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A novel metric for measuring multiple antennas system capacity over energy consumption requirements

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Abstract—In this paper, we evaluate the capacity to the total energy consumption per bit ratio of multiple antennas systems. The wireless communication system is assumed to operate in indoor propagation environment. A scattering model of wireless communication channel is presented. The channel model considers both the line of sight (LOS) and the NLOS (non line of sight) components. Computer simulations are carried out for the capacity to the total energy consumption ratio by varying both the distance separation between the transmitter and the receiver and the number of transmit antennas. We show in this paper, that the gain in capacity increases with the number of antennas but it is still limited by the total energy consumption. As such, we find by simulations the limits for increasing the number of transmit antennas. This could be determined by a new metric which is the “capacity to energy ratio”.

Index Terms—MIMO capacity, energy efficiency, capacity to energy ratio.

I. INTRODUCTION

Multiple antennas system [1], [2], [3], [4] has been considered as a really significant foundation on which to build the future generations of wireless networks. Multiple Input Multiple Output (MIMO) technology is currently adopted by high throughput commercial standards such as WiMax, Wi-Fi and Long Term Evolution (LTE) systems. MIMO technology brings significant advances in spectral efficiency by employing several antennas at both ends of the communication system. Such technology could be also implemented in a distributed fashion on emerging wireless networks such as wireless sensor networks (WSNs) [5] and peer to peer systems (P2P) which could be limited in energy. Nevertheless, it should be mentioned that even the use of multiple antennas significantly improves the spectral efficiency of the communication system, it could be costly in terms of energy consumption. This paper is to present our investigations of the behavior of the cost in terms of the total energy consumption as a function of the maximum achieved system capacity. This will contribute to optimal design for the low-power high-efficiency communication system which corresponds to the number of antennas for which we can get the lowest costs in energy consumption for a required level of system capacity.

II. COMMUNICATION SYSTEM MODEL

We carry out our analysis over the multiple antennas system model with N_T transmit antennas and N_R receive antennas. The MIMO channel model with additive noise signal is then [1]:

$$y = H \cdot x + n \quad (1)$$

y , H , x and n respectively denote the $(N_R \times 1)$ vector of the received signal, the $(N_R \times N_T)$ channel matrix, the $(N_T \times 1)$ vector of the transmitted signal and the $(N_R \times 1)$ vector of the additive noise signal. The presented model may be adopted by wireless networks which perform the distributed MIMO system model where a set of N_T transmit sensor nodes communicate with N_R receive sensor nodes.

We consider the Rician fading channel modeling. We assume that the channel coefficients vary in function of the square value of the distance separation. The channel matrix coefficients h_{ij} , $i = 1, \dots, N_R$, $j = 1, \dots, N_T$ are then expressed as:

$$h_{ij} = \frac{1}{\sqrt{1+K}} \cdot h_{ij}^{NLOS} + \sqrt{\frac{K}{1+K}} \cdot h_{ij}^{LOS} \quad (2)$$

In rich scattering environment with L_S scatterers, the NLOS components are given by:

$$h_{ij}^{NLOS} = \frac{1}{\sqrt{L_S}} \sum_{l=1}^{L_S} \alpha_l \cdot \frac{1}{(d_{il} + d_{lj})^2} \quad (3)$$

- α_l is a random scattering coefficient from the l th scatterer, $l = 1, \dots, L_S$.
- d_{il} is the distance between the i th receive antenna and the l th scatterer, $i = 1, \dots, N_R$, $l = 1, \dots, L_S$.
- d_{lj} is the distance between the l th scatterer and the j th transmit antenna, $l = 1, \dots, L_S$, $j = 1, \dots, N_T$.

The LOS components are expressed as:

$$h_{ij}^{LOS} = \frac{1}{d_{ij}^2} \quad (4)$$

d_{ij} denotes the distance between the i th receive antenna and the j th transmit antenna, $i = 1, \dots, N_R$, $j = 1, \dots, N_T$.

III. CAPACITY TO ENERGY RATIO ANALYSIS

We define the metric R_0 which equals the total energy consumption per bit to the capacity ratio by:

$$R_0 = \frac{\bar{C}}{E_{bt}} \quad (5)$$

- \bar{C} is the ergodic system capacity (in $bits/s/Hz$).
- E_{bt} is the total energy consumption per bit (in J).

The computation of both the system capacity and the total energy consumption are addressed in the following sections.

A. Channel capacity evaluation

The instantaneous channel capacity associated to the multi-antennas communication system model is [1]:

$$C(H) = \log_2 \left[\det \left(I_{N_R} + \frac{\gamma_T}{N_T} \cdot H H^H \right) \right] bits/s/Hz \quad (6)$$

γ_T denotes the transmit signal to noise ratio. The ergodic channel capacity \bar{C} is evaluated as the expected value of the instantaneous channel capacity C over all the channel matrix realizations. The channel capacity expression given by equation (6) corresponds to the case when no channel state information (CSI) is available at the transmitter. If the CSI is available at both the transmitter and the receiver, the channel capacity may be computed in more optimal way by performing the water-filling algorithm.

$$C_{WF}(H) = \sum_{p=1}^R \log_2 \left[\left(\frac{\lambda_{H,p} \cdot \mu}{\sigma_n^2} \right)^+ \right] bits/s/Hz \quad (7)$$

- R is the rank of the channel matrix H
- σ_n^2 is the noise signal power
- $a^+ = \max(a, 0)$
- μ is a constant scalar that satisfies the total power constraint
- $\lambda_{H,p}$ is the p th singular value of the channel matrix H

B. Analysis of the total energy consumption

We evaluate the power consumption for each antenna at both the transmit and receive sides. The transmitter block model with complex modulator is shown in Fig.1

The power consumption of multiple antennas systems with N_T transmit antennas and N_R receive antennas is derived based on two main components which are [6], [7]:

- 1) The power consumption of the amplifiers: P_{PA}
- 2) The power consumption of the circuit blocks: P_C

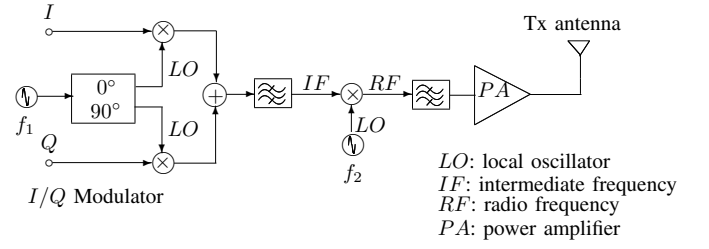


Fig. 1. The transmit block diagram for one transmit antenna

The power consumption of the amplifiers is expressed as:

$$P_{PA} = \frac{\xi}{\eta} \cdot P_{out} \quad (8)$$

- ξ is the peak to average ratio which is evaluated in function of the modulation constellation size M as:

$$\xi = 3 \cdot \frac{M - 2\sqrt{M} + 1}{M - 1} \quad (9)$$

- η is the drain efficiency.

The output power for a distance separation between the transmitter and the receiver d is expressed as:

$$P_{out} = E_b \cdot R_b \cdot \frac{(4\pi)^2}{G_t G_r \lambda^2} \cdot d^\rho \cdot M_l \cdot N_f \quad (10)$$

- E_b is the transmission energy per bit. The required energy per bit could be evaluated at a fixed bit error rate (BER) or bounded for a given signal to noise ratio [6].
- R_b is the bit rate.
- G_t is the transmit antenna gain.
- G_r is the receive antenna gain.
- λ is the wavelength.
- ρ is the path loss exponent.
- M_l is the link margin.
- N_f is the receiver noise figure.

The path loss exponent is assumed to be the same for all the links. Case of indoor propagation environment, the path loss exponent at a carrier frequency of 2.4 GHz is reported to 3.3 [8]. The total power consumption is evaluated by computing the power consumption of both the transmitter circuit blocks and the receiver circuit blocks as:

$$P_C \approx N_T \cdot (P_{MOD} + P_{DAC} + P_{mix} + P_{filt}) + 2 \cdot P_{syn} + N_R \cdot (P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC} + P_{DeMOD}) \quad (11)$$

- P_{MOD} : power consumption of the modulator
- P_{DAC} : power consumption of the digital-to-analog converter
- P_{mix} : power consumption of the mixer
- P_{filt} : power consumption of the active filter at the transmitter
- P_{syn} : power consumption of the frequency synthesizer
- P_{LNA} : power consumption of the low-noise amplifier
- P_{IFA} : power consumption of the intermediate frequency amplifier

- P_{filr} : power consumption of the active filter at the receiver
- P_{ADC} : power consumption of the analog-to-digital converter
- P_{DeMOD} : power consumption of the demodulator

The total energy consumption per bit is then:

$$E_{bt} = \frac{(P_{PA} + P_C)}{R_b} \quad (12)$$

IV. SIMULATION RESULTS AND OBSERVATIONS

In the following, we introduce the simulation parameters.

A. Simulation parameters

In order to evaluate the metric “capacity to energy ratio”, we carry out a computer based Monte-Carlo simulation for both the distributed MIMO system capacity and the total energy consumption per bit following the communication system model as introduced in section II. Table I summarizes the system setting. The number of receiver antennas N_R is set to 4. The metric “capacity to energy ratio” is evaluated for different transmitter configurations with variable number of transmit antennas N_T . Furthermore, we investigate the analysis of the effect of distance separation between the transmitter and the receiver on the “capacity to energy ratio” for each transmitter antennas configuration.

SIMULATION PARAMETER	VALUE
Constellation size, M	2
Carrier frequency	2.4 GHz
Bandwidth	2.4 MHz
Bit rate, R_b	10 kbit/s
Antenna gain product	$G_t \cdot G_r = 5$ dB
Drain efficiency, η	0.35
Link margin, Ml	40 dB
Receiver noise figure, Nf	10 dB
Noise power spectral density	-174 dBm/Hz
Number of scatterers, L_S	30
Path loss exponent, ρ	3.3
P_{MOD}, P_{DeMOD}	30 mW
P_{DAC}	40 mW
P_{ADC}	40 mW
P_{mix}	30.3 mW
P_{filt}, P_{filr}	2.5 mW
P_{syn}	50 mW
P_{LNA}	20 mW
P_{IFA}	3 mW

TABLE I
SIMULATION PARAMETERS

B. Capacity simulation

The ergodic capacity grows with the number of transmit antennas and is shown to be improved via optimal power allocation strategy when performing the water-filling algorithm [1]. Note that we make normalization for the channel matrix H so that to satisfy $\|H\|_F^2 = N_T N_R$. Once the channel matrix is normalized, the variation of the system capacity as a function

of the number of transmit antennas and distance separation between the transmitter and the receiver at a fixed transmit signal to noise ratio, $\gamma_T = 8$ dB and a distance separation between the transmitter and the receiver of 20 m is depicted in Fig.2. The simulated capacity is shown to be improved as well as more antennas are deployed at the transmitter.

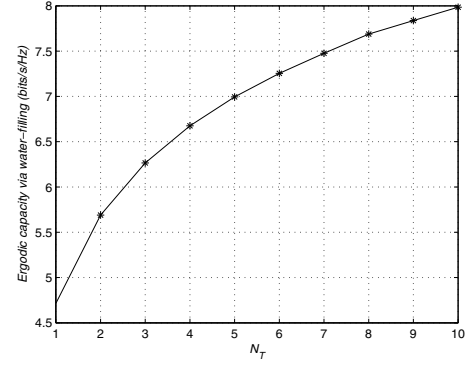


Fig. 2. Behavior of the multiple antennas system capacity, $\gamma_T=8$ dB

C. Energy simulation

The total energy consumption per bit is simulated for distance separation between the transmitter and the receiver in the range from 1 m to 20 m. The total energy consumption is shown to increase in function of the distance separation between the transmitter and the receiver. In addition, the use of additional antennas at the transmitter results in higher energy consumption requirements as depicted in Fig.3.

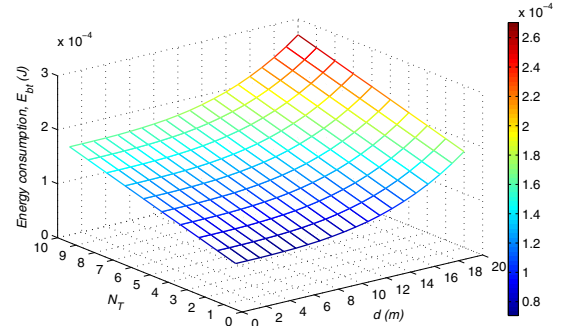


Fig. 3. Total energy consumption per bit over distance separation and variable number of transmit antennas

According to simulation results for the multiple antennas system capacity and the total energy consumption, we conclude that even the use of multiple antennas improves the system capacity, it leads to more requirements in the total energy consumption. As such, we propose in the following to study by simulations the behavior of the metric R_0 .

D. Capacity to energy ratio simulation

The metric “capacity to energy ratio” represents the amount of energy required for a given system capacity. The

simulation of the metric R_0 is targeted to examine how much the use of additional antennas could improve the metric “capacity to energy ratio”. The simulation results of the metric R_0 are sketched in Fig.4. The capacity to energy ratio still decreases as well as the distance separation between the transmitter and the receiver is increased and more antennas are deployed. The behavior of R_0 is expected since the multiple antennas system capacity is affected by the distance and more energy is required for additional antennas.

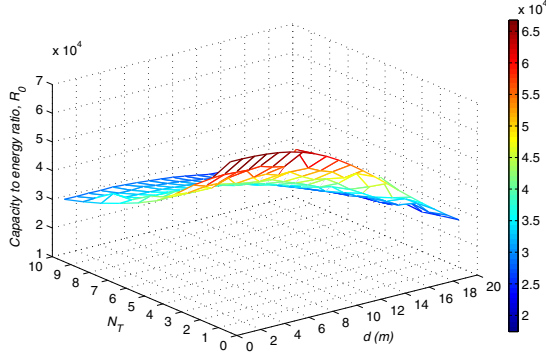


Fig. 4. Capacity to energy ratio over the number of transmit antennas and distance separation

In the following, we analyze the behavior of the capacity to energy ratio when water-filling algorithm is performed. The capacity to energy ratio is sketched in Fig. 5. The metric R_0 still decreases as well as the distance separation between the transmitter and the receiver is higher. Nevertheless, we note a growth in R_0 when more transmit antennas are deployed. This behavior is limited by the number of receive antennas N_R . In fact, Fig. 5 shows no more improvement in the capacity to energy ratio when N_T is superior to N_R . In addition, the variation of R_0 over the number of transmit antennas becomes almost negligible.

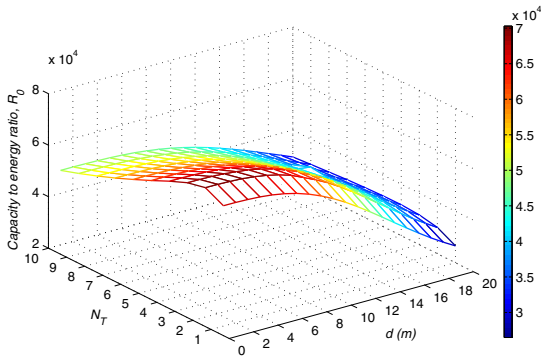


Fig. 5. Capacity to energy ratio over the number of transmit antennas and the distance separation via water-filling

We report in Fig. 6 the improvement in the capacity to energy ratio when performing water-filling algorithm. The capacity to energy ratio is shown to be improved via water-filling. The improvement in the capacity to energy ratio R_0

still depends on the number of antennas but seems to be insensible to the distance separation between the transmitter and the receiver.

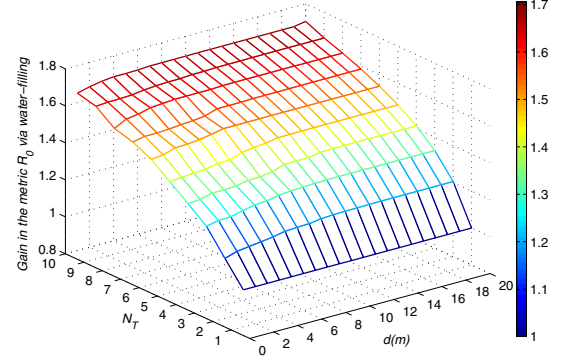


Fig. 6. Improvement in the capacity to energy ratio via water-filling

V. CONCLUSION

Throughout this paper, we have made the analysis of a new metric for multiple antennas systems which evaluates the cost in energy consumption for a given amount of the communication system capacity. Our analysis has been carried out over the Rician channel model with scatterers. Simulation of the capacity to energy ratio has been presented for variable number of transmit antennas and different ranges of the distance separation between the transmitter and the receiver. We have presented our results when optimal transmit power allocation is exploited and we have shown that even the use of multiple antennas improves the system capacity, it is still be limited by the total energy consumption.

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