Distributed STBC Transmit Diversity In The Presence of CCI From Adjacent Macro-Cells

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Abstract— **Small-cell structured network using distributed antennas significantly improves the spectrum and energy efficiencies simultaneously, and is a good candidate for the 5th generation (5G) mobile communications systems. To provide a good transmission quality over a macro-cell area, distributed space-time block coded transmit diversity (STBCTD) can be used to exploit distributed antennas close to a user equipment (UE). In this paper, we introduce transmit frequency-domain equalization (FDE), receive FDE, and cyclic delay transmission (CDT) into distributed STBCTD. In any cellular network, co-channel interference (CCI) from adjacent macro-cells limits the transmission quality. We evaluate by computer simulation the achievable OFDM downlink capacity using distributed STBCTD in the presence of CCI from adjacent macro-cells. It is shown that transmit FDE achieves higher capacity than receive FDE and CDT. Also shown is that by increasing the number of transmit antennas, transmit FDE improves the OFDM downlink capacity, but receive FDE and CDT do not.**

Keywords—small-cell network, distributed antennas, STBC, FDE, OFDM

I. Introduction

In the 5th generation (5G) cellular mobile communications systems, high quality broadband data services are demanded. However, due to the path loss, shadowing loss, and frequency-selective fading, providing high quality broadband data services uniformly over the macro-cell area is a difficult challenge under the limited bandwidth and transmit power. As a promising solution, we have been studying small-cell structured network using distributed antennas (hereafter, distributed antenna small-cell network) [1], where many distributed antennas (DAs) are deployed over each macro-cell area and they are connected by optical cables to macro-cell base station (MBS). Two or more distributed antennas nearby a user equipment (UE) can be found and they can be used as the spatial diversity branches to improve the transmission performance. One promising spatial diversity scheme is space-time block coded transmit diversity (STBCTD) [2], [3]. To obtain the frequency diversity gain in addition to the spatial diversity, frequency-domain equalization (FDE) can be combined with STBCTD. There are two types of FDE: transmit FDE and receive FDE. The number of transmit antennas for STBCTD is limited [4]. However, an arbitrary number of transmit antennas can be used by introducing the cyclic delay transmission (CDT) to STBCTD [5]. Furthermore, receive diversity can be combined to further enhance the transmission performance. Distributed STBCTD combined with either receive FDE, joint CDT/receive FDE (hereafter, referred to simply as CDT), or transmit FDE is an attractive diversity scheme for distributed antenna small-cell network.

The same frequency must be reused in any cellular network because the available bandwidth is limited. Therefore, CCI from adjacent macro-cells limits the transmission performance. In the case of distributed antenna small-cell network, both downlink transmitting points and uplink receiving points are distributed over each macro-cell area. This suggests that the CCI from adjacent macro-cells may affect differently from the case of traditional macro-cell networks (i.e., all transmitting/receiving antennas are collocated at MBS). However, this issue has not been fully discussed yet. This motivates us to investigate distributed STBCTD in the presence of CCI from adjacent macro-cells.

In this paper, we consider the OFDM [6], [7] downlink of distributed antenna small-cell network and evaluate by computer simulation the achievable downlink capacity using distributed STBCTD in the presence of CCI from adjacent macro-cells. The rest of this paper is organized as follows. Sect. II gives the distributed antenna small-cell network model. Sect. III describes the distributed STBCTD transmitter/receiver structure for OFDM downlink. Sect. IV introduces the capacity equations of OFDM downlink with distributed STBCTD. Computer simulation results are provided in Sect. V. The OFDM downlink capacity distribution and the impact of the number of distributed transmit antennas are discussed. Sect. V offers some concluding remarks.

II. Cellular and Propagation Channel Models

DAs to be used in distributed STBCTD are selected depending on channel condition. Therefore describing distributed STBCTD in Sect. III, the cellular model and propagation channel model are presented.

A. *Cellular model*

Figure 1 shows the cellular model consisting of 7 macro-cells each with N_{DA}=7 distributed antennas. The c=0th (center) macro-cell is the cell of interest and the c=1~6th adjacent macro-cells in the 1st-tier are considered. R and R' denote macro-cell radius and small-cell radius, respectively. In this paper, we consider a certain resource block and assume that the single user equipment (UE) having N_r receive antennas in each macro-cell is assigned this resource block by scheduling. Because of scheduling, the locations of co-channel UEs, which are assigned the same resource block, are related to each other, however in this paper, the location of each UE is randomly generated in each macro-cell area. The STBCTD selects N_t transmit antennas among 7 distributed antennas based on the instantaneous power criterion.

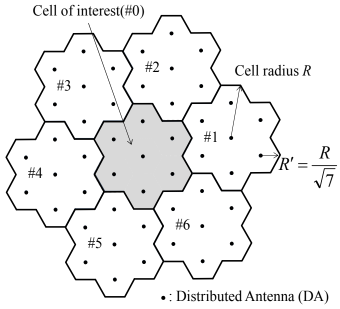


Fig.1 Cellular model (N_{DA}=7).

B. *Propagation channel model*

The broadband wireless propagation channel is characterized by distance-dependent path loss, log-normally distributed shadowing loss and L-path frequency-selective fading [8]. The channel between a particular UE and DA is modeled as either Nakagami-Rice fading or Rayleigh fading, depending on the distance between receive antenna of UE and transmit DA. The distance between the n_rth receive antenna of UE of interest in the 0th macro-cell and the n_tth transmit DA in the c(=0~6)th macro-cell is denoted by $d_{c,0}(n_t,n_r)$. It is assumed that the channel experiences Nakagami-Rice fading (K>0) if $d_{c,0}(n_t,n_r)$ is equal to or shorter than $R/\sqrt{7}$, otherwise the channel experiences Rayleigh fading (K=0), where K is the so-called K factor and defined as the direct-to-sum of delay paths power ratio.

The channel impulse response $h_{c,0}(\tau;n_t,n_r)$ between the n_rth receive antenna of UE of interest in the 0th macro-cell and the n_tth transmit DA in the c(=0~6)th macro-cell can be expressed as

$$h_{c,0}(\tau;n_t,n_r)=\left(d_{c,0}(n_t,n_r)\right)^{-\frac{\alpha}{2}}\sqrt{10^{-\frac{\eta_{c,0}(n_t,n_r)}{10}}}\times\left\{\begin{array}{l}\sqrt{\dfrac{K}{K+1}}\exp\left(j\theta_{c,0}(n_t,n_r)\right)\delta\left(\tau-\tau_{c,0}(n_t,n_r)\right)\\+\sqrt{\dfrac{1}{K+1}}\sum_{l=0}^{L-1}\xi_{c,0}(l;n_t,n_r)\delta\left(\tilde{\tau}_{c,0}(l;n_t,n_r)\right)\end{array}\right\}, \quad (1)$$

where α is the pass loss exponent and $\eta_{c,0}(n_t,n_r)$ is the shadowing loss in dB having zero-mean and standard deviation σ. $\theta_{c,0}(n_t,n_r)$ is the phase of direct path which is assumed to be uniformly distributed and $\tau_{c,0}(n_t,n_r)$ is the delay time of direct path. $\xi_{c,0}(l;n_t,n_r)$ and $\tilde{\tau}_{c,0}(l;n_t,n_r)$ are the complex-valued path gain following the zero-mean Gaussian distribution and the l-th path delay time, respectively.

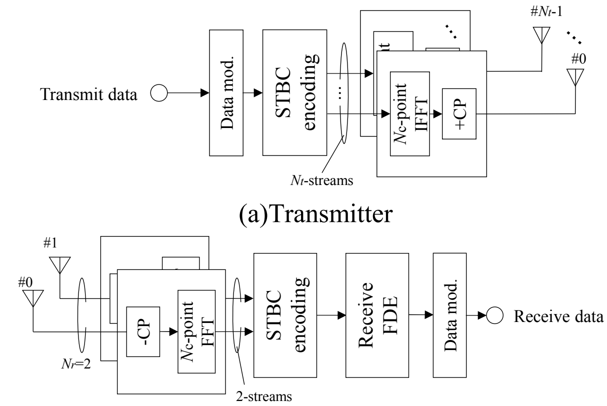
III. Operation Princple of Distributed Antenna STBCTD for OFDM Downlink

OFDM with N_c subcarriers is considered. N_t (≤ 7) DAs among 7 DAs are used for downlink transmission. UE is equipped with N_r receive antennas. Below, STBCTD combined with receive FDE is described first and then, those combined with joint CDT/receive FDE and with transmit FDE are described.

A. *STBCTD combined with receive FDE*

Figure 2 shows the transmitter/receiver structure of STBCTD combined with receive FDE for the case of N_r=2 receive antennas (note that N_r can be an arbitrary number). At the transmitter, a data-modulated symbol sequence is generated according to the bit sequence to be transmitted and is divided into blocks of N_c symbols each. Then, a sequence of J data-modulated blocks is STBC encoded into N_t parallel streams, each stream consisting of Q blocks. For the operation principle of STBCTD, refer to Ref. [9]. After applying N_c-point IFFT to each block in each stream, a sequence of Q cyclic prefix (CP)-inserted blocks is transmitted from one of N_t transmit antennas. The transmission power is equally allocated to each antenna. Table 1 shows the relationship among N_t, J, Q, and STBC code rate $R_{\mathrm{STBC}}=J/Q$ for STBCTD combined with Receive FDE. The spatial diversity gain can be increased by increasing the value of N_t, but R_{STBC} reduces.

At the receiver, the CP-removed received signal on each antenna is decomposed by N_c-point FFT into N_c subcarrier components. Receive FDE using N_r received signals and then, STBC decoding are carried out successively to obtain a sequence of J signal blocks. For the operation principle of receive FDE, refer to Ref. [10]. Finally, data de-modulation is carried out. STBCTD combined with receive FDE achieves the $N_t\times N_r$th order spatial diversity.



(a)Transmitter

(b) Receiver

Fig.2 STBCTD combined with receive FDE.

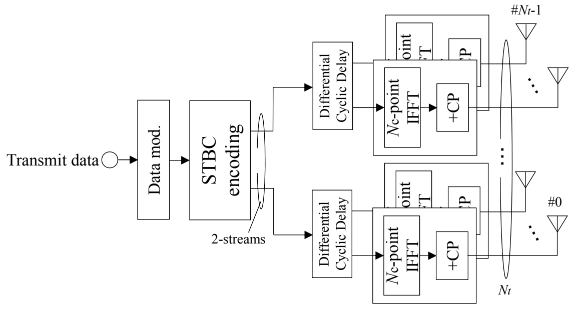
Table 1 Relationship among N_t, J, Q, and R_{STBC}.

N_t	J	Q	R_{STBC}
1	1	1	1
2	2	2	1
3	3	4	3/4
4	3	4	3/4
5	10	15	2/3
6	20	30	2/3

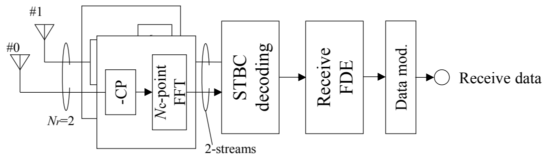
B. *STBCTD combined with CDT*

Figure 3 shows transmitter/receiver structure of STBCTD combined with CDT. The STBC encoding/decoding of (J,

Q)=(2,2) can be used to keep R_{STBC}=1 always regardless of N_t. N_t transmit antennas are equally divided into 2 antenna groups. 2 data streams are outputted from (2,2) STBC encoder. For CDT, a differential cyclic delay is added to each stream [11] to generate $N_t/2$ cyclic delay-added copies to be transmitted from one of two antenna groups after N_c-point IFFT and CP insertion. The transmission power is equally divided to each antenna. At the receiver, exactly the same reception procedure as STBCTD combined with receive FDE is carried out.



(a)Transmitter

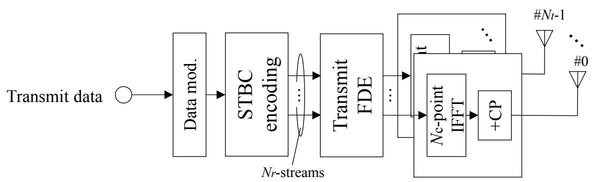


(b)Receiver

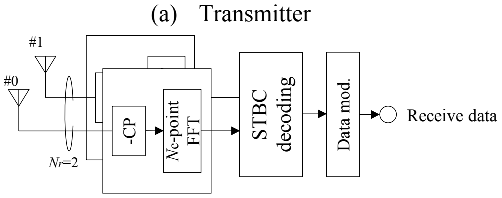
Fig.3 STBCTD combined with CDT.

C. *STBCTD combined with transmit FDE*

Figure 4 shows the transmitter/receiver structure of STBCTD combined with transmit FDE. In the case of receive FDE, the number N_t of transmit antennas determines the STBC encoding parameters: J, Q, and R_{STBC}. However, in the case of transmit FDE, it is the number N_r of receive antennas, which determines J, Q, and R_{STBC}, as shown in Table 2 [9]. Below, the encoding/decoding procedures are omitted for the sake of brevity. After STBC encoding, N_r parallel streams are obtained, each stream consisting of Q blocks. Transmit FDE generates N_t pre-equalized symbols from N_r input symbols for each subcarrier. For the operation principle of transmit FDE, refer to Ref. [12]. Note that the transmit power allocation among N_t antennas depends on the channel condition and is determined by transmit FDE.



(a) Transmitter



(b)Receiver

Fig.4 STBCTD combined with transmit FDE.

Table 2 Relationship among N_r, J, Q and R_{STBC}.

N_r	J	Q	R_{STBC}
1	1	1	1
2	2	2	1
3	3	4	3/4
4	3	4	3/4
5	10	15	2/3
6	20	30	2/3

IV. OFDM Downlink Capacity With Distributed STBCTD

UE measures the instantaneous received signal powers from 7 DAs of own macro-cell. N_t (≤ 7) transmit DAs having largest received signal power are selected among 7 DAs. The downlink capacity for UE in the c=0th macro-cell is considered. The adjacent macro-cells are indexed as c=1~6. Below, N_t transmit DAs in each macro-cell are indexed as $n_t(=0\sim N_t-1)$ in the descending order of the received signal power.

The downlink capacity (bps/Hz) can be computed from

$$C=R_{STBC}\frac{1}{N_c}\sum_{k=0}^{N_c-1}\log_2\left(1+\gamma(k)\right),\qquad(2)$$

where $\gamma(k)$ is the instantaneous received signal-to-interference plus noise power ratio (SINR) after STBC decoding and is given by [10], [12], [13]

$$\gamma(k)=\begin{cases}\dfrac{\dfrac{1}{N_t}\dfrac{E_s}{N_0}\left|\displaystyle\sum_{n_t=0}^{N_t-1}\sum_{n_r=0}^{N_r-1}W_0^{Rx}(k;n_t,n_r)H_{0,0}(k;n_t,n_r)\right|^2}{\left[\begin{array}{l}\dfrac{1}{N_t}\dfrac{E_s}{N_0}\displaystyle\sum_{c=1}^{6}\sum_{n_t=0}^{N_t-1}\sum_{n_r=0}^{N_r-1}\left|W_c^{Rx}(k;n_t,n_r)H_{c,0}(k;n_t,n_r)\right|^2\\+\displaystyle\sum_{n_t=0}^{N_t-1}\sum_{n_r=0}^{N_r-1}\left|W_0^{Rx}(k;n_t,n_r)\right|^2\end{array}\right]} & \text{for receive FDE, (3a)}\\[2ex]\dfrac{\dfrac{1}{N_t}\dfrac{E_s}{N_0}\left|\displaystyle\sum_{n_t'=0}^{1}\sum_{n_r=0}^{N_r-1}W_0^{CDT}(k;n_t',n_r)\widetilde{H}_{0,0}(k;n_t',n_r)\right|^2}{\left[\begin{array}{l}\dfrac{1}{N_t}\dfrac{E_s}{N_0}\displaystyle\sum_{c=1}^{6}\sum_{n_t'=0}^{1}\sum_{n_r=0}^{N_r-1}\left|W_c^{CDT}(k;n_t',n_r)\widetilde{H}_{c,0}(k;n_t',n_r)\right|^2\\+\displaystyle\sum_{n_t'=0}^{1}\sum_{n_r=0}^{N_r-1}\left|W_0^{CDT}(k;n_t',n_r)\right|^2\end{array}\right]} & \text{for CDT, (3b)}\\[2ex]\dfrac{\dfrac{1}{N_r}\dfrac{E_s}{N_0}\left|\displaystyle\sum_{n_t=0}^{N_t-1}\sum_{n_r=0}^{N_r-1}W_0^{Tx}(k;n_t,n_r)H_{0,0}(k;n_t,n_r)\right|^2}{\left[\begin{array}{l}\dfrac{1}{N_r}\dfrac{E_s}{N_0}\displaystyle\sum_{c=1}^{6}\sum_{n_t=0}^{N_t-1}\sum_{n_r=0}^{N_r-1}\left|W_c^{Tx}(k;n_t,n_r)H_{c,0}(k;n_t,n_r)\right|^2\\+1\end{array}\right]} & \text{for transmit FDE, (3c)}\end{cases}$$

where E_s/N_0 is the total downlink transmit signal-to-noise power spectrum density ratio. $\widetilde{H}_{c,0}(k;n_t',n_r)$ for CDT is the equivalent channel between the n_t' (=0 or 1)th transmit DA group in the c(=1~6)th macro-cell and the n_rth receive antenna of UE in the 0th macro-cell, given by

$$\widetilde{H}_{c,0}(k;n_t',n_r)=\sum_{g=0}^{N_t/2-1}\begin{matrix}H_{c,0}(k;2g+n_t',n_r)\\ \times\exp(-j2\pi\cdot k\cdot g\cdot\theta/N_c)\end{matrix},\qquad(4)$$

where the parameter θ represents the cyclic delay. Note that $H_{0,0}(k;n_t,n_r)$ for CDT represents the equivalent channel between the n_t' (=0 or 1)th transmit DA group and the n_rth receive antenna of UE both in the 0th macro-cell. $W_c^{Rx}(k;n_t,n_r)$, $W_c^{CDT}(k;n_t',n_r)$, and $W_c^{Tx}(k;n_t,n_r)$ are respectively the FDE weight for STBCTD combined with receive FDE, CDT, and transmit FDE, in the c(=0~6)th macro-cell. In this paper, the maximum SINR based FDE weight is used, which is given by

$$W_c^{Rx}(k;n_t,n_r)=\frac{H_{c,c}^*(k;n_t,n_r)}{\left(\frac{1}{N_t}\frac{E_s}{N_0}\right)^{-1}\left(\frac{I_{0,CCI}(n_r)}{N_0}+1\right)},\qquad(5a)$$

$$W_c^{CDT}(k;n_t',n_r)=\frac{\widetilde{H}_{c,c}^*(k;n_t',n_r)}{\left(\frac{1}{N_t}\frac{E_s}{N_0}\right)^{-1}\left(\frac{I_{0,CCI}(n_r)}{N_0}+1\right)},\qquad(5b)$$

$$W_c^{Tx}(k;n_t,n_r)=\frac{\dfrac{H_{c,c}^*(k;n_t,n_r)}{\left(\frac{1}{N_r}\frac{E_s}{N_0}\right)^{-1}\left(\frac{I_{0,CCI}(n_r)}{N_0}+1\right)}}{\sqrt{\frac{1}{N_c}\sum_{k=0}^{N_c-1}\sum_{n_t=0}^{N_t-1}\sum_{n_r=0}^{N_r-1}\left|\dfrac{H_{c,c}(k;n_t,n_r)}{\left(\frac{1}{N_r}\frac{E_s}{N_0}\right)^{-1}\left(\frac{I_{0,CCI}(n_r)}{N_0}+1\right)}\right|^2}},\qquad(5c)$$

where $I_{0,CCI}(n_r)$ is the block-averaged CCI power spectrum density from adjacent macro-cells transmit DAs on the n_rth receive antenna of UE in the cth macro-cell. $H_{c,c}(k;n_t,n_r)$ is the channel between the n_t th transmit DA and the n_rth receive antenna of UE both in the cth macro-cell. The channel state information (CSI) is required at MBS for STBCTD combined with transmit FDE while it is required at UE for STBCTD combined with receive FDE and CDT.

V. SIMULATION RESULTS

Computer simulation conditions are summarized in Table 3. The channel is assumed to be a quasi-static frequency-selective block Nakagami-Rice or Rayleigh fading channel having symbol spaced L=16 path uniform power delay profile with decay factor α. In this paper, the perfect CSI is assumed. The co-channel interference limited environment ($E_s/N_0\rightarrow\infty$) is assumed. This assumption is reasonable because, in distributed antenna small-cell network, the distance between UE and DA is short and hence, the interference from adjacent macro-cells becomes a dominant factor limiting the transmission performance. By computer simulation, we evaluate the OFDM downlink capacity. As the performance measure, the 5% outage capacity is used, which represents the 5th percentile of the capacity distribution.

Table 3 Computer simulation conditions.

Cellular	No. of Destributed Antennas	N_{DA}=7
	Small-cell radius	$R'=R/\sqrt{7}$
Transmitter/ Receiver	No. of FFT block size	N_c=128
	Guard interval length	N_g=16
	No. of Transmit Antennas	N_t=1,…,6
	No. of Receive Antennas	N_r=2
Channel	Path loss exponent	α=3.5
	Shadowing loss standard deviation	σ=7.0(dB)
	Channel estimation	Ideal
	Frequnecy-Selective Block Nakagami-Rice/ Rayleigh Fading	
	Nakagami-Rice K-factor	K=10(dB)
	Delay profile	16-path uniform
	Interference-limited	

A. *Downlink capacity distribution*

Figure 5 shows the cumulative distribution function (CDF) of the OFDM downlink capacity for three STBCTD schemes when N_t=4. It can be seen from Fig.5 that the transmit FDE achieves the highest downlink capacity among three STBCTD schemes. The reason can be described as follows. In the case of receive FDE, the STBC code rate $R_{\rm STBC}$ reduces to 3/4 when N_t=4. Although, in the case of CDT, the code rate of 1 is kept even when N_t=4 (the STBC encoding/decoding of (J, Q)=(2,2) can be always used irrespective of the value of N_t), however, only the N_r=2th order spatial diversity is obtained. Therefore, the additional frequency-diversity gain is marginal since the channel frequency-selectivity is already strong enough. On the other hand, transmit FDE achieves the highest order of spatial diversity, which is the ($N_t\times N_r$)th order.

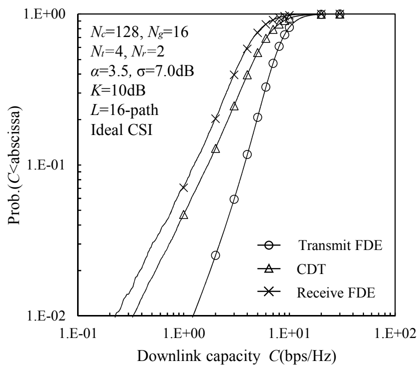


Fig.5 CDF of OFDM downlink capacity when N_t=4.

B. *Impact of N_t*

Below, how the downlink capacity is affected by the value of N_t is discussed. Figure 6 plots the 5% outage downlink capacity as a function of N_t. When combined with either receive FDE or CDT, the downlink capacity is degraded by increasing the value of N_t. This is because, as N_t increases, probability of choosing the DAs far away from the target UE and closer to the macro-cell edge increases. In the case of equal power allocation among DAs, the transmit power from DAs far away from the target UE are wasted. Furthermore, stronger CCI is given to adjacent macro-cells. This suggests that equal power allocation is not appropriate.

In contrast, in the case of transmit FDE, the downlink capacity improves by increasing the value of N_t. Higher transmit power is allocated to DA closer to UE. Therefore, the transmit power allocated to a DA near the macro-cell edge can be much lower than the cases of receive FDE and CDT on average. This suggests that adjacent macro-cells CCI can be weaker than the cases of receive FDE and CDT. Furthermore, even if more DAs are involved, most of transmit power is always allocated to DAs near UE and hence, no transmit power waste is caused.

However, even when combined with transmit FDE, the downlink capacity improvement gets smaller as N_t increases. By increasing N_t from 1 to 6, the downlink capacity improves by 17% only. This is because more distant DAs from UE are selected as N_t increases. This means that in order to further improve the downlink capacity, macro-cell cooperation needs to be introduced so as to make the macro-cell edge disappear.

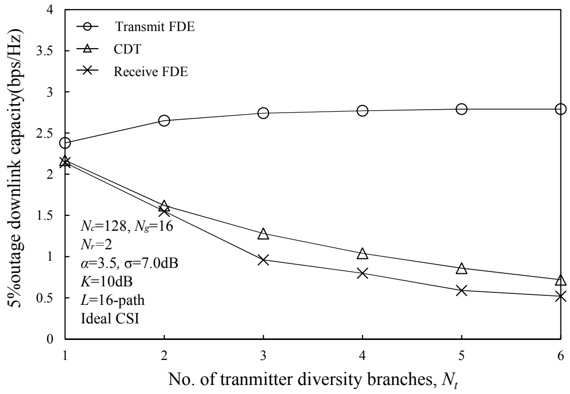


Fig.6 5% outage downlink capacity as a function of N_t.

VI. CONCLUSIONS

We evaluated by computer simulation the OFDM downlink capacity achievable with distributed STBCTD in the presence of CCI from adjacent macro-cells. We considered three STBCTD schemes, namely, STBCTD combined with receive FDE, CDT, and transmit FDE. It was shown that transmit FDE provides the largest OFDM downlink capacity among three STBCTD schemes. Also shown was that by increasing the number of transmit DAs, the use of transmit FDE improves the downlink capacity, however, the use of either receive FDE or CDT does not. An arbitrary number of transmit antennas can be used for STBCTD combined with transmit FDE. Therefore, the use of transmit FDE is the best for STBCTD downlink. On the other hand, for the STBCTD uplink, receive FDE can be employed. In this case, an arbitrary number of receive antennas can be used. As a consequence, FDE signal processing for both STBCTD downlink and uplink transmissions can be implemented at MBS and the signal processing required at UE can be kept low.

In this paper, we considered the case of single UE being served in each macro-cell area. However, in practical systems, there are many active UEs in each macro-cell area. Scheduling to select one UE from among many active UEs must be considered. This scheduling issue for distributed STBCTD in a distributed antenna small-cell network is an important technical issue. Furthermore, in this paper, we assumed ideal channel estimation. However, in any practical system, the channel estimation error exists. Impact of the channel estimation error on STBCTD is also another important issue. They are left as our important future study.

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