# An Performance Study for Sectorised Antenna based Doppler Diversity in High-Speed Railway Communications

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**Abstract.** *The wireless channel of High-Speed Railway communication system is rapidly time-varying. The orthogonal frequency division multiplexing transmitting over this channel will be exposed to the intercarrier interference caused by large Doppler spread. The sectorised antenna can be employed for Doppler mitigation and obtaining Doppler diversity gain. In this paper the performance of this directional antenna is analyzed. The preferable partition scheme for the omnidirectional antenna and the optimal Doppler compensation frequency are addressed firstly. The uncorrelated property of the signal received from the different sectorised antennas is demonstrated originally which can be utilized for Doppler diversity gain. Finally, it is proved by the simulation results that this architecture will allows us to achieve remarkable performance under high-mobility conditions.*

## Keywords

Doppler diversity, sectorised antenna, High-Speed Railway.

## 1. Introduction

The development of China Railway High Speed attracts the world's attention. In Dec. of 2010, China's CRH-380A train set a new speed record for unmodified commercial use at 486.1 km/h on a test run on the Beijing-Shanghai high-speed railway [1]. However, there is a technology bottleneck between high mobility scenario and broadband wireless data transmission either the services for the passengers' wireless demands or for railway control system in High-Speed Railway Communications (HRC). Orthogonal frequency division multiplexing (OFDM) can transmit data at a high speed over a frequency selective channel. However, the longer duration of the OFDM symbol will be affected by the rapidly time-varying channel resulting from severe Doppler frequency shift which introduces intercarrier interference (ICI).

ICI caused by the Doppler spread cannot be corrected by auto-frequency control (AFC) because Doppler shift is random and in multipath channel the received signal is composed of many incidence waves with different Doppler frequency shifts due to arriving angles. To handle ICI, numerous ICI mitigation methods have been developed such as time domain windowing [2], all phase OFDM system [3] and ICI self-cancelation [4]. The frequency efficiency of some algorithms is lower which is not competent for high data transmission in HRC. Klenner in [5], [6] applied the sectorised antenna architecture for multiple directional reception. This scheme facilitates high speed data transmission in isotropic and larger Doppler spread channel. With the directional antenna, the Doppler spectrum is divided into a set of sub-spectra which can be compensated by corresponding frequency. Each sub-spectrum is narrowed so that the time selectivity is alleviated due to the fact that it experiences a fraction of the full spread.

Our main concern in this paper is analysis of the performance of this scheme theoretically. Firstly, various partition schemes for isotropic antenna will be investigated and it can be concluded that Equal Doppler Spread method outperforms others. Then the optimal Doppler compensation shift scheme will be proposed. In order to obtain the Doppler diversity, we will originally prove that the received signals from different directional antennas are uncorrelated under Jakes' Doppler spectrum model. Finally, the simulation results show that sectorised antenna used in HRC is able to improve the performance of communication system. And the results of the special cases that line of sight as Rice component takes a dominant position and two rays with the opposite Doppler shift occur in High-Speed Railway scenario are firstly presented.

This paper is organized as follows. In Section 2 the relationship between the partition scheme and time selectivity is analyzed. Section 3 presents the preferable partition scheme of the directional antenna. In Section 4 the uncorrelated property of the signal from different directional antenna is demonstrated. Section 5 depicts the performances of this directional scheme in HRC channel model. Finally, the conclusions are drawn in Section 6.

# 2. Relationship between Doppler Spectrum and the Time Selectivity

For Jakes' model [7], the classical Doppler spectrum is

$$p_f(f) = \begin{cases} \frac{1}{\pi f_{max}\sqrt{1-(f/f_{max})^2}} & |f| \le f_{max} \\ 0 & |f| > f_{max} \end{cases} \quad (1)$$

where $f_{max}$ is the maximum Doppler frequency shift. Here, the spectrum is based on the following three assumptions: (a) The propagation of the electromagnetic waves take place in a two-dimensional plane, and the receiver is located in the center of an isotropic scattering area. (b) The angles of arrival waves reaching the antenna are uniformly distributed in the interval $[-\pi, \pi)$. (c) The antenna at the receiver side is circular-symmetrical (omnidirectional antenna). The flat fading case is assumed for simplicity. If the scatters are dense and uniformly distributed, the received signal can be written as a sum of signals. Then the spectrum as (1) can be divided into several sub-spectra. In [8] an Equal Doppler Contribution (EDC) partition method is proposed. The angular interval can be obtained by the following equations which we will investigate in Section 3 as

$$\begin{aligned} &\sqrt{\phi_K - \phi_{K-1}}\left(\sin(\phi_K) - \sin(\phi_{K-1})\right) \\ &= \sqrt{\phi_{K-1} - \phi_{K-2}}\left(\sin(\phi_{K-1}) - \sin(\phi_{K-2})\right) \\ &= \cdots \ \cdots \\ &= \sqrt{\phi_1 - \phi_0}\left(\sin(\phi_1) - \sin(\phi_0)\right) \end{aligned} \quad (2)$$

where $\phi_k(k = 0, 1, \cdots K)$ is the angle limit of each directional angle. If the EDC is employed, the Doppler frequency shift factor can be compensated before demodulation as

$$\zeta_k = \cos\left(\frac{\phi_{k-1} + \phi_k}{2}\right). \quad (3)$$

After Doppler adjustment, the relationship between the time correlation and the Doppler spectrum $P_{sector}(f)$ as Fourier transformation is

$$R(\tau) = \int_{S_{k-1}}^{S_k} P_{sector}(f) e^{-j2\pi f \tau} df \quad (4)$$

where $S_k$ is the frequency bound of the $k^{\text{th}}$ sector. Then the sub-spectrum is to be combined after Doppler compensation, we can obtain the time correlation as

$$\begin{aligned} R(\tau) &= \frac{1}{\pi} \sum_{k=0}^{K-1} e^{-j2\pi f_{\max}\zeta_k \tau} \\ &\cdot \left( \int_{S_k}^{S_{k+1}} \frac{1}{f_{\max}\sqrt{1-(f/f_{\max})^2}} e^{-j2\pi f \tau} df \right). \end{aligned} \quad (5)$$

Here we give the numerical integration results of the relationship between the fading rate and Doppler spread partition from (5) as in Fig. 1. It is known that the correlation function of the Jakes' Doppler spectrum is the $0^{\text{th}}$-order Bessel function of the first kind. Here the EDC sector angle limits are used in [8]. It can be found that correlation value of the combined signal with Doppler frequency compensation is increasing with the amount of the sector antenna at a given time index normalized $\tau$. This means that the signal exhibits less time-variant behavior when more antennas are used.

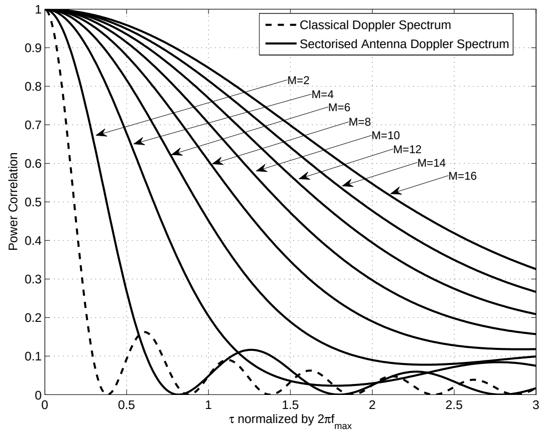

**Fig. 1.** Correlation versus normalized time.

# 3. Different Partition Schemes for the Omnidirectional Antenna and the optimal Doppler Compensation Frequency

## 3.1 Different Partition Schemes for the Omnidirectional Antenna

The fading rate mainly depends on the width of the Doppler spread. In order to guarantee the equal fading rate after frequency compensation of each sector output, three schemes are compared. Due to the angle symmetry, we only consider the incidence angle of the arriving wave located in $[0, \pi)$. $K$ antennas are employed where the angle limits are $\phi_k(k = 0, 1, \cdots, K)$, where $\phi_0$=0 and $\phi_K$=π.

(1) Equal Angle (EA): The beam width of each sector is equal, and $\phi_k$ is obtained as

$$\begin{cases} \phi_0 = 0, \\ \phi_1 = \Delta\phi, \\ \quad \vdots \\ \phi_K = K \cdot \Delta\phi \end{cases} \quad (6)$$

where $\Delta\phi = \frac{\pi}{K}$.

(2) Equal Doppler Spread (EDS) [6], [9]: The whole Doppler spread spectrum is divided into $K$ equal sub-spectra. To achieve this criteria, the following equation has to be satisfied [9]

$$\phi_k = \arccos\left(\frac{K - 2k}{K}\right), k = 0, 1, \cdots, K. \quad (7)$$

(3) EDC [8]: Because the average of Doppler profile is not uniform, this algorithm works based on the fact that each beam contributes the equal Doppler effect. Then $\phi_k$ can be obtained as (2).

Here we give an example of $K = 4$ for comparing these schemes. The angle limits are listed in Tab. 1.

In Fig. 2 it can be found that all the three schemes perform lower time selectivity than the omnidirectional antenna case. The solid lines and the broken lines are the power correlation of separated antenna sector respectively. The solid line stands for the sector near 90°, and the broken line is for the sector near 180°. The power correlation decreases with the $\tau$ increasing. Also we can see the fading rate (or correlation property) of EDC yields the largest correlation value, whereas the EDS has a very significant improvement over EDC, which exhibits closely related value. Note that when OFDM is applied, if the channel fluctuates differently after Doppler compensation, the ICI of each sectorised antenna appears at different level. When Maximum Ratio Combining (MRC) is employed, the performance will degrade due to the poor antenna. Therefore, EDS is superior to other methods.

| | $\phi_0$ | $\phi_1$ | $\phi_2$ | $\phi_3$ | $\phi_4$ |
|---|---|---|---|---|---|
| EA | 0° | 45° | 90° | 135° | 180° |
| EDS | 0° | 60° | 90° | 120° | 180° |
| EDC | 0° | 34.1° | 90° | 145.9° | 180° |

**Tab. 1.** Limits of angles of sectorised antenna with different partition.

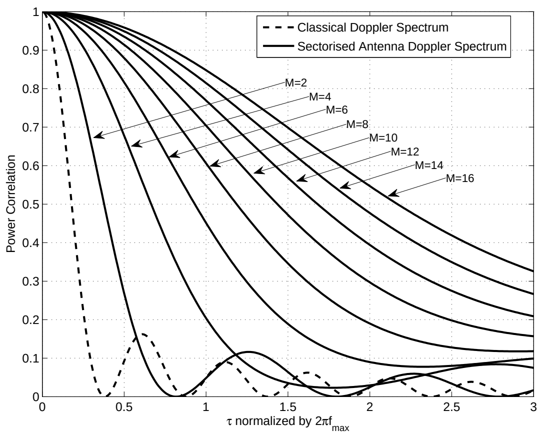


**Fig. 2.** Correlation with different partition.

### 3.2 The Optimal Doppler Compensation Frequency Algorithm

For OFDM system, the ICI deteriorates the performance in high-speed mobility scenario. The ICI power $P_{ICI}$ is as [9], [10]

$$P_{ICI} = 1 - \int_{-1}^{1}\int_{-\pi}^{\pi}(1-|x|)p(\phi)e^{j2\pi f_{max}T_s x\cos\phi}\,d\phi dx$$
$$= 1 - \int_{-\pi}^{\pi} p(\phi)\,\mathrm{sinc}^2[f_{max}T_s\cos\phi]\,d\phi \qquad (8)$$

where $P(\phi)$ denotes the probability distribution function of the arrival angle and $T_s$ is the sample interval of the system. After frequency adjustment $P_{ICI}$ is as follows

$$P_{ICI} = 1 - \int_{-\pi}^{\pi} p(\phi)\,\mathrm{sinc}^2\{f_{max}T_s[\cos\phi-\zeta]\}\,d\phi \qquad (9)$$

where $\zeta$ is the correction factor for frequency tracking algorithm. Because the sub-spectrum of each sector antenna is not uniform, the optimal Doppler compensation frequency is the barycenter of the $k^{\text{th}}$ sub-spectrum as

$$f_k^{op} = \frac{\int_{\phi_{k-1}}^{\phi_k} f\cdot P_{sector}(f)\,df}{\int_{\phi_{k-1}}^{\phi_k} P_{sector}(f)\,df}. \qquad (10)$$

When this is applied in practice, the computation complexity is intractable. Sometimes (10) normalized by $f_{max}$ can be approximated as [9]

$$\zeta_k^1 = \cos(\frac{\phi_{k-1}+\phi_k}{2}), \qquad (11)$$

which corresponds to the center of the sub-spectrum. Additionally, the precise moving speed of the train can be employed in HRC as prior information which accompanied by the maximum Doppler frequency shift $f_{max}$. Then real-time Doppler compensation frequency can be obtained naturally.

## 4. The Uncorrelated Property of Received Signals from the Different Sectorised Antennas

Here the Clarke model [11] assumes that incidence signal at the receiver is composed of $N$ scattered waves with random phase and equal average amplitude. The scattered waves experience a similar fading over small scale distance. Then the received signal represented as the sum of all incidence multipath waves is

$$r(t) = \sum_{i=1}^{N} c_i exp(j(2\pi f_{max}\cos\phi_i t + \theta_i)) \qquad (12)$$

where $c_i$, $\phi_i$ and $\theta_i$ are the amplitude, incidence angle and the random phase of the $i$th wave respectively. For the omnidirectional antenna, $\phi_i \in [-\pi,\pi)$. Due to the equal average amplitude in Clarke model, it satisfies that $c_i = c_j, i, j \in [1,N]$. The expected power value of all the multipath waves is 1, then $\sum_{i=1}^{N}|c_i|^2 = 1$ can be obtained, so

$$c_i = 1/\sqrt{N} \qquad i \in [1,N]. \qquad (13)$$

Then (12) can be rewritten as

$$r(t) = \frac{1}{\sqrt{N}}\sum_{i=1}^{N} exp(j(2\pi f_{max}\cos\phi_i t + \theta_i))$$
$$= \frac{1}{\sqrt{N}}\sum_{i=1}^{N} cos(2\pi f_{max}\cos\phi_i t + \theta_i) \qquad (14)$$
$$+ j\frac{1}{\sqrt{N}}\sum_{i=1}^{N}\sin(j(2\pi f_{max}\cos\phi_i t + \theta_i)).$$

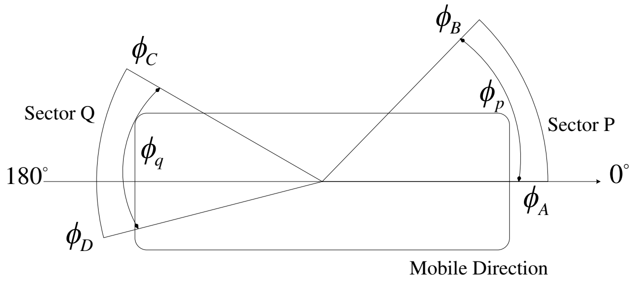


**Fig. 3.** Sectorised antennas used on the vehicle.

When sectorised antennas are used as in Fig. 3, the received components in directional antenna P and Q become

$$\begin{aligned} r^P(t) &= \frac{1}{\sqrt{N_P}} \sum_{p=1}^{N_P} \cos\left(2\pi f_{\max}\cos\phi_p t + \theta_p\right) \\ &+ j\frac{1}{\sqrt{N_P}} \sum_{p=1}^{N_P} \sin\left(2\pi f_{\max}\cos\phi_p t + \theta_p\right) \end{aligned} \quad (15)$$

and

$$\begin{aligned} r^Q(t) &= \frac{1}{\sqrt{N_Q}} \sum_{q=1}^{N_Q} \cos\left(2\pi f_{\max}\cos\phi_q t + \theta_q\right) \\ &+ j\frac{1}{\sqrt{N_Q}} \sum_{q=1}^{N_Q} \sin\left(2\pi f_{\max}\cos\phi_q t + \theta_q\right) \end{aligned} \quad (16)$$

where $\phi_p \in [\phi_A, \phi_B]$ and $\phi_q \in [\phi_C, \phi_D]$. $N_P$ and $N_Q$ are the amounts of the incidence waves satisfying

$$\begin{aligned} N_P &= N\frac{\phi_B - \phi_A}{2\pi}, \\ N_Q &= N\frac{\phi_D - \phi_C}{2\pi}, \end{aligned} \quad (17)$$

and $\theta_p, \theta_q \in [0, 2\pi]$. For simplicity, $\theta$ is used instead of $\theta_p$ and $\theta_q$. Then the mathematic expectation of $r^p(t)$ is

$$\begin{aligned} E\left[r^P(t)\right] &= \frac{1}{\sqrt{N_P}} \sum_{p=1}^{N_P} E\left[\cos\left(2\pi f_{\max}\cos\phi_p t + \theta\right)\right] \\ &+ j\frac{1}{\sqrt{N_P}} \sum_{p=1}^{N_P} E\left[\sin\left(2\pi f_{\max}\cos\phi_p t + \theta\right)\right] = 0. \end{aligned} \quad (18)$$

Similarly, the mean value of $r^Q(t)$ is

$$E[r^Q(t)] = 0. \quad (19)$$

and the correlation of received signal from P and Q directional antenna is

$$\begin{aligned} R_{PQ}(t_1, t_2) &= E\left(r^P(t_1)\left(r^Q(t_2)\right)^*\right) \\ &= \frac{1}{\sqrt{N_P N_Q}} \sum_{p=1}^{N_P} \sum_{q=1}^{N_Q} \{R_1 - R_2\} + j\frac{1}{\sqrt{N_P N_Q}} \sum_{q=1}^{N_Q} \sum_{p=1}^{N_P} \{I_1 + I_2\} \end{aligned} \quad (20)$$

where

$$\begin{aligned} R_1 &= E\left[\cos\left(2\pi f_{\max}\cos\phi_p t_1 + \theta\right)\cos\left(2\pi f_{\max}\cos\phi_q t_2 + \theta\right)\right], \\ R_2 &= E\left[\sin\left(2\pi f_{\max}\cos\phi_p t_1 + \theta\right)\sin\left(2\pi f_{\max}\cos\phi_q t_2 + \theta\right)\right], \\ I_1 &= E\left[\cos\left(2\pi f_{\max}\cos\phi_p t_1 + \theta\right)\sin\left(2\pi f_{\max}\cos\phi_q t_2 + \theta\right)\right], \\ I_2 &= E\left[\sin\left(2\pi f_{\max}\cos\phi_p t_1 + \theta\right)\cos\left(2\pi f_{\max}\cos\phi_q t_2 + \theta\right)\right]. \end{aligned} \quad (21)$$

After some mathematical operations, we have

$$R_{PQ}(t_1, t_2) = 0. \quad (22)$$

From (18) – (21) it can be found that the received signals at the sector P and Q are uncorrelated, and the correlation value is not allied to beam width of each sector. The Doppler full diversity gain can be derived due to uncorrelated property in each directional antenna. Similarly, the signal after Doppler compensation is also uncorrelated.

# 5. Simulation Results

In this section, we present results for an OFDM communication system with parameters listed in Tab. 2. The virtual subcarriers and the DC tone are ignored and the central frequency is set to 2.4 GHz. Here we define the normalized Doppler frequency as $f_N = T_{sys} \cdot f_{max}$, where $T_{sys}$ is the OFDM symbol duration. Because the high speed railway is usually built in the open, the radio propagation channel performs distinctively from the mobile cell channel in the urban area. Generally, the line of sight or direct path called Rice path takes a dominant role. Here COST 207 rural area (RA) channel model [12] is used for simulation. The angle limits of each sectorised antenna are presented in [6], [8]. The velocity we consider belongs to the range 0 km/h – 500 km/h.

| | |
|---|---|
| Bandwidth | 10MHz |
| FFT/IFFT | 2048 |
| CP Length | 256 |
| Mapping | Coherent BPSK |
| Pilot Interval | 32 |
| Channel Estimation | Transform Domain Method |
| Combined Scheme | MRC |

**Tab. 2.** OFDM system simulation parameters.

Fig. 4 depicts the Bit Error Rate (BER) performance of the OFDM system versus the normalized Doppler frequency, where $f_N \in [0 \sim 1]$. The pentagram line shows that the system is affected by the maximum Doppler frequency $f_{\max}$ without Doppler compensation. The square line works under the same condition but with Doppler compensation. The circle lines from S1∼S7 represent the directional antennas with beam widths $[-\pi/2, \pi/2]$, $[-1.2310,\ 1.2310]$, $[-1.2310,\ 1.2310]$, $[-1.0472,\ 1.0472]$, $[-0.9273,\ 0.9273]$, $[-0.8411,\ 0.8411]$, $[-0.7752,\ 0.7752]$ and $[-0.7227,\ 0.7227]$ respectively. The approximation for the Doppler compensating frequency is $f_{\max}$ corresponding to $\xi_k^1 = \cos\left((\phi_k + \phi_{k-1})/2\right)$. After Doppler correction, the BER performance improves. When the beam is reduced to the minimum width, the system performs as the square line corresponding to the pure Doppler case.

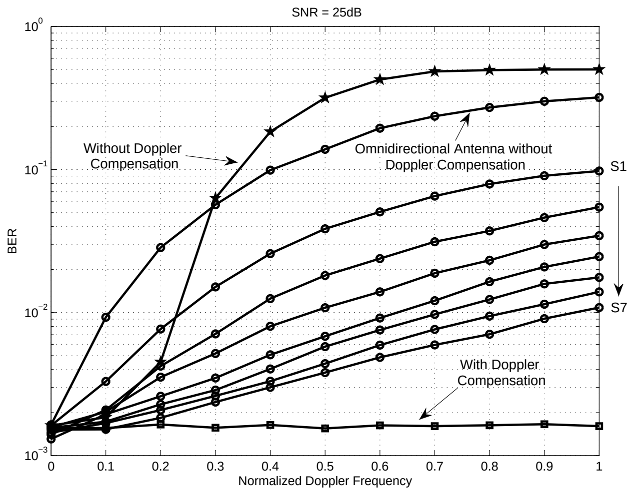


**Fig. 4.** BER performance of sectorised antenna reception versus normalized Doppler frequency shift.

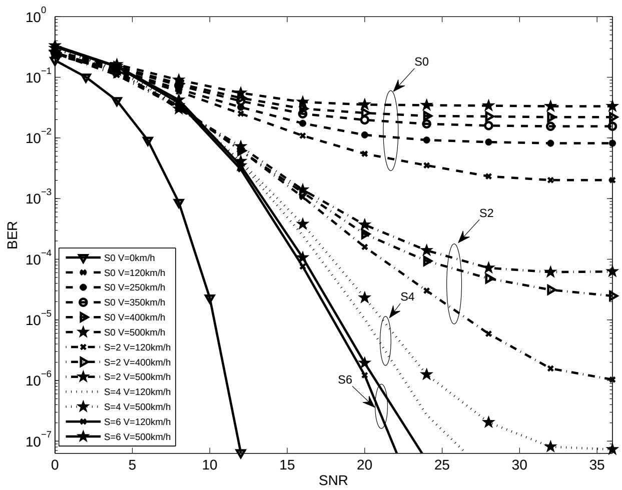


**Fig. 5.** BER performance of sectorised antenna reception under COST 207 RA channel model.

Fig. 5 gives the BER performances of sectorised antenna under COST 207 RA channel model with different velocities. Compared with omnidirectional antenna, it can be seen that improvement is significant when sectorised reception scheme is employed. The error floor level decreases with increasing sectorised antenna number. It can be found that when $S = 6$ is employed, error floor nearly disappears. Reducing time selectivity alleviates the ICI upon each subcarrier which brings more reliable data detection. Additionally, Doppler diversity gains can be obtained when multiple directional antennas are used which push the performances to the non-time selectivity cases.

In high mobility scenarios, in order to decrease the handover times Base Band Unit (BBU) + Remote Radio Unit (RRU) architecture is proposed [13] as in Fig. 6. The core idea is to separate several RRUs apart from the BBU component so that the BBU is placed in the central location, and the RRU is connected with the optical fiber which can enlarge the cell scale. However, a bad special case occurs when the train travels at the middle area of two RRUs. Two rays with opposite Doppler frequency shift reach the receiver at the same time. The omnidirectional antenna architecture can not cope with this condition well.

We depict the BER performance of this two rays scenario in Fig. 7. For simplicity, one ray from each RRU is assumed. The Doppler spectrum is Rice spectrum as the first path in COST 207 RA channel [12]. The average path gains of the two rays are [0, 0] dB and [0, -6] dB. We observe using sectorised reception also bring benefits under this condition. Time selectivity is alleviated. Error floor is avoided when $S = 4$ directional antennas are used.

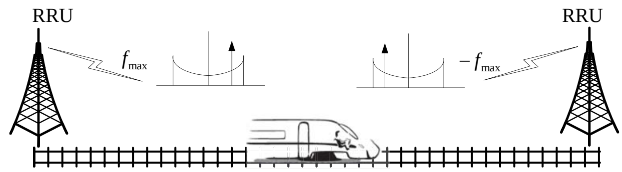


**Fig. 6.** Distributed BBU + RRU principle.

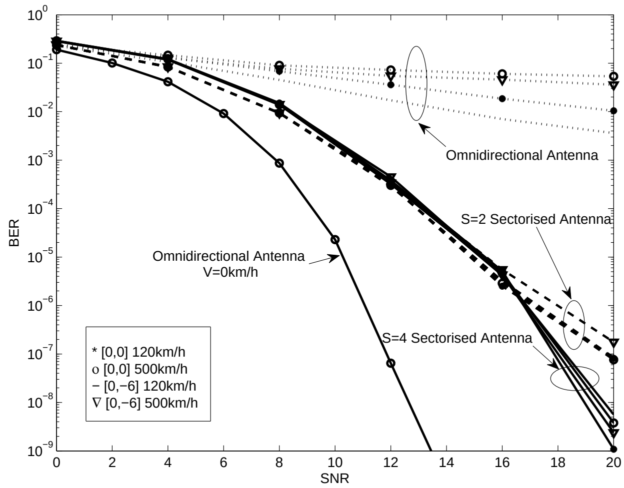


**Fig. 7.** BER performance of sectorised antenna reception under two rays model.

# 6. Conclusion

In this paper, we analyze performance of the Doppler diversity based on sectorised antenna architecture. It can provide the improvement of reducing the time selectivity and diversity gain for transmission. We have shown that after Doppler frequency compensation, in EDS partition scheme similar a fading rate appears and can be applied for MRC directly without considering weighted value. It is demonstrated that the signals received from different directional antennas are uncorrelated and after the approximated Doppler frequency compensation this scheme can reduce the ICI power by reducing the Doppler spread and mitigating the error floor under high mobility condition. Moreover, the special case that two rays with opposite Doppler frequency shift in HRC is considered that the benefits can be obtained with this sectorised antenna scheme.

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