ATM Based Ultra-Wide Bandwidth Multiple-Access Radio Network For Multimedia PCS

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Abstract— **Personal Communications System (PCS) promises to provide a variety of information exchanges among users with any type of mobility, at any time, in any place, through any available device. To achieve this ambitious goal, two of the major challenges in the system design are: (i) to provide a high speed wireless subsystem with large capacity and acceptable Quality of Service (QoS); and (ii) to design a network architecture capable of supporting the multimedia traffic and various kinds of user mobility. A novel time-hopping spread-spectrum wireless communication system called Ultra-Wide Bandwidth (UWB) radio is employed to provide low power, high data rate, fade-free, and relatively shadow-free communications in a dense multipath environment. Performance of such communications systems in terms of multiple-access capability is estimated for digital data modulation formats under ideal multiple access channel conditions. In our work, an Asynchronous Transfer Mode (ATM) network is used as the backbone network for PCS due to its high bandwidth, fast switching capability, flexibility, and well developed infrastructure. To minimize the impact caused by user mobility on the system performance, a hierarchical network control architecture is postulated. A wireless virtual circuit (WVC) concept is proposed to improve the transmission efficiency and simplify the network control in the wireless subsystem. The key advantage of this network architecture and WVC concept is that the handoff can be done locally most of the time due to the localization behavior of PCS users. The results of UWB signal propagation experiment demonstrate the feasibility of the UWB radio, its robustness in the multipath environment, and its potential to support multimedia traffic.**

I. Introduction

A. Introduction to Combined Wired/Wireless Network

PERSONAL Communications System (PCS) promises to provide a variety of information exchanges (e.g., video, image, voice, data service, etc.) among users with any type of mobility, at any time, in any place, through any available device [1]. The success of PCS relies on the efficient amalgamation of broadband network technology, advanced radio transmission technique, and the personal communication concept. PCS will be characterized by packet- or cell-based transport, bandwidth-on-demand, multimedia traffic integration, seamless connection, and customized service to the unique need of a given user. It implies that the system should be able to handle the multimedia traffic transmission in the harsh radio environment with acceptable Quality of Service (QoS), which is more difficult than in the traditional wired system, and to deal with the frequent handoffs when the user is roaming, which is a new challenge to the system designer [2]–[4].

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To achieve this ambitious goal, two of the major challenges in the system design are: (i) to provide a high speed wireless subsystem with large capacity and acceptable Quality of Service (QoS); and (ii) to design a network architecture capable of supporting the multimedia traffic and various kinds of user mobility. In this paper, a novel time-hopping spread-spectrum wireless communication system called Ultra-Wide Bandwidth (UWB) radio is employed to provide low power, high data rate, fade-free, and relatively shadow-free communications in dense multipath environment [5]–[7]. This radio communication technique has both commercial and military applications, especially for short-range or indoor wireless communications, e.g., high-speed wireless LANs, wireless full-motion video communications, augmented industrial workplace, high quality studio applications, platoon-level covert communications for the military, etc.

Furthermore, an Asynchronous Transfer Mode (ATM) based network model is presented which merges both the concepts of broadband network and personal communications. This model is based upon: 1) a broadband wired ATM backbone network supporting cell transport, and 2) high speed UWB radio subsystem. ATM network is chosen due to its high bandwidth, fast switching capability, and flexibility. A high speed UWB radio subsystem consists of:

- Enhanced Mobile Switching Center (EMSC), which connects to the ATM network on one side and to base stations on the other side;
- radio base station which serves as the interface between the wired network and the portable communication units;
- portable communication unit which is the interface between the end user and the communication system, which transforms the user generated signal into a suitable form to be transmitted over the radio channel.

As will be explained, this model generalizes and exploits the ATM concept in the wireless scenario to deal with the high data rate radio transmission and frequent handoffs among base stations.

ATM is originally designed in the wired scenario for stationary users. The user-network interface is a fixed port which remains stationary during the connection. The basic transmission mechanisms in ATM are virtual path (VP) and virtual circuit (VC), which need to be established at the beginning of a connection, maintained throughout the connection, and terminated afterwards. After the connection is established, certain amount of bandwidth will be reserved along the path from the source to the destination to guarantee the QoS. Since the user is stationary, the established connection and corresponding bandwidth allocation remain the same during the lifetime of the connection. However, in PCS, user mobility or changes in channel conditions will cause the user's network access point to change from time to time. The user's connection needs to be re-routed to the new base station once handoff happens, which, in principle, implies that the connection has to be re-established and the bandwidth has to be re-allocated. If the connection setup and re-setup are controlled by the network call processor, frequent handoffs, especially in the microcell or picocell systems, will involve the network call processor many times during the lifetime of one connection, causing it to be the bottleneck and severely degrade the system performance. Our proposed solution to this problem is based on the hierarchical network configuration and wireless virtual circuit (WVC) concept. In our system, EMSC isolates the wireless subsystem and the fixed ATM backbone network. Generalizing the virtual circuit concept of ATM in the wireless scenario, there are two types of virtual circuits in the network, WVC connecting the portable units to EMSC and ATM VCs providing the connection in the fixed network. When the user is roaming, the fixed portion of VP/VC pair need not be changed as long as the user remains in the same EMSC serving area. Only the wireless portion should be updated as the user moves to a new cell. The wireless virtual circuit number (WVCN) is assigned by the EMSC, which remains the same until the user handoffs to another EMSC. The advantage of WVC will be explained in detail in the following sections.

B. Introduction to Impulse Radio Systems

The term *wideband*, as applied to communication systems, can have different meanings. When applied to conventional systems, it refers to the data modulation bandwidth. In that case, the more wideband a system is, the higher its data transmission rate. In this paper, a spread-spectrum system [8], [9] is described in which the transmitted signal, even in the absence of data modulation, occupies an extremely large bandwidth. In this case, with a fixed data modulation rate, as the transmitted signal bandwidth increases, the signal may become more covert because its power density is lower, may have higher immunity to the effects of interference, and may have improved time-of-arrival resolution.

The spread-spectrum radio system described here is unique in another regard: It does not use sinusoidal carriers to raise the signal to a frequency band in which signals propagate well, but instead communicates with a time-hopping baseband signal composed of subnanosecond pulses (referred to as *monocycles*). Since its bandwidth ranges from near d.c. to several GHz, this *impulse radio* signal undergoes distortions in the propagation process, even in very benign propagation environments. On the other hand, the fact that an impulse radio system operates in the lowest possible frequency band that supports its wide transmission bandwidth, means that this radio has the best chance of penetrating materials that tend to become more opaque at higher frequencies.

Finally it should be noted that the use of signals with GHz bandwidths implies that multipath is resolvable down to path differential delays on the order of a nanosecond or less, i.e., down to path length differentials on the order of a foot or less. This significantly reduces fading effects, even in indoor environments, and the resulting reduction of fading margins in link power budgets leads to reduced transmission power requirements. The modulation format described in this paper can be supported by current technology. The receiver processing and performance predictions, for digital data modulation format, are considered under ideal multiple access channel conditions. Real indoor channel measurements and their implications for Rake receiver design [10]–[12] will be discussed in a sequel.

II. Network Architecture

The general aim of this work is to design a broadband wireless network to provide seamless extensions of wired ATM network capabilities in the radio environment in a relatively transparent and efficient manner. There are several factors that tend to favor the use of ATM, including: flexible bandwidth allocation, fast switching, multiple service type selection, etc. However, ATM is originally designed for stationary users in the wired scenario. To use it in the wireless environment, the mobility impact on the network architecture should be taken into account.

A. Hierarchical Network Control Architecture

A hierarchical network control architecture is illustrated in Fig. 1, which supports fixed ATM connections as well as radio connections. There are two levels of controllers in the wireless subsystem of PCS, namely, the Base Station (BS), each of which serves one particular cell, and the Enhanced Mobile Switching Center (EMSC), each of which manages a group of BSs in a relatively large area. The BS is the UWB radio access point of mobile users and is responsible for the control and maintenance of connections between the EMSC and the mobile user. The EMSC acts as the interface between the wireless subsystem and the ATM backbone network. Every transmission request generated by a mobile user will be sent to EMSC through an appropriate base station and examined by EMSC. Note that the identification number (ID) of the currently serving base station, which can be obtained through the downlink (base station to mobile) broadcast channel, will be included in this request message and recorded by EMSC in its lookup table if admission is granted. If the destined user is within the service area of the same EMSC, the connection will be established directly between these two users through the EMSC and the appropriate BSs. Otherwise, EMSC will set up and maintain a wireline connection between the BSs serving these two users through the ATM network.

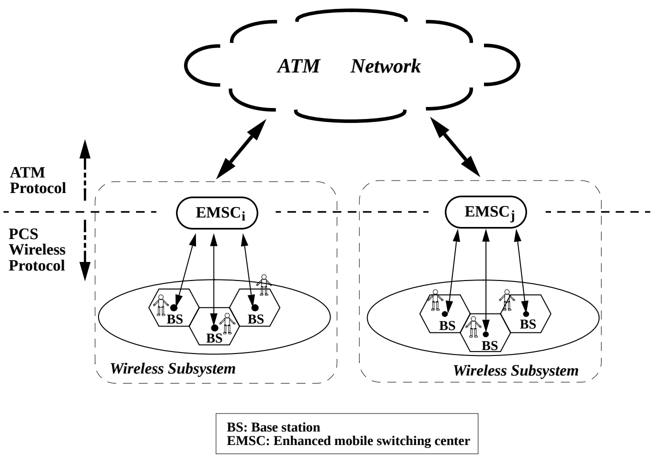

Fig. 1. The hierarchical network architecture for high-speed PCS

The call setup procedure is executed in two steps. First, the wireless virtual circuit will be established between the EMSC and the portable unit by assigning a wireless virtual circuit number (WVCN) to the user and reserving certain amount of bandwidth along the wireless virtual path. The WVCN will be maintained until the user handoffs to another EMSC. Only the actual wireless connection needs to be changed when the user handoffs from one base station to another. Note that in order to implement this hierarchical architecture, two fields in the wireless data packet format are necessary, namely, the WVCN field and the base station ID field. Of course, there are other fields needed for control and error correction purposes. Second, the fixed portion of the virtual connection is established between EMSC and the appropriate fixed point of the wired network (the destined wired user or the corresponding EMSC of the destined radio user). As long as the user remains in the same EMSC serving area, this fixed portion of the virtual connection needs not be changed.

EMSC translates WVCN to the virtual circuit number (VCN) which is needed to switch the ATM cells along the appropriate wired path. EMSC records the currently serving base station ID in the look-up table associated with WVCN to facilitate the downlink transmission. When intra-EMSC handoff occurs, the user simply transmits the packets with the same WVCN but different base station ID in the corresponding fields. The traffic will flow from the user to the new base station and to the EMSC, through the fixed portion of the network, and to the final destination. The old wireless virtual circuit connection will be terminated after the transition to the new base station is completed successfully.

When the user reaches the boundary of an EMSC serving area, it will seek admission to a new EMSC. This is referred to as inter-EMSC handoff. At this point, the fixed portion of the connection needs to be modified to reflect this change. Several techniques can be used, including, virtual connection tree algorithm [2], entire virtual connection re-establishment, partial virtual connection re-build, simple extension with loop reduction, etc. [13]. However, since the geographical area controlled by EMSC is relatively large compared to the size of a radio cell, the rate of inter-EMSC handoff is expected to be low.

B. Protocol Layering for Wireless Subsystem

With the network architecture defined above, the wireless protocol layers are designed based on the wireless subsystem characteristics, as illustrated in Fig. 2. The existing ATM protocols are used for the backbone network to take advantage of the well developed ATM infrastructure. Among all the network control functions on the mobile user side, the most distinguished ones are to establish and maintain the WVC. To simplify the functionality and reduce the cost of BS, only two layers are designed at the BS to handle the wireless connection – the physical layer and the data link layer. The physical layer deals with the mechanical, electrical, procedural interfaces, and the physical transmission medium which lies below it. The major functions in the data link layer are to manage the media access, and to provide the basic error control and flow control capability.

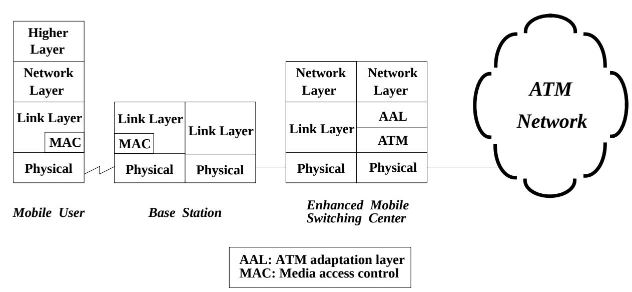

Fig. 2. The protocol layer design for the wireless subsystem.

Most of the network control functions are implemented in the EMSC. Besides traditional functions in the Mobile Switching Center (MSC) in the cellular system, the EMSC in our system has the enhanced capabilities to manage the WVCs and ATM VP/VC pairs, to provide the admission control and sequence assignment, to convert the message format between the wireless packet and the ATM cell, etc. Two stacks of protocols are implemented in the EMSC, one for the wireless subsystem and another for the ATM network. Note that there are other proposals using the same stack of ATM protocols for both wired and wireless systems by adding new features to handle the special needs of radio channels, e.g. [3]. Which way is better is still an open problem and currently under investigation.

C. Time-Hopping Spread-Spectrum Multiple Access (TH-SSMA)

There is much debate regarding which multiple access scheme should be used in wireless ATM to provide high spectrum efficiency. In this paper, a time-hopping spread-spectrum technique is employed for multiple access purposes because of its advantages in the presence of interference and multipath fading typical of the radio medium, especially in the indoor environment. Each user who initiates the communication will send a request to the corresponding base station and EMSC through the uplink request channel. Upon receiving this request, EMSC makes the admission decision based on the availability of both wired and radio resources. Each admitted user will be assigned a unique time-hopping sequence and start the data transmission. TH-SSMA operates *asynchronously* in a resource sharing packet mode, which is quite efficient for providing multimedia services. Specifically, in TH-SSMA, any user can transmit at any time without coordination among each other with a unique hopping sequence at a desired data rate.

In our wireless subsystem, both connectionless and connection-oriented services can be supported. For example, the total bandwidth in the uplink is divided into two parts: uplink request channel and uplink traffic channel. The request channel is designed for the transmission of various control information, channel access request, handoff request, and short data messages. The random access mode is employed in this channel. The connectionless transmission will go through the uplink request channel directly without waiting for the assignment of time-hopping sequence in order to offer short access latency and simplify the network control. The connection-oriented transmission is provided by the normal traffic channel using the UWB time-hopping technique.

D. Wireless Virtual Circuit

The basic transmission mechanisms in ATM are virtual path (VP) and virtual circuit (VC), which need to be established at the beginning of a connection, maintained throughout the connection, and terminated afterwards. However, in the wireless subsystem, since the user is moving frequently, it is difficult to maintain an end-to-end ATM connection. Therefore, the idea is to divide the end-to-end connection into two portions: the conventional wired ATM portion and the wireless last hop. The wired portion is maintained as long as possible and the wireless portion is changing along with the user's movement. We extend the ATM virtual circuit concept into the wireless portion, referring it as wireless virtual circuit (WVC).

Another advantage of this division is that the error control can be implemented in EMSC preventing transmission errors from propagating into the wired network. In the conventional ATM system, error control is not performed inside the network and only end-to-end protection is provided in the transport layer because of the extremely low transmission error rate [14]. Due to the harsh condition of the radio channel, the error rate is much higher than that in the wired system. Therefore, the conventional end-to-end protection is not efficient in terms of the wasted bandwidth in the wired system when frequent retransmissions occur due to the transmission errors in the radio channel. One way to solve this problem is to correct most of the radio channel errors before they enter the wired network. Different error control schemes, including both Forward Error Correction (FEC) and retransmission depending on the service type, can be used for different portions of the connection and finally, the end-to-end protection is provided in the transport layer.

The integration of a WVC and an ATM VP/VC is illustrated in Fig. 3, using the connection between two mobile users as an example. The WVCs from the initiating mobile user to its EMSC and from the ending EMSC to the destined mobile user are connected by an ATM VP/VC. If the mobile user only changes its serving BS but not the EMSC, the existing ATM VP/VC need not be changed. Only the WVC needs to be maintained from time to time when the handoff occurs. The key advantage of this network architecture and WVC concept is that the handoff can be done quickly and easily by the local EMSC most of the time due to the localization behavior of PCS users.

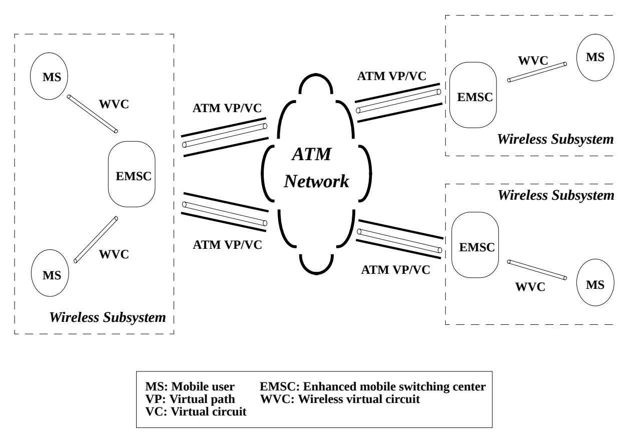

Fig. 3. An illustration of the wireless virtual circuit (WVC)

III. UWB Radio: The Physical Layer

A. Time-Hopping Format Using Impulses

A typical time-hopping format employed by an impulse radio in which the $k^{\underline{\text{th}}}$ transmitter's output signal $s_{\text{tr}}^{(k)}(u, t^{(k)})$ is given by

$$s_{\text{tr}}^{(k)}(u, t^{(k)}) = \sum_{j=-\infty}^{\infty} w_{\text{tr}}(t^{(k)} - jT_{\text{f}} - c_j^{(k)}(u)T_{\text{c}} - d_j^{(k)}(u)) ,$$

where $t^{(k)}$ is the transmitter's clock time, and $w_{\text{tr}}(t)$ represents the transmitted monocycle waveform that nominally begins at time zero on the transmitter's clock.

The *frame time* or *pulse repetition time* T_{f} typically may be a hundred to a thousand times the monocycle width, resulting a signal with a very low duty cycle. To eliminate catastrophic collisions in multiple accessing, each user (indexed by k) is assigned a distinct pulse shift pattern $\{c_j^{(k)}(u)\}$, called *a time-hopping sequence*, which provides an additional time shift to each pulse in the pulse train. The $j^{\underline{\text{th}}}$ monocycle undergoing an additional shift of $c_j^{(k)}(u)T_\text{c}$ seconds, where T_c is the duration of addressable time delay bin. The addressable time-hopping duration is strictly less than the frame time since a short time interval is required to read the output of a monocycle correlator and to reset the correlator.

The sequence $\{d_j^{(k)}(u)\}_{j=-\infty}^{\infty}$ is a sample sequence from a wide-sense stationary random process $d^{(k)}(u,t)$, with samples taken at a rate of T_f^{-1}. A pulse position data modulation is considered as an example. For simplicity, it is assumed that the data stream is balanced so that the clock tracking loop S-curve can maintain a stable tracking point. With more complicated schemes, pulse shift balance can be achieved in each symbol time.

B. The Multiple Access Channel

When N_u users are active in the multiple-access system, the composite received signal $r(u,t)$ at the output of the receiver's antenna is modeled as,

$$r(u,t) = \sum_{k=1}^{N_\text{u}} A_k s_\text{rec}^{(k)}(u, t - \tau_k(u)) + n(u,t)\,, \qquad (1)$$

in which A_k represents the attenuation over the propagation path of the signal $s_\text{rec}^{(k)}(u, t-\tau_k(u))$ received from the $k^{\underline{\text{th}}}$ transmitter. The random variable $\tau_k(u)$ represents the time asynchronisims between the clocks of transmitter k and the receiver, and $n(u,t)$ represents other non-monocycle interferences (e.g., receiver noise) present at the correlator input.

The number of transmitters N_u on the air and the signal amplitudes A_k are assumed to be constant during the data symbol interval. The propagation of the signals from each transmitter to the receiver is assumed to be ideal, each signal undergoing only a constant attenuation and delay. The receiving antenna modifies the shape of the transmitted monocycle $w_\text{tr}(t)$ to $w_\text{rec}(t)$ at its output. A typical received pulse shape $w_\text{rec}(t)$ is shown in Fig. 4. This channel model ignores multipath, dispersive effects, etc.

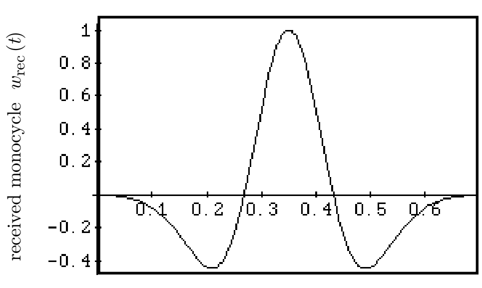

Fig. 4. A typical received monocycle $w_\text{rec}(t)$ at the output of the antenna subsystem as a function of time in nanoseconds.

C. Receiver Signal Processing

The objective of the digital UWB radio receiver is to determine a reasonable model for the signal processing necessary to demodulate one symbol of the transmission from the first transmitter with binary modulation. Specifically, $d_j^{(k)}(u) = \delta D_{\lfloor j/N_\text{s}\rfloor}^{(k)}$ where the data sequence $\{D_i^{(k)}(u)\}_{i=-\infty}^{\infty}$ is a binary (0 or 1) symbol stream that conveys information in some form, and N_s is the number of monocycles per transmitted symbol. Here the notation $\lfloor x \rfloor$ denotes the integer part of x. It is assumed that the receiver has perfectly achieved both clock and sequence synchronization for the signal transmitted by the first transmitter.

The optimal detection in a multi-user environment leads to complex receiver designs [15], [16]. However, if the number of users is large and no such multi-user detector is feasible, then it is reasonable to approximate the combined effect of the other users as a Gaussian random process [5], [6]. In this case, the optimum receiver is the correlation receiver [17], [18], which can be reduced to

$$\text{“decide } d_0^{(1)} = 0\text{ ”} \quad \Longleftrightarrow \qquad (2)$$

$$\underbrace{\sum_{j=0}^{N_\text{s}-1} \overbrace{\int_{\tau_1 + jT_\text{f}}^{\tau_1+(j+1)T_\text{f}} r(u,t) v(t - \tau_1 - jT_\text{f} - c_j^{(1)}T_\text{c}) dt}^{\text{pulse correlator output} \,\triangleq\, \alpha_j(u)}}_{\text{test statistic} \,\triangleq\, \alpha(u)} \;>\; 0\,,$$

where $v(t) \triangleq w_\text{rec}(t) - w_\text{rec}(t-\delta)$.

While the assumptions that make the rule in (2) optimal are not strictly valid, this decision rule will be used in the following to evaluate the performance of UWB radio as a simple suboptimal means of making decisions because it is theoretically simple and suggests practical implementations. The statistic $\alpha(u)$ in (2) consists of summing the N_s correlations of the *correlator's template signal* $v(t)$ at various time shifts with the received signal $r(u,t)$. The signal processing corresponding to the decision rule in (2) is shown in Fig. 5. A graph of the template signal is shown in Fig. 6 using the typical received waveform given in Fig. 4.

D. Signal-to-Noise Ratio Calculation

The output signal-to-noise ratio of the UWB radio is calculated in [5] as

$$SNR_\text{out}(N_\text{u}) = \frac{(N_\text{s} A_1 m_\text{p})^2}{\sigma_\text{rec}^2 + N_\text{s}\sigma_\text{a}^2 \sum_{k=2}^{N_\text{u}} A_k^2}\,, \qquad (3)$$

where σ_rec^2 is the variance of the receiver noise component at the pulse train integrator output. The parameters m_p and σ_a^2 are defined to be,

$$m_\text{p} = \int_{-\infty}^{\infty} w_\text{rec}(x-\delta) v(x) dx, \qquad \text{and}$$

$$\sigma_\text{a}^2 = T_\text{f}^{-1} \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} w_\text{rec}(x-s) v(x) dx \right]^2 ds\,,$$

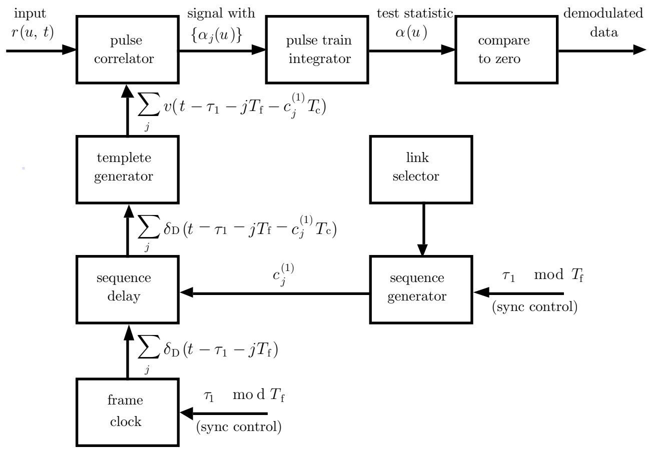

Fig. 5. Receiver block diagram for the reception of the first user's signal. Clock pulses are denoted by Dirac delta functions $\delta_D(\cdot)$.

respectively.

E. Performance Measures of UWB Radio

Performance of the impulse radio is described in this section in terms of multiple access capacity (MAC). Multiple access capacity is defined as the number of users that a multi-user communication system can support for a given level of uncoded bit error probability performance, data rate, and other modulation parameters.

The $SNR_{\text{out}}(N_u)$ of the UWB radio can be rewritten as

$$SNR_{\text{out}}(N_u) = \left\{ SNR_{\text{out}}^{-1}(1) + M \sum_{k=2}^{N_u} \left(\frac{A_k}{A_1} \right)^2 \right\}^{-1}, \tag{4}$$

where the parameter M is given by

$$M^{-1} \triangleq \frac{N_s m_p^2}{\sigma_a^2}. \tag{5}$$

The $SNR_{\text{out}}(N_u)$ can be interpreted as the required signal-to-noise ratio at the receiver demodulator to achieve a specified average bit error probability in the presence of the other $N_u - 1$ users. If only user 1 were active, then there would be no multiple access interference and the signal-to-noise ratio at the input of the receiver demodulator would increase to $SNR_{\text{out}}(1)$. In this case the bit error probability would be clearly reduced from the specified value by as much as several orders of magnitude. Therefore the ratio of $SNR_{\text{out}}(1)$ to $SNR_{\text{out}}(N_u)$ represents the fractional increase in every transmitter's power required to maintain its signal-to-noise ratio, at a level equivalent to $SNR_{\text{out}}(1)$ in its receiver, in the presence of multiple access interference caused by $N_u - 1$ other users. Therefore it is convenient to define the fractional increase in required power (in units of dB) as $\Delta P \triangleq 10 \log_{10} \{SNR_{\text{out}}(1)/SNR_{\text{out}}(N_u)\}$.

Under the assumption of perfect power control, the number of users that multi-user communication system can support for a given data rate is shown in [7] to be

$$N_u(\Delta P) = \left\lfloor M^{-1} SNR_{\text{out}}^{-1}(N_u) \left\{ 1 - 10^{-(\Delta P/10)} \right\} \right\rfloor + 1, \tag{6}$$

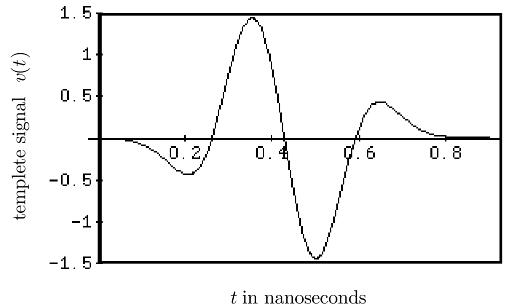

Fig. 6. The template signal $v(t)$ with the modulation parameter δ chosen to be 0.156 ns. Since the template is a difference of two pulses shifted by δ, the non-zero extent of the template signal is approximately δ plus the pulse width, i.e., about 0.86 ns.

which is a monotonically increasing function of ΔP. Therefore

$$\begin{aligned} N_u(\Delta P) &\leq \lim_{\Delta P \to \infty} N_u(\Delta P) \\ &= \left\lfloor M^{-1} SNR_{\text{out}}^{-1}(N_u) \right\rfloor + 1 \triangleq N_{\max}. \end{aligned} \tag{7}$$

This result states that the number of users at a specified bit error rate (BER) can not be larger than $N_{\max}$, no matter how large the power of each user's signal is. In other words, when the number of active users is more than $N_{\max}$, then the receiver can not maintain the specified level of performance regardless of the additional available power. Similar results for direct sequence code division multiple-access system can be found in [19].

F. Performance Evaluation of Multiple Access Systems

The performance of the impulse radio multiple access receiver is evaluated using a specific example given in the following. A duration of the single symbol used in these examples is $T_s = N_s T_f$. For a fixed frame (pulse repetition) time T_f, the *symbol rate* R_s determines the number N_s of monocycles that are modulated by a given binary symbol, via the equation $R_s = \frac{1}{T_s} = \frac{1}{N_s T_f}$ sec^{-1}.

As an example for UWB radio with digital modulation, consider the binary pulse position modulation (BPPM). The modulation parameter δ, which affects the shape of the template signal $v(t)$, appears only in m_p and σ_a^2 implicitly, and can be adjusted to maximize $SNR_{\text{out}}(N_u)$ under various conditions. When the receiver noise dominates the multiple-access noise, e.g., when there is only one user or when there is a strong external interferer, then it can be shown that the optimum choice of modulation parameter is the one that maximizes $|m_p|$, namely $\delta \approx 0.156$. On the other hand, when the receiver noise is negligible and $SNR_{\text{out}}(1)$ is nearly infinite, then the optimum choice of δ, suggested by (3), is the one that maximizes $|m_p|/\sigma_a$, namely $\delta \approx 0.144$. Little is lost in choosing either of these values, and δ is chosen to be $\delta = 0.156$ ns. When $\delta = 0.156$ and $T_f = 100$ ns, then $m_p = -0.1746$ and $\sigma_a^2 = 0.006045$. In this case, the unitless constant that is required for calculating M^{-1} in (5) is $m_p^2/\sigma_a^2 \approx 504$. With the above choice of δ, $T_m = 0.2877$ ns, $T_f = 100$ ns, and data rate $R_s = 19.2$ kbps, the quantity M^{-1} is calculated to be 2.63×10^5.

The number of users versus additional required power is plotted in Fig. 7 for typical BERs. To maintain BER of 10^{-3}, 10^{-4}, and 10^{-5} in a communications system with no error control coding, $SNR_{\text{out}}(N_{\text{u}})$ must be 12.8 dB, 14.4 dB, and 15.6 dB respectively. These curves are plotted using the parameters described in previous section. Note that the number of users increases rapidly as the ΔP increases from 0 to 10 dB. However, this improvement becomes gradual as ΔP increases from 10 to 20 dB. After this point, only negligible improvement can be made as ΔP increases and finally reaches $N_{\max}$. In practice, impulse radios are expected to operate in regions where the increase in the number of users as a function of ΔP is rapid. Furthermore, Fig. 7 quantitatively provides the trade-off between the number of additional users and the additional power required to maintain the respective BER. The value of $N_{\max}$ is calculated to be 27488, 19017, and 14426 for BERs of 10^{-3}, 10^{-4}, and 10^{-5}. The significance of (7) is also clear from Fig. 7, in that the number of users are less than $N_{\max}$.

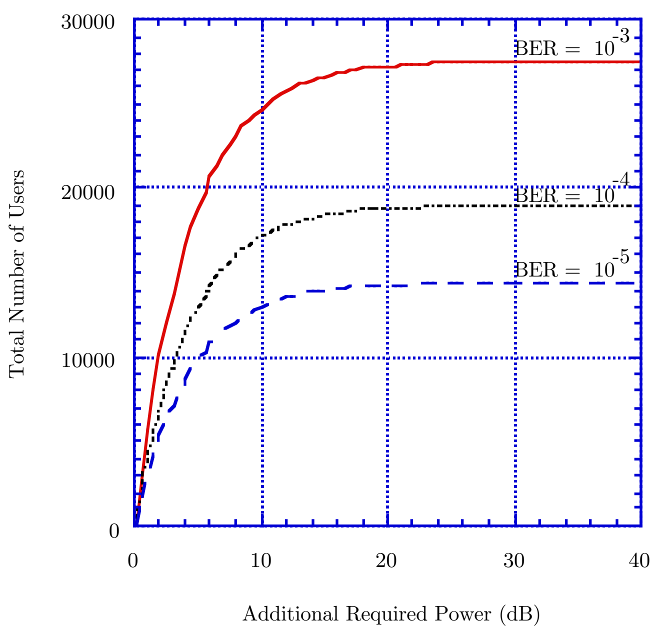

Fig. 7. Total number of users versus additional required power (dB) for UWB radio. This figure is plotted for three different performance levels with the data rate of 19.2 Kbps for Digital Impulse Radio Multiple Access (DIRMA) systems.

IV. Preliminary Experimental Results

Multipath channel propagation experiment is performed inside a typical modern office building using the bandwidth in excess of one GHz [10], [11]. The experimental results indicate the robustness of UWB signal transmission in a fading environment and that UWB radio has the potential for fade-free communications even in this severe indoor multipath environment. In many situations, the transmitted power can be reduced by 10-30 dB, since only a small fading margin in communication link budgets is required to guarantee the reliable communication of UWB radio.

V. Conclusion

An ATM based time-hopping spread-spectrum multiple access network for multimedia PCS has been presented. A hierarchical network control infrastructure and wireless virtual circuit concept are proposed to reduce the impact of frequent handoffs in the wireless subsystem on the ATM backbone network. The basic idea is to break the end-to-end ATM virtual connection into two parts: the fixed wired ATM portion and the wireless last hop. The wired portion is maintained as long as possible and the wireless portion is changing when the handoff occurs. Enhanced Mobile Switching Center is implemented for this purpose, which acts as an interface between the wireless subsystem and the wired ATM network and is responsible for the establishment and maintenance of WVC. UWB radio is used to provide low power, high data rate, fade-free, and relatively shadow-free communications in a dense multipath environment. Performance of such radio is evaluated in terms of multiple access capacity under ideal propagation conditions. The multiple access capacity is shown to increase rapidly as additional required power increases. However these improvements become gradual after certain point and finally reach the limit which is referred to as maximum multiple access capacity. The results of UWB signal propagation experiment demonstrate that UWB signal does not suffer fades. Therefore, very little fading margin is required to guarantee the reliable communication.

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