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A Hybrid TDMA/CDMA System Based on Filtered Multitone Modulation for Uplink Transmission in HFC Networks

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Abstract

We present a novel hybrid TDMA/CDMA system for uplink transmission in multiple-access networks. This hybrid multiple-access system is based on a modulation technique related to orthogonal frequency-division multiplexing, called filtered multitone modulation (FMT). In this paper, we consider an application to uplink transmission in hybrid fiber/coax (HFC) networks. After describing the principles of FMT modulation and discussing the characteristics of the proposed system, we address the problem of initial ranging and power adjustment of unregistered stations. Finally, we introduce a new collision resolution algorithm in conjunction with FMT modulation that uses iterative identification of the competing stations to achieve high throughput on the collision channel. System performance is investigated by simulations.

I. INTRODUCTION

We consider a multiple-access system, in which a head-end controller (HC) broadcasts data and medium-access control (MAC) information over a set of downlink channels to several stations. These stations send information to the HC over a set of shared uplink channels. Examples of systems exhibiting these characteristics are the emerging two-way hybrid fiber/coax (HFC) systems [1-4] and their wireless counterparts, i.e., multichannel multipoint distribution service (MMDS) and local multipoint distribution service (LMDS) [5].

The HC modem transmitter and station modem receivers for downlink transmission are designed for transmission rates on the order of 30 to 45 Mbit/s per downlink channel. Owing to the continuous broadcast mode of downlink transmission over a channel with low distortion and a high signal-to-noise ratio (typically $\geq$42 dB by regulation), well-known signal-processing techniques can be applied. In the uplink, implementation of physical (PHY) layer transmission and MAC layer functions poses considerable technical challenges. First, because signals may be transmitted in bursts, HC receivers with fast synchronization capabilities are essential. Second, individual station signals must be received at the HC at defined arrival times and power levels. Therefore, it is important to determine the round-trip delay between the HC and each individual station as well as the individual transmit power control for each station to compensate for widely varying attenuations in the uplink direction. Third, the uplink channel generally is noisier and subject to more distortion than the downlink channel.

Transmission schemes based on single-carrier quadrature-amplitude modulation (QAM) may be regarded as a solution for uplink transmission in multiple-access networks. Single-carrier modulation, however, is generally less robust in the presence of impulse noise and narrow-band interference and less spectrally efficient than multicarrier modulation, also known as orthogonal frequency division multiplexing (OFDM) [6]. Examples of OFDM techniques are discrete multitone (DMT) modulation and discrete wavelet multitone (DWMT) modulation, which are also considered for application to digital subscriber line technologies [7, 8]. Here we propose for uplink transmission in multiple-access networks a technique related to OFDM, called filtered multitone (FMT) modulation, which exhibits significantly lower spectral overlapping between adjacent subchannels than DMT and DWMT. The general description of FMT modulation as well as its application to very high-speed digital subscriber line (VDSL) transmission is given in [9, 10].

A multiple-access uplink transmission system would ideally have to be suitable for transmission of short messages in burst mode, and to ensure reliable communications in the presence of impulse noise and possibly time-varying narrow-band interference. To accommodate these requirements, we propose a novel hybrid time-division multiple access (TDMA)/code-division multiple access (CDMA) system based on FMT modulation, which we describe with reference to uplink transmission in HFC networks.

The choice of hybrid TDMA/CDMA based on FMT modulation is further motivated by the solution to two problems that are usually encountered in multiple-access systems. First,we have the problem of the initial ranging and power adjustment of a station joining the network in the course of the so-called registration process. During this process, a station has no knowledge of the correct transmit power setting and round-trip delay compensation. If classical multicarrier schemes are employed, whereby adjacent subchannel spectral characteristics exhibit significant overlap, signals that are received with improper timing phase cause severe inter-channel interference (ICI) [11]. It turns out that the level of spectral containment achieved by FMT results in negligible ICI, independent of the timing phase of the received signals, thus allowing a straightforward procedure for registration. Second, there is the problem of resolving collisions between signals received simultaneously at the HC during so-called contention request intervals. Currently, slotted-Aloha or ternary-tree algorithms are considered [12]. Here we introduce a new collision resolution algorithm in conjunction with FMT modulation that uses iterative identification of the competing stations and yields a significantly higher throughput on the collision channel than the slotted-Aloha and ternary-tree algorithms.

The paper is organized as follows. In Section II, a brief overview of HFC networks is given. The principles of FMT modulation are discussed in Section III. The proposed hybrid TDMA/CDMA scheme based on FMT modulation for uplink transmission in HFC networks is described in Section IV. Algorithms for the initial registration of stations joining the network, and for the resolution of contentions among stations seeking access to the uplink channel, are presented in Sections V and VI, respectively.

II. HFC NETWORKS

An HFC system is a point-to-multipoint, tree and branch access network in the downlink, with downlink frequencies in the 50–860 MHz bandwidth, and a multipoint-to-point, bus access network in the uplink, with uplink frequencies in the 5–42 MHz bandwidth. The IEEE 802.14 working group was chartered with creating PHY layer and MAC layer specifications for HFC systems, and has produced a draft document [1]. The Multimedia Cable Network System (MCNS), an industry consortium, has also contributed a document with PHY and MAC layer specifications [2]. The topology of an HFC network is illustrated in Figure 1. The number of subscriber stations per node is usually limited to 500. The maximum round-trip delay between the HC and a station is of the order of 1 ms.

In the downlink, continuous broadcast operation is specified. The ITU J.83 recommendation defines two transmission schemes referred to as Annex A and B by which data rates in the range of 30–45 Mbit/s are achieved in 6 or 8 MHz channel bandwidths. With the specified modulation schemes, spectral efficiencies of 5–8 bit/s/Hz are obtained [13]. In the uplink, impulse noise and narrow-band interference are the main disturbances. These interferences stem mainly from home appliances and HF radio, and accumulate on the return path to the head end. They are usually referred to as “ingress noise” and exhibit time-varying characteristics. Owing to the high level of these impairments, spectral efficiencies for uplink transmission are limited to about 2–4 bit/s/Hz.

The spectrum of the noise suggests that uplink transmission must have an inherent capability of frequency-agile operation with various modulation rates and spectral efficiencies. In [2], single-carrier QAM with 4 or 16-point signal constellations is defined. Carrier frequency, modulation rate, and spectral efficiency are selected by the HC and are sent as MAC information to the stations. Modulation rates up to 2.560 MBaud are defined. The receiver at the HC must have burst synchronization as well as equalization capability.

In [2] a TDMA scheme is considered where uplink transmission is divided into a stream of mini-slots. Each mini-slot is numbered relative to a master reference clock maintained by the HC. The HC distributes timing information to the cable modems by means of Time Synchronization (SYNC) messages, which include time stamps. From these time stamps, the stations establish a local time base slaved to the time base of the HC. For uplink transmission, access to the mini-slots is controlled by Allocation Map (MAP) messages, which describe transmission opportunities on available uplink channels. A MAP message includes a variable number of information elements (IE), each of which defines the modality of access to a range of mini-slots in an uplink channel, as illustrated in Figure 2.

At the beginning of the registration process, a station tunes its receiver to a downlink channel over which it receives SYNC messages from the HC. The acquired local time base is retarded by the propagation delay from the HC to the station. The station then monitors the downlink channel until it receives a MAP message with an Initial Maintenance IE, which specifies a time interval during which new stations may send a Ranging Request (RNG-REQ) message to join the network. At the time specified in the MAP message, the station sends a first RNG-REQ message with lowest transmit power level.

If the station receives no response within a time-out period, either RNG-REQ messages from several stations have collided, or the employed transmit power level was too low. To reduce the probability of repeated collisions, a random backoff algorithm is specified in [2] for contention resolution. After a backoff time interval has elapsed, the station looks for a new MAP message with an Initial Maintenance IE, and at the specified time retransmits a RNG-REQ message with a higher transmit power level. These steps are repeated until the HC eventually detects a RNG-REQ message, from which the HC can determine the round-trip delay and the power correction value to be used by the station for future uplink transmission. In particular, the round-trip delay compensation is determined such that, when the round-trip delay compensation is applied at the station, future uplink transmissions of this station arrive at defined time instants (epochs) at the HC. The HC then sends to the station the round-trip delay compensation and the transmit power adjustment value for future transmission in a Ranging Response (RNG-RSP) message.

As mentioned above, the HC controls the access of registered stations to the uplink channel by means of MAP messages. In particular, MAP messages include Request IEs to provide mini-slots in which stations may send requests for uplink data transmission. The HC determines whether requests for resource allocation from multiple stations have collided. A random backoff algorithm is also employed to reduce the probability of repeated collisions of request messages.

III. FMT MODULATION

The equivalent baseband signals of an OFDM system are defined in the fundamental frequency band $(-M/2T, M/2T)$, where M denotes the number of subchannels and T denotes the modulation interval. The vector $\mathbf{A}_n = \{A_n^{(i)},\ i = 0, ..., M-1\}$ denotes the block of complex symbols transmitted in the n-th modulation interval. The equivalent baseband transmitted signal x_k is expressed by

$$x_k = \sum_{n=-\infty}^{\infty} \sum_{m=0}^{M-1} A_n^{(m)} h_{k-nM}(m)\,, \tag{1}$$

where $h_k(i)$, $i = 0, ..., M-1$, are the impulse responses of M filters with frequency responses given by $H_i(f) = \sum e^{-j2\pi fkT/M} h_k(i), i = 0, ..., M-1$. For uplink transmission in an HFC network, the baseband signal is translated into a carrier frequency f_c. The baseband received signal is filtered by a bank of M filters with impulse responses $g_k(i)$, $i = 0, ..., M-1$. The filter output signals are sampled at the modulation rate $1/T$, and the samples are used to determine an estimate of the sequence of transmitted symbols. To ensure that transmission is free of intersymbol interference (ISI) within a subchannel and interchannel interference (ICI) between subchannels, the following orthogonality conditions must hold [14]. Assume the channel is ideal and the transmit and receive filters satisfy the symmetry conditions $g_k(i) = h^*_{-k}(i)$, $i = 0, ..., M-1$, where the asterisk denotes complex conjugation. Then in the time domain the criterion for perfect signal reconstruction is given by

$$\sum_k h_k(i) h^*_{k-nM}(j) = \delta_{i-j}\delta_n, \quad 0 \le i, j \le M-1, \tag{2}$$

where δ_i is defined as the Kronecker delta.

The complexity of an OFDM system is substantially reduced by resorting to the polyphase implementation of a uniform filter bank, where filtering operations are performed by frequency-shifted versions of a baseband prototype filter. Let $H(f)$ and $G(f)$ be the frequency responses of the prototype filters for the transmit and receive filter banks, respectively, and let the M carrier frequencies be given by $f_i = i/T$, $i = 0, ..., M-1$. We consider a causal FIR transmit prototype filter of length γM, i.e., the filter impulse response $\{h_k\}$ may assume nonzero values only for $k = 0, ..., \gamma M - 1$, and a receive prototype filter with an impulse response given by $g_k = h^*_{\gamma M - k}$. We recall that the filtering elements with impulse responses $h^{(i)}_\ell = h_{\ell M + i}$, $i = 0, ..., M-1$, are known as the polyphase components of the prototype filter, with frequency responses denoted by $H^{(i)}(f)$, $i = 0, ..., M-1$. It can be shown that a uniform transmit filter bank can be implemented by an inverse discrete Fourier transform (IDFT) followed by an M-branch polyphase network and a parallel-to-serial (P/S) converter [15]. In a similar manner we find that the receive filter bank can be implemented by a serial-to-parallel (S/P) converter, an M-branch polyphase network, and a discrete Fourier transform (DFT). Note that all filtering operations are performed at the low rate $1/T$. The efficient implementation of an OFDM system employing uniform transmit and receive filter banks is illustrated in Figure 3.

DWMT and DMT represent variants of OFDM that are considered for applications. In practice, equalization must be employed in both schemes to cope with nonideal channel characteristics [8, 16]. Let us assume that uplink transmission in an HFC network is based on DWMT. A DWMT signal is generated by real-valued input symbols and real-valued filter impulse responses, so that the signal spectrum has Hermitian symmetry around the frequency $f = 0$. The passband signal can be obtained by single side-band (SSB) or vestigial side-band (VSB) modulation. It turns out that SSB and VSB modulation schemes for digital passband transmission are characterized by inferior performance compared to double side-band amplitude and phase modulation (DSB-AM/PM), owing to the difficulties that these schemes present for carrier-phase recovery [17]. To obviate this problem, pilot tones are usually employed to provide carrier-phase information [18]. Transmission of pilot tones, however, would not be practical in the multiple-access environment we are considering.

Assume now that uplink transmission is based on DMT. In this case the passband signal can be obtained by double side-band amplitude and phase modulation (DSB-AM/PM) with zero excess bandwidth. Carrier-phase recovery does not represent a problem. Recall, however, that in DMT systems orthogonality conditions are satisfied only if the individual subchannel signals are received in proper synchronism. Because of the large amount of spectral overlap between contiguous subchannels, reception of a signal with improper timing phase results in ICI, i.e., the signal will disturb several other subchannel signals and vice versa. This situation cannot be avoided when a cable modem sends a request for registration in a subchannel specified by the HC with no prior knowledge of the correct timing phase and transmit power level [11].

To solve the dilemma posed by passband OFDM transmission in a multiple-access environment we propose FMT modulation, i.e., a filter-bank modulation technique where the filters are frequency-shifted versions of a prototype filter that yields a high level of subchannel spectral containment, such that the ICI is negligible compared to the level of other noise signals [9, 10]. The design of filtering elements for FMT systems turns out to be easier if some amount of ISI is allowed within a subchannel. In this paper, the amplitude characteristic of the prototype filter approximates the frequency response of an ideal filter given by

$$H_{\text{ideal}}(f) = \begin{cases} \left|\frac{1+e^{-j2\pi fT}}{1+\rho e^{-j2\pi fT}}\right| & \text{if } -1/2T \le f \le 1/2T \\ 0 & \text{otherwise}\,, \end{cases} \tag{3}$$

where the parameter $0 \le \rho \le 1$ controls the spectral roll-off of the filter. Note that for the assumed modulation interval equal to T, zero excess bandwidth for transmission within a subchannel is obtained, and the frequency response (3) exhibits spectral nulls at the band edges. The general case of an FMT system where excess bandwidth within a subchannel is also allowed is addressed in [9, 10]. Figure 4 illustrates the level of subchannel spectral containment achieved by an FMT system with $M = 64$ subchannels, and a linear-phase FIR prototype filter designed for $\rho = 0.1$ and $\gamma = 10$.

The frequency responses of FMT subchannels are characterized by steep roll-off towards the band-edge frequencies, where they exhibit near-spectral nulls. This suggests that per-subchannel decision-feedback equalization be performed to recover the transmitted symbols. In transmission systems with trellis coding, the function of decision-feedback filtering is preferably performed at the transmitter by employing precoding techniques [19]. Optimal detection is achieved by implementing at the receiver only the equalizer forward section, which approximates the whitened matched filter, and by implementing at the transmitter the feedback section as a Tomlinson–Harashima (TH) precoder [20, 21]. In particular, trellis-augmented precoding has been introduced as a suitable approach for joint trellis coding and precoding for transmission over channels with spectral nulls [22]. Here we consider uncoded FMT transmission employing per-subchannel TH precoding. The transmitter and receiver of an FMT passband system and the baseband equivalent FMT system are shown in Figures 5 and 6, respectively.

In Figure 7, the performance of FMT modulation is compared with that of DMT in terms of the complementary cumulative distribution of achievable rates for a single station transmitting over all subchannels and an average signal-to-noise ratio at the HC input of 30 dB. The number of bits per modulation interval that can be loaded on the i-th subchannel is given by [23]

$$b_i = \log_2\left(\frac{\text{SNR}_i\,\gamma_{\text{code}}}{\Gamma\,\gamma_{\text{margin}}} + 1\right)\,, \tag{4}$$

where SNR_i is the signal-to-noise ratio at the i-th equalizer output, γ_{code} is the coding gain assumed equal to 3 dB, Γ denotes the "SNR gap" of 8 dB that must be accounted for to achieve an error probability of 10^{-5} with uncoded transmission, and γ_{margin} denotes the required additional margin assumed equal to 6 dB. The achievable bit rate for given channel characteristics is therefore obtained by summing the values given by (4) over the subchannels allocated for uplink transmission and by multiplying the result by the modulation rate. Uplink transmission with $M = 64$ subchannels over the 5–37 MHz band is considered, with channel distortion introduced by four bidirectional amplifiers as well as (a) weak or (b) strong reflections at random points in the network. Figure 8 illustrates the amplitude characteristics of channel responses obtained in the two cases. The distributions are obtained with 100 channel realizations. In the FMT system considered here, the same linear-phase prototype filter designed for parameter values $\rho = 0.1$ and $\gamma = 10$ is used for the realization of the transmit and receive filter banks. Per-subchannel equalization is performed by employing a TH precoder with 8 taps at the transmitter and a linear equalizer with 16 taps at the receiver. In the DMT system, a cyclic prefix of 16 samples, no time-domain equalizer and one-tap frequency equalizers are employed. The coefficients of the equivalent minimum mean-square error decision-feedback equalizers for FMT and of the one-tap frequency equalizers for DMT are computed assuming perfect knowledge of the channel characteristics.

IV. Hybrid TDMA/CDMA system based on FMT modulation

CDMA is well suited for uplink transmission in HFC networks because it represents a robust transmission technique in the presence of narrow-band interference [24, 25]. Furthermore, adjustment of the transmitted signal power during the initial registration process avoids the near-far problem. On the other hand, some or all of the stations might only occasionally access the channel and transmit in burst mode. To accommodate this type of traffic, which requires fast synchronization capabilities at the HC receiver, TDMA is preferable. The above observations motivated the proposal of a hybrid TDMA/CDMA scheme for uplink transmission in HFC networks. According to the time-varying characteristics of the disturbances present in the channel, and to the requests for resource allocation of each individual station, the HC dynamically assigns to each station a subchannel or a set of subchannels for uplink transmission. The HC also specifies whether during a mini-slot a subchannel is entirely dedicated to uplink transmission of a single station (TDMA), or whether it may be shared by several stations using different signature codes (CDMA).

A hybrid TDMA/CDMA scheme based on FMT modulation allows the HC to allocate uplink channel resources efficiently to each individual station for a wide range of data rates. FMT transmission by a single station was described in Section III. If application in a TDMA environment is considered, however, the two following remarks are appropriate.

Remark 1. During initial registration of a station, the HC may compute the round-trip delay compensation value and the precoder coefficients such that proper equalization is achieved at the output of a predefined subchannel by using a fixed linear equalizer; the HC may then allocate that subchannel for uplink transmission of those stations requiring fast detection of transmitted signals.

Remark 2. If transmission of a message over a subchannel has a finite duration, a “tail” of length equal to L modulation intervals will be observed after the last symbol of the message has been detected; to avoid the need for large guard intervals between consecutive messages, cancellation of the tail may be performed.

In the remaining part of this section, we will describe a synchronous CDMA scheme in conjunction with FMT modulation. In a synchronous CDMA environment, the signals transmitted over the same subchannel as the signal to be detected can be modeled as cyclostationary interference, which is synchronous with the disturbed signal. In an HFC network, synchronism is due to common timing information provided by the HC to all stations in the network. It has been shown in [26] that $K-1$ synchronous interferers having a modulation interval equal to T' can be suppressed by expanding the bandwidth of the signals by a factor of K, and by employing adaptive equalization with T'/K-spaced taps at the receiver. Interference suppression achieved in this manner can be interpreted as a frequency diversity technique. Here we consider the presence of narrow-band asynchronous interferers as well.

In general, depending on the desired transmission rates and interference characteristics, various configurations for FMT-CDMA over each subchannel may be chosen by the HC. We consider a system where K_i stations transmit over the i-th subchannel. Each input symbol sequence is transmitted at a modulation rate of $1/KT$, with $K_i \leq K$. At the HC receiver, after demodulation by the DFT, assuming that only narrow-band interferers having spectral content within the i-th subchannel represent nonnegligible noise signals, the i-th subchannel output signal is given by

$$V_n^{(i)} = \sum_{k=0}^{K_i-1} \sum_{m=-\infty}^{\infty} \left[\sum_{\ell=0}^{K-1} s_\ell^{(k)} \tilde{A}_{m-\ell}^{(i,k)} \right] h_{n-m}^{(i,k)} + \sum_{j=0}^{J-1} U_n^{(i,j)} , \tag{5}$$

where $\{\tilde{A}_n^{(i,k)}\}$ denotes the interpolated sequence of k-th user symbols input to the i-th subchannel, $\{s_n^{(k)}\}$ is the k-th user signature code sequence with length K, $h_n^{(i,k)}$ denotes the overall i-th subchannel impulse response for the k-th station, and $U_n^{(i,j)}$, $j = 0, ..., J-1$, are narrow-band interferers with spectral components in the frequency bands $\mathcal{B}^{(i,j)}$, $j = 0, ..., J-1$. We assume that the bands $\mathcal{B}^{(i,j)}$, $j = 0, ..., J-1$, correspond to compact frequency intervals in the frequency band $(-1/2T, 1/2T)$, and that the bandwidths of the interfering signals are less than $1/KT$, i.e.,

$$\int_{\mathcal{B}^{(i,j)}} df \leq \frac{1}{KT}, \quad j = 0, ..., J-1 . \tag{6}$$

Let us consider a system where the signal $V_n^{(i)}$ is filtered by a bank of K_i fractionally-spaced adaptive equalizers with T-spaced taps and KT-spaced equalizer output signals. Let $\tilde{H}^{(i,k)}(f) = S^{(k)}(f)H^{(i,k)}(f)$ denote the overall frequency response from the k-th user symbol source of the i-th subchannel to the i-th DFT output, and $C^{(i,k)}(f)$ denote the frequency response of the k-th adaptive equalizer of the i-th bank. We define the matrix of channel responses $\tilde{\mathbf{H}}^{(i)}(f) = \left[\tilde{H}^{(i,k)}\left(f - \frac{\ell}{KT}\right)\right]$, $k = 0, ..., K_i - 1$, $\ell = 0, ..., K-1$, and the column vectors of equalizer responses $\tilde{\mathbf{C}}^{(i,k)}(f) = \left(C^{(i,k)}(f), ..., C^{(i,k)}\left(f - \frac{K-1}{KT}\right)\right)'$, $k = 0, ..., K_i - 1$. Interference-free reception of the K_i symbol sequences $\{A_{nK}^{(i,0)}\}, ..., \{A_{nK}^{(i,K_i-1)}\}$ is obtained if, for every frequency in the interval $-1/2KT < f < 1/2KT$ and for every index $k = 0, ..., K_i - 1$ there exists a solution to the equation

$$\tilde{\mathbf{H}}^{(i)}(f)\mathbf{C}^{(i,k)}(f) = \mathbf{e}_k , \tag{7}$$

where $\mathbf{e}_k$ denotes the vector with the k-th element equal to 1 and all other elements equal to 0, subject to the constraint

$$C^{(i,k)}(f) = 0, \quad f \in \bigcup_{j=0}^{J-1} \mathcal{B}^{(i,j)} , \quad k = 0, ..., K_i - 1. \tag{8}$$

Assuming infinite equalizer length, in the absence of interferers a solution to (7) exists if the matrix $\tilde{\mathbf{H}}^{(i)}(f)$ is of rank K_i. In the presence of narrow-band interferers, a solution exists if the condition $J \leq K - K_i$ is verified, and the matrix $\tilde{\mathbf{H}}^{(i)}(f)$ is such that, for every frequency in the interval $-1/2KT < f < 1/2KT$, by setting J columns arbitrarily to 0, the rank of the resulting matrix is still equal to K_i. For a practical implementation a compromise between equalizer length, noise enhancement, and achieved interference suppression has to be made.

Figure 9 illustrates the performance of a FMT-CDMA scheme employing Walsh-Hadamard codes. Uplink FMT transmission with $M = 64$ subchannels in the 5–37 MHz band is considered. Each active station transmits CDMA signals in the subchannel centered at 21 MHz. A narrow-band interferer with 62.5 kHz bandwidth and center frequency also at 21 MHz is added to the received signals, i.e., $J = 1$. Figure 9 shows the achievable aggregate rate versus interference-to-signal ratio for various numbers of users, $K = 8$, uplink channel responses obtained assuming weak reflections at random points in the network, and an average signal-to-noise ratio at the subchannel output in the absence of interferers of 21.5 dB. Symbol detection for each user is performed by a 24-tap fractionally $T/8$-spaced linear equalizer and K_i 2-tap cross-coupled feedback filters [27, 28], with coefficients computed assuming perfect knowledge of the subchannel characteristics.

V. RANGING AND POWER ADJUSTMENT

In this section, we describe an algorithm for the realization of the ranging and power adjustment process using FMT modulation. As in the case of ranging and power adjustment when single-carrier QAM is employed, a station first tunes its receiver to a downlink channel that conveys MAC information and acquires the global timing reference provided by the HC. Thereafter, when a MAP message with an Initial Maintenance IE is received, the station sends a RNG-REQ message in the specified subchannel, which results in negligible ICI in adjacent subchannels, as mentioned in Section III. If a Ranging Response (RNG-RSP) message is not received, subsequent RNG-REQ messages are sent with increasing transmit power, e.g., incremented by 1 dB steps.

For RNG-REQ messages, one may consider a transmission format with a preamble containing a constant-amplitude zero autocorrelation (CAZAC) sequence [29] of length P, e.g., $P = 16$, which is repeated R times, e.g., $R = 8$, followed by a special start-of-message (SOM) sequence. The CAZAC and SOM sequences may be specified in the MAP message.

Detection of periodic CAZAC sequences at the HC may be performed as described in [30]. Upon detection of the CAZAC sequence, the HC performs channel identification using, for example, a least-squares algorithm [31]. From the amplitude and phase characteristics of the identified channel response a transmit power level adjustment and a timing phase $\Delta_T \in [0, T]$ are derived. The timing phase is needed to compute the round-trip delay compensation so that the FMT signal is received in proper synchronism. The detection of the signature sequence provides the HC with further timing information that is used to determine the total round-trip delay from the head-end node to the station, and hence the round-trip delay compensation.

After determining the transmit power level adjustment and the round-trip delay compensation, the HC sends this information to the station as part of a RNG-RSP message. The station then waits for a MAP message with an individual Station Maintenance IE, and sends at the specified time a RNG-REQ message using the power level and timing corrections. The HC receives the RNG-REQ message in proper synchronism at the T-spaced filter bank output. The HC returns another RNG-RSP message to the station with information about any additional fine tuning required. The ranging request/response steps are repeated until the response contains a Ranging Successful notification.

VI. COLLISION RESOLUTION ALGORITHM

In this section we address the problem of collision resolution, which arises when several stations send request messages in a mini-slot specified in a Request IE. Various methods other than the simple random backoff algorithm mentioned in Section VI have been proposed [12]. For example, in [1] a collision resolution algorithm is specified based on a ternary tree algorithm [32]. For collision resolution we propose here a new algorithm based on iterative identification of the competing stations that exploits the characteristics of uplink FMT transmission.

We consider a blocked-access algorithm, i.e., new arrivals are held until the current contention has been resolved. Request messages that identify the stations consist of pseudorandom signature sequences of N bits, and are transmitted using differentially encoded binary phase-shift keying (BPSK) modulation over a subchannel specified by the HC. We assume ideal uplink transmission for all stations sending request messages in the specified contention subchannel, i.e., we assume that the registered stations are perfectly synchronized and that proper signal equalization on the contention subchannel is performed by a fixed equalizer, as mentioned in Section IV. The request messages are then received at the subchannel output in the absence of ISI and ICI. Because of possible multiple frequency translations of the uplink signals that take place at intermediate nodes of the network, the received symbols of a request message are rotated by a random phase, which is assumed to be constant over N modulation intervals. The phases associated with different messages are assumed to be independent.

If K stations transmit request messages in a contention slot specified over the i-th subchannel in the time interval $(0, NT)$, the received sequence is given by

$$V_n^{(i)} = \sum_{k=0}^{K-1} A_n^{(i,k)} e^{j\theta_k} + w_n\,, \quad n = 0, ..., N-1\,, \tag{9}$$

where $A_n^{(i,k)} \in \{-1, +1\}$, $\theta_k \in (0, 2\pi)$, and w_n is a complex additive white Gaussian noise sample with zero mean and variance σ_w^2. If $K = 1$, we assume that the HC will correctly identify the station sending the contention request.

We now describe the collision resolution algorithm. Note that the N points $\{V_n^{(i)}\,,\ n = 0, ..., N-1\}$ on the complex plane determine the set of non-negative values $\{\xi_j\,,\ j = 0, ..., N(N-1)/2-1\}$, possibly not all distinct, which represent the distances between points.

If $\xi_j \in (0, 2-\epsilon) \cup (2+\epsilon, \infty)$, $\epsilon > 0$, $\forall j$, the HC selects two points, $V_{\ell_0}^{(i)}$ and $V_{\ell_1}^{(i)}$, such that $|V_{\ell_0}^{(i)}| = \max |V_\ell^{(i)}|$ and $|V_{\ell_1}^{(i)}| = \min |V_\ell^{(i)}|$, and splits the group of competing stations into two groups by asking that each station transmit a new request message in one of two slots. The retransmission rule is such that stations having a signature sequence whose symbols differ in the ℓ_0-th and ℓ_1-th positions send a new request message in the first slot, and the remaining stations send a new request in the second. With high probability, the problem is reduced to resolving sequentially two contentions between smaller groups of stations.

If one of the distances ξ_{j_0} is such that $\xi_{j_0} = |V_{\ell_0} - V_{\ell_1}| \approx 2$, it is likely that all the stations but one have signature sequences whose symbols in the ℓ_0-th and ℓ_1-th positions are equal. Then if $\xi_{j_0} = |V_{\ell_0} - V_{\ell_1}| \in (2-\epsilon, 2+\epsilon)$, and $|\xi_{j_0} - 2| = \min |\xi_j - 2|$, the HC specifies a new slot where only those stations that have a signature sequence whose symbols in the ℓ_0-th and ℓ_1-th positions are different are allowed to send a new request message. Three cases must be considered.

- Only one station with index k_0 transmits a new message. Then the HC correctly detects it. We also assume that the HC produces a correct estimate $\{\hat{A}_n^{(i,k_0)} e^{j\hat{\theta}_{k_0}}\}$ of the k_0-th message sequence in (9), i.e., $\{\hat{A}_n^{(i,k_0)}\} = \{A_n^{(i,k_0)}\}$ and $\hat{\theta}_{k_0} = \theta_{k_0}$. From the recovered information, the HC then computes a new sequence

$$V_n^{(i)\prime} = V_n^{(i)} - \hat{A}_n^{(i,k_0)} e^{j\hat{\theta}_{k_0}} + w_n\,, \quad n = 0, ..., N-1\,, \tag{10}$$

and a new set of associated distances $\{\xi_j'\,,\ j = 0, ..., N(N-1)/2-1\}$. The algorithm is then applied to resolve the contention between the remaining stations.

- Several stations transmit a new message. The HC resolves first the contention between the stations that have retransmitted, then it asks that the remaining stations retransmit, and resolves the contention between these stations.

- No new message is transmitted. In this event, the HC then discards ξ_{j_0} and proceeds by applying the algorithm with a reduced set of distances.

The above steps are repeated until all stations participating in the initial contention are identified. Note that if two stations send a contention request, they are identified with high probability with only one retransmission. In fact, in this event it is very likely that the HC will find a distance of $\xi_{j_0} \approx 2$, leading to retransmission by only one station, and (10) yields a sequence that allows the reliable identification of the remaining station. Figure 10 illustrates the performance of the collision resolution algorithm described here in terms of τ, which is the average number of slots needed to resolve a collision, versus λ, the average number of new packets generated at each slot, for a Poisson generation process, $N = 16$, $\epsilon = 0.2$, and various values of $\text{SNR} = 1/\sigma_w^2$. For comparison purposes, the performance of a ternary tree algorithm with blocked access is also shown. We recall that for a Poisson new arrival process the maximum stable throughput of a ternary tree algorithm with blocked access is 0.3662 (packets/slot) [33], and that the maximum stable throughput on the collision channel with binary (collision/no-collision) feedback is bounded by 0.583 (packets/slot) [34]. Therefore the simulation results shown in Figure 10 indicate that significantly higher throughput than that achieved by algorithms relying only on binary feedback can be attained by using more sophisticated signal processing techniques.

VII. CONCLUSIONS

The proposed hybrid TDMA/CDMA multiple-access system based on FMT modulation is well suited for uplink transmission in the presence of narrow-band interference signals with time-varying spectral characteristics. TDMA is adopted over subchannels that are free of interference to accommodate the traffic of stations transmitting in burst mode. CDMA is employed over noisy subchannels for stations that require access for extended periods and transmit at low rates. The high level of spectral containment of individual subchannels achieved by FMT modulation allows ranging and power adjustment of unregistered stations to be performed without disturbing uplink transmission on adjacent subchannels. Furthermore, the characteristics of FMT modulation permit the application of signal processing techniques for contention resolution algorithms. These algorithms provide significantly higher throughput on the collision channel than that achieved by algorithms relying only on binary feedback.

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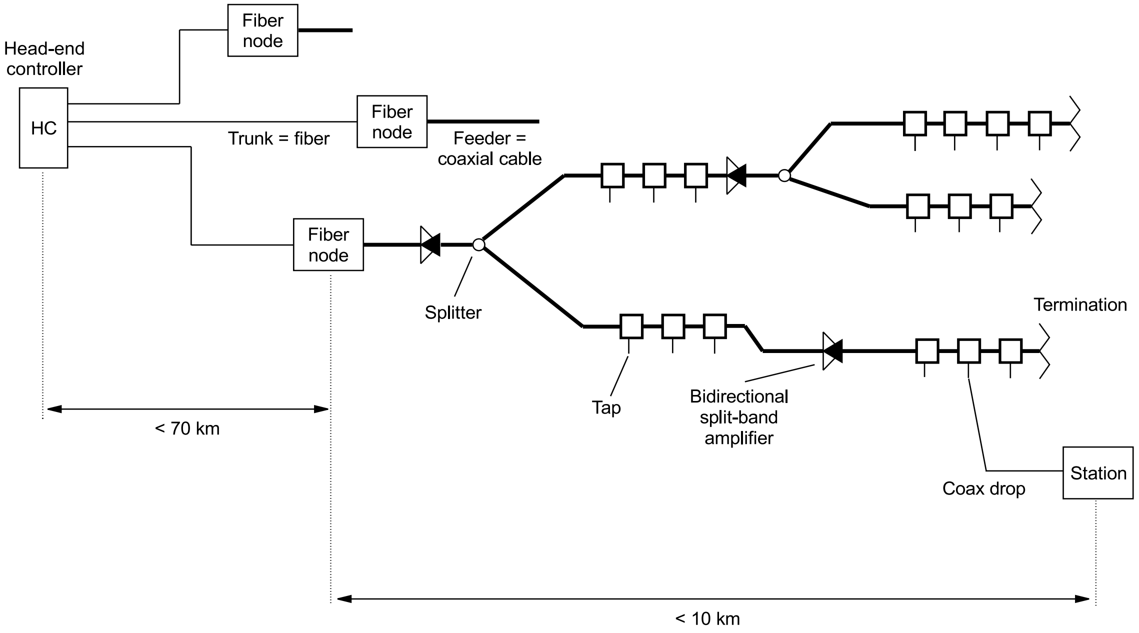

Fig. 1. HFC network topology.

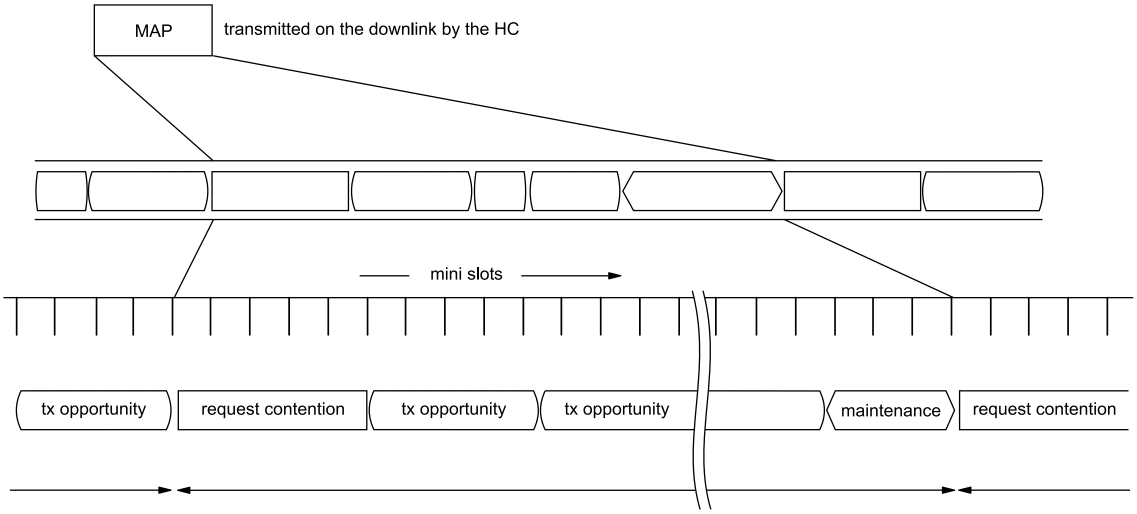

Fig. 2. Example of a MAP message

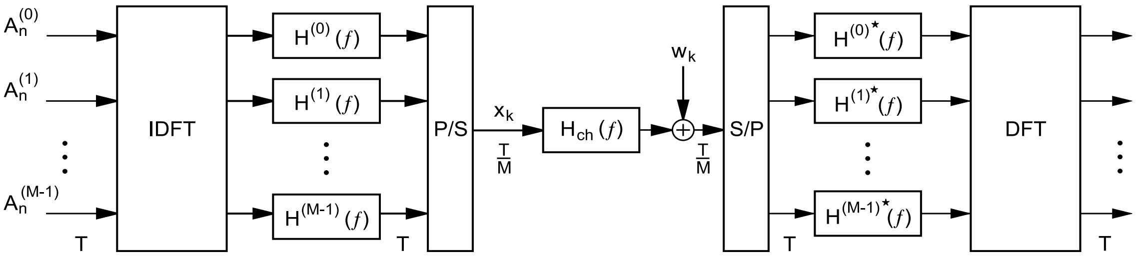

Fig. 3. Block diagram of an OFDM system with efficient implementation.

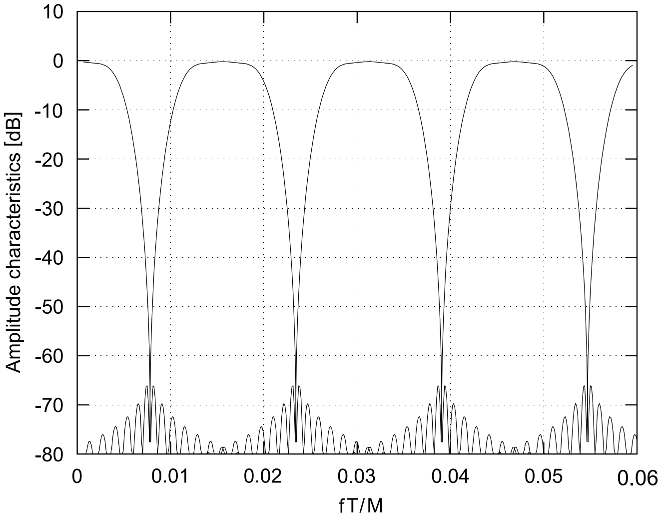

Fig. 4. Frequency responses for $f \in (0, 0.06\,M/T)$ of subchannel filters in an FMT system with $M = 64$ and prototype filter designed for $\rho = 0.1$ and $\gamma = 10$.

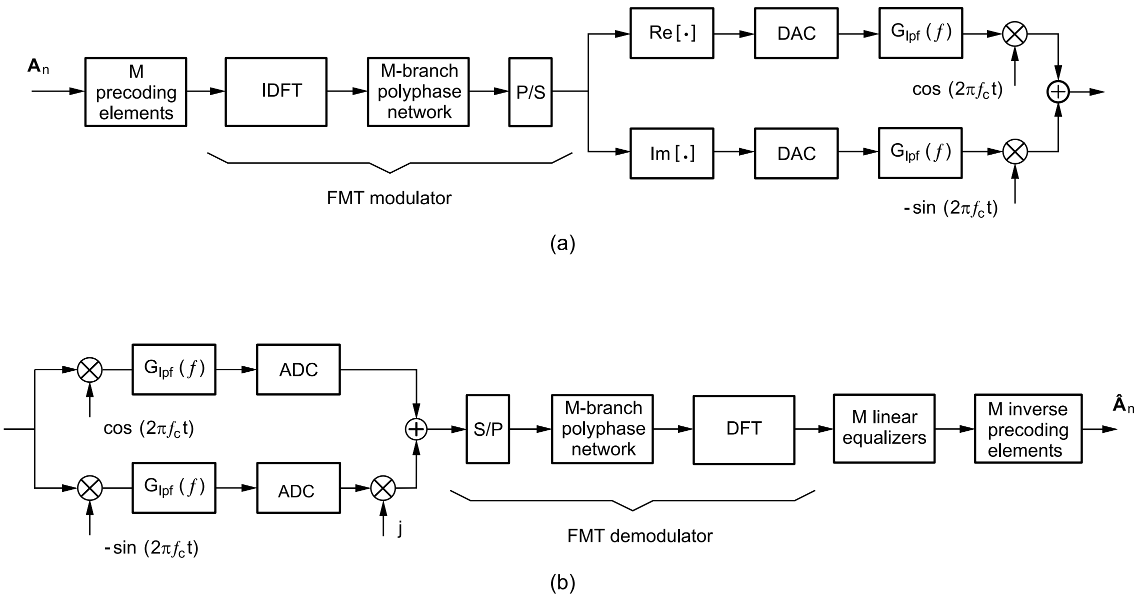

Fig. 5. Block diagram of (a) transmitter and (b) receiver of a passband FMT system.

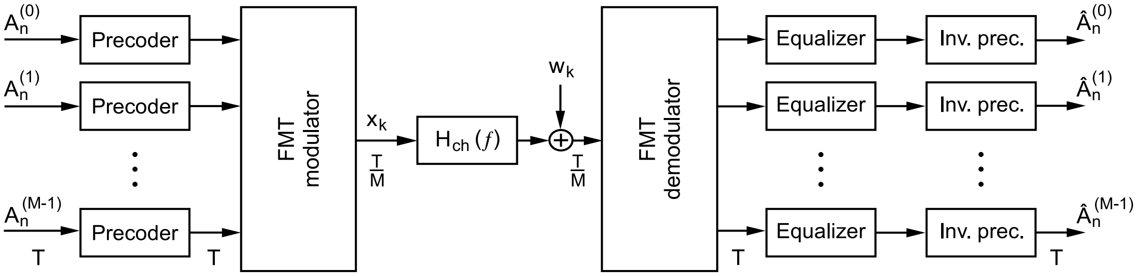

Fig. 6. Block diagram of the baseband equivalent FMT system.

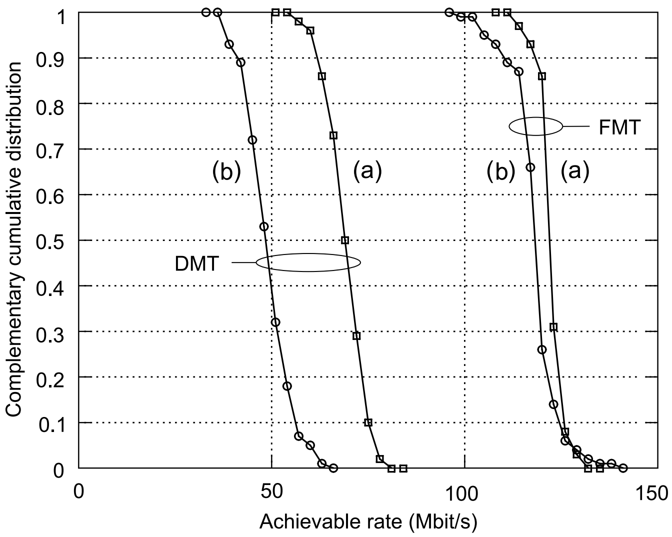

Fig. 7. Complementary cumulative distribution of achievable rates for FMT and DMT uplink transmission systems with $M = 64$ subchannels.

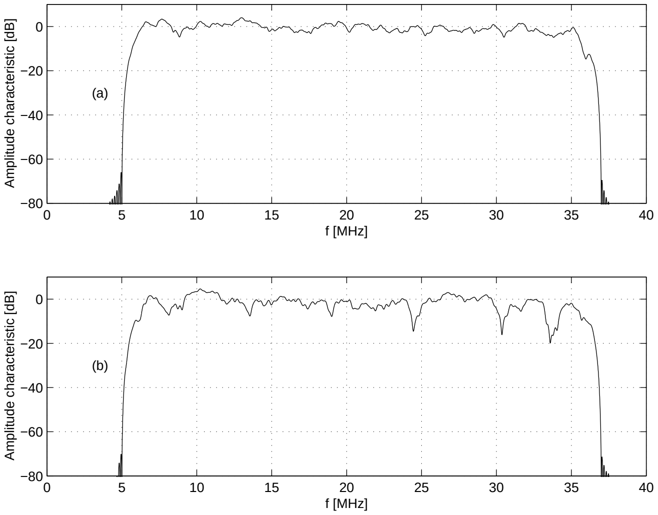

Fig. 8. Amplitude characteristics of channel responses obtained by assuming (a) weak or (b) strong reflections at random points in the network.

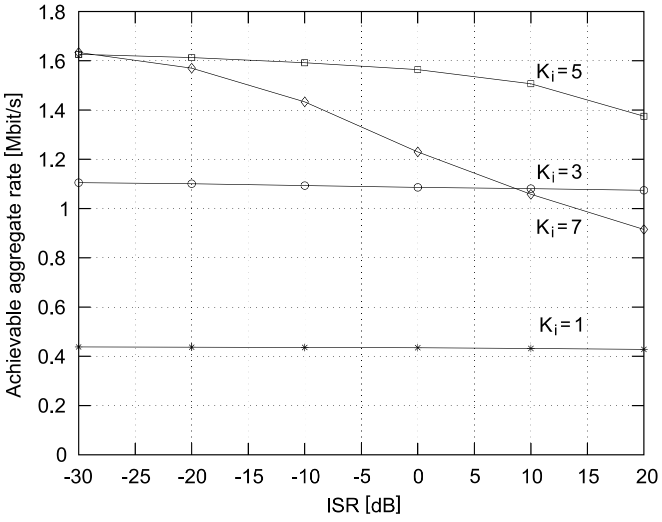

Fig. 9. Aggregate achievable rates versus interference-to-signal ratio for various numbers of users sharing a subchannel in an FMT-based CDMA uplink transmission system.

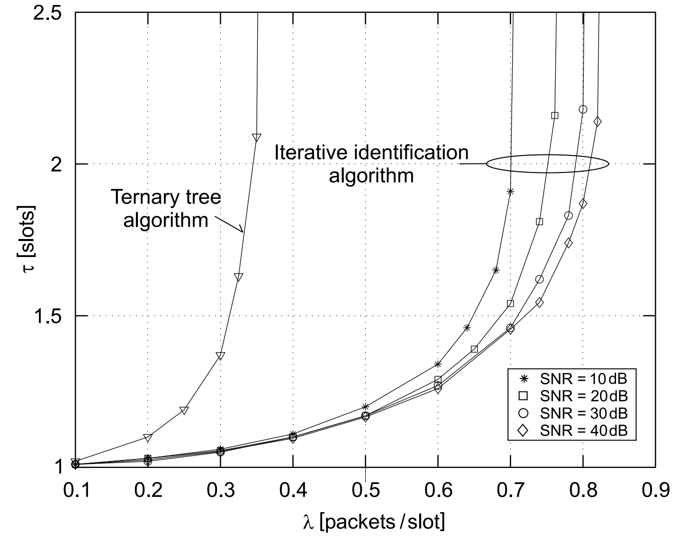

Fig. 10. Average number of slots needed to resolve a collision, τ, versus average number of new packets generated at each slot, λ, for a Poisson arrival process.