RAKE Receiver

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***Abstract*—RAKE receiver is used in CDMA-based (Code Division Multiple Access) systems and can combine multipath components, which are time-delayed versions of the original signal transmission. Combining is done in order to improve the signal to noise ration at the receiver. RAKE receiver attempts to collect the time-shifted versions of the original signal by providing a separate correlation receiver for each of the multipath signals. This can be done due to multipath components are practically uncorrelated from another when their relative propagation delay exceeds a chip period.**

This paper presents the basics of RAKE receiver technique, implementation, and design in cellular systems. Also the usage of RAKE receiver is introduced in CDMA-based systems such as IS-95 and WCDMA (Wideband Code Division Multiple Access).

***Index Terms*—RAKE receiver, CDMA, multipath, receiver, maximal-ratio combining.**

I. INTRODUCTION

In CDMA (Code Division Multiple Access) spread spectrum systems, the chip rate is typically much greater than the flat fading bandwidth of the channel. Where as conventional modulation techniques require an equalizer to undo the inter-symbol interference (ISI) between adjacent symbols, CDMA spreading codes are designed to provide very low correlation between successive chips. Thus, propagation delay spread in the radio channel merely provides multiple versions of the transmitted signal at the receiver. If these multipath components are delayed in time by more than one chip duration, they appear like uncorrelated noise at a CDMA receiver, and equalization is not required.

RAKE receiver, used specially in CDMA cellular systems, can combine multipath components, which are time-delayed versions of the original signal transmission. This combining is done in order to improve the signal to noise ratio (SNR) at the receiver. RAKE receiver attempts to collect the time-shifted versions of the original signal by providing a separate correlation receiver for each of the multipath signals. This can be done due to multipath components are practically uncorrelated from another when their relative propagation delay exceeds a chip period.

The basic idea of A RAKE receiver was first proposed by Price and Green. These fellows also filed the RAKE receiver patent in 1956. [1]

II. RAKE RECEIVER

Due to reflections from obstacles a radio channel can consist of many copies of originally transmitted signals having different amplitudes, phases, and delays. If the signal components arrive more than duration of one chip apart from each other, a RAKE receiver can be used to resolve and combine them. The RAKE receiver uses a multipath diversity principle. It is like a rake that rakes the energy from the multipath propagated signal components. [2]

A. Multipath Channel Model

Multipath can occur in radio channel in various ways such as, reflection and diffraction from buildings, and scattering from trees presented in Figure 1.

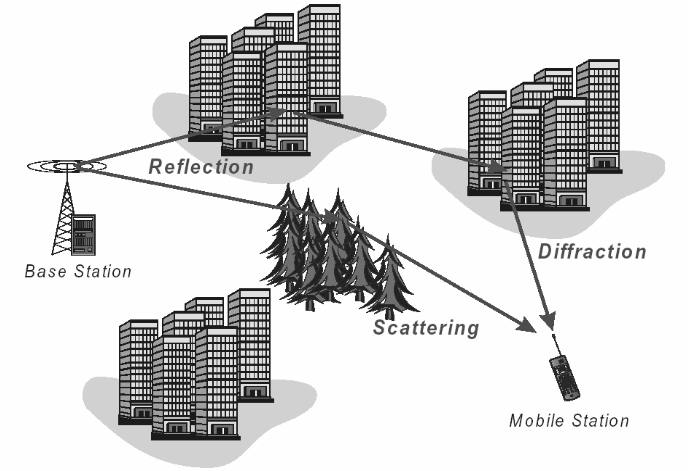

Figure 1. Propagation mechanisms

An M-ray multipath model is shown in Figure 4, which is an extension to the multipath channel model presented in [3]. Each of the M paths has an independent delay, τ, and an independent complex time-variant gain, G.

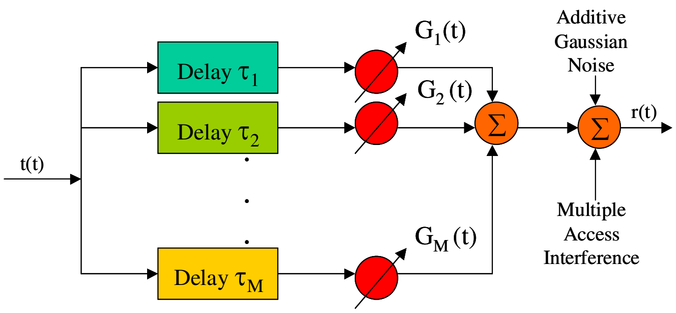

Figure 2. Multipath channel model

B. *M-finger RAKE Receiver*

A RAKE receiver utilizes multiple correlators to separately detect M strongest multipath components. The outputs of each correlator are weighted to provide better estimate of the transmitted signal than is provided by a single component. Demodulation and bit decisions are then based on the weighted outputs of the M correlators. [1]

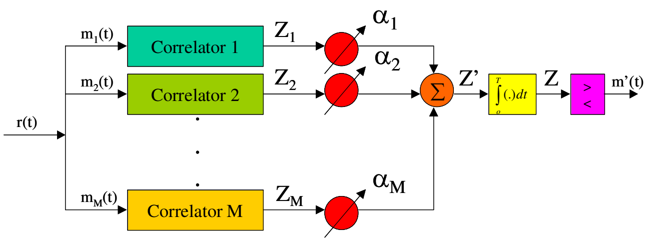

Figure 3. An M-branch RAKE receiver implementation

Each correlator detects a time-shifted version of the original CDMA transmission, and each finger of the RAKE correlates to a portion of the signal, which is delayed by at least one chip in time from the other fingers.

Assume M correlators are used in a CDMA receiver to capture M strongest multipath components. A weighting network is used to provide a linear combination of the correlator output for bit decision. Correlator 1 is synchronized to the strongest multipath m_1. Multipath component m_2 arrived t_1 later than m_1 but has low correlation with m_1.

The M decision statistics are weighted to form an overall decision statistic as shown in Figure 3. The outputs of the M correlators are denoted as Z_1, Z_2,…, and Z_M. They are weighted by α_1, α_2,…, and α_M, respectively. The weighting coefficients are based on the power or the SNR (Signal-to-Noise Ratio) from each correlator output. If the power or SNR is small out of a particular correlator, it will be assigned a small weighting factor, α. If maximal-ratio combining is used, following equation 1 can be written for Z'.

$$Z' = \sum_{m=1}^{M} \alpha_m Z_m \tag{1}$$

The weighting coefficients, α_m, are normalized to the output signal power of the correlator in such a way that the coefficients sum to unity, as shown in following equation 2.

$$\alpha_m = \frac{Z_m^2}{\sum_{m=1}^{M} Z_m^2} \tag{2}$$

As in the case of adaptive equalizers and diversity combining, there are many ways to generate the weighting coefficients. However, due to Multiple Access Interference (MAI), RAKE fingers with strong multipath amplitudes will not necessarily provide strong output after correlation. Choosing weighting coefficients based on the actual outputs of the correlator yields better RAKE performance. [1]

C. *RAKE Receiver Block Diagram*

When a signal is received in a matched filter over a multipath channel, the multiple delays appear at the receiver, as depicted in Figure 4. The RAKE receiver uses several baseband correlators to individually process several signal multipath components. The correlator outputs are combined to achieve improved communications reliability and performance. [2]

Bit decisions based only a single correlation may produce a large bit error rate as the multipath component processed in that correlator can be corrupted by fading. In a RAKE receiver, if the output from one correlator is corrupted by fading, the others may not be, and the corrupted signal may be discounted through the weighting process. [1]

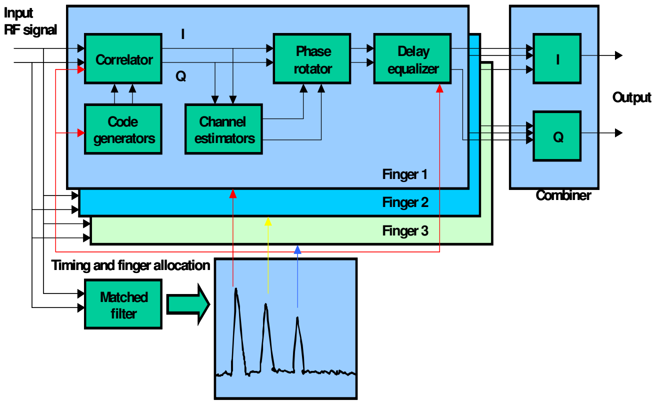

Figure 4. Block diagram of a RAKE receiver

Impulse response measurements of the multipath channel profile are executed through a matched filter to make a successful de-spreading. It reveals multipath channel peaks and gives timing and RAKE finger allocations to different receiver blocks. Later it tracks and monitors these peaks with a measurement rate depending on speeds of mobile station and on propagation environment. The number of available RAKE fingers depends on the channel profile and the chip rate. The higher the chip rate, the more resolvable paths there are, but higher chip rate will cause wider bandwidth. To catch all the energy from the channel more RAKE fingers are needed. A very large number of fingers lead to combining losses and practical implementation problems.

III. RAKE RECEIVER IN IS-95 SYSTEM

In the implementation of the IS-95 system, the mobile receiver employs a “searcher” receiver and three digital data receivers that act as fingers of a RAKE in that they may be assigned to track and isolate particular multipath components of a single cell site, a single base station in softer handover and multiple base stations in soft handover. The PN chip rate of 1,2288 MHz allows for resolution of multipaths at time intervals of 1,2288 x 10^{-6} s = 0,814 µs, which means that multipath difference in meters can be around 244 m. [4]

A. *Downlink*

The searcher receiver scans the time domain about the desired signal’s expected time of arrival for multipath pilot signals from the same cell site and pilot signals and their multipaths from other cell sites. Searching the time domain on the downlink signals is simplified because the pilot channel permits the coherent detection of signals. The search receiver indicates to the mobile phone’s control processor where, in time, the strongest replicas of the signal can be found, and their respective signal strengths. In turn, the control processor provides timing and PN code information to the tree digital data receivers, enabling each of them to track and demodulate a different signal. [4]

If a another cell site pilot signal becomes significantly stronger than the current pilot signal, the control processor initiates handover procedures during which the downlinks of both cell sites transmit at the same call data on all their traffic channels. When both sites handle the call, additional space diversity or macro diversity is obtained. [4]

The data from all three digital receivers are combined for improved resistance to fading. Different base stations or sectors are distinguished by different short PN code offsets. The downlink performs coherent post-detection combining after ensuring that the data streams are time-aligned; performance is not compromised by using post-detection combining because the modulation technique is linear. Coherent combining is possible because the pilot signal from each base station provides a coherent phase reference that can be tracked by the digital data receivers. [4]

B. *Uplink*

On the uplink, the base station receiver uses two antennas for space diversity reception, and there are four digital data receivers available for tracking up to four multipath components of a particular subscriber’s signal. The searcher receiver at the base station can distinguish the desired mobile signal by means of its unique scrambling long PN code offset, acquired before voice or data transmission begins on the link, using s special preamble for that purpose. [4]

During soft handover from one base station site to another, the voice data that are selected could result from combining up to eight multipath components, four at each site. The uplink transmission, not having a coherent phase reference like the downlink’s pilot signal, must be demodulated and combined non-coherently; maximal-ratio combining can be done by weighting each path’s symbol statistics in proportion to the path’s relative power prior to demodulation and decoding decision. [4]

IV. RAKE RECEIVER IN WCDMA SYSTEM

A basic implementation of RAKE receiver presented in Figure 5 despreads data from different multipath components, combines the multipath components, and detects combined data to soft bits.

A WCDMA base station RAKE receiver contains the following functions to enable the receiving of CDMA type of multipath signals. [5]

1. Channel delay estimation for multipath components. This can also called as Impulse Response (IR) Measurement.
2. RAKE receiver finger allocation based on the channel delay estimation
3. RAKE receiver fingers to perform the descrambling and despreading operations
4. Adaptive channel estimation
5. Maximal-Ratio Combining (MRC)

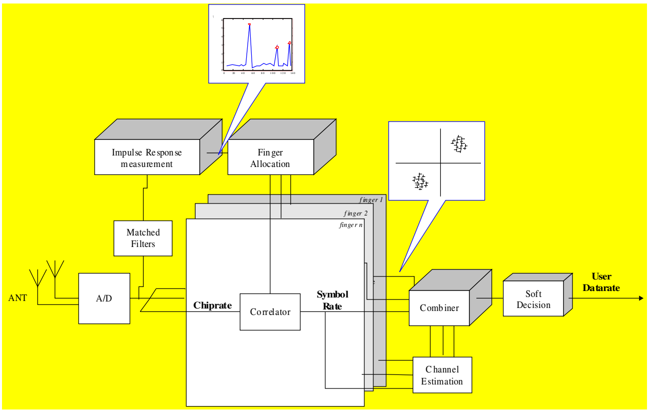

Figure 5. RAKE receiver in WCDMA

A. *Channel Delay Estimation*

The channel Impulse Response Measurement (IRM) is performed by using Matched Filter (MF) type of correlators that correlate the received signal with known reference code sequence such as pilot channel code.

The MF resources contain shorter filters (length of 64 chips time period for RACH and 32 chips time period for DPCCH), which can be concatenated in time domain to enable the proper delay estimation also in large cells with large delay spreads (e.g. hilly terrain environments). [5]

To improve the delay estimation performance and to increase signal to noise ratio the results of MFs are further processed by coherent and non-coherent averaging. The length of the coherent IR averaging is typically one time slot while the noncoherent averaging is typically done over radio frames. The length of the averaging operations can be selected by parametrization. The accuracy of the IR measurement is ¼ chip (65,1 ns). [5]

B. *RAKE Receiver Finger Allocation*

The purpose of the RAKE finger allocation procedure is to define the optimal finger delay positions that maximize the receiver performance. The allocation procedure defines the correct delay positions for despreading (in RAKE fingers) the received wideband signal to symbol level information. In the case of receiver antenna diversity the finger allocation procedure combines information from separate receiver antennas. In softer handover the allocation procedure defines the optimal finger delay positions by taking into account the information from all the sectors involved in the handover situation. [5]

The finger allocation procedure contains algorithms, which eliminate the unnecessary changes in the finger time positions between successive allocations. Thus the despreading of a certain multipath component is kept on the same RAKE finger as long as possible to maximize the performance of channel estimation and maximal-ratio combining. [5]

In the finger allocation procedure also the shape of the channel impulse response is taken into account when defining the optimum finger delay positions. It has been confirmed that the allocation must be done differently for the channels where the taps are very close to each others (so called "fat finger") than for channels with clearly separate taps. [5]

Typically the allocation frequency in normal operation mode is one allocation for a code channel in every 25 ms (accuracy of ¼ chip), which is enough for all the practical situations. Code tracking with accuracy of 1/8 chip is further used in RAKE fingers to track and compensate small delay deviations in multipath component timing. The change in the timing can be caused by the movement of the UE or by the transmission timing adjustment of the UE. [5]

C. *RAKE Receiver Finger Descrambling and Despreading*

The despreading operation for DPDCH (Dedicated Physical Data Channel) and DPCCH (Dedicated Physical Control Channel) is performed in RAKE fingers to recover the receiver wideband signal to symbol level information - multiplying of incoming signal by complex conjugate of scrambling code and channelization code and accumulating the results over symbol periods. In the base station receiver 8 fingers are allocated for each code channel (i.e. 8 multipath components can be despread for a single user). [5]

Code tracking is used to track and compensate small deviations in multipath component delays i.e. the Code tracking performs the fine adjustment of the delay used in the despreading. The tracking is done for every finger and the accuracy is 1/8 chip. Like in the main finger allocation procedure the shape of the channel impulse response is taken into account when defining the despreading timings. [5]

Typically the delay updating by code tracking is performed once in each or every second 10 ms radio frame. [5]

D. *Adaptive Channel Estimation*

The goal adaptive channel estimation is to estimate the characteristics of the time-variant channel. In WCDMA the solution is Pilot Symbol Aided plus adaptive filtering. [5]

The channel estimation is used to remove distortion caused by radio channel and it is based on the known pilot symbols on DPCCH. The channel estimator filter adapts to the Doppler power spectrum (both frequency and the shape of the spectrum). The estimation is done for each finger separately. The use of adaptive filter ensures good performance in all kind of propagation conditions. The advantage of adaptive filter coefficients compared to use of fixed coefficient is evident since the solution with fixed coefficients would perform well only in a constricted set of propagation conditions. [5]

In the case of multiple receiver antennas the performance of channel estimation is further improved by combining the power spectrum information available from different receiver antennas. [5]

The combining process is based on maximal-ratio combining, which decreases the effect of additive noise, which can further be decreased by channel decoding.[5]

E. *Maximal-Ratio Combining (MRC)*

Maximal-Ratio Combining, first discussed by Brennan, is the optimal form of diversity combining because it yields the maximal SNR achievable. It requires the exact knowledge of SNRs as well as the phases of the diversity signals. [4]

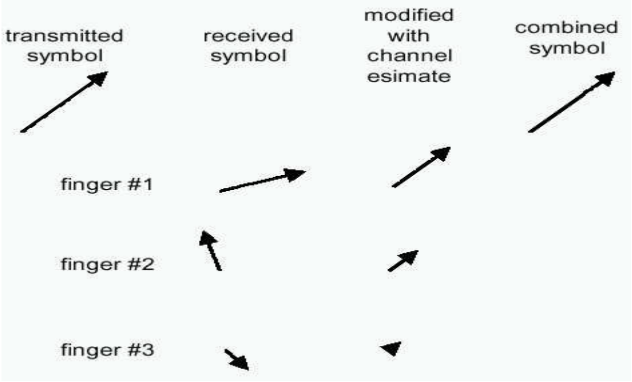

Figure 6. Maximal Ratio Combining in RAKE

After despreading the received symbol from transmitter via radio channel the symbols from allocated fingers are maximal-ratio-combined to construct the “combined” symbol. The output symbols from different fingers are multiplied with complex conjugate of the channel estimate and the result of multiplication is summed together into the “combined” symbol. This is illustrated in Figure 6 and Figure 7. [5]

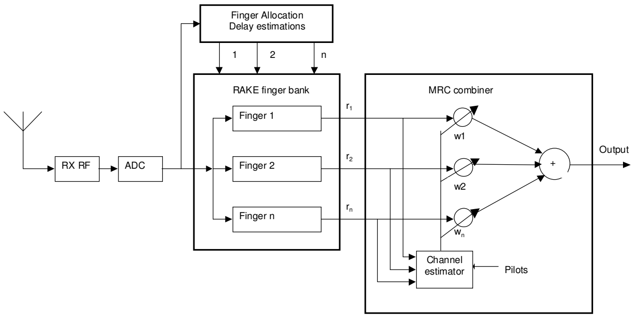

Figure 7. RAKE receiver using MRC

F. Practical RAKE Receiver Requirements

High bandwidth (5 MHz in WCDMA) and dynamic interference inherent to WCDMA requires that RF and IF parts have to operate linearly with large dynamic range.

In practical RAKE receivers synchronization sets some requirements. Automatic Gain Control (AGC) loop is needed to keep the receiver at the dynamic range of the A/D converter. AGC must be fast and accurate enough to keep receiver at the linear range. Frame-by-frame data range change may set higher AGC and A/D (Analog-to-Digital) converter requirements. The high sampling rates of few tens of MHz and high dynamics of the input signal (80 dB) require fast A/D converters and high resolution. [5]

Automatic Frequency Control (AFC) loop compensates for drift of the local oscillator and possibly compensates the Doppler shifts. Synchronization is required for channel impulse response measurements and scanning for RAKE finger allocation. Also channel delay tracking needs synchronization for fine-adjustment and tracking of multipath components. [5]

V. CONCLUSION

This paper has introduced the basic operation and requirements of RAKE receiver used in CDMA based systems such as IS-95 and WCDMA. RAKE receiver attempts to collect the time-shifted versions of the original signal by providing a separate correlation receiver for each of the multipath signals. The RAKE receiver uses several baseband correlators to individually process several signal multipath components. The correlator outputs are combined to achieve improved communications reliability and performance.

The basic functions of RAKE receiver are Channel delay estimation for multipath components, RAKE receiver finger allocation, descrambling and despreading operations, adaptive channel estimation, and Maximal-Ratio Combining.

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HOMEWORK

1. Explain shortly the basic functions in a RAKE receiver.

2. How many fingers can a Mobile Station RAKE receiver's matched filter or "searcher" allocate from a following multipath tapped delay line channel in WCDMA and IS-95 systems? Don't guess!

Tap	**1**	**2**	**3**	**4**	**5**	**6**
Avg. power (dB)	0	-1,5	-6,0	-4,5	-9,0	-15,5
Relative delay (ns)	0	310	500	1090	2430	2510