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LETTER

Power Efficient Transmission Scheme with Adaptive Cyclic Prefix for an Uplink of OFDMA Systems**

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SUMMARY A novel adaptive cyclic prefix (CP) transmission scheme is proposed for the uplink of orthogonal frequency division multiple access (OFDMA) systems to reduce the power consumption of mobile stations (MSs). In the proposed scheme, an MS adaptively changes its CP length in each frame, while the guard interval is maintained at a fixed duration to avoid frame synchronization problem and the interference problem with frames of other users. Using the proposed scheme, MSs can save power by not transmitting signal during the time difference between the guard interval and the duration of the adaptive CP. We numerically analyze the performance of the proposed scheme in terms of achievable capacity, the amount of power saving, and the feedback overhead of CP values. The result shows that the proposed scheme can reduce MS power consumption by about 20% with a small amount of additional feedback overhead.

key words: *cyclic prefix, guard interval, OFDMA system, power saving, cellular uplink*

1. Introduction

Recently, a number of orthogonal frequency division multiple access (OFDMA)-based wireless systems have been proposed [1]–[3]. In the uplink of OFDMA systems, each user utilizes certain sub-bands in frequency domain in order to transmit its data and the other user utilize different sub-bands, and then their transmit signals on frequency domain are received and added at base station (BS) in time domain. In addition, each user inserts cyclic prefix (CP) in the guard interval in OFDMA systems for eliminating both the inter-symbol interference (ISI) and the inter-carrier interference (ICI). If the CP duration is shorter than a given multipath delay spread, then the performance of OFDM systems degrades because of ISI. On the contrary, a long CP duration, compared with a given multipath delay spread, wastes time and transmission power.

We can find an optimum CP value if channel delay spread is given [4]. However, it is well known that the delay spread of a wireless channel is time-variant. Hence, it is natural to consider a transmission scheme with a variable CP in order to reduce the resource waste. A variable CP transmission scheme for wireless local area network (WLAN) was proposed in [5]. The authors proposed to use the time reduced by adaptive CP length for transmitting data and showed that it improved the throughput of the WLAN systems. However, in uplink of OFDMA systems, if each user changes the guard time with CP dynamically according to its channel characteristics, then the frame-synchronization is not possible and the inter-carrier interference occurs in the uplink of OFDMA systems because the start point of the OFDM symbol of each user is not the same. In this letter, we propose a new adaptive CP transmission scheme without causing frame synchronization and interference problems in the reverse link of OFDM cellular systems. In the proposed scheme, each MS maintains a fixed guard interval in order to eliminate the frame synchronization and interference problems and inserts the CP in a part of the guard interval according to the feedback information from a BS. The MS does not transmit data during the time difference between the guard interval and the duration of the CP, so that the MS can save its transmission power.

2. Proposed Adaptive CP Transmission Scheme

In frequency division duplex (FDD)-based cellular systems, the feedback of CP length values from a BS to MSs and the update of the CP length values in the MSs is performed in each frame. A channel is assumed to be time-invariant during a frame duration. Figure 1 shows the conceptual operation of the proposed scheme in FDD-based systems.

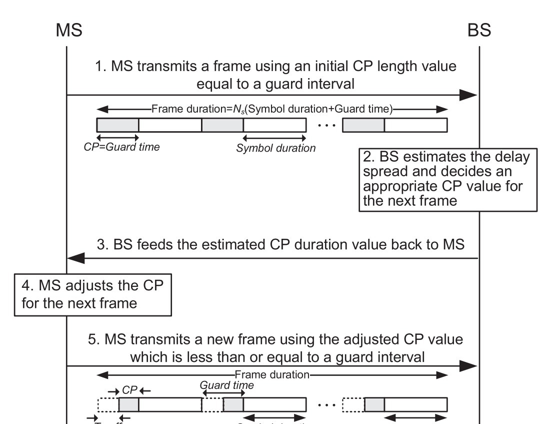

Fig. 1 The conceptual diagram of the proposed scheme in FDD-based systems.

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- An MS transmits a frame with a CP length value which is initially set to a given guard interval Δ.
- A BS estimates its channel and determines the CP length value for the next frame as an estimated maximum delay spread (τ) value. The delay spread can be estimated by the proposed way in [5]. The BS feeds this value back to the MS after quantizing. We consider Q quantization bits (that is, 2^Q quantization levels). The BS quantizes the CP length value as follows:

$$CP = \begin{cases} \frac{\Delta i}{2^Q}, & \frac{\Delta(i-1)}{2^Q} < \tau \leq \frac{\Delta i}{2^Q}, i = 1, \cdots, 2^Q \\ \Delta, & \tau > \Delta. \end{cases} \quad (1)$$

- The MS changes its CP length in each frame according to the feedback information. The MS turns off its power during the time difference between the guard interval and the adjusted CP length value and then wakes up to transmit data.

In time division duplex (TDD)-based cellular systems, the downlink and uplink channel are reciprocal each other, and each MS can estimate its delay spread of the wireless channel from the common pilot symbol in downlink. Thus, feedback overhead is not needed.

3. Performance Evaluation

3.1 SINR in a Multipath Environment

We first consider the m-th multipath with a relative delay τ_m in an N_{paths} multipath model. It has a normalized relative signal power ratio p_m $\left(\sum_{m=1}^{N_{paths}} p_m = 1\right)$, which consists of signal ($p_{s,m}$) and interference ($p_{i,m}$) parts. Introducing a bias function [4] defined as

$$B(\tau_m) = \begin{cases} 1, & 0 \leq \tau_m < \Delta \\ \frac{T_s - \tau_m + \Delta}{T_s}, & \Delta \leq \tau_m < T_s + \Delta \\ 0, & T_s + \Delta \leq \tau_m, \end{cases} \quad (2)$$

where T_s denotes the OFDM symbol time, we can derive $p_{s,m}$ and $p_{i,m}$ as follows:

$$p_{s,m} = B(\tau_m)^2 p_m, \quad p_{i,m} = p_m - p_{s,m} = \left(1 - B(\tau_m)^2\right) p_m. \quad (3)$$

Given a channel with N_{paths} multipaths, the SINR per subcarrier (Γ) can be expressed as

$$\Gamma = \frac{P_s}{P_i + r^n \frac{P_n}{P_{tx}}}, \quad (4)$$

where P_s and P_i are expressed, respectively, as

$$P_s = \sum_{m=1}^{N_{paths}} p_{s,m} \text{ and } P_i = \sum_{m=1}^{N_{paths}} p_{i,m} = 1 - P_s.$$

The terms P_{tx}, P_n, r, and n denote the transmit power per subcarrier, the thermal noise power, the distance from a transmitter and a receiver and the path loss exponent, respectively. The fading and shadowing are not considered. In order to obtain the density function of the maximum delay spread τ, we assume a simple two-ray multipath model for mathematical simplicity, where there are two dominant multipaths in a system ($N_{paths} = 2$) and the relative delay of the second multipath signal corresponds to the maximum delay spread τ, that is, $\tau = \tau_2$. This model is widely used to analyze the effect of CP or multipath because the primary interest is not the number of multipaths but the maximum delay spread if the CP value is determined by the maximum delay spread. It is well known that the root-mean-square delay spread (τ_{rms}) increases with an increasing distance from a transmitter and a receiver and is log-normally distributed [7]. Therefore, τ_{rms} can be expressed as:

$$\tau_{rms} = T_m r^{\epsilon} y, \quad (5)$$

where T_m, ϵ, and y are the median of τ_{rms}, an exponent related to the dependency of τ_{rms} on r, and a log-normal random variable, respectively. $Y = 10 \log y$ is a Gaussian random variable with zero mean and standard deviation σ_y and its density function is given as

$$f_Y(y) = \frac{10}{\sqrt{2\pi} \ln 10 \sigma_y y} \exp\left(-\frac{(10 \log_{10}(y))^2}{2\sigma_y^2}\right). \quad (6)$$

For $N_{paths} = 2$, τ_{rms} can be described as

$$\tau_{rms}^2 = \tau_2^2 p_2 - (\tau_2 p_2)^2 = \tau^2 p_2 - (\tau p_2)^2, \quad (7)$$

and then, τ can be derived as

$$\tau = \frac{\tau_{rms}}{\sqrt{p_2 - p_2^2}} = \frac{T_m r^{\epsilon}}{\sqrt{p_2 - p_2^2}} y = \frac{y}{\zeta}, \quad (8)$$

where ζ is defined as $\sqrt{p_2 - p_2^2}/(T_m r^{\epsilon})$. Then, we can derive the conditional density function of the maximum delay spread in the two-ray multipath model for a given r as follows:

$$\begin{aligned} f_{T|R}(\tau|r) &= \zeta f_Y(\zeta\tau) \\ &= \frac{10\zeta}{\sqrt{2\pi} \ln 10 \sigma_y \tau} \exp\left(-\frac{(10 \log_{10}(\tau\zeta))^2}{2\sigma_y^2}\right). \end{aligned} \quad (9)$$

3.2 System Capacity

The time overhead in the proposed scheme is $\Delta/(T_s + \Delta)$ because the fixed guard interval is set to Δ, which is the same as that of the existing OFDM systems. Therefore, the capacity of the proposed scheme is equivalent to that of the existing scheme with a fixed CP length equal to the guard interval. For a given guard interval, the average capacity (C) over a cell can be derived as

$$C = \frac{T_s}{T_s + \Delta} \int_0^R \left[f_R(r) \int_0^{\infty} f_{T|R}(\tau|r) \right.$$

$$\times \log_2\left(1+\frac{P_s(\tau)}{1-P_s(\tau)+r^n\frac{p_n}{p_{tx}}}\right)d\tau\Bigg]dr, \tag{10}$$

where the density function of a distance from the BS and a MS for a given cell radius R is expressed as $f_R(r) = 2r/R^2$. P_s becomes a function of τ if a channel profile is varying. Using Eqs. (2), (3) and (5), $P_s(\tau)$ for a given channel profile can be given by

$$P_s(\tau)=\begin{cases} p_1+p_2, & 0\le\tau<\Delta \\ p_1+\left(\frac{T_s+\Delta-\tau}{T_s}\right)^2 p_2, & \Delta\le\tau<T_s+\Delta \\ p_1, & T_s+\Delta\le\tau. \end{cases} \tag{11}$$

Equation (10) can be rewritten as Eq. (12) if $P_s(\tau)$ in Eq. (10) is replaced by Eq. (11).

$$\begin{aligned} C=&\frac{T_s}{T_s+\Delta}\int_0^R f_R(r)\Bigg[\int_0^\Delta f_{T|R}(\tau|r) \\ &\cdot\log_2\left(1+\frac{p_1+p_2}{1-(p_1+p_2)+r^n\frac{p_n}{p_{tx}}}\right)d\tau \\ &+\int_\Delta^{T_s+\Delta} f_{T|R}(\tau|r) \\ &\cdot\log_2\left(1+\frac{p_1+p_2\left(\frac{T_s+\Delta-\tau}{T_s}\right)^2}{1-\left(p_1+p_2\left(\frac{T_s+\Delta-\tau}{T_s}\right)^2\right)+r^n\frac{p_n}{p_{tx}}}\right)d\tau \\ &+\int_{T_s+\Delta}^\infty f_{T|R}(\tau|r)\log_2\left(1+\frac{p_1}{1-p_1+r^n\frac{p_n}{p_{tx}}}\right)d\tau\Bigg]dr. \end{aligned} \tag{12}$$

3.3 Power Saving Ratio

We define the power saving ratio $g(\tau)$ as the ratio of transmission-off period to the overall OFDM symbol duration in a frame for a given maximum delay spread τ. Contrary to the previous case of capacity, this power saving ratio is affected by the quantization of the CP value. Therefore, $g(\tau)$ can be represented as

$$g(\tau)=\begin{cases} \frac{\left(\Delta-\frac{i\Delta}{2^Q}\right)}{(T_s+\Delta)}, & \frac{(i-1)\Delta}{2^Q}<\tau\le\frac{i\Delta}{2^Q}, i=1,\cdots,2^Q \\ 0, & \tau>\Delta. \end{cases} \tag{13}$$

The average power saving ratio over the entire cell area can be calculated as

$$\begin{aligned} G&=\int_0^R f_R(r)\int_0^\infty f_{T|R}(\tau|r)g(\tau)d\tau dr \\ &=\int_0^R f_R(r)\int_0^\Delta f_{T|R}(\tau|r)g(\tau)d\tau dr \\ &=\int_0^R f_R(r)\cdot\sum_{i=1}^{2^Q}\left(\int_{\frac{(i-1)\Delta}{2^Q}}^{\frac{i\Delta}{2^Q}} f_{T|R}(\tau|r)\frac{\Delta-\frac{i\Delta}{2^Q}}{T_s+\Delta}d\tau\right)dr. \end{aligned} \tag{14}$$

Table 1 Parameters used for performance evaluation.

Parameters	Values
Number of subcarriers (N)	1024
Channel bandwidth (W)	100 MHz
OFDM symbol duration (T_s)	10.24 μsec
Transmitter power per subcarrier (P_{tx})	(200/N) mW
Noise density (N_0)	−174 dBm/Hz
Cell Radius (R)	1000 m
Path loss exponent (n)	3
Relative power of the second delay spread (p_2)	0.5
Median of rms delay spread (T_m)	1 μsec
Exponent related to τ_{rms} (ϵ)	0.5

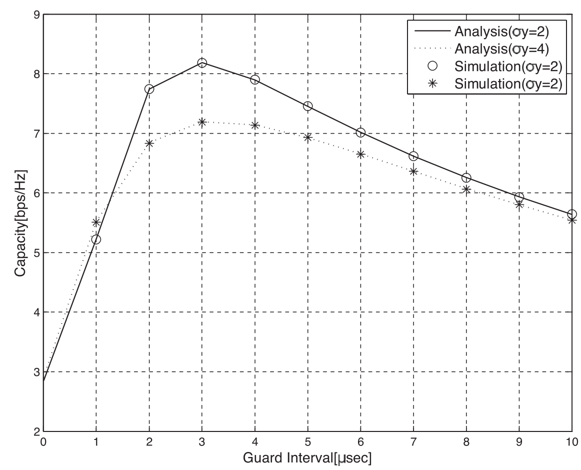

Fig. 2 Capacity for two different standard deviations of log-normal distribution (σ_y).

Table 2 Power saving ratio (%).

Δ (μs)	σ_y=2				σ_y=4			
	Analysis		Simulation		Analysis		Simulation	
	$Q=6$	$Q=\infty$	$Q=6$	$Q=\infty$	$Q=6$	$Q=\infty$	$Q=6$	$Q=\infty$
2	3.99	4.07	3.99	4.07	4.87	4.94	4.88	4.93
3	9.74	9.88	9.70	9.88	9.63	9.75	9.54	9.76
4	15.62	15.80	15.59	15.78	14.53	14.68	14.62	14.65
5	21.00	21.21	20.90	21.19	19.22	19.41	19.17	19.39

For evaluating the performance of the proposed adaptive CP scheme, we use the parameters in Table 1. The OFDM symbol duration is set to be 10.24 μs, while the guard interval can be controllable as long as it is shorter than the OFDM symbol duration. The simulations are performed with Monte-Carlo method (10^5 times for average) and the delay spread are generated by Eq. (9). Figure 2 shows the capacity for varying guard interval values. The capacity is maximized when the guard interval is approximately 3 μsec. If the guard interval is less than 3 μsec, the capacity degrades because of ISI. On the other hand, a longer guard interval degrades the capacity because of a larger time overhead. In the practical systems, the guard interval tends to be longer than the optimum guard interval analyzed in Fig. 2 due to the stability of the system.

Table 2 represents the average power saving ratio of the proposed adaptive CP scheme, which can be calculated from Eq. (14). The number of quantization bits is set to be 6 in Table 2 and it yields nearly the same performance as the case that $Q = \infty$. When the optimal guard interval (3 μs) is applied, the power saving ratio is around 10%. The analytical results agree with the simulation results. The power saving ratio increases around 20% when the guard interval is set to be 5 μs.

4. Conclusions

In this letter, we proposed an adaptive CP transmission scheme in the uplink of OFDM-based cellular systems. In the proposed scheme, MSs still use a fixed guard interval in order to maintain frame synchronization. On the other hand, MSs alter their CP lengths frame by frame according to the feedback information from the BS in FDD mode. In the TDD-based OFDMA systems, the proposed adaptive CP scheme does not require any signaling overhead, because each MS estimates its delay spread of the wireless channel by using the common downlink pilot symbol. The proposed scheme yields a power saving ratio of 20% with a small amount of additional feedback overhead for the guard interval of 5 μsec. In addition, the proposed scheme guarantees the same capacity as the conventional system. The proposed scheme can be a good candidate technique in the uplink of OFDMA-based next generation cellular systems where mobile stations are power-limited.

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