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Capacity Enhancement for High Data Rate Wireless Communication System

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ABSTRACT

Wireless communication systems have advanced significantly in the past years and played an extremely important role in our society. It is rapidly becoming the most popular solution to deliver voice and data services due to flexibility and mobility that can be offered at moderate infrastructure costs. It is foreseen that future wireless communication system will experience an enormous increase in traffic due to increased number of users as well as new high bit rate data services (multimedia) being introduced. The increase in channel capacity and high transmission rates for wireless communications requires technologies for power saving and efficient frequency usability. One of the most promising techniques to achieve this is the Multiple Input Multiple Output (MIMO) system. This paper proposed a combined spatial multiplexing MIMO scheme with beamforming for high data rate wireless communication. The proposed transmission scheme combines the benefits of both techniques and the system was able to transmit parallel data streams as well as provide beamforming gain. Actually, these diverse techniques, share the same requirement of multiple antenna elements, but differ in the antenna element spacing necessary for the different schemes to work. Thus, smart antenna array was proposed as a possible solution and was adopted at both the transmitter and receiver. The proposed hybrid technique improved the system spectral efficiency performance significantly than the conventional MIMO, spatial multiplexing and beamforming techniques when used alone under the same simulation environment.

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1. INTRODUCTION

Meeting the demands that are expected from future wireless generation networks poses intriguing challenges for today's wireless system designers. The demand for higher data rate and better quality of service (QoS) in wireless communications continue to grow tremendously in the past few years. Traditionally, low bit rates wireless applications were voiced-centric while the higher bit rate applications such as file transfer or video and audio streaming, VoIP, video conferencing were wireline applications. Today, there has been a shift to wireless multimedia applications, which is reflected in the convergence of wireless networks and the Internet. The increase in these wireless multimedia services becomes challenging for wireless communication systems due to the problems of channel, multi-path fading, higher power loss and bandwidth limitations.

A Single-Input Single-Output (SISO) antenna system where there is only one antenna at both transmitter and receiver suffers a bottleneck in terms of capacity due to the Shannon-Nyquist criterion [1, 2] and future wireless services demand much higher data bit-rate for transmission. In order to increase the capacity of the SISO systems to meet such demand, the bandwidth and transmission power have to be increased significantly. Recently, a lot of research developments have shown that using Multiple Input Multiple Output (MIMO) systems could increase the capacity (higher data rate) in wireless communication substantially without increasing the transmission power and bandwidth [3, 4]. This can provide diversity gain, multiplexing gain and beamforming gain for the wireless communication systems. Considering the advantages of these various MIMO techniques, there is a need to integrate them so that the whole wireless system can benefit from these techniques. In this paper, a hybrid MIMO technique is conceived as a promising solution for spectrally efficient transmission technique for wireless communication system. These diverse techniques, share the same requirement of multiple antenna elements, but differ in the antenna element spacing necessary for the different schemes to work [5]. That is, under the beamforming technique, the antenna spacing must be small in order to provide the required high channel correlation, but spatial multiplexing technique requires the antenna spacing to be large enough that the correlation between the MIMO channels is low. The use of smart antenna arrays at transmitter and/or receiver terminals provides a possible solution for the antenna spacing problem so that the system would have high-correlation and low-correlation scenarios simultaneously necessary for these different techniques.

Various hybrid MIMO technique schemes have been proposed in the past to improve the performance of wireless communication systems. Most of the earlier proposals focus on combining beamforming with diversity techniques [6-9]. This resulted in a technique that was able to make systems achieve both diversity gain and beamforming gain thereby improving the system performance, without improving the system spectrum efficiency since the two techniques function mainly in combating fading. Based on this limitation, a system of hybridizing beamforming with spatial multiplexing technique was proposed in this paper. This proposed technique improved the system spectral efficiency significantly as well as the gain.

2. SYSTEM MODEL

As illustrated in figure 1, the proposed MIMO system is configured in such a way that both the transmitter and the receiver were equipped with one or more smart antenna array. There are M_T antenna arrays at the transmitter with each array having N antenna elements and M_R antenna arrays at the receiver with each array having K antenna elements. The spacing between the antenna arrays should be larger than the wavelength (more than 10λ), while the antenna element spacing of each antenna array is a half wavelength (λ/2). The vectors W and Z are called the transmit beamforming coefficient and receive beamforming vectors, respectively. Also, we assumed that the channel state information (CSI) is only known to the receiver and that independent identical Rayleigh distribution (i.i.d) flat fading channels exist between the transmitter and the receiver.

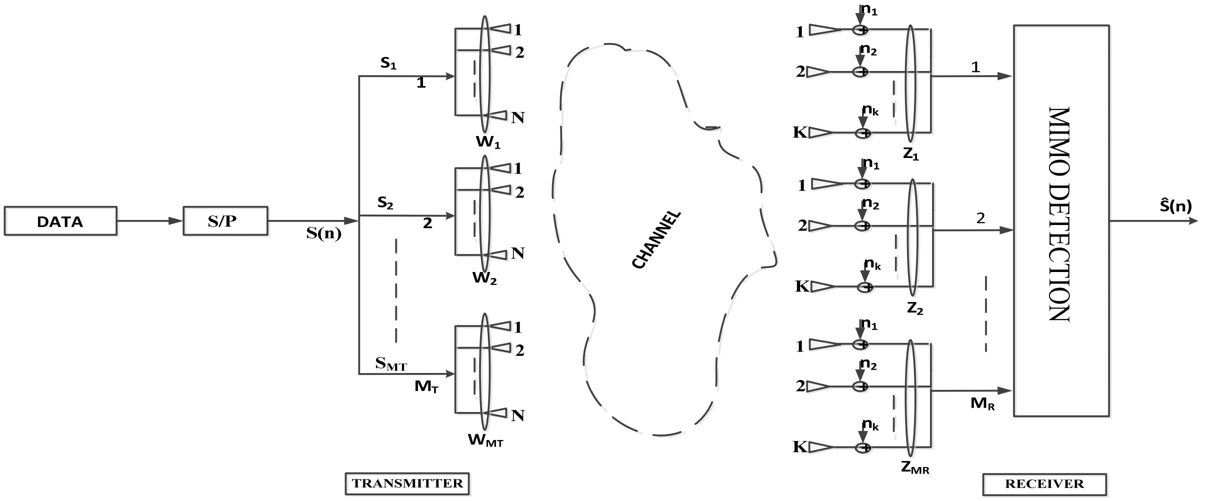

Figure 1. Proposed Wireless MIMO System with Smart Antenna Array

2.1 Analysis

Conventionally, the MIMO channel impulse response of MIMO systems with M_T transmit antennas and M_R receive antennas is given as [10]:

$$H = \begin{pmatrix} h_{11} & h_{12} & \cdots\cdots\cdots h_{1M_T} \\ h_{21} & h_{22} & \cdots\cdots\cdots h_{2M_T} \\ \vdots & \vdots & \cdots\cdots\cdots \\ h_{M_R1} & h_{M_R2} & \cdots\cdots\cdots h_{M_RM_T} \end{pmatrix}_{M_R \times M_T} \qquad (1)$$

Where $h_{i,j}(\tau)$ shows the channel impulse response between the j^{th} transmitter to the i^{th} receiver element and is given as:

$$h_{i,j}(\tau) = \sum_{n=1}^{L} \alpha_n \delta(\tau - \tau_n) \qquad (2)$$

Where $h_{i,j}(\tau)$ is the multipath channel impulse response, L is the number of paths, α_n shows the amplitude of the n^{th} path and it obeys i.i.d, $\delta(.)$ represents the impulse function and τ_n represents the delay of the n^{th} arriving path.

Applying this to multiple antenna arrays as in figure 1, the channel matrix becomes $KM_R \times NM_T$ matrix.

$$H = \begin{pmatrix} h_1^1 & h_1^2 & \cdots\cdots\cdots h_1^{M_T} \\ h_2^1 & h_2^2 & \cdots\cdots\cdots h_2^{M_T} \\ \vdots & \vdots & \cdots\cdots\cdots \\ h_{M_R}^1 & h_{M_R}^2 & \cdots\cdots\cdots h_{M_R}^{M_T} \end{pmatrix}_{KM_R \times NM_T} \qquad (3)$$

Where h_1^1 is channel fading vector from j^{th} antenna array at the transmitter to i^{th} antenna array at the receiver.

$$h_i^j = \begin{pmatrix} h_{i,1}^{j,1} & h_{i,2}^{j,1} & \cdots\cdots\cdots h_{i,K}^{j,1} \\ h_{i,1}^{j,2} & h_{i,2}^{j,2} & \cdots\cdots\cdots h_{i,K}^{j,2} \\ \vdots & \vdots & \cdots\cdots\cdots\cdots \\ h_{i,1}^{j,N} & h_{i,2}^{j,N} & \cdots\cdots\cdots h_{i,K}^{j,N} \end{pmatrix}_{K \times N} \qquad (4)$$

At the transmitter, the transmit signal split into M_T parallel signals $S_1(n), S_2(n) \cdots\cdots\cdots\cdots S_{M_T}(n)$ through the splitter (demultiplexer) and is sent to the different antenna array to perform beamforming such that the transmit signal becomes:

$$\hat{S}_j(n) = W_j S(n) \qquad (5)$$

Where W_j is the transmit beamforming weight vector and is given as:

$$W_j = \left[a_T(\theta_j)\right]^* \tag{6}$$

$$a_T(\theta_j) = \left[1, e^{-j2\pi d_t Sin\theta_j/\lambda}, \ldots\ldots\ldots\ldots\ldots, e^{-j2\pi(N-1)d_t Sin\theta_j/\lambda}\right]^T \tag{7}$$

θ_j is the angle of departure (AOD), d_t is the distance between the antenna element in the j^{th} transmitter antenna array, λ is carrier wavelength, N is the number of elements in the j^{th} transmitter antenna array and $a_T(\theta_j)$ is transmit array steering response. After beamforming, $S(n)$ becomes $N \times 1$ column vector $\hat{S}_j(n)$. At the receiver side, the receive signal at i^{th} array element is denoted as vector $X(n)$ and is given as:

$$X_j(n) = HW_j S(n) \tag{8}$$

The receive beamforming is then weighted on $X(n)$ and the output signal after beamforming at the i^{th} receive element antenna array becomes:

$$r_i(t) = \sum_{j=1}^{M_T} Z_i^H \left(X_j(n) + g_i(n)\right) \tag{9}$$

$$r_i(t) = \sum_{j=1}^{M_T} Z_i^H H \hat{S}_j(n) + Z_i^H g_i(n) \tag{10}$$

Where Z_i is the received beamforming weight vector and is given as:

$$Z_i = [a_R \theta_i] \tag{11}$$

$$a_R(\theta_i) = \left[1, e^{-j2\pi d_r Sin\theta_j/\lambda}, \ldots\ldots\ldots\ldots\ldots, e^{-j2\pi(K-1)d_r Sin\theta_j/\lambda}\right] \tag{12}$$

θ_i is the AOA (Angle of Arrival), d_r is the distance between the antenna element in i^{th} transmitter array, λ is the carrier wavelength, K is the number of elements in the i^{th} receiver antenna array and $a_R(\theta_i)$ is the receive array steering response.

$$r_i(n) = \sum_{j=1}^{M_T} Z_i^H H \hat{S}_j(n) + \eta_i(n) \tag{13}$$

Where $\eta_i(n)$ spatially uncorrelated complex Gaussian noise with entry is distributed as ~ CN (0, N_o) and is given as:

$$\eta_i(n) = Z_i^H g_i(n) \tag{14}$$

From equation 5,

$$r_i(t) = Z_i^H h_i^1(n) W_1 S_1(n) + ... + Z_i^H h_i^{M_T}(n) W_{M_T} S_{M_T}(n) + \eta_i(n) \tag{15}$$

In matrix form:

$$\begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_{M_T} \end{bmatrix} = \begin{bmatrix} Z_1^H h_1^1 W_1 & Z_1^H h_1^2 W_2 .... & Z_1^H h_1^{M_T} W_{M_T} \\ Z_2^H h_2^1 W_2 & Z_2^H h_2^2 W_2 .... & Z_2^H h_2^{M_T} W_{M_T} \\ \vdots & \vdots & .... \\ Z_{M_R}^H h_{M_R}^1 W_1 & Z_{M_R}^H h_{M_R}^2 W_2 .... & Z_{M_R}^H h_{M_R}^{M_T} W_{M_T} \end{bmatrix} \begin{bmatrix} S_1(n) \\ S_2(n) \\ \vdots \\ S_{M_T}(n) \end{bmatrix} + \begin{bmatrix} \eta_1 \\ \eta_2 \\ \vdots \\ \eta_{M_T} \end{bmatrix} \tag{16}$$

$$r = \tilde{H} S + \eta \tag{17}$$

Where $\tilde{H}$ is effective channel matrix and is defined as:

$$\tilde{H} = \begin{bmatrix} Z_1^H h_1^1 W_1 & Z_1^H h_1^2 W_2 .... & Z_1^H h_1^{M_T} W_{M_T} \\ Z_2^H h_2^1 W_2 & Z_2^H h_2^2 W_2 .... & Z_2^H h_2^{M_T} W_{M_T} \\ \vdots & \vdots & .... \\ Z_{M_R}^H h_{M_R}^1 W_1 & Z_{M_R}^H h_{M_R}^2 W_2 .... & Z_{M_R}^H h_{M_R}^{M_T} W_{M_T} \end{bmatrix} \tag{18}$$

This shows that the channel matrix consists of MIMO channel fading and information concerning AOD and AOA. As a result of this, $\tilde{H}$ is converted from a channel matrix $KM_R \times NM_T$ to a $M_R \times M_T$ channel matrix H. Due to the strong spatial correlation existing in each antenna array, according to the fading of the first element of each antenna array, the entire steering response of the antenna array is [11]:

$$h_i^j(\tau, t) = \sum_{i=0}^{L-1} [a_R \theta_i] \beta_{i,j}(t) [a_T \theta_j]^T \delta(\tau - \tau_n) \tag{19}$$

Where the channel fading vector h_i^j is a matrix of $K \times N$ according to equation (4), $\beta_{i,j}(t)$ is the multipath fading components coupling the first element of the j^{th} antenna array at the transmitter to the i^{th} antenna array at the receiver and it also obeys i.i.d.

Since the channel is assumed to be flat, equation (17) becomes

$$h_i^j(t) = [a_R \theta_i] \beta_{i,j}(t) [a_T \theta_j]^T \tag{20}$$

Then, the effective channel fading element $\tilde{H}_{i,j}$ can be roughly obtained as:

$$\tilde{H}_{i,j} = [a_R \theta_i]^H [a_R \theta_i] \beta_{i,j} [a_T \theta_j]^T [a_T \theta_j]^* \tag{21}$$

Since $\|a_R \theta_i\| = \sqrt{K}$ and $\|a_T \theta_j\| = \sqrt{N}$

Where $\|.\|$ is the Euclidean Vector Norm, thus the effective channel fading element $\tilde{H}_{i,j}$ can be approximately obtained as:

$$\tilde{H}_{i,j} = KN.\beta_{i,j} \tag{22}$$

Therefore, the corresponding entire channel matrix can be formed as:

$$\overset{\square}{H} = KN.\begin{bmatrix} \beta_{1,1} & \beta_{1,2} & \cdots\cdots & \beta_{1,M_T} \\ \beta_{1,1} & \beta_{1,1} & \cdots\cdots & \beta_{2,M_T} \\ \vdots & \vdots & \cdots\cdots & \cdots\cdots \\ \beta_{M_R,1} & \beta_{M_R,2} & \cdots\cdots & \beta_{M_R,M_T} \end{bmatrix} \tag{23}$$

Since the element of $\beta_{i,j}$ and $h_{i,j}$ has the same distribution (i.i.d), then the effective channel matrix in equation (16) becomes:

$$\overset{\square}{H} = KN.H \tag{24}$$

To detect the transmit signal *s*(*n*), Zero forcing (ZF) and Minimum Mean Square Error (MMSE) detection algorithms were considered in the design of the receiver. Thus, the receive signal is:

$$r(n) = \overset{\square}{H}S + \eta \tag{25}$$

The detected signal is

$$\hat{S} = Gr \tag{26}$$

$$\hat{S} = G\overset{\square}{H}S + G\eta \tag{27}$$

For ZF detection algorithm:

$$G_{ZF} = (\overset{\square}{H}^{H}\overset{\square}{H})^{-1}\overset{\square}{H}^{H} \tag{28}$$

For MMSE detection algorithm:

$$G_{MMSE} = [\overset{\square}{H}^{H}\overset{\square}{H} + \frac{I_{KM_R}}{\gamma_o}]^{-1}\overset{\square}{H}^{H} \tag{29}$$

If the system uses ZF and MMSE detection algorithms, the effective detection SNR of the q^{th} data streams with linear ZF and MMSE equalizer at the receiver is expressed as [12,13]:

$$\gamma_q^{ZF+Bf} = \frac{\gamma_o}{(\overset{\square}{H}^{H}\overset{\square}{H})^{-1}_{q,q}} \qquad ; q = 1, 2, \ldots\ldots\ldots\ldots M_T \tag{30}$$

$$\gamma_q^{MMSE+Bf} = \frac{\gamma_o}{[\overset{\square}{H}^{H}\overset{\square}{H} + \frac{I_{KM_R}}{\gamma_o}]^{-1}_{q,q}} - 1 \qquad ; q = 1, 2, \ldots\ldots\ldots\ldots M_T \tag{31}$$

Where γ_o is the average SNR at each receiver antenna array and is obtained as:

$$\gamma_o = \frac{P_q}{KN_o} \tag{32}$$

Where P_q is the transmit power at each j^{th} transmit antenna array.

If the transmit power is equally allocated across the transmit antenna array,

$$P_q = \frac{P_o}{M_T N} \tag{33}$$

Then,

$$\gamma_o = \frac{P_o}{M_T K N N_o} \tag{34}$$

Where P_o is the total transmitted power

By substituting for γ_o in the equation (30) and (31),

$$\gamma_q^{ZF+Bf} = \frac{P_o}{\left(H^H H\right)^{-1}_{q,q} K N N_o M_T} \quad ; q = 1, 2, ...M_T \tag{35}$$

$$\gamma_q^{MMSE+BF} = \frac{P_o}{M_T K N N_o \left[[H^H H + \frac{I_{KM_R}}{\gamma_o}]^{-1}_{q,q} \right]} - 1 \qquad ; q = 1, 2, ...M_T \tag{36}$$

According to equation (21), equations (34) and (35) become:

$$\gamma_q^{ZF+Bf} = \frac{P_o N K}{(H^H H)^{-1}_{q,q} N_o M_T} \qquad ; q = 1, 2, ...M_T \tag{37}$$

$$\gamma_q^{MMSE+BF} = \frac{P_o}{M_T K N N_o \left[[(H^H H) K^2 N^2 + \frac{M_T K N N_o I_{KM_R}}{P_o}]^{-1}_{q,q} \right]} - 1 \quad ; q = 1, 2, ...M_T \tag{38}$$

Thus, the system capacity for wireless system is given by [13,14]:

$$C = \sum_{q=1}^{NM_T} \log_2 (1 + \gamma_q) \tag{39}$$

According to equation (38), the capacity of the proposed system is obtained as:

$$C_{ZF+Bf} = \sum_{q=1}^{NM_T} \log_2 (1 + \frac{P_o N K}{(H^H H)^{-1}_{q,q} N_o M_T}) \tag{40}$$

$$C_{MMSE+Bf} = \sum_{q=1}^{NM_t} \log_2 \left(\frac{P_o}{M_T K N N_o \left[[(H^H H) K^2 N^2 + \frac{M_T K N N_o I_{KM_R}}{P_o}]^{-1}_{q,q} \right]} \right) \tag{41}$$

3. SIMULATION RESULTS

Spectral efficiency of a wireless system is the capacity which shows the amount of maximum attainable information that can be sent by a reliable wireless communication system. Conventionally, this can be increased by the factor of $\min\{M_R, M_T\}$ without using additional transmits power or spectral bandwidth. However, in this paper, it was shown that by increasing the number of elements in each antenna array both at the transmitter and receiver sides; it is possible for the system to attain high spectral efficiency. Thus, the simulation results of the proposed method of enhancing data rate for wireless communication system are provided in this paper. The performance metric in terms of spectral efficiency of Conventional MIMO technique, Spatial Multiplexing scheme and the Beamforming scheme are compared with the proposed hybrid MIMO technique. The transmitter and the receiver are assumed to have 2 smart antenna arrays at both ends and we examine N and K to be equal to 2, 4 and 8 elements in each array. The spacing between antenna arrays is larger than 10λ, while the spacing between antenna elements is λ / 2. The angle spread in each of the transmitter antenna array is 30 degrees and 70 degrees at the receiver side. The channel has the Rayleigh fading distribution, and spatially uncorrelated complex Gaussian noise is added to the faded signal at the receiver. 16-QAM modulations were used to modulate the symbols at the transmitter and ZF and MMSE detection were adopted at the receiver for the entire schemes

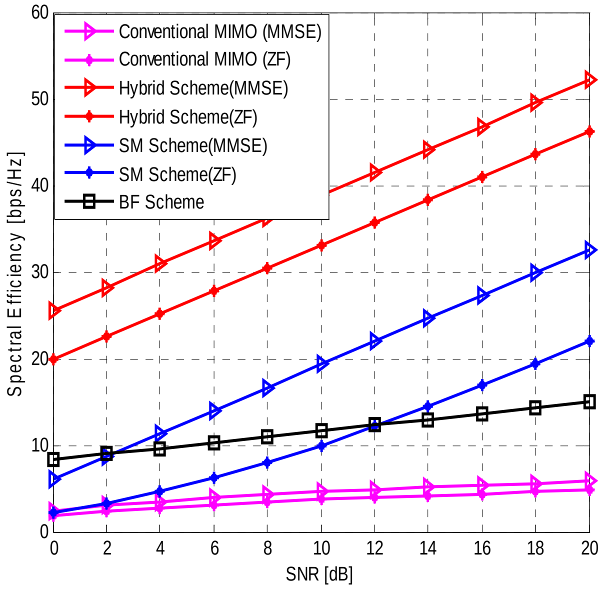

Figure 2. Spectral Efficiency for the Proposed Wireless MIMO System when $M_T = 2$, $M_R = 2$, K=2 and N=2

Figure 2 shows the spectral efficiency performance of the proposed system with ZF and MMSE detection when $M_T = 2$, $M_R = 2$, K=2 and N=2. This result indicates that the hybrid scheme has the best performance with average spectral efficiency of 38.86b/s/Hz when MMSE was considered as detection and 33.08b/s/Hz for ZF detection than spatial multiplexing scheme with the average spectral efficiency of 21.73b/s/Hz and 14.24b/s/Hz for MMSE and ZF detection respectively; and beamforming scheme will produce 11.62b/s/Hz. The result further shows that the Conventional MIMO system with $M_T = 2$ and $M_R = 2$ has an average spectral efficiency of 4.38b/s/Hz when MMSE detection was used and 3.54b/s/Hz for ZF detection which obviously indicate that the Conventional MIMO scheme has a poor capacity performance compared to the other schemes.

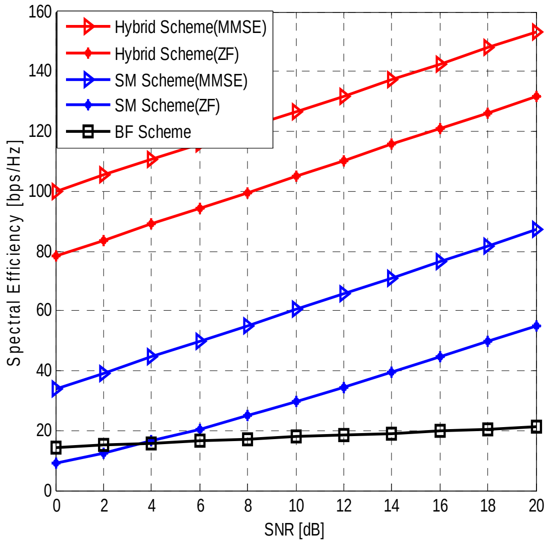

Figure 3. Spectral Efficiency for the Proposed Wireless MIMO System when $M_T = 2$, $M_R = 2$, K=4 and N=4

Figure 3 shows the simulation result of hybrid scheme compared with spatial multiplexing scheme and beamforming scheme. With the M_R and M_T antenna arrays remain constant and element K and N were increased from two to four, the simulation result shows that the capacity performance of hybrid scheme is better than individual scheme and it will provide an average spectral efficiency 126.59b/s/Hz when MMSE detection is used and 104.93b/s/Hz for ZF detection. This shows that hybrid scheme has an increment of 87.73b/s/Hz for MMSE detection and 71.87b/s/Hz for ZF detection when the antenna array element was increased. This shows that maximum spectral efficiency can be attained by increasing the number of elements within each antenna array. Also, it can be seen that a similar result was achieved when K and N are equal to eight as shown in figure 4. The hybrid scheme has an average spectral efficiency of 360.11b/s/Hz and 285.78b/s/Hz for MMSE and ZF detection respectively than other schemes. This proves that the capacity of MIMO system can be enhanced by increasing the number of antenna element in each array at the transmitter and receiver rather than increasing the number of antenna array which was conventionally carried out by the Gans et al [3]. Also, it can be deduced from all indications that MMSE detection performs more efficiently than ZF detection for both conventional MIMO and Smart antenna MIMO system.

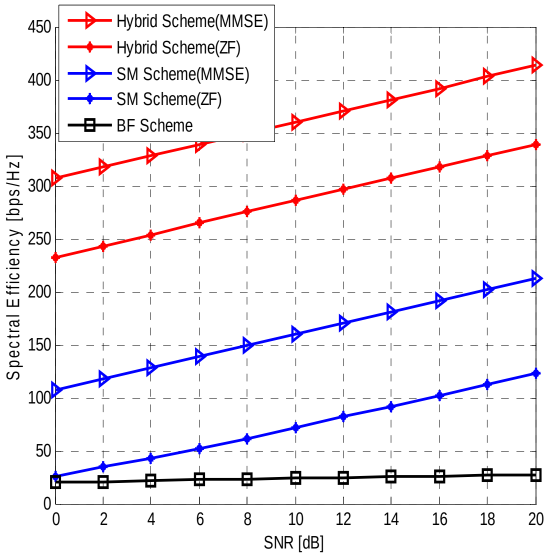

Figure 4. Spectral Efficiency for the Proposed Wireless MIMO System $M_T = 2$, $M_R = 2$, K=8 and N=8

4. CONCLUSION

Capacity enhancement for high data rate wireless communication system was proposed in this paper. A hybrid scheme which involves the combination of spatial multiplexing and beamforming technique was used as a transmission scheme for a smart antenna MIMO system and the system was able to transmit parallel data streams as well as obtain beamforming gain. The MMSE and ZF MIMO detection algorithm was employed at the receiver. The simulation results show that the hybrid scheme outperforms the spatial multiplexing and beamforming scheme and each of these is better than the Conventional MIMO scheme. It was found that the higher the antenna array element the higher the system capacity. The results also show that the MMSE detection has a better performance in all schemes when compared to the ZF detection.

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