Successive Interference Canceller with Residual Interference Reduction for M2M Wireless Access System

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Abstract—**This paper proposes two residual interference reduction schemes for the successive interference canceller (SIC) in M2M wireless access systems. In general, it's difficult for SIC to completely eliminate interference due to channel estimation errors. Such errors are a serious problem if there are many terminals and the environment is multi-path. The first scheme, the Pre-FDE scheme, employs frequency domain pre-equalization (Pre-FDE) at the terminal side to alleviate the effect of multi-path propagation; it allows the base station to estimate the channel state information (CSI) precisely and also to reduce the residual interference. In the second scheme, the Path-SIC scheme, the base station estimates the CSI accurately by dealing with the interference replica of one path, not one terminal in one subtraction. Both schemes are simulated using actual temporal channel variations obtained by experiments. The simulation results show that the Pre-FDE scheme and the Path-SIC scheme improve the number of terminals transmitting simultaneously from 6 to over 10 compared with the conventional one. However, the PER performance of the Pre-FDE scheme degrades as the environmental speed increases.**

Keywords*—*M2M; successive interference canceller; frequency domain pre-equalization;

I. Introduction

Machine to machine (M2M) networking is being examined intently as a part of 3GPP, oneM2M, and METIS[1]-[3]. The basic assumptions for 3GPP[1], wide coverage area and low power consumption, are also extremely important to support the wireless access of M2M terminals. Cisco Systems predicts that the number of networked devices around the world will total some 50 billion in 2020[4]. Hence, M2M terminals will be very densely distributed and system capacity enhancements are needed.

To improve system capacity, many techniques are being studied such as Full Duplex[5], massive MIMO[6] and Successive Interference Caneller (SIC)[7]-[9]. Full Duplex means transmitting and receiving are performed simultaneously. In theory, Full Duplex doubles the system capacity if uplink traffic equals downlink traffic. Massive MIMO increases the system capacity by simply installing additional antennas at existing base stations. Massive MIMO can reduce thermal noises, interference, and channel estimation errors significantly, particularly if the base station has more antennas than supported terminals. In SIC, the interference replica of one terminal is generated after detecting the terminal's signal. Multi-access interference (MAI) can be reduced by subtracting the replica from the received signal before detecting the next terminal's signal. As a result, SIC can increase system capacity. These techniques appear to be the key elements of any future wireless access system.

When we consider M2M use cases, however, the above solutions have some shortcomings. Full Duplex has limited effectiveness in many M2M use cases because uplink and downlink traffic will not be balanced. In addition, the base station with massive MIMO requires very large space given the many large antennas needed to establish the VHF or UHF band communication needed for wide coverage areas. On the other hand, SIC improves the system capacity but only if extra computation power is added to the base station. The extra computation also burdens the base station, but not as much as massive MIMO because processor speed is rapidly increasing. Therefore, we select SIC as the most important solution for M2M access.

SIC has been added to CDMA and FDMA systems[7][8]. In CDMA, RAKE combining[10] can be used to improve SINR and achieve wide coverage areas. Therefore, CDMA with SIC is considered in this paper.

While CDMA with SIC is attractive, it does have some problems[9]. First, the computation load linearly increases with terminal number if all terminals are to be supported. Therefore, latency will be high in environments where the number of terminals is large such as M2M. Second, residual interference degrades the system capacity. The residual interference is what is left after subtracting the replica from the received signal due to channel state information (CSI) estimation errors. In CDMA with SIC in M2M environments, the causes of channel estimation errors are MAI from many terminals and the interference created by multi-path propagation. In summary, the key problems of CDMA with SIC are high latency and residual interference.

Some M2M applications such as metering and environment monitoring [11] accept high latency levels because their communications are intermittent. Therefore, we focus on residual interference in this paper and propose two schemes. The first one employs frequency domain pre-equalization (Pre-FDE)[12] at the terminal side. This scheme can reduce the effect of multi-path propagation and improve the accuracy of CSI estimation. In the second one, the interference replica of only one path is generated and subtracted after the path's signal is detected. This scheme can detect and remove interference more completely than the conventional approach.

In the first scheme, the temporal channel variation degrades

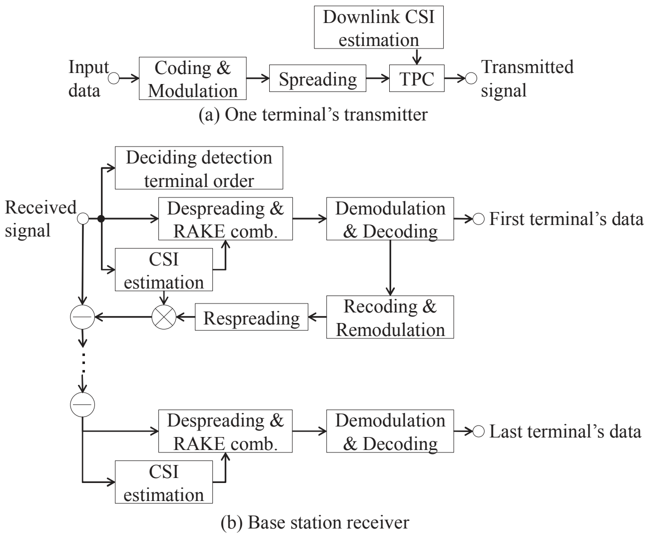

Fig. 1. Conventional CDMA with SIC system

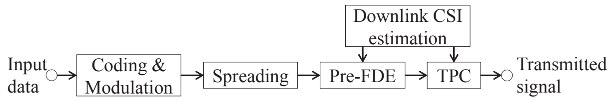

Fig. 2. Terminal transmitter in Pre-FDE scheme

system capacity because the scheme utilizes the downlink beacon signal. Therefore, we conduct simulations to confirm the effectiveness of the two schemes using parameters measured in two actual environments that are quite different.

This paper is organized as follows. Section II explains a conventional CDMA with SIC system and its problems. Section III introduces the two proposed schemes. Section IV presents the experiments conducted to determine temporal channel variations in actual environments. Section V shows the results of simulations made using the measured results. Finally, Section VI summarizes this paper.

II. Conventional CDMA with SIC

Fig. 1 shows a conventional CDMA with SIC system. In this system, the input data is first coded and modulated at each terminal's transmitter. Next, the modulated signal is spread using the terminal's unique spreading code such as a Gold sequence. After the transmit power control process, the signal is transmitted. At the base station side, the received power of each terminal is estimated using a matched filter to decide the detection order. Subsequently, the signal of the first terminal is detected. In the detection process, the CSIs of all paths for the first terminal are estimated for RAKE combining and for generating the interference replica. To estimate the CSIs, correlations are calculated between training signals and received signals. Next, despreading, RAKE combining, demodulation and decoding are sequentially applied to the received signal to extract the first terminal's data. In the SIC technique, the interference replica is generated by recoding, remodulation and adding the CSI to the first terminal's data. MAI is reduced after subtracting it from the received signal before detecting next terminal's data. The base station obtains all data transmitted in low MAI conditions by iterating the process from the first terminal to the last one.

In general, CDMA with SIC has two problems. The first one is the computation cost, which linearly increases with the number of terminals and causes high latency. The second one is residual interference, the interference that remains after subtracting the interference replica distorted by CSI estimation errors. These errors become serious due to MAI from other terminals and multi-path waves. If the orthogonality of the spreading code used is perfect, residual interference is not a problem. Unfortunately, the Gold sequence used in W-CDMA has imperfect orthogonality, so the residual interference can degrade the system capacity. With each iteration of the SIC process, the residual interference accumulates and negatively impacts the decoding processes for the following terminals. Especially in M2M, the number of terminals is so large that the accumulation of residual interference is far more significant than is true in other use cases.

III. Proposed Residual Interference Reduction Schemes

This section introduces the two schemes proposed for residual interference reduction.

A. The Pre-FDE scheme

Fig. 2 shows the terminal transmitter in the first proposed scheme, the Pre-FDE scheme. Compared with the conventional approach shown in Fig. 1, Pre-FDE[12] executes equalization prior to transmission to reduce the impact of multi-path propagation. In this scheme, the computation load increases for Pre-FDE at terminal side, but we assume applications which accept high latency as mentioned in Sec. I. Therefore, we consider the computation load negligible.

The performance of Pre-FDE matches that of Post-FDE[13] if the CSI is estimated with the same level of accuracy. In [12], Pre-FDE is introduced as a technique to migrate some of the computation loads of the receiver to the transmitter. This paper, however, considers that Pre-FDE has superior performance for two reasons. First, there are fewer base stations transmitting beacon signals simultaneously in the downlink than terminals in the uplink. Therefore, there is less interference in the downlink than the uplink. As a result, the accuracy of estimated CSI can be improved. Second, CAZAC sequences[14] provide better performance than Gold sequences as the spreading code for downlink beacon signals. However, the number of Gold sequences equals the spreading factor and it can be increased by using code scrambling as in [15]. This means that Gold sequences are appropriate given the sheer number of M2M terminals, all of which need a unique spreading code. Therefore, Gold sequences are used for uplink transmission in this paper. On the other hand, CAZAC sequences have better orthogonality than Gold sequences. This means that each path is detected clearly by using CAZAC sequences. Therefore, CAZAC sequences are used for downlink transmission in this paper. Note that the paucity of CAZAC sequences is not a serious problem because there are few base stations that are transmitting simultaneously. As a result, Pre-FDE improves the

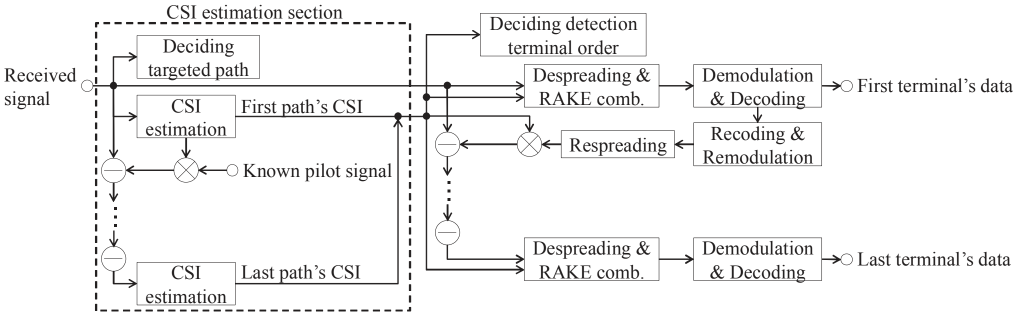

Fig. 3. Base station receiver in Path-SIC scheme

accuracy of estimated CSI. For these reasons, the performance of Pre-FDE is superior to that of Post-FDE.

In this scheme, the base station only has to cancel the first path in SIC process because Pre-FDE reduces the impact of multi-path propagation and then only the first path remains except for the second and latter ones. Therefore, the Pre-FDE scheme is expected to achieve better performance than conventional one.

However, the temporal channel variation degrades the performance of this scheme. Therefore, simulations conducted to confirm system performance must consider the temporal channel variation. The simulations in this paper use actual parameters obtained through experiments in actual environments.

B. The Path-SIC scheme

Fig. 3 shows the base station receiver in the second proposed scheme, the Path-SIC scheme. Unlike the conventional approach in Fig. 1, the receiver includes a CSI estimation section for all paths prior to deciding the terminal detection order, instead of CSI estimation after deciding the detection order. In this CSI estimation section, a process like SIC is performed to estimate the CSI of each path separately and precisely. A signal from one path of a terminal interferes with other signals from other paths of the same terminal due to the non-orthogonality of the spreading code. Therefore, if the CSI of each path is estimated without these interferences, the CSI estimates are more precise. The process is explained as follows:

1) Estimate all delay profiles of all terminals. If no amplitude of any path exceeds the threshold or the number of iterations reaches the predetermined threshold, the process terminates.
2) Select the path with largest amplitude excluding past estimated paths.
3) Estimate the amplitude and phase of the selected path.
4) Generate the interference replica for the selected path using the known pilot signal and the estimated amplitude and phase.
5) Subtract the interference replica from the received signal, return to 1).

As a result, the receiver obtains the CSIs of all terminals more precisely than the conventional approach. These CSIs are used in executing the subsequent processes, such as deciding detection terminal order, RAKE combining, and generating the interference replica of each terminal.

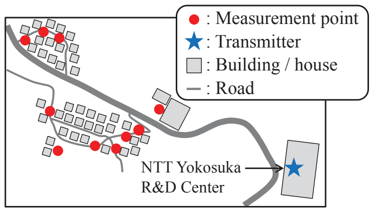

Fig. 4. Environment image of Yokosuka city

To realize the Path-SIC scheme more simply, it's also possible to increase the number of iterations in Fig. 1 from the number of terminals to the number of all paths of all terminals. However, RAKE combining is difficult in this simple scheme because different results are obtained from detecting each path of the same terminal. Therefore, in this paper, the scheme shown in Fig. 3 is adopted to perform RAKE combining.

In this scheme, the computation load increases because generating and subtracting the interference replica for each path. However, we consider the computation load negligible as well as the Pre-FDE scheme.

Section V confirms the performance of this scheme along with that of the Pre-FDE scheme.

IV. Measuring Temporal Channel Variation in Actual Environments

As mentioned in Section III, the temporal channel variation degrades the performance of the Pre-FDE scheme. In this paper, experiments are conducted to identify the parameters of the speed of the temporal channel variation in two different environments, Yokosuka city in Kanagawa and Musashino city in Tokyo. Fig. 4 and Fig. 5 show environment images of Yokosuka city and Musashino city, respectively. The traffic was slow and infrequent around the measurement point in Fig. 4 while it was fast and heavy in Fig. 5. In the experiments, Non-line-of-sight (NLOS) environments were selected as the measurement points, and the positions of the transmitter and the receiver were static to replicate major M2M use cases, such as metering and environment monitoring.

Table I shows the measurement parameters. The frequency of the transmitting signal is 923.4MHz, which lies in the

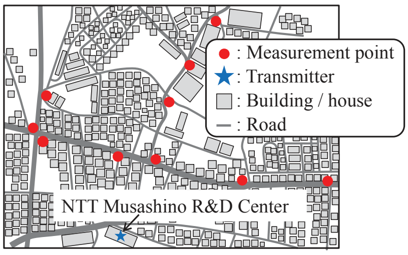

Fig. 5. Environment image of Musashino city

TABLE I. MEASUREMENT PARAMETERS

Parameter	Value
Frequency	923.4 MHz
Signal form	CW
Sending duration	100 msec
Pause duration	900 msec
Tx antenna	Omni-direction
Rx antenna	Omni-direction
Assumed processing time of terminal	10 msec

unlicensed band established for M2M in Japan[16]. To obtain the temporal channel variation, the level of the received signal is compared every 10 msec. We assume 10 msec as the processing time of the terminal for trigger transmission after receiving the downlink beacon signal.

The measured results are compared with simulation results yielded by the delay profile of channel model F in [17]. This model is selected because the method of how to modify the tap spacing to suit the bandwidth is described in [18]. [18] assumes that its approach is valid only for bandwidths above 20 MHz, but the simulations in Section V consider 6.4 MHz. We are convinced, however, that the approach can be used at lower bandwidths, so we modify the channel model F in [17] using the technique described in [18]. Table II shows the result of the modification in which the spacing is adjusted to the inverse of the total bandwidth, 6.4 MHz. The total power of all taps is normalized to conserve energy, and all clusters are summed up because the angle characteristic is not important in our simulations.

It is necessary to compare the measured results with the simulation results to determine the speed of surrounding objects in actual environments. This speed, defined as environmental speed in [17], determines the intensity of the temporal channel variation, and is expressed as

$$v = f_d \lambda \tag{1}$$

where v denotes environmental speed, f_d denotes Doppler frequency and λ denotes wavelength. [17] takes 1.2 km/h to be the typical environmental speed for W-LANs. Using f_d in (1), the frequency power spectrum of the simulation results is expressed as

$$S(f) = \frac{1}{1 + 9(f/f_d)^2} \tag{2}$$

TABLE II. MODIFIED DELAY PROFILE MODEL F

Tap index	1	2	3	4	5	6	7	8
Delay [ms]	0/6.4	1/6.4	2/6.4	3/6.4	4/6.4	5/6.4	6/6.4	7/6.4
Power [dB]	5.88	2.99	-1.39	-3.66	-7.50	-12.86	-16.40	-20.90

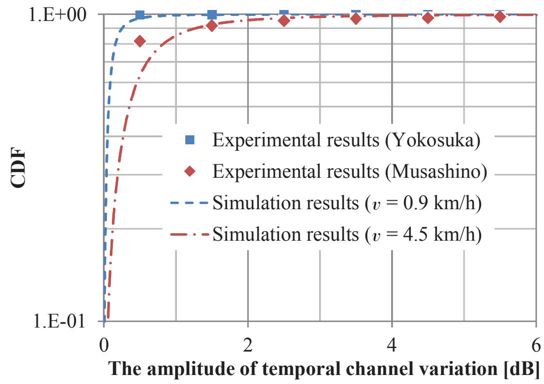

Fig. 6. CDF of the amplitude of temporal channel variation

TABLE III. SIMULATION PARAMETERS

Parameter	Value
The number of cells	1
Frequency	920 MHz
Total bandwidth	6.4 MHz
Modulation	QPSK
Packet size	16 Byte
Coding rate	1/2
Spreading code for downlink beacon	CAZAC sequence Spread factor 64
Channelization code for uplink signal	OVSF sequence Spreading factor 64
Scrambling code for uplink signal	Gold sequence [15] Spreading factor 1
Cell radius	300 m
Transmitting power of base station	250 mW
Maximum transmitting power of terminals	20 mW
Target SNR of transmitting power control	10 dB
Path Loss model	Okumura-Hata model for urban
Shadowing standard deviation	6 dB
Delay profile model	Modified model F [17]
Environmental speed	0.9 km/h / 4.5 km/h
Time interval	10 msec

where f denotes frequency. The simulation results of the temporal channel variation are obtained by the following processes.

1) Signals that follow a complex Gaussian distribution in the time domain are passed through the filter given by (2).
2) Iterate process 1) for all taps and modify the power of each tap according to Table II.
3) Synthesize all signals obtained in 2) considering each delay.

In the experiments, the signal is an intermittent continuous wave (CW). Therefore, the measured results are compared with the simulation results at one point of the frequency spectrum.

Fig. 6 shows the CDFs of the amplitude of the temporal channel variation obtained in Yokosuka city and Musashino city. It also shows the fitting curves for the simulation results setting v = 0.9 km/h and v = 4.5 km/h for the results of Yokosuka city and Musashino city, respectively. Based on these results, the following simulations take 0.9 km/h and 4.5 km/h as the actual environmental speeds.

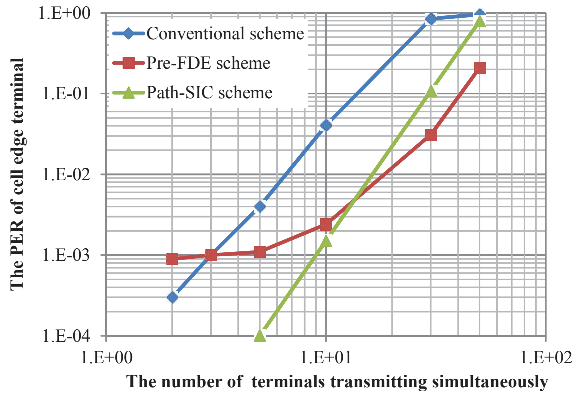

Fig. 7. The PER of cell edge terminal vs. The number of terminals transmitting simultaneously with $v = 0.9$ km/h

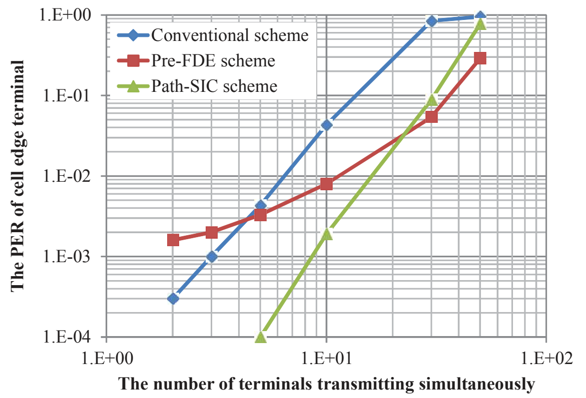

Fig. 8. The PER of cell edge terminal vs. The number of terminals transmitting simultaneously with $v = 4.5$ km/h

V. Simulation Results

In this paper, the proposed schemes are evaluated while varying the number of terminals transmitting simultaneously at PER = 10^{-2} because it is directly related to system capacity.

Table III shows the simulation parameters. In the simulations, transmitting signals are spread using channelization codes and scrambling codes to increase the number of spreading codes because it is assumed that more terminals exist than simultaneous transmitting terminals. Environmental speeds are 0.9 km/h and 4.5 km/h. Transmitting powers of all terminals are controlled to achieve the target SNR at the base station. If the path loss is too large to achieve the target SNR, the transmitting power of the terminal is the maximum limit. If the transmitting powers of all terminals don't reach the maximum limit, they are controlled again to make the maximum transmitting power of all terminals the maximum limit. The path loss is estimated as the average power of transmitting signal after applying Pre-FDE, where the power of the original transmitting signal is normalized. This is because the signal power decreases based on the above path loss in the Pre-FDE scheme. The above power control is not only applied in the Pre-FDE scheme, but also in the other schemes for fairness.

Fig. 7 and Fig. 8 show the simulation results with $v = 0.9$ km/h and $v = 4.5$ km/h, respectively. Focusing on PER = 10^{-2}, these results show that the Pre-FDE scheme and the Path-SIC scheme improve the terminal limit from 6 (conventional scheme) to over 10. However, the PER performance of the Pre-FDE scheme degrades as the environmental speed increases. These results indicate that both of the two schemes improve the terminal limit compared with the conventional one when the environmental speed is slow, and besides, the Path-SIC scheme improves it even when the environmental speed is fast.

VI. Conclusion

In this paper, two schemes, the Pre-FDE scheme and the Path-SIC scheme, were proposed to reduce the residual interference of CDMA with SIC for M2M wireless access systems. Experiments were conducted in two actual environments to measure the environmental speeds and thus the temporal channel variation because this variation aggravates the performance of the Pre-FDE scheme. The measurements yielded 0.9 km/h and 4.5 km/h as the environmental speeds in two different environments. Simulations using these speeds showed that the Pre-FDE scheme and the Path-SIC scheme improve the number of terminals transmitting simultaneously from 6 to over 10 compared with the conventional one. However, the PER performance of the Pre-FDE scheme degrades as the environmental speed increases.

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