Invited Paper: Antenna Selection in Energy Efficient MIMO Systems: A Survey

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Abstract: With the explosive growth and need for high-speed wireless communications, more and more energy is consumed to support the required quality of service. Therefore, energy efficient or green communication has become a very hot topic under the ground of limited energy resource and environmentally friendly transmission schemes. MIMO technique is capable of reducing the transmission power thanks to its diversity and multiplexing gain. Moreover, antenna selection (AS) is an alternative to extract many of the benefits in MIMO systems with a reduced cost of complexity and power. Although many works including several survey papers have investigated AS in MIMO systems, the goal of these works is only the capacity maximization or error rate minimization, which fails to guarantee the optimality of the energy efficiency in MIMO systems. In this paper, we overview the state of the art in the AS schemes in energy efficient MIMO systems, the goal of which is to optimize the energy efficiency of the whole system. Specifically, we introduce energy efficient AS in point-to-point MIMO, cooperative MIMO, multiuser MIMO and large-scale MIMO systems, respectively. Several challenging and practical issues in this area are also addressed.

Keywords: antenna selection; energy efficient; holistic power model; MIMO

I. INTRODUCTION

The amount of energy consumption for information and communication technology (ICT) is increasing dramatically with the explosive demand for services and ubiquitous access. More than 4 billion subscribers around the world rely on their mobile phones for their everyday lives, which inevitably comes at a cost of increasing consumption of energy [1]. Meanwhile, due to this rapid increase in energy consumption, the ICT is having more and more impact on the global greenhouse gas emissions. The whole ICT sector has been estimated to represent about 2 percent of global CO_2 emissions [2]. Wireless communications, as an important part of ICT, has the responsibility to make sure that the whole systems are energy-saving and friendly to our environment. From the service providers' or operators' perspective, saving the energy consumption in their systems has both ecological and economic benefits. On the side of users, energy efficient wireless communications is also imperative since the development of the newest battery technology is much slower than the increase of energy consumption. It is not uncommon to hear users' complaints about battery endurance especially when they switch to 3G services. Therefore, green communications or energy efficient communications has

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attracted increasing attention in both academic research and industry activities recently.

As the key technique in 4G wireless systems, MIMO (multiple-input-multiple-output) is capable of providing diversity gain and multiplexing gain. Specifically, we can achieve the diversity gain by sending the same information via different paths between the transmitter and receiver as the probability of simultaneous deep fading in all paths is rather low, and thus we can always find one path with good channel condition to use. Multiplexing gain can be obtained by transmitting independent information streams via the parallel channels in the space degree. Therefore, MIMO technique could increase the system capacity without the cost of more bandwidth, and hence is able to consume much less transmission power to achieve a certain QoS (quality of service) [3]. In practice, however, the main limitation of MIMO systems is the cost for the multiple RF chains and the high computational complexity required for signal processing at both the transmitter and receiver. Therefore, an efficient way to extract the benefits of MIMO systems at reduced cost is of vital importance to the practical application of MIMO systems.

Antenna selection (AS) in which only a subset of available antennas are active for transmitting or receiving is a good choice to reduce the cost of MIMO systems. The performance of MIMO systems with AS has been shown to be significantly better than that of the systems using the same number of antennas without selection process [4]. However, the optimal method to select the best antennas to improve the performance is only the exhaustive search, which requires an exponentially growing computations with the total number of the antennas available. Therefore, many works on AS have focused on the design of low complexity AS algorithms and the analysis of them, which will be reviewed in details in the next section as the background knowledge. The goal of these previous works is just to select an optimal subset of antennas to minimize the error rate or maximize the system capacity under the constraint of transmission power. However, most of these previous works on AS ignored the corresponding increasing circuit power consumption associated with the use of multiple antennas at both the transmitter and receiver. With MIMO transmission, more antennas mean more RF chains, which would cost more circuit power. A comprehensive and holistic power consumption model of MIMO that considers all signal processing units at the transmitter and receiver was proposed in [5]. Based on this holistic model which includes the circuit power as well as the transmission power, it has been shown that MIMO is not always more energy efficient than SISO [6], in which the energy efficiency (EE) metric is chosen as the most popular one, i.e., 'bits-per-joule', which is defined as the ratio between the throughput and overall energy consumption. Therefore, it is becoming more and more urgent to shift our perspective from maximizing the system capacity to optimizing the corresponding EE when design future MIMO systems [7].

In this paper, we intend to overview and introduce the state-of-art on AS in energy efficient MIMO systems, in which the main goal is to save energy and make MIMO systems more energy efficient. Specifically, AS in energy efficient MIMO systems have been investigated in various and different wireless scenarios, such as point-to-point MIMO, cooperative MIMO systems, multiuser MIMO communication systems and large-scale or massive MIMO systems. We overview the up-to-date energy efficient AS algorithms and performance analysis in all the aforementioned settings. It is worth pointing out that the main difference between the conventional AS and energy efficient AS is that the number of active antennas is also a key optimization parameter as the circuit power consumption is taken into account in energy efficient communication systems. In other words, activating more antennas is not always the best choice since more power would be consumed in the circuits part to support the additional RF chains. Therefore, the most vital problem which must be seriously addressed in energy efficient

MIMO systems with AS is the fundamental tradeoff between the transmission power and the spatial degrees of freedom. This fundamental trade-off is particularly indicated by the number of active antennas L. By dynamically adjust the value of L, different trade-offs could be achieved. As shown in the works on energy efficient AS, the best trade-off mainly depends on the transmission distance. More specifically, for long distance transmission, less active antennas is preferred. On the other hand, in short distance transmission, activating more antennas is often the best choice. In addition to theoretic analysis of AS in energy efficient AS, we also clarify several practical issues and point out future research direction that might be considered in this topic.

The reminder of this paper is organized as follows. In Section II, we review several classic conventional AS schemes so as to lay a foundation for the following discussions. The state of the art in energy efficient AS is introduced in Section III with a focus on point-to-point MIMO, cooperative MIMO, multiuser MIMO and massive MIMO systems, respectively. Section IV presents the discussions on several practical issues in energy efficient AS. Finally, the paper is concluded in Section V.

II. Review of Conventional Antenna Selection

In this section, we would like to first review several classic works on AS in MIMO systems. Since MIMO technique is capable of improving the system performance with the advantage of the diversity gain and multiplexing gain, the conventional works on AS in MIMO systems also mainly focus on the optimization of either SNR (signal-to-noise-ratio) or capacity in MIMO systems under the constraint of the transmission power. It has been shown that AS is a low-complexity and low-cost method to grasp the advantages of MIMO technique while with little performance loss. In the following, we give an overview of conventional AS in MIMO systems in the context of SNR optimization and capacity maximization, respectively. It is worth pointing out that having the knowledge of these classic conventional AS methods or algorithms is a necessary preparation for the discussions of energy efficient AS. This is because conventional AS and energy efficient AS share some key ideas in the design of different schemes, which will be discussed in detailed in the following parts.

2.1 SNR and diversity

In this subsection, we look back on the conventional AS methods that capture diversity gain and improve the SNR of MIMO system. Diversity methods could be adopted at both the transmitter and the receiver with the exploitation of space-time coding or the RAKE receiver. Among all diversity combining methods, maximal ratio combining (MRC) is the most popular diversity combining method as it often achieves better performance than other methods as it makes combining decisions based on an optimal linear combination of different path signals. The authors in [8] derived the mean and variance of the combiner output SNR of H-S/MRC (hybrid selection/maximal ratio combining) in a multipath fading scenario for any values of the selected L branches out of N diversity branches. In [9], the average error probability of the combined AS adopted at the transmitter with MRC diversity scheme used at the receiver in flat Rayleigh channels was derived. It showed that the simple combined transmit/receive diversity scheme could achieve an order of diversity which equals the product of the numbers of transmit and receive antennas. Moreover, the impact of non-ideal selection on the bit-error probability was also investigated. Furthermore, it was shown that TAS/MRC scheme outperforms some more complex space-time codes of the same spectral efficiency only with a cost of a low-rate feedback channel in [10]. In addition, [10] verified that channel estimation errors based on pilot symbols have no impact on the diversity order over quasi-static fading channels.

2.2 Capacity and spatial multiplexing

Following the discussions of the AS in the context of diversity or SNR, we turn to review several classic AS works which focused on the issue of capacity maximization in MIMO systems. The pioneer work [4] investigated the capacity behavior of MIMO systems when AS is adopted at one link-end. Specifically, the bounds for the capacity of AS were derived, and several low complexity AS algorithms were proposed to avoid the use of exhaustive search over all possible antenna subsets. In [11], the authors studied the problem of receive AS in MIMO spatial multiplexing systems from the perspective of both theory analysis and practical application. In particular, the authors proved that the capacity with receive AS is statistically lower bounded by the capacity of a set of parallel independent SIMO (single input multiple output) channels. Two simplified AS algorithms: incremental and decremental selection were proposed to fast select the best receive antenna subset. The authors of [12] developed a new fast receive AS algorithm which select one antenna that brings the largest capacity increment at each step, which is similar to the incremental selection scheme in [11] but with a lower computational complexity. Moreover, a QR decomposition based interpretation of the proposed algorithm was provided, which showed that antenna subset selection procedure depends on the rank properties of the channel matrix. A concise joint transmit and receive antenna selection algorithm is proposed in [13]. A joint iterative user scheduling and AS algorithm is proposed for massive MIMO systems in [14]. It can be seen that all the fast AS algorithms enjoy the feature of greedy selection, which is also the main idea in many energy efficient AS algorithms discussed in the next section. In contrast to the aforementioned works, the work [15] approximated the problem of receive antenna subset selection by a constrained convex relaxation which thus can be solved using standard low complexity techniques adopted from optimization theory.

III. Energy Efficient Antenna Selection

In this section, we review works on green AS or equivalent selections such as relay selection, remote radio head selection, etc. In sharp contrast to conventional works, the authors in these works consider a holistic power model, which includes the power consumption of RF chains, cooling and baseband signal processing, as well as the transmission power.

3.1. Point-to-point MIMO

We first start with the antenna selection in p2p MIMO system with a holistic power model, which includes the circuit power consumption as well as the transmission power. In terms of capacity maximization, the pioneer work [16] derived the iterative formula for the channel capacity in p2p MIMO with AS under a holistic power model. Based on this formula, the authors proposed an iterative AS algorithm to determine both the optimal number and subset of active antennas at the transmitter or the receiver which are capable of achieving the maximum capacity. Moreover, the authors also mathematically proved that the marginal benefit of adding one more antenna is diminishing and even may be negative when the circuit power is taken into account. This result theoretically verifies the important fact that activating more antennas is not always the best choice under a holistic power model. Due to this, a dynamical adjustment of the number of active antennas is necessary for the maximization of capacity in green MIMO systems. However, the capacity maximization under a holistic power model cannot guarantee the global energy efficient. Therefore, in order to achieve this goal, many works have focused on the direction of energy efficiency maximization with AS in p2p MIMO systems with the consideration of circuit power. Specifically, for single-stream MIMO systems, the authors in [17] compare the EE of two common spatial diversity schemes, i.e., TAS (transmit antenna selection) and TBF (transmit beamforming), considering a realistic power consumption model. One important result shown by the analysis and simulations in [17] is that TAS can be very energy efficient solution even though it is not the best in terms of outage probability. The authors in [18] explored to find the most energy-efficient number of antennas for a given outage probability in MIMO-MRC systems. In [19], the authors jointly optimized the transmission power, number of active RF chains, and antenna subsets so as to maximize the system energy efficiency. In order to exploit the multiplexing gain in MIMO systems, the authors in [20] investigated the EE maximization with AS in multi-stream MIMO systems. Compared to the EE maximization with AS in single-stream MIMO, the EE maximization in multi-stream is much more complicated and the simple norm-based AS algorithm is not a good choice in this case. What makes this optimization problem even more convoluted is the fact AS is dependent on the transmission power. In other words, the optimization of antenna subset and transmission power is coupled. To address this problem, the authors in [20] proposed an iterative algorithm to jointly optimize the transmit antenna subset and the transmission power so as to maximize the EE. More specifically, the fundamental idea of the proposed algorithm has two key points: 1) judiciously select one transmit antenna which achieves the largest increment of EE under a given transmission power based on the derived EE update formula. 2) calculate the optimal transmission power for the selected antenna subset and set the new transmission power as the given transmission power for the next antenna selection. In addition, the authors proved that in high and low SNR regimes, AS is independent with the transmission power, which helps to reduce the complexity in the iteration process and achieve the optimal performance with a greater probability. The work [21] investigated the switch scheme between single-stream mode (SIMO) and multi-stream mode (MIMO) to save overall system energy consumption. This work also showed that mode switching benefits are more significant when channels are correlated.

3.2 Cooperative communication systems

In this subsection, we intend to review works on green AS or equivalent selection in cooperative communication systems. More specifically, we focus on the pure MIMO relaying systems and virtual or cooperative MIMO systems, respectively.

(1) Relaying Systems or Networks: Wireless MIMO relaying is an extensively studied technique to increase the reliability, data rate and coverage for communications systems. However, more power is consumed associated with the use of multiple antennas under a holistic power model. Therefore, it becomes more and more important to design energy efficient MIMO relay systems. Moreover, it is worth noting that many studies have focused on the relay antenna selection. This is because the relay node is often power-limited and has a great impact on the overall performance of the relaying systems. The authors in [22] studied the relay antenna selection for capacity maximization in AF MIMO relay systems with the consideration of circuit power. To avoid exhaustive search, an iterative equation for the capacity with relay AS is derived. Based on this equation, a joint iterative AS (JIAS) algorithm is proposed to jointly select a pair of receive and transmit antenna that achieves the largest capacity increment for each iteration. To further reduce the complexity, a separable iterative antenna selection (SIAS) algorithm is proposed in which the receive antenna is first selected, followed by the selection of the transmit antenna for each iteration. In order to achieve the global optimal EE, the authors in [23] investigated EE maximization with relay antenna selection in AF MIMO relay systems. An iterative algorithm is proposed to jointly select the best active receive and transmit antennas at the relay, as well as optimize the transmission power of the source and relay node. More specifically, the antenna selection process is based on a derived iterative property

of EE, which helps to select a pair of receive and transmit relay antennas that achieves the largest increment of EE under an initial transmission power at each step. Then a power adaptation is adopted where the optimal transmission power is calculated with the adoption of fractional programming and the new power is set as the initial one for the next selection. On the other hand, two-way relaying is becoming a hot research topic and constitutes an appealing spectral efficient transmission protocol as it is capable of compensating the spectral efficiency loss in one-way relaying. In this context, energy efficient two-way MIMO relaying also attracts more and more attention. In [24], the authors adopt a similar method as in [22] to maximize the sum-rate in AF MIMO two-way relay channels (TWRCs) combined with relay antenna selection under a holistic power model. The proposed greedy selection algorithm is capable of significantly reducing the computational complexity, whilst attaining near-optimal performance compared to exhaustive search. The EE maximization with relay AS in AF MIMO TWRCs is investigated in [25]. An iterative energy efficient AS algorithm was proposed to jointly select the best relay antenna subsets, as well as optimize the transmission power at the two sources and relay. The proposed algorithm enjoys a low complexity and achieves near-optimal performance. Moreover, it is capable of improving the EE, whilst reducing transmission power consumption.

In addition to AF MIMO relay, energy efficient DF MIMO relay is also becoming more and more popular. The authors in [26] conducted the pioneer research on this topic. Three iterative properties on the capacity bounds are first derived. Based on these properties, an iterative AS algorithm was developed to improve the performance of DF MIMO relay systems by the maximization of the upper and lower bounds. It greatly reduces the computational complexity yet with litter performance loss when compared to exhaustive search. The same authors also investigated the EE maximization in DF MIMO relaying with AS when a holistic power model is considered [27]. By adopting the tool of fractional programming and the Dinkelbach method, the authors incorporated the power adaptation into the AS of each step. Simulations showed that the proposed DF scheme has a significant EE performance gain over the conventional DF protocol. In terms of AS at the source node, the authors in [28] showed that selecting the antennas from the source w.r.t. to the destination is in general the best option when compared with w.r.t. to the relay node. Also, the performance of different cooperative MIMO transmission schemes in terms of the EE were compared and outage expression for each scheme was derived in [28].

(2) Distributed Antenna Systems (DAS): As one of promising green techniques, DAS has been introduced for the next wireless communication systems attributed to the advantages of increasing capacity, reducing transmission power and extending coverage [29]. Different from a traditional collocated antenna system (CAS) where all antennas at the base station are located at the center of a cell, remote access units (RAUs) in the DAS systems are placed at different locations in a cell and collected to a baseband processing unit (BPU) through optical fibers. Therefore, by flexible antenna configuration, adaptive power allocation and dynamic rate adjustment, DAS can improve system performance. The work [30] focused on the EE maximization problem in downlink DAS with delay performance taken into account by jointly considering AS and power adaptation. The problem is formulated as a stochastic optimization model and an energy efficient transmission scheme is proposed based on Lyapunov optimization technique. However, the maximization of the revenue-cost (RC) function used in [30] only ensures to be Pareto optimal in terms of EE maximization and thus cannot guarantee the global optimality of EE. The authors in [31] concentrated on devising globally optimal algorithm to maximize the system EE in downlink DAS by taking both AS and power adaptation into account. In particular,

an iterative algorithm has been proposed to solve the formulated mixed-integer nonlinear programming (MINLP). This algorithm could serves as an important benchmark to evaluate performances of other heuristic algorithms owing to the guarantee of global optimality. In [32], EE maximization problem for large-scale distributed antenna system (L-DAS) with AS is studied. The power consumption of L-DAS transmitter has been modeled and iterative algorithms to adapt the number of assigned antennas have been considered to improve the EE.

3.3 Multiuser MIMO (MU-MIMO) communications

In multiuser MIMO (MU-MIMO) systems, the base station communicates with multiple users rather than a single user. For the downlink, i.e., the MIMO broadcast channel, the base station sends different data streams to the users. Downlink MU-MIMO is becoming the key technology for the next generation of cellular networks such as 3GPP LTE-Advanced because the sum rate can scale with the minimum of the number of based station antennas and the sum of users times the number of antennas per user. Previous works mainly focused on the study of the capacity or spectral efficiency (SE) in MIMO BC. The pioneer research work on the EE of MIMO-BC is [33]. In contrast to the research on SE of MIMO-BC which only considers transmission power, a comprehensive understanding on the power consumption of downlink MU-MIMO systems is necessary for the study of EE. As the main part of power consumption in a typical cellular network, the power consumption of the base station, besides the transmission power, includes power consumption such as circuit, processing, and cooling. In particular, when the base station is deployed with multiple antennas, the overall power consumption is highly related to the number of active antennas. In this context, activating all transmit antennas and using high sum transmission power, which could guarantee the optimality for SE optimization, are not always optimal for EE maximization. To address the problem, the authors in [33] proposed a new optimization approach jointly with transmit covariance optimization and active antenna selection to maximize the EE of the MIMO-BC. More specifically, the proposed scheme could be decomposed into two procedures. First, a globally optimal energy efficient iterative water-filling scheme is devised to obtain the best covariance under fixed active transmit antenna subsets. Then, exhaustive search and norm-based antenna selection are developed to determine the active transmit antenna subset. The problem of maximizing EE in the downlink of multi-cell systems is addressed in [34]. The authors in [35] investigated the EE maximization in downlink MIMO systems with the exploitation of the multiuser diversity. For the EE maximization in the uplink MIMO systems with AS, a low complexity EE maximization method is proposed to jointly select the active antennas and the user, as well as optimize the transmission power in [36]. In [37] and [38] , the authors investigated the optimal energy efficient uplink MUMIMO with dynamic antenna management in which users can choose to turn off circuit operations when some antennas are not used. The results showed that some antennas should not be used even when they have good channel states because turning them on consumes too much circuit power, which again directly validates that dynamic adjustment of the number of active antennas is of vital importance to energy efficient MIMO systems.

3.4 Large-scale (massive) MIMO

Recently, there has been a great deal of interest in large scale or massive MIMO systems, which means that the base station has nearly a hundred antennas or more. Extra antennas help by focusing the transmission and reception of signal energy into ever-smaller regions of space. This brings huge improvement in throughput, in particularly when combined with simultaneously scheduling of a large number of users. In this case, circuit power consumption of all the RF chains is significant and thus AS is a promising way to alleviate this problem. Besides, since the channel hardening phenomenon exists in large scale MIMO systems, AS in this scenario enjoys specific features. We would highlight these features by reviewing corresponding works in this area. In [39], the authors performed transmit antenna selection to improve the EE of large scale MIMO systems. In particular, in the case when the circuit power consumption is comparable to or even dominates the transmit power, there exists an optimal number of selected antennas to maximize the EE. In [40], a good approximation of the distribution of the mutual information in large-scale MIMO systems with AS was derived for the first time, from which channel hardening phenomenon can be observed. Furthermore, two simple but efficient AS algorithms are proposed to obtain the maximum EE in large-scale MIMO systems. An iterative offline AS and power allocation algorithm was proposed for large-scale MIMO systems with the adoption of energy harvesting in [41]. Moreover, the relationship among the maximum EE, selected antennas number, battery capacity, and EE-SE trade-off are analyzed. In [42], the authors determined the optimal number of active antennas in various circumstances, and showed that with large-scale MIMO, simple random AS can provide significant EE gain. Moreover, they verified that if the EE optimal antenna number is larger than a certain threshold, the random AS is already very close to the optimum AS. These results help to highlight the main features and difference of AS in large-scale MIMO systems due to the use of massive antennas at the base station. On the other hand, these works also verified the number of active antennas in large-scale MIMO systems plays an important role in optimizing the corresponding EE.

Table I *Comparison of different AS schemes*

	Conventional AS	Capacity-Centric Energy Efficient AS	EE-Centric Energy Efficient AS
Power Model	transmission power only	holistic power model: transmission power + circuit power	holistic power model: transmission power + circuit power
Optimization Objective	capacity maximization	capacity maximization	EE maximization
Optimization Parameters	active antenna subsets	active antenna number & subsets	transmission power & active antenna number & subsets
Optimization Result	SE-optimal	local EE-optimal	global EE-optimal

IV. Practical Issues

In this section, we intend to address several practical and implement issues with AS in communication systems. The works [43]–[45] investigated the impact of non-ideal channel estimation on the selection performance. It is also worth pointing out that most of the mentioned works ignore the energy consumption for obtaining the CSI (channel state information). Therefore, if the cost of signaling for CSI is taken into account, there might exist a trade-off between the CSI accuracy and total power consumption. In order to obtain the CSI, we often depend on training method, in which pilots are sent to estimate the channel gains. Training methods designed for AS were presented in [46], [47]. In particular, the authors in [47] proposed a new training method tailored for AS. This method chooses to assign less energy to 'selection pilots', which are used for the selection of antenna subset. It instead allocates more energy to an extra last pilot to refine the channel estimates for the antenna subset selected for data reception. The problem of mutual coupling in AS was addressed in [48].

V. Discussion and Conclusion

This article outlined the technical roadmaps of antennas selection (AS) in MIMO systems, from the conventional AS to the main focus of energy efficient AS, which have been summarized in Table 1. AS is capable of reducing the hardware cost and the complexity of signal processing for MIMO systems. Exhaustive search which is complexity undesirable is the only optimal method to find the best antenna subset that maximizes the capacity or minimize the error rate. Therefore, many AS works focused on the design of low complexity AS schemes. However, in those conventional AS works, they ignored the circuit power consumption which make those proposed AS algorithms not energy efficient when the performance metric is chosen as the system energy efficiency, which is defined as the ratio between the throughput and overall power consumption. In contrast to conventional AS works, energy efficient AS considers the selection process based on a holistic power model, which includes the circuit power as well as the transmission power. On account of the circuit power, the optimization and dynamic adjustment of the number of active antennas is a key problem existing in energy efficient AS. This is because the value for the number of active antennas plays a vital role in the trade-off between the transmission power and spatial degrees of freedom in MIMO systems. The results in energy efficient AS have shown that in long distance transmission scenario, fewer active antennas is preferred as more power could be allocated to increase the received SNR. On the contrary, for short distance transmission, activating more antennas is often a good choice since the system performance is limited by the degrees of freedom in this case and more antennas help to increase the capability of multiplexing in MIMO systems. It is also noting that under these two scenarios the achievable rate or capacity is able to satisfy the minimum QoS requirement for each system, which indicates that energy efficient AS is capable of maximizing the system EE without a big loss of SE. However, it is also noting that current research results are still quite preliminary and many challenges remain.

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