PC-notebook based mobile networking: Algorithms, Architectures and Implementation

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1. Abstract

The integration of multimedia adaptive wireless networking capabilities in a PC-notebook platform are investigated. To support mobile networking, while providing compatibility with the wired infrastructure, new functions are required for topology creation using multihop protocols. To support mobility in a wireless environment, power control and bandwidth allocation are required in conjunction with adaptive wireless modems and rate-adaptive video codecs. A prototype implementation of a wireless node with these capabilities reveals several performance and complexity limitations with current technology. In particular the DOS operating system, the PC shared bus architecture and traditional partitioning of the network and modem functions lead to severe performance losses that are detrimental in wireless networking. For mobile wireless nodes, these limitations are unacceptable. In conclusion several ideas are presented for re-architecting the PC-notebook for wireless netwokring nodes that can substantially improve bandwidth efficiency while overcoming complexity and power limitations of current technology.

2. Introduction: Functional Requirements

Figure 1 illustrates the basic functionality desired in the wireless PC-notebook node.

2.1 Multimedia applications:

Current network applications are typically text based (e.g. Telnet, FTP, etc.). Others, such as MOSAIC, present multimedia information to the user, but the information is not captured and coded real-time, and downloaded to the local machine (so the network does not have to support real-time data flow). Advanced applications, such as video conferencing, require the ability to capture live multimedia information (video or voice), and display it on the local and remote screen. To achieve this, requires new applications which can interact with the multimedia sources to create, code/decode, and synchronize these real-time data streams. These applications require new network control functions to handle the delivery problems (i.e.: throughput and delay constraints) associated with real-time services.Also, in a wireless environ-

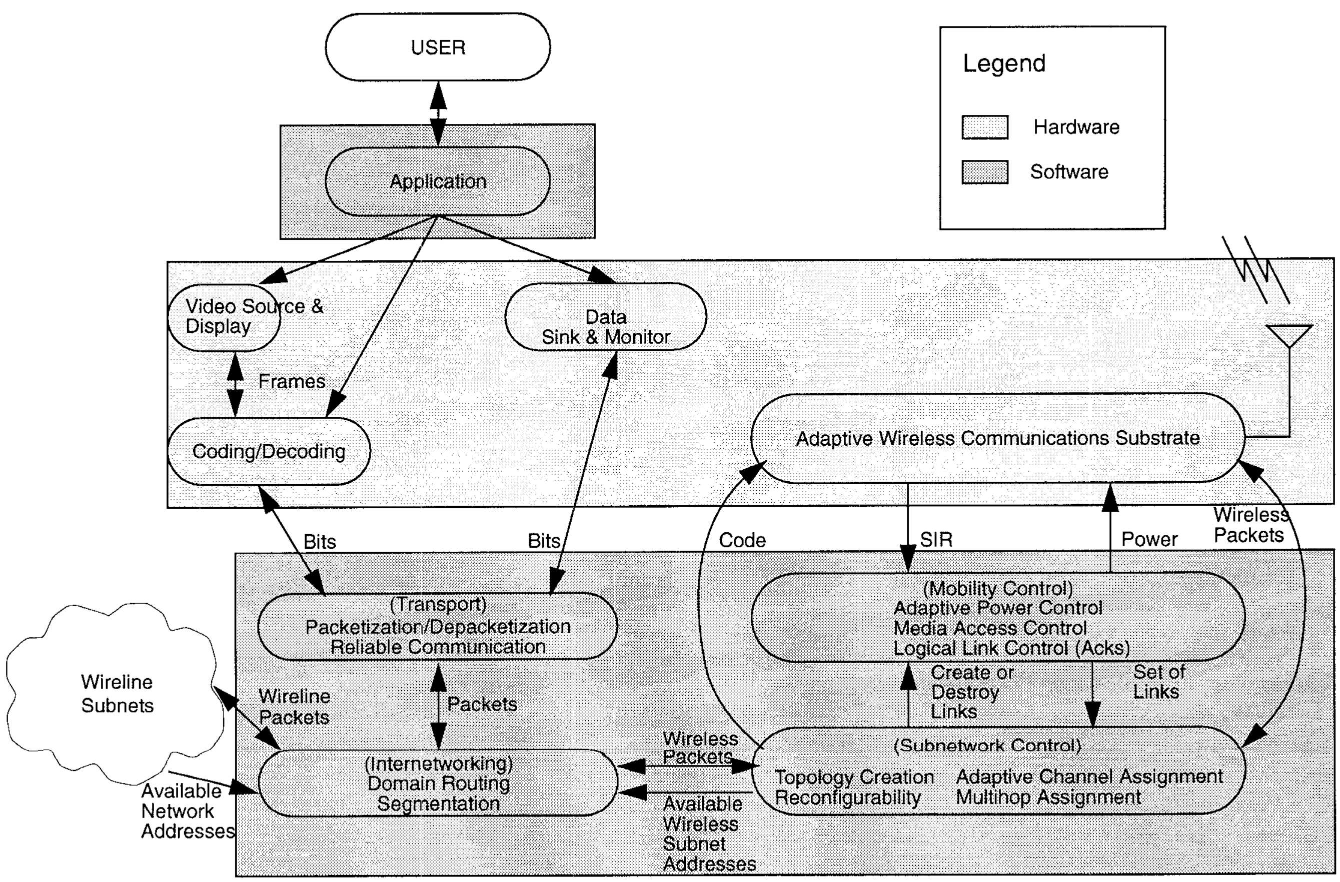

Figure 1 Node Functionality

ment a low bit-rate adaptive video codec is required for efficient bandwidth utilization.

2.2 Transport and internetworking

Internetworking is desired to support large scale connectivity across multiple communication substrates (fiber, coax, satellite, and radio). The Internet Protocol of the TCP/IP protocol suite is a time proven protocol, which can support this internetworking for static (non-mobile or non-portable) hosts. In order to remain compatible with the internet, the proposed wireless network architecture supports TCP/IP. To support large scale mobility (movement of nodes from one area of the internet to another), protocols like Mobile IP[1] can be used. To have the option of being able to function without connectivity to the internet and support an instant infrastructure, a wireless subnet is used to control local connectivity. This wireless subnet is viewed as another network on the internet where independent and specific algorithms such as multihop routing and topology creation can be done independently of constraints imposed by other infrastructures, networks, and communication substrates.

2.3 Sub-network control for wireless topology

This proposed wireless subnet has new networking layer functions that do not exist in wired networks today. This new functionality includes reconfiguration and dynamic control over the topology to instantly setup an infrastructure such as when new nodes start up and adapt to mobility and failure of nodes. This wireless subnet is viewed as a virtual topology which is setup among the nodes by selecting or creating a set of links to local neighbors. Various algorithms can determine when and how to create new links using various techniques such as clustering[8][10], power minimization [6], or highest reliability [7] where the best code and power level are chosen to create a reliable link amongst neighbors. A simple example is a completely distributed algorithm which performs code assignment to support CDMA by listening to available codes and using that code which has the least amount of interference (including background and co-channel interference.) A quasi-distributed algorithm such as clustering can provide code assignment for Code Division Multiple Access (CDMA) and synchronization via Time Division Multiple Access (TDMA) between the links. TDMA is used to make sure a node will be listening on the appropriate code at the appropriate time so that packet forwarding from one link to another can take place. To prevent the need for global synchronization, CDMA is used to make sure one cluster doesn't interfere with another cluster.

Other new functionality include the ability to support wireless multihop communication when a wireless node can not directly communicate with the wired/wireless gateway node or the topology creation algorithms determines it to be inefficient. All wireless nodes have this ability to function in a multihop mode and thus algorithms to support multihop routing are also needed as part of the instant and reconfigurable wireless domain. Protocols like TCP/IP can view this new topology as a virtual network (thus providing a level of abstraction from the wireless link.).

2.4 Mobility control using adaptive communications

When nodes move on a smaller scale the topology should be maintained to minimize the overhead due to reconfiguration. This can be achieved by adapting communication parameters such as power. The appropriate power level to create the link is maintained by adjusting the transmitter power to keep the Signal/Interference ratio at every receiving node at a certain threshold or target Signal/Interference Ratio. A unique function of the power control algorithm used is admission control into the network [2]. If a desirable Signal/Interference ratio can not be maintained by all the nodes, the new link fails to be admitted into the network, to avoid destroying already existing links. When a new node wants to get admitted to the network, it initializes and synchronizes into the network on a fixed control channel following a TDMA based channel access scheme. The code assignment and power control algorithms along with TDMA access to the control channel, allows the topology to be dynamically created and maintained in presence of mobility, node failures, and environmental constraints. Since radio channels are prone to more bit errors then wired channels, it is efficient to utilize link level error control. Within the wireless sub-network, reduced error rates can be achieved by maintaining the SIR at a desirable threshold. This is achieved by adjusting the transmit power which in turn feeds back into the topology creation algorithm. To combat the increased packet loss rates in the wireless network, logical link error control is provided by using a positive acknowledgment protocol. An adaptive modem is required to support these functions.

2.5 Relation to OSI Model:

As figure 2 shows, in terms of the network control, the function-

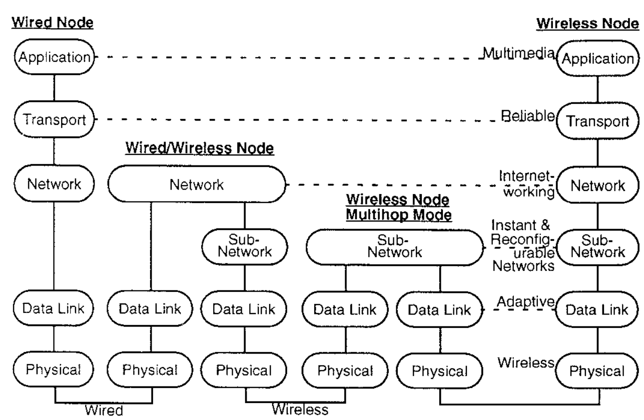

Figure 2 Network View

ality in figure 1 can be accomplished by adding the new sub-network layer to the standard OSI layer model, and modifying the data link and physical layers to support the new functions.

3. Architecture and Implementation

A wireless node was implemented, as shown in figure 3, which supports the functions defined earlier in figure 1. In this section we describe the node architecture and the implementations of the network control, video compression and modem components as

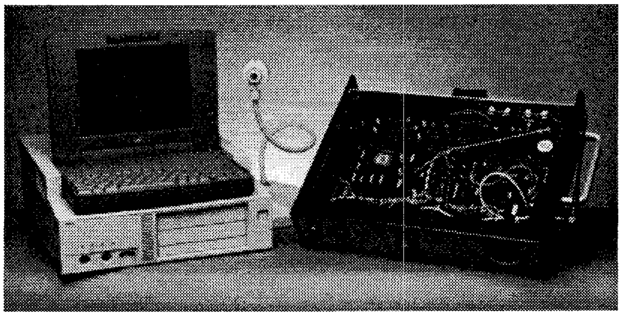

Figure 3 Picture of Implemented Node

well as the interfaces between these as defined in figure 1. Off-the-shelf technology is used where possible along with specially designed wireless network control software and adaptive modem and video codec circuits. The performance of the actual node is analyzed in section 4.

3.1 Network Control Components

There are numerous software components available which can be used to support self-configuring, multihop, multimedia networking. These components can be broken down into operating systems, interfacing components, network algorithms and protocols, and applications. The operating system is responsible for the underlying functionality of the network control components. The interfacing is responsible for making sure the operating system, hardware components, networking algorithms and protocols, and application can all properly communicate with each other. The network control algorithms and protocols are responsible for making sure the data between applications are transferred via the communicate channel as efficiently as possible in support of the necessary requirements. And finally the applications are needed for interaction between the computer and the user. The integration of the various compnenets is illustrated in figure 4.

3.1.1 Applications

The standard set of TCP/IP protocol suite applications support text based services like remote login or file transfers. New applications are now appearing which support multimedia (Mosaic and video conferencing applications). In order see the effect and demonstrate multimedia on this new self configuring, multihop, multimedia network, a video conferencing application was developed. This application (VideoTALK) brings together video, which uses UDP, and data, which uses TCP, into a single application on the laptop. In order to test the performance of the system, testing tools were developed to measure throughput, delay, packet loss, etc. A program called SPEED was developed to measure the throughput using TCP. BER was developed to measure the packet loss and delay using UDP. TOPO was developed to graphically analyze the virtual topology of the wireless multihop subnet. WMONITOR was developed to measure and track link, subnet, and network parameters such as packet throughput, percentages of various packet types, and various adaptive parameters such as code, power, and spreading factor.

3.1.2 Transport and internetworking

Since internetworking requires compatibility with existing networks and protocols, the TCP/IP protocol suite has been implemented without any modifications. Since the Internet Protocol can be used in conjunction with various communication substrates, most of the new algorithm development takes place below the network layer, as we can see in figure 2. Above the network layer, the transport protocols (TCP and UDP) provide the required support for end-to-end reliability, congestion control, etc. These transport protocols interact with the applications described in the previous section by using sockets to buffer the bit stream so packetization can take place.

3.1.3 Sub-network control for wireless topology

The functionalities which support instant and reconfigurable networks are new and have been added into the TCP/IP stack (figure 4). Since many of the proposed schemes for supporting instant and reconfigurable network topologies are based upon TDMA to control channel contention, we choose to implement a version of the clustering algorithm [10] which is heavily based on TDMA control and synchronization to test the feasibility of and overhead of implementing this functionality in software, as we'll analyze under the performance evaluation section (sec. 4).

3.1.4 Mobility control using adaptive communications

The link control is used for setting appropriate hardware parameters such as the power level. Feedback measurements such as Signal to Interference radio are fed back into the link control algorithms to do power control and minimize the power consumption of the link, reduce interference, and possibly do admission control. A version of the power control algorithm described in [6] was implemented and verified that the power control algorithm is able to set the minimum power level necessary to reach the desired SIR threshold. To support this, new interfaces had to be developed (section 3.3.1).

3.1.5 Operating System

To integrate all these network control components together, an operating system is desired such as we see in figure 4. There are

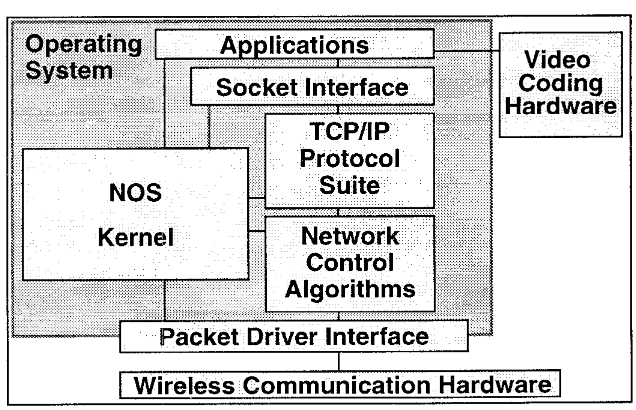

Figure 4 Wireless Adaptive Mobile Network Operating System Components

numerous operating systems available today such as Microsoft Windows, PC-Disk Operating System, and UNIX, but these systems aren't designed for ease of programmability or flexibility for the types of functionality described above. A network operating system s should be able to function on a layer on top of an existing native operating system and provide the required network functionality and services. A public domain Network Operating System (NOS), also known as KA9Q (developed by Phil Karn) for supporting packet radio meets these requiremnets. It runs on top of DOS and includes its own multitasking scheduler. The benefit of a multitasking operating system is that each algorithms or protocols necessary to support this network can be developed as its own process. The multitasking kernel allows these algorithms and protocols to multitask, sharing the CPU, and yet provide semantics such as wait and signal semaphores for interprocess (inter-algorithm) communication. Time processing routines, such as TDMA, are able to sleep a processes for a defined period of time, and can be used to allow other protocols and algorithms to run without halting or bogging down the CPU. Memory buffers (*mbufs*), also found in BSD UNIX system buffers, are used to minimize overhead in having to copy packets in memory by linking together memory buffers for performing encapsulation, packetization, etc.

3.2 Video DSP and Modem Functions

The previous section illustrates the implementation of the network protocols and their integration with the operating system. To complete the picture in terms of the functionality shown in figure 1, we must implement the video acquisition and display, adaptive low-bit rate video coding, and adaptive modem functions. These also need to be interfaced to the network operating system (running on the CPU) shown in figure 4. To meet the needs of adaptation we have used special devices (described below) in conjunction with off-the-shelf hardware for the interfacing to the PC (figure 5).

3.2.1 Adaptive video codec

To achieve high compression ratios in the wireless domain with low complexity a full frame wavelet transform based technique [9] is used instead of the common wireline techniques such as motion compensation, and block based compression. Wavelet based compression can be also optimized for low power operation, (allows longer battery life), by using simple power of two multiplier coefficients. Inter-frame techniques such as motion compensation can help to further reduce bit-rate but they are significantly more computationally intensive (thus dissipate more power), and are sensitive to data loss (dropped frames). A wavelet based scheme has been developed which results in low power, and is configurable to adapt the compression ratio and quantization under network control corresponding to changes in available bandwidth and channel errors. The low complexity of the algorithm allowed an integration in an FPGA [5] for prototyping in the wireless node.

3.2.2 Adaptive wireless modem

To support experimentation with multiple schemes for the subnetwork topology configuration and adaptation to mobility, a digital direct-sequence spread-spectrum modem has been designed [3] and implemented in a single chip [4]. It uses coherent demodulation to cover a BER range that is suitable for both video and data transmission as required in multimedia applications. This is interfaced to a 900 MHz RF front-end built with off-the-shelf parts. The modem chip uses a novel serial acquisition algorithm that reduces complexity and also makes the adaptation of codes, spreading factor and bit-rate very simple - these can be adjusted by simply changing the clock rate of the system. The RF front end uses an attenuator to provide adjustable transmit power levels. With these features the topology and mobility control algorithms can optimize the network capacity and link quality.

3.3 Interface design

Interfacing the video and modem functions to the network control (figure 1) essentially requires interfaces from the video compression FPGA and spread-spectrum modem to the CPU in the PC-notebook platform. In the prototype shown in figure 3,, this interfacing is done using the ISA bus (figure 5). This is a shared bus which enables components attached to it to communicate with the host CPU. As figure 1 shows, the applications and network protocols execute in software, on the host CPU. Thus, to use the adaptive functionality of the video compression and modem components, these must be interfaced to the ISA Bus.

3.3.1 Modem interface

As depicted in figure 1, to interface the wireless modem to the network protocols, requires a method to communicate the data packets as well as the control/measurement signals for adaptation: power, code, and SIR. The modem requires a synchronous bit-serial interface for transferring packets to and from the CPU. Conversion circuitry is required to group the bits into bytes and handle the transfer of data across the bus to system memory and the network protocols. For the prototype, a commercial ISA bus interface called the PI card was used (figure 5).

To support the adaptation signals (power, code, and SIR) requires an application-specific interface because the implementation of these parameters is unique to this system. To control the code and power from the network requires a bus interface to the computer, and direct connection to the adaptation sockets on the modem. The SIR measurement requires calculations on the soft-decision outputs from the modem These functions were implemented on a separate card using FPGAs (figure 5).

Finally, to interface these modem interfaces to the network control software (via the PC bus), a device independent software interface was used. The Packet Driver Specification from FTP Inc. was the basis of the software interface. However, we expanded the interface to enable support for the adaptation parameters. This interface abstraction allows us to isolate the implementation details of the adaptation and data interfaces from the network control software.

3.3.2 Video interface

To interface the video codec to the system (figure 5), we must provide a mechanism to transfer uncompressed, digitized images to the codec, and a method to send the decompressed images to the display. Additionally, there must be a mechanism to transfer the compressed images between the codec and PC memory so that the compressed data can be packetized for transmission on the network and the depacketized received data can be sent to the codec for decompression. A commercial interface, the DT2867 from Data Translation was used to implement these transfer mechanisms. This interface digitizes live images, and provides a separate bus to send uncompressed images to the codec, and read the compressed data from the codec. It also allows the digitized images (original and uncompressed) to be read back, over the ISA bus, to CPU memory. Control messages (frame capture and data transfer) from the network and applications software are sent to this interface using the ISA bus. Once the uncompressed images are stored in PC memory, a graphics routine can send the images to the display. An alternate method for sending data to the display, is to have a direct connection between the decoder and the display. However, such an interface is impossible to implement when using current commercial PC notebook because the display adapter is integrated into the notebook.

Implementing the above interfaces results in the system architecture shown in figure 5.

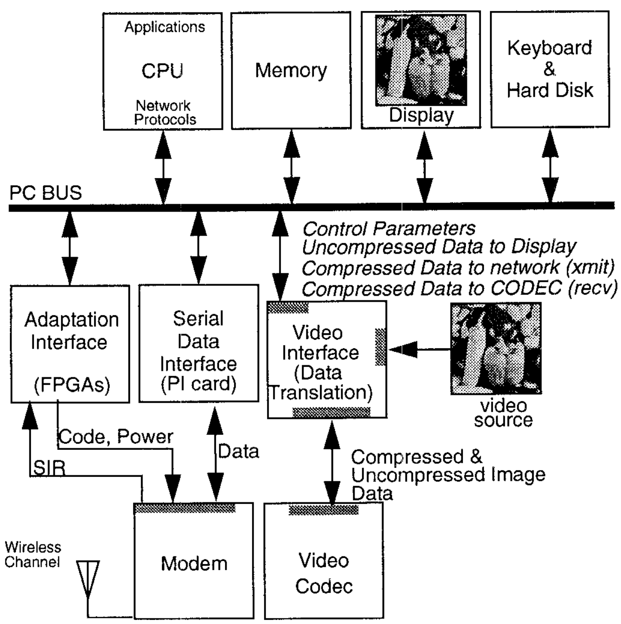

Figure 5 System Architecture

4. Performance Analysis

The prototype wireless node (figure 3) implements the algorithms described in section 2 with the software architecture shown in figure 4 and the hardware architecture in figure 5. These are being used for wireless network experiments. In this section we analyze the consequences of the particular implementation choices made to provide the desired functionality and conclude with ideas for next generation PC-notebook wireless nodes that are more highly integrated, portable and support wireless mobile networking.

4.1 Multimedia applications

While the wavelet based video codec and the UDP protocol executing on the CPU are able to support real-time video, a performance bottleneck observed in the system is the display update speed. One of the design constraints of our system is the native graphics display used for video output. Using a commercial notebook platform means that a direct connection to the display for the decoded output is not possible. This implies that the uncompressed video image must be merged with the other computer generated (ascii) data for the screen. Then, the resulting data can be transferred to the screen using a software display driver. However, the rate of display is dependent on the speed of the PC Graphics routines. In the case of our prototype, the graphics refresh rate is 1 frame/sec. There are higher performance drivers available, but since the maximum rate at which data can be transferred between memory and the ISA bus video card is fixed, there will be some upper bound on refresh rate. An alternative approach would be to use a video card on a faster bus (e.g. PCI) or re-architect the system to allow a direct connection between the video decoder and the graphics display.

The shared ISA bus interface also presents a bottleneck to the network performance. To display the uncompressed image to the local display requires that the image be read into memory across the bus, and then transferred to the video card across the bus. Additionally, we must also read the compressed image across the bus, and send it to the modem across the bus. Thus, to support the target video specification of 10 fps at 64Kbytes/frame video rate, and assuming a 20:1 compression ratio, the bus must perform 1.4Megatransfers/sec of 8bit data. Since the CPU must halt for every bus transfer, this implies that 17.6% of the CPU cycle time is wasted because of the video transfers. This loss impacts the speed at which the network algorithms execute causing delays in packet processing and loss of throughput. This problem can be attacked by using wider buses (16 or 32 bit) which will reduce the number of transfers, by using higher speed busses or by using direct connections to isolate the multimedia data from the shared bus.

Description	% of Raw Channel Rate (1 hop)	% of Raw Channel Rate (2 hops)
1. Data Bandwidth	46.0	18.4
2. Acquisition Time	24.6	23.3
3. Packet Loss/Time-outs	19.8	21.2
4. CPU Processing	2.8	1.6
5. Protocol Headers	2.2	2.1
6. Tail Time	1.2	1.2

Table 1: UCLA Radio Performance

Description	% of Raw Channel Rate (1 hop)	% of Raw Channel Rate (2 hops)
7. Multihop Overhead	0.0	24.1
8. Misc.	3.4	8.0

Table 1: UCLA Radio Performance

4.2 Transport and internetworking

Table 1 shows the performance of the node using the direct-sequence modem operating at 32 Kbps and 15 chips/bit for a data application. It indicates the effective bandwidth utilization for the link is 46% and points out the bandwidth losses due to various factors. TCP/IP was used to provide internetworking and reliability. The TCP protocol which is used to support the reliable datagram transport service is responsible for 20% of the loss in throughput as we can see in table 1. This loss is due to time-outs, waiting for an acknowledge, necessary for reliable communication, of a packet which was lost. The time-out (RTO) is the average time for the data to propagate to the destination and an acknowledgment to return. Packet loss can be caused from bit errors, failure of a receiver radio to lock onto the sender, or congestion in the network. In the wireless domain, packet loss is due to noise interference. Experiments show approximately 10% of packets are lost due to bit corruption or failed acquisition. For a single hop, the RTO was on the order of 2200ms. However, as the network grows to have more hops, this time will also dramatically increase since the radio links are only half duplex. To compensate for this packet loss, rather then having to wait for the RTO time-out, a link level hop-by-hop based positive acknowledge protocol can be used to improve the throughput but eliminating packet loss on the transport layer. A passive acknowledgment like that used in packet radio can't be used since multihopping takes place on different codes and a radio can only be tuned to 1 code at a time (i.e.: it can't be receiving a packet on one code while listening for acknowledgment on a different code while the packet is being forwarded.) It is still possible to have a time-out occur due to congestion or buffer overflow in the network, thus a backoff algorithm used with the RTO is useful.

The fairest way to deal with congestion in the network is to use an exponential backoff. However, exponential backoff is not always best. When congestion control is provided for by contention free protocols like TDMA in conjunction with bandwidth reservation and virtual circuits, or when no congestion exists since only a single hop (point to point link) is being used, no link level acknowledgment is necessary and a linear backoff algorithm can be used which would result in shorter time-outs and higher bandwidth utilization.

4.3 Sub-network control for wireles topology

The protocol stack implementation enables us to experiment with protocols that will enable topology reconfiguration and multihop routing. One such protocol is a TDMA based clustering algorithm. It was determined that the software implementation of this algorithm reduced data efficiency in a 2 node network to approximately 8Kbits/sec (25% effective bandwidth utilization). This was due to the fact that the uncertainties in the time that TDMA process would be active, and thus required large guard times (200ms) between each TDMA slot. This uncertainty in when the network algorithm will get control is exacerbated when the system is under a heavy load. Ideally a pre-emptive O.S. should be used to enable the TDMA process to wake up at the desired time slots. Even though the prototype node is based upon DOS (a non-preemptive O.S.), which provided the capability to rapidly implement the algorithm, this would not be an efficient way to implement such control in the future. Implementing the TDMA algorithm with a dedicated or special purpose processor would also help by alleviating the contention for the main CPU.

4.4 Mobility control using adaptive communications

From table 1 we see that the acquisition delay in the spread-spectrum modem accounts for 24.6% of bandwidth loss. This is caused by the fact that we chose a serial acquisition scheme for the adaptive DS-SS modem. The benefit of this scheme is that is leads to low complexity and power while allowing easy adaptation of codes spreading factors to changes in bandwidth and BER requirements. Additionally, this loss occurs because the adaptive modem supports asynchronous packet transfer which means that in a point-to-point link we must re-acquire for every packet received. This make it easier to implement a distributed network control for mobile networking. The trade-off between reducing acquisition time and the overhead for synchronous multiple access

The adaptation requirements also lead to additional complexity in the interface hardware (figure 5) since the commercial PI card only handles transfer of data packets and does not t handle adaptive control signals. Future implementations could combine the adaptive control and data interfaces reducing the total complexity and power consumption. In the long tern both these interfaces should be integrate in the modem decide.

4.5 Network software/hardware partitioning

To analyze the performance of the wireless node using a higher bandwidth channel, experiments were done using the same network software and applications with a commercial higher bandwidth wireless PCMCIA 1.6Mbps Proxim Rangelan 2 modem. It was found that as the bandwidth of the channel increases, the relative amount of bandwidth lost by CPU processing time also increases, and the effective bandwidth utilization decreases to only 10% as shown in table 2.

At this bandwidth, CPU processing delays cost ~64% of the bandwidth. In ethernet and other high speed networks, similar performance losses are noted. However, since the high speed wired media is usually shared by many people, while one host is busy processing, other hosts can use the substrate. However, if a TDMA system was to be used where each user wants to transmit on a slot, the CPU should be able to keep up with transmitting

Description	% of Raw Channel Rate
1. CPU Processing (Rx + Tx)	63.9
2. Interfacing and Link Layers	24.9
3. User Data (Efficiency)	10.1
4. TCP/IP/Ethernet Header	1.0
5. Time-outs (Packet Loss)	0.0

Table 2: PROXIM Radio Performance

packets fast enough to fill the reserved slots or the network will suffer a performance loss. This observation also indicates that the traditional partitioning of software/hardware needs to be re-architected to take reduce the CPU overhead.

5. Conclusion

Capabilities have been integrated with the PC-notebook for multimedia applications, TCP/IP internetworking, and wireless multi-hop networking supported by an adaptive modem and video codec. The performance and complexity limitations have been studied. In order to completely integrate these capabilities for mobile multimedia networking in PC notebooks in the future with a high performance in terms of network throughput several changes need to be made to counter the drawbacks of the PC-shared bus, the DOS operating system, the overhead of executing network control on the host CPU. f To combat these problems, new architecture is being investigated as shown in figure 6. This

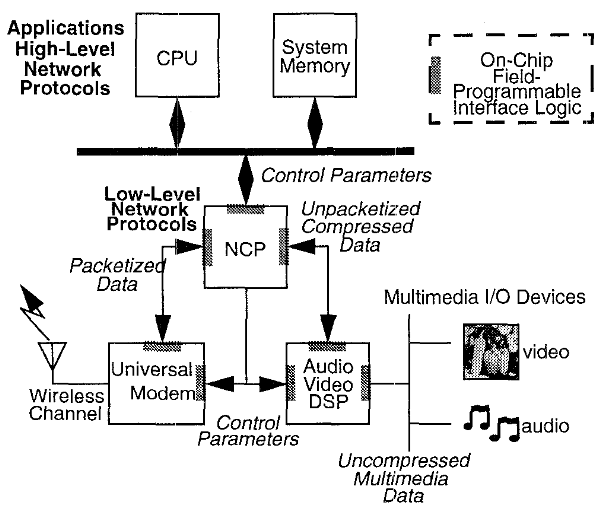

Figure 6 Future System Architecture

architecture centers around a new component we designate, the network control processor (NCP). By moving some of the network functionality into this NCP, we can prevent some of the unnecessary bus cycles and CPU processing necessary to forward packets. Furthermore, interfacing the video codec and modem to the NCP rather than the CPU can provide a better level of service (and fewer transfers over the shared bus). The partitioning of network protocols between the CPU and NCP will be non-trivial, but one partition which seems evident is at the sub-network layer. It is this layer which will handle the packet forwarding. Most levels above that would not be changed due to the multihop multimedia nature of this network. Thus, a partitioning at this level seems somewhat optimal from the perspective of modularity and support for the required capabilities.

6. Acknowledgments

Charles Chien and Brian Schoner at UCLA implemented the modem and video codec together with the interfaces. We also appreciate valuable technical discussions with Dr. Bill Mangionne-Smith at Motorola. This work was supported by ARPA/CSTO under contract no. J-FBI-93-112.

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