Radio-Efficient Adaptive Modulation and Coding: Green Communication Perspective

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Abstract- **To lessen the environmental impact of the communication industry, Green Communications has achieved increasing attention from government, academia, and industry. However, how to define a green communication system has been an open topic. In this paper, we carry out a comprehensive analysis of the b/s/Hz bandwidth efficiency, the b/s/Hz/m^2 area spectral efficiency, the b/TENU power efficiency, the b/s/Hz/W power efficiency, and the (b·m)/s/Hz/W green efficiency of a wireless link. After comparing the performance of the green efficiency with the other efficiencies, we present an adaptive modulation and coding scheme to approach the maximum green efficiency, which provides an effective way to Green Communications.**

Keywords- **Green Communications, Efficiency, Adaptive Modulation and Coding**

I. INTRODUCTION

Given that there is a worldwide growth in the number of mobile subscribers, with the majority of the tele-traffic evolving from low data rate speech and modest-rate text messaging towards high data rate multimedia services (e.g., online music and video), an increasing contribution of information technology to the overall energy consumption of the world is observed. Therefore, there is a need to reduce the energy requirements of radio access networks. Hence, energy consumption will become a more important constraint in the design of future mobile communications systems [1-2].

It has become clear that 3GPP Long Term Evolution (LTE) is the preferred technology for the next generation mobile communications systems. Novel transmission technologies, such as multiple input and multiple output (MIMO), and orthogonal frequency division multiplexing (OFDM), will be adopted for LTE. However, the development of such mobile broadband communications systems comes at a significant energy cost, which is unsustainable and unsuitable for future-proof communications.

Therewith, over past two years, Green Communications has received much attention from government, academia, and industry [3]. The aim of Green Communications is to investigate and create innovative methods for the reduction of the total power needed to operate the future mobile communications systems and to identify appropriate network architectures and radio technologies which facilitate the required power reduction. Up to now, the continuous investment in Green Communications brings about a wealth of theoretical knowledge and practical engineering solutions, which can mainly be departed into two categories. The first part considers highly efficient power amplifier designs. For example, [4] presented high efficiency class F amplifiers. The second part focuses on network topology, MAC protocol, and routing designs [5-6], which is also called Green Networks.

However, a widely accepted choice of a criterion characterizing the overall efficiency of a wireless network remains an open problem [7]. Our work has provided a uniform efficiency for green network design and discussed the b/s/Hz/W power efficiency and the b/s/Hz bandwidth efficiency of wireless mesh networks [8].

Hence, firstly, in section II we present of a novel definition of green efficiency. Secondly, as much investment in wireless systems aims at improving the bandwidth efficiency [9] and the power efficiency [10-11], in section III, we carry out a comprehensive analysis of the bandwidth, power and green efficiency of a wireless link. Thirdly, in section IV, based on the bandwidth, power, and green efficiency criteria, we present a heuristic approach for a wireless system to achieve the maximum band, power, and green efficiency. Fourthly, in section V simulation studies are carried out to evaluate the performance of the proposed approach. Finally, the concluding remarks and the subjects for further study are given in Section VI.

II. GREEN EFFICIENCY CRITERION FOR WIRELESS SYSTEMS

By definition, efficiency is the ratio of the attained utility to the consumed resources. Clearly, therefore, the notion of efficiency is closely related to the definition of the utility and the resources.

In wireless communications, a user aims at transmitting its packets successfully under its quality-of-service (QoS) requirements and available resources constraints over a certain distance to its receivers. Hence, the radio utility metrics should include the successfully packets in bit, QoS metrics (such as bandwidth in b/s, delay and jitter in second, and packet loss rate) and the transmission distance in meter. Hence, the definition of green efficiency can be expressed as

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$$\arg\max \text{ Radio Efficiency} \quad (1)$$

S.T.1 (satisfying the minimal QoS requirements)

$$\begin{cases} \text{Bandwidth} > \text{Bandwidth}_{\min} \\ \text{Delay} < \text{Delay}_{\max} \\ \text{Jitter} < \text{Jitter}_{\max} \\ \text{PacketLossRate} < \text{PacketLossRate}_{\max} \end{cases}$$

where $Bandwidth_{\min}$ is the minimum required bandwidth, $\text{Delay}_{\max}$, $\text{Jitter}_{\max}$, and $\text{PacketLossRate}_{\max}$ are the maximum tolerant delay, jitter, and packet loss rate respectively.

S.T.2 (satisfying the constraints of available resources)

$$\begin{cases} \text{Allocated timeslots} \le \text{Available timeslots} \\ \text{Allocated subcarriers} \le \text{Available subcarriers} \\ \text{Allocated antennas} \le \text{Available antennas} \\ \text{Transmitted power} \le \text{Max transmission power} \end{cases}$$

There has been a lot of work on the use of utility functions in the networking area. And some of these works [12] could be applied here too.

However, unfortunately, the above problem has been proven to be NP-hard [13], so we cannot hope an algorithm that can find the theoretical optimum and runs in polynomial time. Hence, if not considering the QoS requirements and resource constraints, the definition of the utility could be simplified as bit-time-meter (b·m).

On the other hand, available radio resources up to now can be classified into five categories, time, frequency, space, code and power in five different domains. Hence, a novel concept of green efficiency is presented in [8], which is defined as the number of bits time transmission distance per resource category in a domain, corresponding to (bit-time-meter)-per-second-per-Hertz-per-antenna-per-code-per-W ((b·m)/s/Hz/antenna/code/W).

This definition is generic and all the five categories of radio resources can be designated. In view of the frequency spectrum and the power, two major resource categories, many researchers consider the b/s/Hz bandwidth efficiency and the b/s/Hz/W power efficiency respectively as the principal efficiency criterion. Obviously, the bandwidth and power efficiency are two special cases of green efficiency.

According to the Shannon-Hartley theorem, the bandwidth efficiency of a communication system is defined as the number of bits per unit bandwidth, which in the case of single-input single-output (SISO) systems corresponds to bit-per-second-per-Hertz (b/s/Hz), while in multiple-input multiple-output (MIMO) systems is equivalent to bit-per-second-per-Hertz-per-antenna (b/s/Hz/antenna). Furthermore, [14] defines the area spectral efficiency as bit-per-second-per-Hertz-per-m^2 (b/s/Hz/m^2). On the other hand, a host of spread-spectrum methods intentionally sacrifice the b/s/Hz performance for the sake of achieving a better bit-per-second-per-Watt (b/s/W) power efficiency. Moreover, [11] defines the power efficiency as the number of bits per thermal noise signal energy unit (TNEU). By no means should these methods be classified as less efficient, since in the appropriate circumstances they are capable of considerable improving the overall performance of the entire network.

For simplicity, in the following, we only consider the b/s/Hz bandwidth efficiency, the b/s/Hz/m^2 area spectral efficiency, the b/TENU power efficiency, the b/s/W power efficiency, and the (b·m)/s/Hz/W green efficiency, and give a comprehensive analysis of the four efficiencies.

III. Efficiencies of A Wireless System

A. Bandwidth, area spectral, and power efficiencies

The system capacity is defined as the maximum possible transmission rate such that the probability of error is arbitrarily small [15], which is quantified by the Shannon-Hartley theorem as:

$$C = B\log_2(1+\gamma_s) \quad (b/s) \quad (2),$$

where B is the channel bandwidth in Hz. $\gamma_s = S/N_0$ is the average signal-to-noise ratio (SNR) in dB recorded at the receiver, where S denotes the signal power, and N_0 denotes the noise power.

The above equation describes the capacity of a Gaussian channel, assuming an infinite duration of the transmitted signal, as well as an infinite detection/decoding complexity.

Subsequently, the b/s/Hz bandwidth efficiency of a communication system is defined as

$$\eta_b = \frac{C}{B} = \log_2(1+\gamma_s) \quad (b/s/Hz) \quad (3).$$

The b/s/Hz/m^2 area spectral efficiency is defined as

$$\eta_{ASE} = \frac{\eta_b}{A} = \frac{\log_2(1+\gamma_s)}{\pi d^2} \quad (b/s/Hz/m^2) \quad (4),$$

where we consider a circle area $A = \pi d^2$, with the transmitter at the center and a radius of d.

The b/TENU power efficiency is defined as

$$\eta_{TENU} = \frac{\eta_b}{\gamma_s} = \frac{\log_2(1+\gamma_s)}{\gamma_s} \quad (b/TENU) \quad (5),$$

where TNEU refers to the amount of signal energy identical to the variance of the complex-valued AWGN samples recorded at the receiver.

The b/s/Hz/W power efficiency is defined as

$$\eta_W = \frac{\eta_b}{P_t} = \frac{\log_2(1+\gamma_s)}{P_t} \quad (b/s/Hz/W) \quad (6),$$

where P_t is the transmitted power in W.

B. The (b·m)/s/Hz/W green efficiency

The (b·m)/s/Hz/W green efficiency is defined as

$$\eta_m = \eta_W \cdot d = \frac{d \cdot \log_2(1+\gamma_s)}{P_t} \quad ((b \cdot m)/s/Hz/W) \quad (7).$$

where d donetes the transmission distance between the transmitter and receiver.

For simplicity, we consider the free-space propagation model in this paper. And the free-space power received by an antenna at a distance d from the transmitter is given by

$$S = P_t \cdot PL = P_t \cdot \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \quad (8),$$

where PL is the propagation loss, G_t and G_r are the transmitter and receiver antenna gain respectively, λ is the wavelength, and L is the system loss not related to propagation ($L \geq 1$).

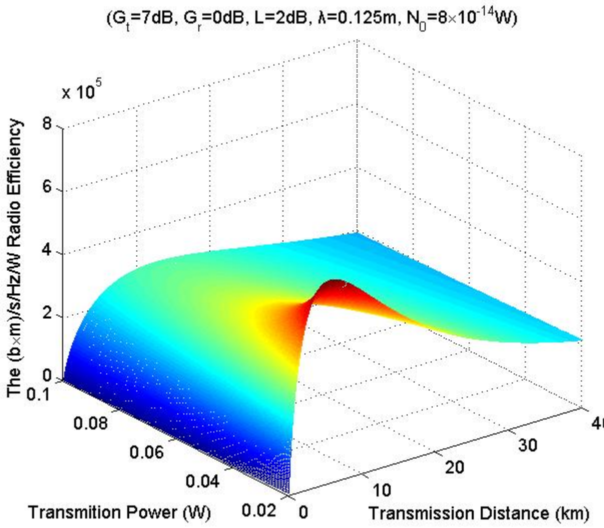

Figure 1. The (b·m)/s/Hz/W green efficiency

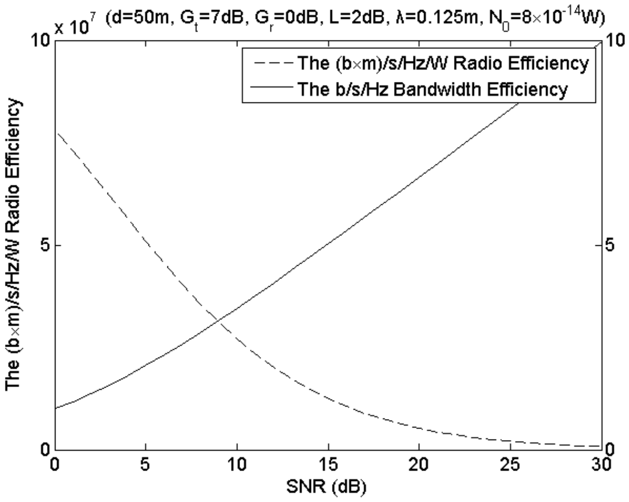

Figure 2. The (b·m)/s/Hz/W green efficiency and the b/s/Hz bandwidth efficiency as a function of SNR

Substituting (8) into (7), we can derive an explicit formula of the green efficiency versus the transmission power and transmission distance,

$$\eta_m = \frac{d \cdot \log_2\left(1 + \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 N_0 d^2 L}\right)}{P_t} \quad ((b \cdot m)/s/Hz/W) \quad (9).$$

Obviously, the green efficiency decreases with the increasing of the transmission power, and increases with the increasing of the transmission distance, as shown in Fig. 1. However, when the transmission distance is larger than about 20km, if the transmission distance continues increasing, the green efficiency will decrease as the bit error rate is very large.

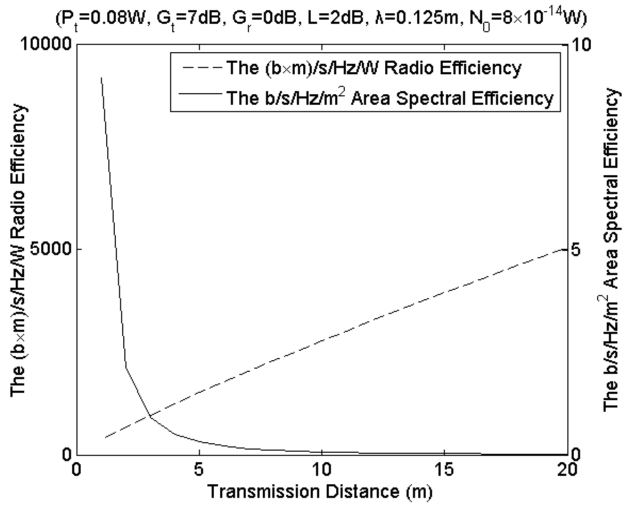

Figure 3. The (b·m)/s/Hz/W green efficiency and the b/s/Hz/m^2 area spectral efficiency as a function of the transmission distance

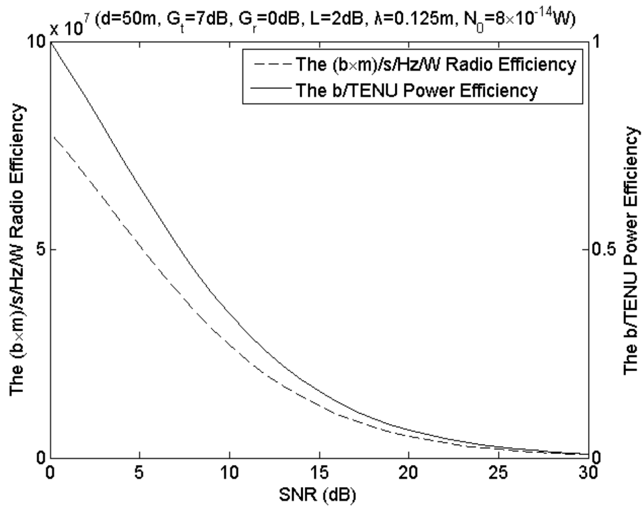

Figure 4. The (b·m)/s/Hz/W green efficiency and the b/TENU power efficiency as a function of SNR

Moreover, the green efficiency is inversely proportional to the bandwidth and area spectral efficiency respectively, as shown in Fig. 2-5, as we consider the power as a category of resources, and the transmission distance as a category of utilities.

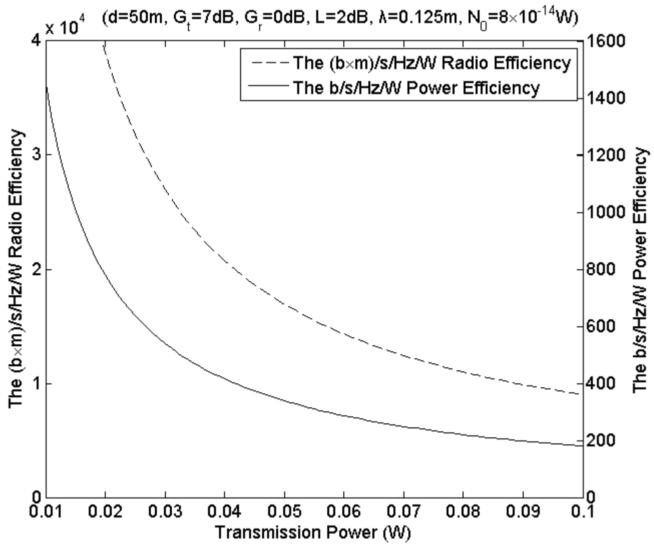

Figure 5. The (b·m)/s/Hz/W green efficiency and the b/s/Hz/W power efficiency as a function of the transmitting power

IV. GREEN EFFICIENT MODULATION AND CODING SCHEME

In most practical scenarios characterized by various performance-limiting factors including channel fading, interference as well as latency and complexity constraints, the actual attainable bandwidth, power, and green efficiency are considerably lower than those predicted by Equations (3-7). However, adaptive modulation and coding (AMC) is a possible solution to approach the above efficiencies.

A. Adaptive modulatin and coding for bandwidth, area spectral, and power efficiencies

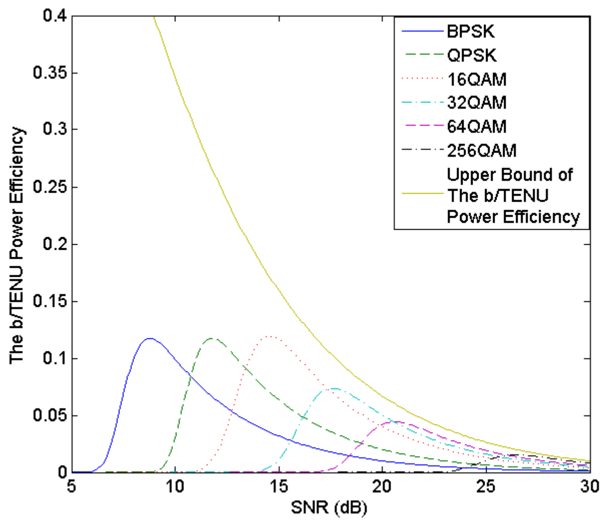

Figure 6. AMC shcemes for the b/TENU power efficiency

By adapting the modulation and coding schemes to the received SNRs, we can approach the optimal b/s/Hz bandwidth efficiency [16] and b/TENU power efficiency, as shown in Fig. 6. However, we cannot approach the optimal b/s/Hz/m^2 area spectral efficiency and b/s/Hz/W power efficiency by means of AMC, as shown in Fig. 7-8. The highest order modulation scheme, 256QAM, works best, but its area spectral efficiency and power efficiency are far below the upper bounds. Moreover, for simplicity, temporal coding is not considered in this paper.

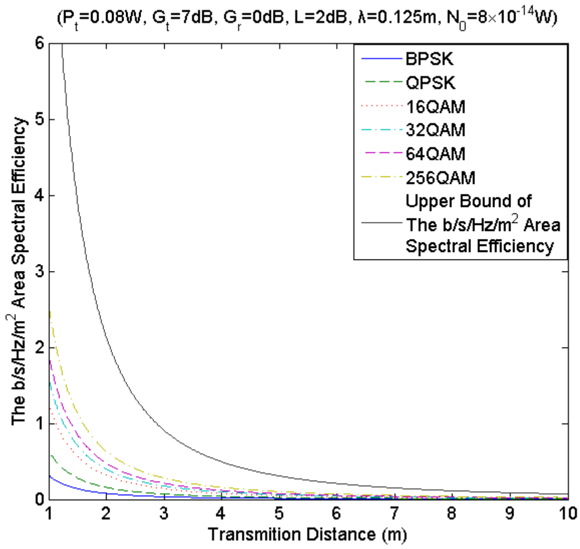

Figure 7. AMC schemes for the b/s/m^2 area spectral efficiency

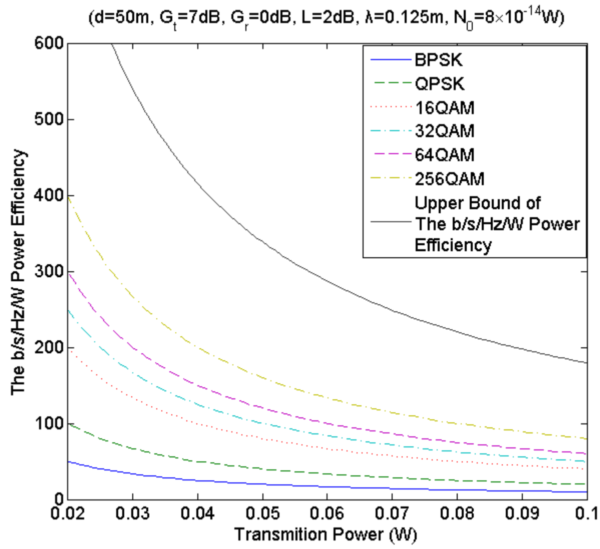

Figure 8. AMC schemes for the b/s/Hz/W power efficiency

B. Adaptive modulatin and coding for the (b·m)/s/Hz/W green efficiency

It is much complex to approach the upper bound of the green efficiency by means of AMC as shown in Fig. 9-10. At a low transmission distance, we adopt a higher order modulation scheme, e.g., 256QAM, as it works better to provide a higher green efficiency. With the increasing of transmission distance, we adopt a lower order modulation scheme, e.g., 16QAM, as it works better to provide a higher green efficiency. However, if the transmission distance continues increasing, no modulation scheme can approach the upper bound of the green efficiency. That is to say, we have to limit the coverage size of a cell.

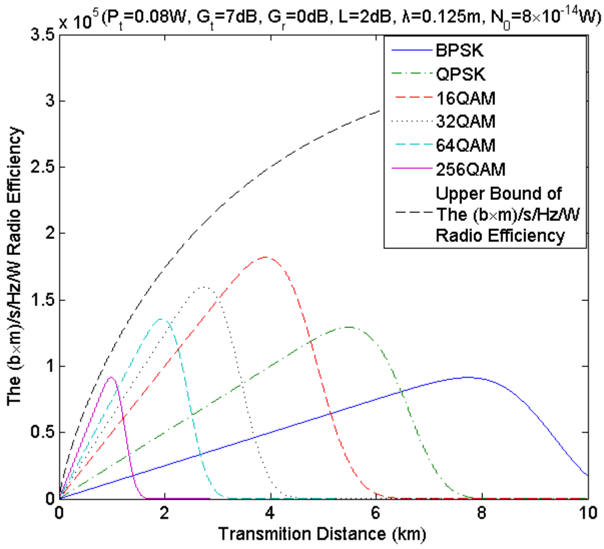

Figure 9. Green efficient AMC schemes vs. transmission distance

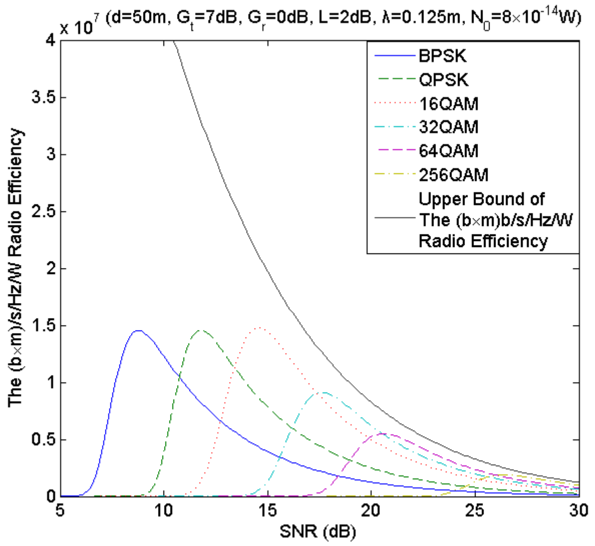

Figure 10. Green efficient AMC schemes vs. SNR

Similarly, at a high SNR, we adopt a higher order modulation scheme, e.g., 256QAM, as it works better to provide a higher green efficiency. With the decreasing of SNRs, we adopt a lower order modulation scheme, e.g., 16QAM, as it works better to provide a higher green efficiency. However, if SNR continues decreasing, no modulation scheme can approach the upper bound of the green efficiency.

I. CONCLUSION

For a greener network, this paper has proposed a new efficiency criterion, the (b·m)/s/Hz/W green efficiency. Firstly, we carried out a comprehensive comparison of the green efficiency with the b/s/Hz bandwidth efficiency, the b/s/Hz/m^2 area spectral efficiency, the b/TENU power efficiency, the b/s/Hz/W power efficiency. Secondly, we present an adaptive modulation and coding scheme to approach the upper bound of the green efficiency.

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