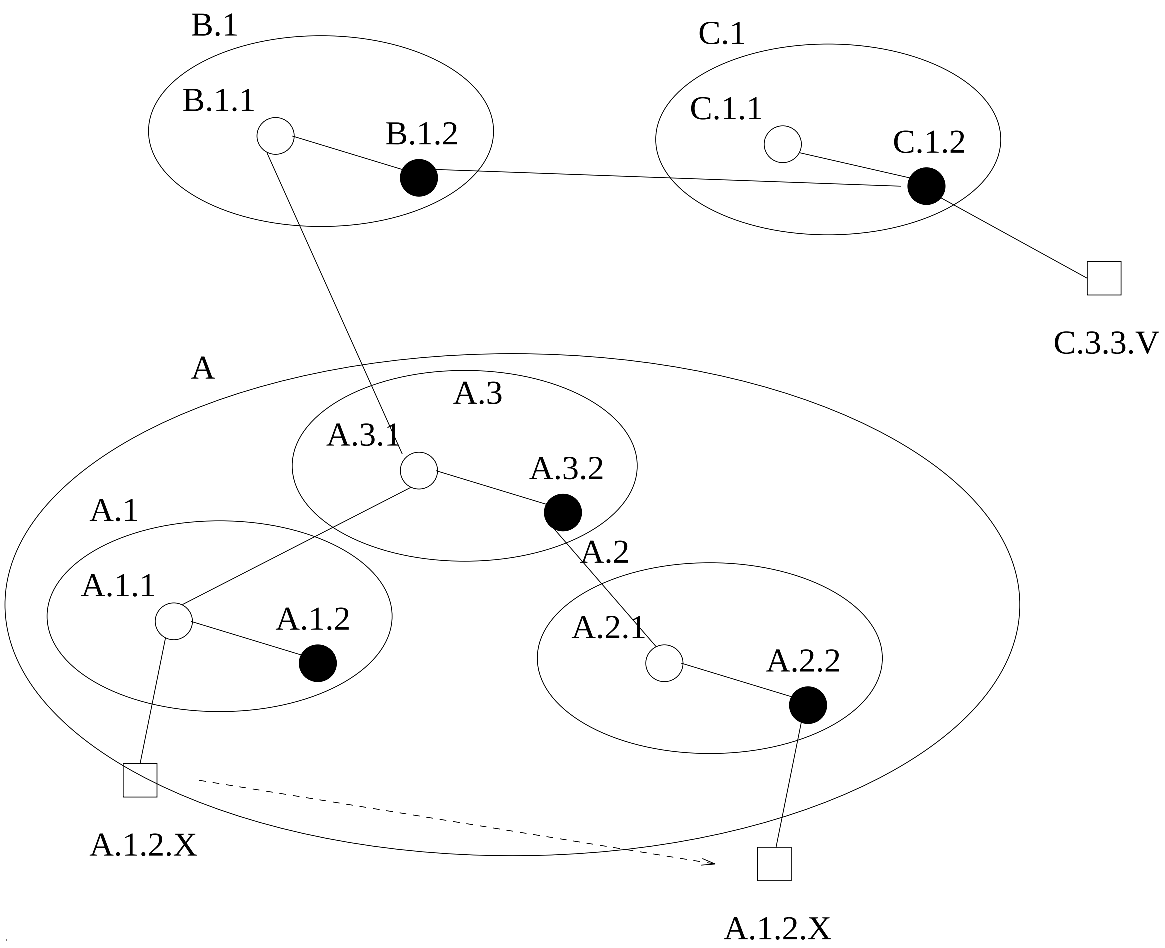


Figure 11. Mobile PNNI Example.

of RNs that can be supported over the orderwire given a minimum required update rate and handoff rate.

6: NCP Performance Analysis

The analysis of the RDRN network configuration time using the protocols proposed earlier, will be divided into three phases. Phase I is the ES-ES configuration, Phase II is the RN configuration, and Phase III is handoff configuration. The specific numerical values used in this section were obtained from Table 2.

6.1: Phase I

In Phase I the ES nodes act in a distributed manner to determine which ES will become the master ES. The master ES collects position information, determines the optimum ES interconnections, and distributes the results back to the ES nodes. The ES nodes determine the master ES by broadcasting **MYCALL** packets and collecting **MYCALL** packets until the MYCALL Timer expires with a prespecified time, T. The **MYCALL** packets contain the callsign and boot-time of each ES. The ES with oldest boot-time is designated as the master. T should be chosen as the smallest value which allows enough time for all **MYCALL** packets to be received. This would be approximately $0.492 * (N-1)$ seconds, where N is the total number of ES nodes. **NEWSWITCH** packets take on the order of 0.439 seconds to transfer, and therefore, it will take $0.439 * (N-1)$ seconds to send these packets. The ES nodes will respond with **SWITCHPOS** packets which will take another $0.679 * (N-1)$ seconds. These events occur after each **MYCALL** packet has been received, and can occur before the MYCALL Timer has expired.

The next step in Phase I is to run the topology algorithm which is based on a consistent labeling algorithm [15]. This algorithm generates all fully connected topologies given ES node locations and constraints on the antenna beams such that beams do not interfere with one another. The information required by the topology module is the GPS location of all ES nodes, transmit and receive beam widths, transmit radius, the number of non-interfering frequency pairs, and an interference multiplier. An interference multiplier of 1.0 assumes adaptive power control, in which case it is assumed that beam power control will be adjusted to exactly match the link distance. The interference multiplier multiplied by a link's actual length will determine the range of interference created by the link. This takes on the order of $K_{top}\left[N^2+(L+1)^R\right]$ seconds where L is the number of available frequency pair combinations with the addition of 1 for no link. Assigning distinct frequencies allows beams to overlap without interfer-

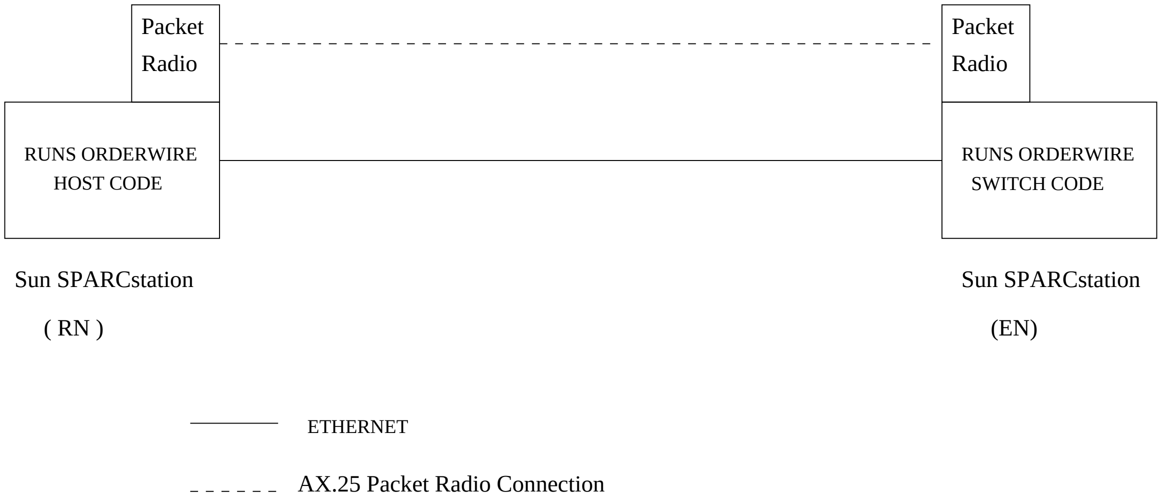


Figure 12. Physical Setup for Packet Radio Timing.

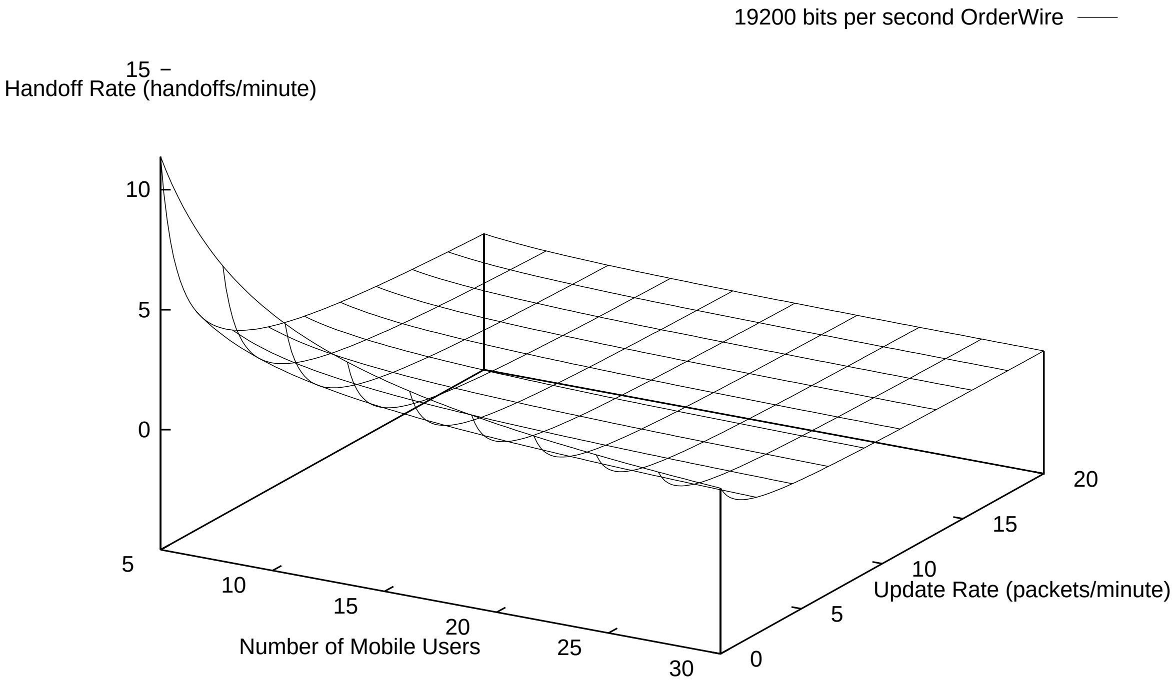


Figure 13. Orderwire Traffic Analysis **without** Virtual Network Configuration.

ence. R is the number of constrained links and K_{top} is a constant. The constraints are based on maximum beam length, beam widths, and number of frequencies which can be supported.

The final step in Phase I is to distribute the topology information to all ES nodes in **TOPOLOGY** packets. This takes approximately $0.664 + (0.1 * (N - 1))$ seconds.

The time for Phase I to complete as a function of N is shown in Equation 1.

$$\begin{aligned} P1(N) \quad = \quad & \max\left[T, 0.439 * (N-1) + 0.492 * (N-1)\right] + \\ & K_{top}\left[N^2 + (L+1)^R\right] + \\ & 0.664 + (0.1 * (N-1)) \end{aligned} \qquad (1)$$

6.2: Phase II

Phase II is the RN configuration phase. Let U be the number of RNs associated with a given ES. The first step is for the ES to receive **USER_POS** packets from each RN. This takes $0.677 * U$ seconds.

The next step is to determine the optimum direction of the beams in order to form a connection with the RNs. This algorithm execution is a linear function of the number of RNs, which takes $K_{bf} * U$ seconds where K_{bf} is a constant. The algorithm is currently implemented in MatLab and takes approximately 7.5 seconds to obtain reasonable convergence of the beam direction to connect with four RNs.

The final step in Phase II is to generate a table of complex weights for antenna beamforming and download this table to the hardware. This is a function of the number of elements in the antenna array, K_{el}, the number of beams, B, and the number of bits per symbol, M. K_{el} tables are created with 2^{M*B} entries per table. This takes on the order of 2 seconds with 4 beams and 8 elements for QPSK modulation on an OSF1 V4.0 386 DEC 3000/400 Alpha workstation.

The entire beamform and table generation module must be repeated for every combination of transmitting RNs. A different table is used depending on which RNs are currently transmitting data. The complete time for Phase II is shown in Equation 2.

$$P2(U) = 0.677 * U + \sum_{r=1}^{U} \binom{U}{r} \left(K_{bf} * r + K_{el} * 2^{M*B}\right) \qquad (2)$$

6.3: Phase III

Phase III, shown in Equation 3, is the time required for the orderwire to perform a hand-off. The current network control code determines RN to ES associations based on distance. When the distance between an RN and an ES other than its currently associated ES becomes smaller than the distance between the RN and its currently associated ES, the current ES initiates a hand-off by sending a **HANDOFF** packet. This takes 0.473 seconds. The RN will then initiate a point-to-point orderwire connection with the new ES. Finally, Phase II must be run again at the new ES, which is the reason for including the function $P2$.

$$P3_{RN} = 0.473 + P2(U+1) \qquad (3)$$

6.4: Orderwire Performance Emulation

The emulation of the orderwire systems satisfies several goals. It allows tests of configurations that are beyond the scope of the prototype RDRN hardware. Specifically, it verifies the correct operation of the RDRN Network Control Protocol in a wide variety of situations. The emulation helps to verify the correctness of the analytical results obtained above. As an additional benefit, much of the actual orderwire code was used by the Maisie [19] emulation allowing further validation of that code. The Edge Switch (ES) and Remote Node (RN) are modeled as a collection of Maisie entities. This is an emulation rather than a simulation because the Maisie code is linked with the working orderwire code and also with the topology algorithm. There is an entity for each major component of the RDRN system including the GPS receiver, packet radio, inter ES links, RN to ES links and the Master, ES, and RN network configuration processors, as well as other miscellaneous entities. The input parameters to the emulation are shown in Tables 3, 4, 5.

The RN VC setup process for connections over the inter ES antenna beams is assumed to be Poisson. This represents ATM VC usage over the physical link. The RN will maintain a constant speed and direction until a hand-off occurs, then a new speed and direction are generated from a uniform distribution. This simplifies the analytical computation. Note that NCP packet transfer times as measured in Table 2 are used here.

6.5: Orderwire Maisie Emulation Design

The architecture for the RDRN link management and control is shown in Figure 14. The topology modules are used only on ES nodes capable of becoming a master ES. The remaining modules are used on all ES nodes and RNs. The beamform module determines an optimal steering angle for the given number of beams which connects all RNs to be associated with this ES. It computes an estimated signal to noise interference ratio (SIR) and generates a table of complex weights which, once loaded, will control the beam formation. Note that this table is not loaded until the table fill trigger is activated. The connection table is used by the Adaptive HDLC and ATM protocol stacks for configuration via the adaptation manager.

The emulation uses as much of the actual network control code as possible. The packet radio driver, GPS driver, and Network Control Protocol state machine are implemented in Maisie; tables, data structures, and decision functions from working NCP code are used. Figure 15 shows the structure of the Maisie entities. The entity names are shown in the boxes and the message types are shown along the lines. Direct communication between entities is represented as a solid line. The dashed lines indicate from where entities are spawned.

The RN entity which performs ATM VC setup (HSLRN entity in Figure 15) generates calls as a Poisson process which the ES node (HSLES entity in Figure 15) will attempt to accept. If the EN moves out of range or the ES has no beam or slot available the setup will be aborted. As the RN moves, the ES will hand off the connection to the proper ES based on closest distance between RN and ES.

Parameter	Definition
NumRN	Number of Remote Nodes
NumES	Number of Edge Switches
ESDist	Inter Edge Switch spacing (forms rectangular area)
T	ES/ES MYCALL configuration time
maxV	Maximum RN speed for uniform distribution
S	Time to wait between node initial startups
ESspd	Initial Edge Switch speed
ESdir	Initial Edge Switch direction
RNspd	Initial Remote Node speed
RNdir	Initial Remote Node direction

Table 3. NCP Emulation Mobility Input Parameters.

Parameter	Definition
EndTime	Emulation end time (tenths of seconds)
VCCallTime	Inter High Speed Connection Setup Times
VCCallDuration	High Speed Connection Life Times

Table 4. NCP Emulation Time Input Parameters.

Parameter	Definition
UseRealTopology	Connect to MatLab and run actual program
Rlink	Maximum beam distance
Fmax	Number of non-interfering frequency pairs
Imult	Interference multiplier
Twidth	Transmitting Beam width
Rwidth	Receiving Beam width

Table 5. NCP Emulation Beam Input Parameters.

7: Emulation Results

This section discusses the current results from the emulation. Some of these results revealed problems which are not immediately apparent from the state diagrams in Figures 5, 6, 7. The emulation produces Network Control Protocol Finite State Machine (NCP FSM) output which shows the transitions based on the state diagrams in Figures 5, 6, 7. The FSM output provides an easy comparison with diagrams to insure correct operation of the protocol.

7.1: Effect of Scale on NCP

The emulation was run to determine the effect on the NCP as the number of ES and RN nodes increased. The dominate component of the configuration time is the topology calculation run by the ES which is designated as the master. Topology calculation involves searching through the problem space of constraints on the directional beams for all feasible topologies and choosing an optimal topology from that set as described in [15]. The units on all values should be consistent with the GPS coordinate units, and all angles are assumed to be degrees. The beam constraint values are Maximum link distance 1000.0, Maximum Frequencies 3, Interference Multiplier 1.0, Transmit Beam Width 10.0, Receive Beam Width 10.0.

The topology calculation is performed in MatLab and uses the MatLab provided external C interface. Passing information through this interface is clearly slow, therefore these results do not represent the exact execution times of the prototype system. However, they do provide a worse case test for the protocol.

A possible speedup may arise through the use of Virtual Network Configuration, which will provide a mechanism for predicting values in advance and also allows processing to be distributed. Another improvement which may be considered is to implement a hierarchical configuration. The network is partitioned into a small number of clusters of nodes in such a way that nodes in each group are as close together as possible. The topology code is run as though these were individual nodes located at the center of each group. This inter-group connection will be added as constraints to the topology computation for the intra-group connections. In this way the topology program only needs to calculate small numbers of nodes which it does relatively quickly.

7.2: MYCALL Timer

The MYCALL Timer, set to a value of T in the analysis section, controls how long the system will wait to discover new ES nodes before completing the configuration. If this value is set too low, new **MYCALL** packets will arrive after the topology calculation has begun, causing the system to needlessly reconfigure. If the MYCALL Timer value is too long, time will be wasted, which will have a large impact on a mobile ES system. Table 6 shows the input parameters and Figure 16 shows the time required for all **MYCALL** packets to be received as a function of the number of ES nodes. These times are the optimal value of the MYCALL Timer as a function of the number of ES nodes because the these times are exactly the amount of time required for all ESs to respond. In order to prevent the possibility of an infinite loop of reconfigurations from occurring, an exponential back-off on the length of the **MYCALL** Timer value is introduced. As **MYCALL** packets arrive after T has expired, the next configuration occurs with an increased value of T.

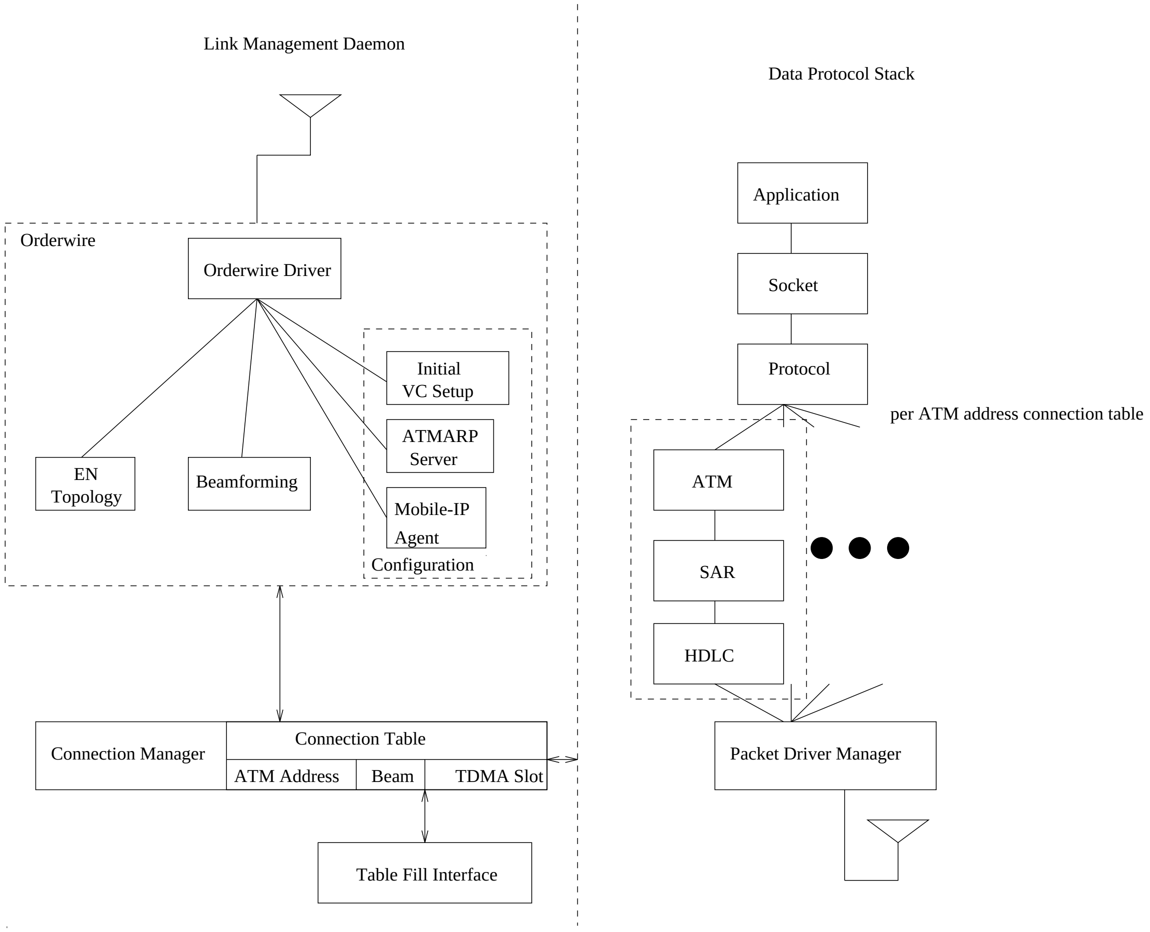


Figure 14. Network Control System Architecture.

Parameter	**Value**
Number of RNs	0
Number of ESs	2 thru 6
Inter-ES Distance	20 m (65.62 ft)
T	20 s
Maximum Velocity	5 m/s (11.16 mi/hr)
Initial ES Speed	0 m/s
Initial ES Direction	0^o
Initial RN Speed	N/A
Initial RN Direction	N/A
Inter-VC Setup Time	1200 s
VC Call Duration	600 s

Table 6. MYCALL Timer Simulation Parameters.

7.3: Link Usage Probability

Multiple RNs may share a single beam using Time Division Multiplexing (TDMA) within a beam. The time slices are divided into slots, thus a $(beam, slot)$ tuple defines a physical link. The emulation was run to determine the probability distribution of links used as a function of the number of RNs. The parameters used in the emulation are shown in Table 7 the results of which indicate the number of links and thus the number of distinct $(beam, slot)$ tuples required. Figure 17 shows the link usage cumulative distribution function for 4 and 7 RNs.

7.4: ES Mobility

ES mobility is a more difficult problem and will be examined in more detail as the research proceeds. The parameters used in an emulation with mobile ES nodes are shown in Table 8. As mentioned in the section on the MYCALL Timer, if a **MYCALL** packet arrives after this timer has expired, a reconfiguration occurs. This could happen due to a new ES powering up or an ES which has changed position. Figure 18 shows the times at which reconfigurations occurred in a situation in which ES nodes were mobile. Based on the state transitions generated from the emulation

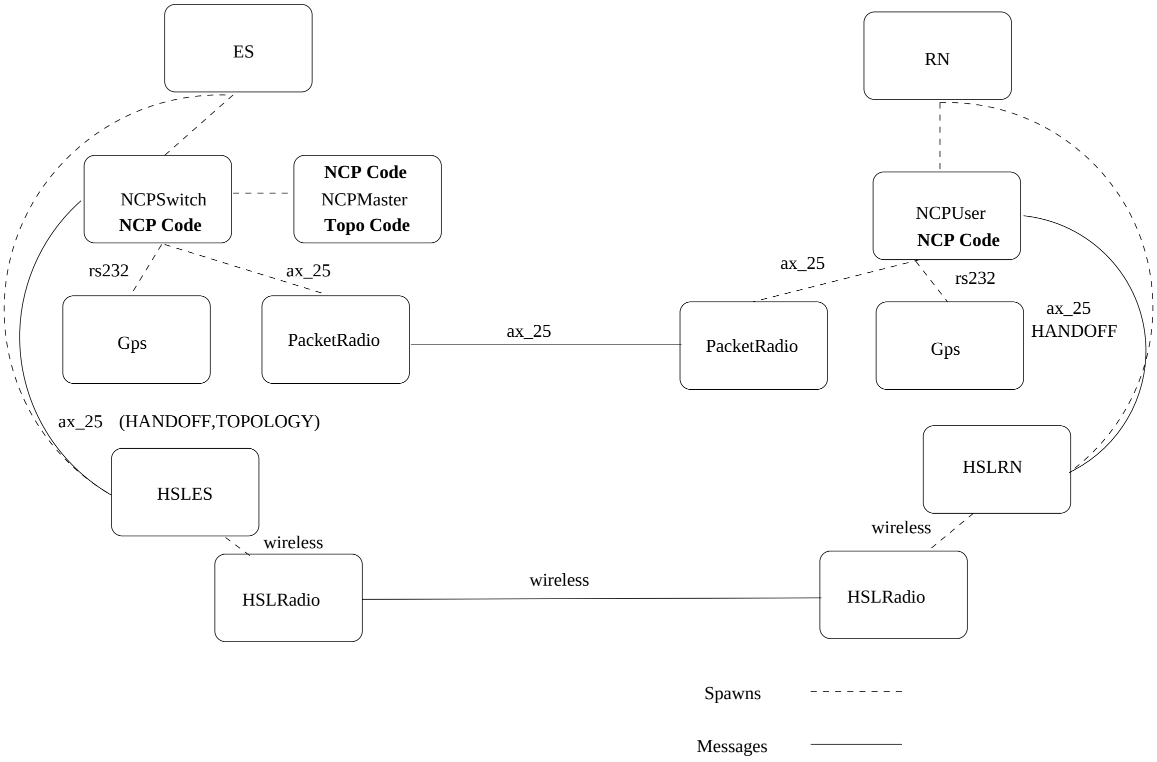


Figure 15. Emulation Design.

Parameter	Value
Number of RNs	4 and 7
Number of ESs	2
Inter-ES Distance	20 m (65.62 ft)
T	20 s
Maximum Velocity	5 m/s (11.16 mi/hr)
Initial ES Speed	0 m/s
Initial ES Direction	0^o
Initial RN Speed	5 m/s (11.16 mi/hr)
Initial RN Direction	0^o
Inter-VC Setup Time	1200 s
VC Call Duration	600 s

Table 7. Link Usage Simulation Parameters.

it is apparent that the system is in a constant state of reconfiguration; no reconfiguration has time to complete before a new one begins. As ES nodes move, the NCP must notify RNs associated with an ES with the new position of the ES as well as reconfigure the ES nodes. To solve this problem, a tolerance, which may be associated with the link quality, will be introduced which indicates how far nodes can move within in a beam before the beam angle must be recalculated, which will allow more time between reconfigurations. It is expected that this tolerance in addition to Virtual Network Configuration will provide a solution to this problem.

7.5: Effect of Communication Failures

The emulation was run with a given probability of failure on each packet type of the Network Control Protocol. The following results are based on the output of the finite state machine (FSM) transition output of the emulation and an explanation is given for each case.

A dropped **MYCALL** packet has no effect as long as at least one of the **MYCALL** packets from each ES is received at the master ES. This is the only use of the AX.25 broadcast mode in the ES configuration. The broadcast AX.25 mode is a one time, best effort delivery; therefore, **MYCALL** packets are repeatedly broadcast at the NCP layer.

The Maisie emulation demonstrated that a dropped **NEWSWITCH** packet caused the protocol to fail. This is because the master ES will wait until it receives all **SWITCHPOS** packets from all ES nodes for which it had received **MYCALL** packets. The **NEWSWITCH** packet is sent over the AX.25 in connection-oriented mode, e.g. a mode in which corrupted frames are retransmitted; the probability of loosing a packet in this mode is very low.

Parameter	Value
Number of RNs	0
Number of ESs	3
Inter-ES Distance	20 m (65.62 ft)
T	20 s
Maximum Velocity	5 m/s (11.16 mi/hr)
Initial ES Speed	1 m/s (2.23 mi/hr)
Initial ES Direction	0^o
Initial RN Speed	N/A
Initial RN Direction	N/A
Inter-VC Setup Time	1200 s
VC Call Duration	600 s

Table 8. Mobile ES Simulation Parameters.

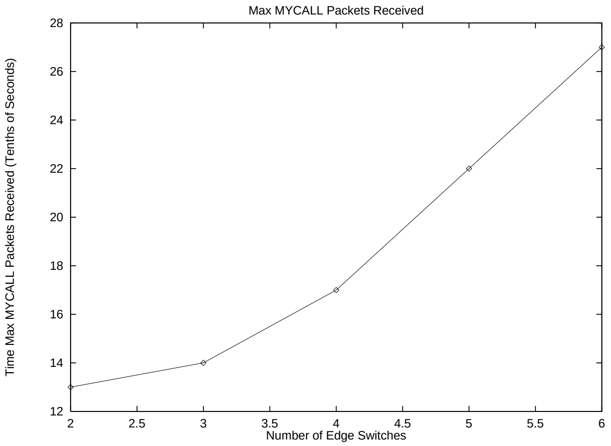


Figure 16. MYCALL Packets Received.

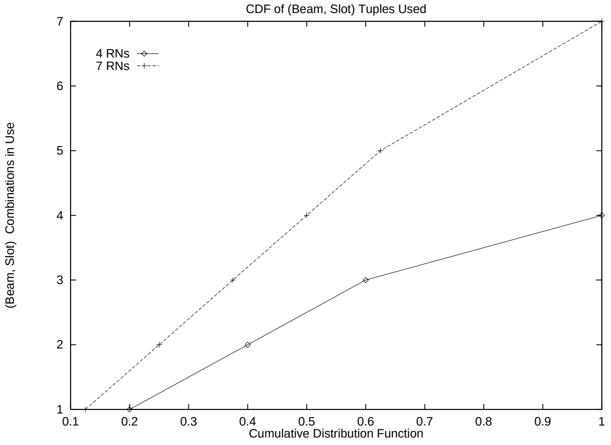


Figure 17. $(Beam, Slot)$ Usage.

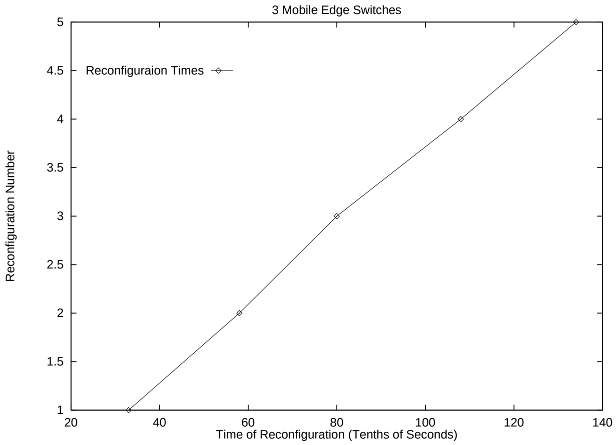


Figure 18. Mobile ES Configuration Time.

A dropped **SWITCHPOS** packet has the same effect as a dropped **NEWSWITCH** packet. In order to avoid this situation, the NCP will re-send the **NEWSWITCH** if no response is received.

Finally, the Maisie emulation showed that a lost **TOPOLOGY** packet results in a partitioned network. The ES which fails to receive the **TOPOLOGY** packet is not joined with the remaining ES nodes; however, this ES node continued to receive and process **USER_POS** packets from all RNs. It therefore attempts to form an initial connection with all RNs. The solution for this condition is not to allow RN associations with an ES node until the **TOPOLOGY** packet is received. Because **MYCALL** packets are transmitted via broadcast AX.25, each ES node can simply count the number of **MYCALL** packets and estimate the time for the master ES node to calculate the topology using the number of **MYCALL** packets as an estimate for the size of the network. If no **TOPOLOGY** packet is received within this time period, the ES node retransmits its **SWITCHPOS** packet to the master ES node in order to get a **TOPOLOGY** packet as a reply.

8: Summary

This paper described the design of a control and management network for a mobile wireless ATM network. The orderwire system consists of a packet radio network which overlays the mobile wireless ATM network and receives GPS information. This information is used to control the beamforming antenna subsystem which provides for spatial reuse. This paper also proposed the design of the VNC algorithm which is a novel concept for predictive configuration. A mobile ATM PNNI based on VNC was also discussed. As a prelude to the system implementation, results of a Maisie simulation of the orderwire system were presented. Finally, the Network Control Protocol was tested, initial problems corrected, and initial performance results were obtained and presented in this paper.

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