

Efficient Transmission Strategy in Wireless Communication Based on MIMO Technology

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Abstract. In today's rapidly evolving wireless society, four key research areas are explored. For point-to-point MIMO WET, a framework based on energy receiver feedback is proposed, with energy quantization performing better with more feedback bits and energy comparison superior with fewer bits. In massive MIMO heterogeneous networks, a decentralized user-centric association framework is examined, converging to Nash equilibrium and often approaching global optimum. For wireless powered communication networks with multi-user MIMO, a joint optimization algorithm for downstream energy precoding, upstream information precoding, and time allocation is presented, significantly improving average sum rate performance. In sensor networks with multi-antenna fusion centers, detection and estimation of Gaussian signals are studied. Neyman-Pearson detectors maintain performance stability as antennas increase if sensor power decreases proportionally. Energy detectors without CSI can achieve constant deflection if the square root of the antenna count is inversely proportional to sensor power, outperforming single-antenna implementations at high power. These advancements contribute to enhancing wireless network efficiency, optimizing resource allocation, and improving signal detection and estimation in various network configurations.

Keywords: Wireless Sensor Networks; wireless energy transfer; User-Cell Station Association.

1. Introduction

Radio frequency (RF) wireless energy transfer has become an up-and-coming technique for powering low-power devices in the Internet of Things and industrial systems [1]. This technology enables permanent, economical, and convenient energy supply for devices like RFID tags and sensor nodes. In RF-based WET systems, energy transmitters (ETs) control and coordinate the transfer of wireless energy to distributed energy receivers (ERs). The ERs convert received RF signals into DC signals using rectennas to charge their batteries. However, WET faces challenges due to significant power loss over distance. To address this, multi-input multi-output (MIMO) techniques have been proposed, employing multiple antennas on both ETs and ERs to enhance efficiency through energy beamforming. The availability of channel state information (CSI) plays a vital role in realizing the benefits of energy beamforming in MIMO WET systems [2].

In the context of 5G and beyond, massive MIMO technique, cell densification, and heterogeneous architectures are being explored to meet the increasing wireless data traffic demands. These advancements involve the intensive deployment of base station antennas, both in densely deployed multi-layer networks of small cells and massive MIMO schemes. Massive MIMO, working in time-division duplex (TDD) mode, promises enhanced spectral efficiency and power efficiency. However, the heterogeneous nature of these networks presents challenges in user-cell association, necessitating more effective solutions than traditional reference signal reception power (RSRP) based methods. Additionally, research in wireless powered communication networks (WPCN) has led to the investigation of systems where users collect energy from hybrid access points (H-APs) in the downlink phase for use in uplink information transmission. Optimizing downstream WET precoding, upstream WIT precoding, and time allocation between phases has shown significant performance gains in multi-antenna WPCN systems. Lastly, in the realm of wireless sensor networks (WSNs), the use of multi-antenna fusion centers (FCs) has been studied to enhance detection probability and estimation error in coherent multiple-access channels, with research focusing on how to leverage multiple antennas to improve energy efficiency in various WSN configurations.

2. Efficient Transmission Strategy in Wireless Communication Based on MIMO Technology

2.1. A General Design Framework of Limited Feedback MIMO Wireless Energy Transfer

To obviously increase the effectiveness of a Wireless Power Transfer (WET) (RF) signal, it is possible to employ a multiantenna or multiple-input multiple-output (MIMO) technology. And the knowledge of channel state information (CSI) must be mastered, then the chance will be got to make the most use of the beamforming gain from energy transmitters. But in the process of practice, channel state information is difficult to obtain due to power and hardware constraints of the energy receiver (ER).

For overcoming above-mentioned difficulty, under the setting of the point-to-point MIMO, a new overall design framework is mentioned which is based on energy measurement feedback of ER. That means ER send collected energy levels from different training intervals which is measured and coded by ER through wired rate feedback link to ET. Based on energy level feedback, MIMO channels are carefully designed, ET should be adjusted transmitting beamforming and used the technology of analytic center cutting plane method (ACCPM) in convex optimization during the subsequent training intervals. Under this framework, there are two concrete feedback plans named energy quantization and energy comparison which can be carried out. In each interval, B feedback bits are generated in the ER. These bits are obtained by quantizing the energy that has been measured at this time period interval, and then comparing it to the B previous intervals. Specially, when $B=1$, the channel learning scheme based on energy comparison degenerates to the channel learning scheme with 1 feedback bit at every interval. After a lot of numerical comparison, the conclusion is that when B is larger, energy quantization is superior to energy comparison. When B is smaller, energy comparison is superior to energy quantization [3].

2.2. Massive MIMO Wireless Networks' Optimal User-Cell Association

Optimization of user-cell association in Massive MIMO heterogeneous networks is studied in this thesis, highlighting its system-level advantages. The maximum utility of convex network can be expressed directly by users, it is different from previous the formulation of integer programming problems and its convex relaxation of the treatment of dependence, and the User-Cell problem can be solved efficiently by subgradient algorithm. Due to the existence of an integer association sequence, global optimal solutions can be physically implemented, approaching the optimal score association arbitrarily closely. Some associated schemes are simple and decentralized and user-centric that may be considered, and every user will be connected with base station which has the maximum committed throughput individually and privately. These schemes, where users make local association decisions probabilistically, can be viewed as a game converging to Nash equilibrium. Under some conditions, the global optimal solutions are close to this Nash equilibrium. Therefore, these decentralized schemes are attractive because they have simply properties and are close to the optimal operation of the system.

System optimization problems are expressed using strict network utility maximization (NUM), where the fairness standard is embodied in the selection of network utility functions. The utility of network is used to a function that focuses on user throughput rather than instantaneous user rate per slot. A related non-cooperative association game is formulated, the user is gamer, base station operates according to local resource allocation rules, the utility of the user is determined by rules. KKT conditions for global optimization problems are compared with conditions maintained by all users due to the game's best response strategy. The comparison result proves that the Nash Equilibrium with purely strategic approach to the overall optimal solution for the central trouble. Further proof, under some technical conditions named as heavy-loaded network, association is a sheer strategy Nash equilibrium in user-centric association game, the premise is that the association is a centralized global optimal containing a distinct association (i.e., no user has a positive activity score for multiple base stations). Furthermore, a user centered decentralized program approaches to a Nash

equilibrium with a probability of one for hard justice (HF) and proportional justice (PF). Therefore, user-centric algorithms are fascinating not only because it is simple and easy to learn and completely decentralized, but also because its operation is close to the social optimal in the system [4].

2.3. Maximizing Sum Rate for MIMO Wireless Powered Multi-User Communication Networks

This paper mainly studies that multi-antenna users use the transferred wireless energy from utilizing multi-antenna hybrid access points (H-AP) at the downstream stage for sending the message to the multi-input multi-output radio power communication network at the upstream stage. An optimization algorithm can connect uplink information precoding matrix with downlink energy precoding matrix to use space division multiple access techniques to maximize the performance of sum rate of uplink. This algorithm also explains how to allocate time between downlink and uplink. First, the optimal energy and information transmitting matrices are obtained for a given time allocation. Then, a simple linear search method is used to determine the optimal time allocation. Traditional method only determines time allocation and precoding matrix, comparing with traditional method, the joint optimal method evidently enhance the performance of average sum rate.

In multi-input multi-output (MIMO) WPCN system, both users and H-AP are equipped with multi-antenna. Downstream WET precoding matrix, upstream WIT precoding matrix, and the time distribution of downstream and upstream phases are optimized to improve the performance of sum rate. Firstly, for a given time assignment, the optimum energy and message transfer covariance matrix are obtained. Then, these matrices are used to find the first-rank time allocation. The consequences show that the best downstream energy covariance matrix is equal and rank-one. Namely, multicast and beamforming are the best strategies for downstreaming WET. Therefore, the H-AP transmits signals with the same energy to all users. The beamforming vector is aligned with the optimal eigenmode of the weighted sum of the downstream channel matrix. An iterative process based on a water-filling scheme is provided to allocate the optimal upstream information covariance matrix. In the end, the simple straight line search method can be used to calculate the optimal time allocation successfully. It can be concluded that the provided joint optimal algorithm has evident functional gain compared with separate design time allocation and traditional schemes such as downstream WET precoding and upstream WIT precoding. The paper examines a MU-MIMO WPCN system where both the user and the H-AP have a plurality of antennas. Solve the optimization problem of joint time allocation and transmission covariance matrix, while using the maximum sum rate as the target. The conclusion is that optimal algorithms bring more functional gain than traditional gain. Schematic diagram for MU-MIMO WPCN, as shown in Fig. 1 [5].

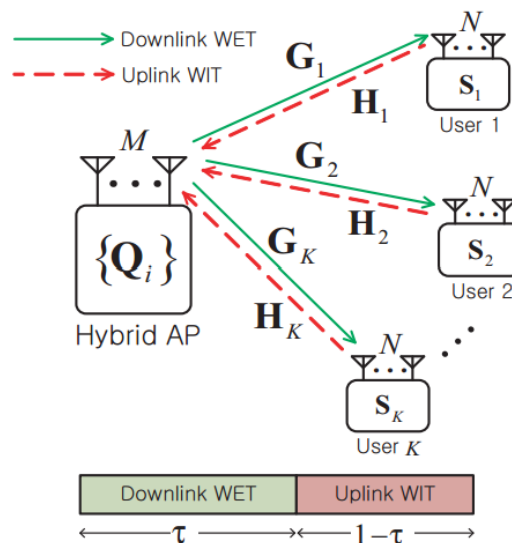


Fig. 1 Schematic diagram for MU-MIMO WPCN [5]

2.4. Massive MIMO on Coherent Multiple Access Channel Wireless Sensing

In the coherent multi-access channel wireless sensor network, the problem of detecting and estimating of zero mean Gaussian signal exists when there are many antennas installed in the fusion center (FC) and the wireless channel between the FC and the sensor node experiences Rayleigh fading. In order to solve detection problems, the optimal value of sensor transmission gain is found in studying of Neyman-Pearson Detector (NP) and Energy Detector (ED). NP Detector, which needs channel state information (CSI), the transmitting power of the sensor is reduced as the number of antennas is increased. However, the detection performance of sensors will become gradually stable with increase of the number of FC antennas and the advantages of multi-antenna of FC will disappear with the increase of transmitting power. Moreover, the results from the NP Detector contribute to estimating the linear least mean square error. For ED that does not need CSI, the optimal gain to maximize the detector deflection coefficient is derived, and constant deflection is asymptotically achieved when the transmitting power of the sensor and the number of FC antennas square root are inverse ratio. Compared with single antenna, the functions of multi-antenna ED will be achieved better, that is different from high sensor power conditions in the NP Detector.

In this thesis, this paper investigates the capability of detecting and estimating wireless sensor network (WSN), which consists of single antenna, and fusion center (FC), which is fitted with many antennas. In this thesis, the target parameter is considered to be zero average circle compound Gaussian variable, and Rayleigh fading occurs in the radio path from the sensor node to FC. Under these assumptions, the performance of Neyman-Pearson (NP) and Energy Detector and Linear Minimum Mean Square Error estimator (LMMSE) are studied out. The relationship between the detection Probability, false Alert Probability, and sensor transmitting power can be derived when the CSI of the sensor node is valid at the FC. In such a case, it is possible to realize a Neyman-Pearson (NP) detector, and to obtain a constant PD in the case of identical PFA, it is possible to decrease the sensor power by $1/M$. However, the optimal transmission gain derived from a sensor that maximizes PD for a fixed PFA which is under constraint of total power is different from assuming that transmission power of each user is equal. A closed form “water-filling” scheme is formulated to calculate the optimal gain. The study concludes that at low power levels, the optimal sensor gain improves the probability of detection (PD) performance more significantly compared to uniform power allocation. For NP detector, under the single-antenna condition, PD approaches PFA at $P \rightarrow 0$, while PD is strictly greater than PFA when the rate of P is decreasing at 0 ($1/M$) or $M \rightarrow \infty$ (and may be evidently greater than PFA). The single-antenna and multi-antenna FC will asymptotically attain the identical detection capacity at $P \rightarrow \infty$, therefore there is no benefit for using multi-antenna to NP Detector under the high signal-to-noise ratio. The performance of Energy Detector is studied for dealing with unknown CSI or calculating easier situation of solution. The deflection coefficient of the Energy Detector is used as an accurate indicator of detector performance. The conclusion is that the Energy Detector will achieve constant deflection when the transmitting power of sensor decreases at $M \rightarrow \infty$ based on $1/\sqrt{M}$ and choose the suitable transmission gain to get maximum deflection under the sum power constraint. When $M \rightarrow \infty$, finding the optimal gain in general can be achieved by quadratic constrained linear programming, and a closed solution for the limit value of the power constraint P is possible. The conclusion that the optimal solution is independent of sensor phase is the same as NP detector. The constant PD can be obtained when the transmit power is reduced to keep constant deflection because it involves an Energy Detector that does not require CSI. What is more, the assumed condition is that it does not include uniform power allocation, but the optimal sensor transmission gain is obtained and when the improvement of detection performance can be evidently demonstrated. For the LMMSE estimator, a constant Mean Squared Error (MSE) can be attained by increasing the number of FC antennas (M) while reducing the transmitting power by $1/M$. This finding generalizes the asymptotic results from the NP Detector to the LMMSE estimator. Both the NP Detector and LMMSE estimator follow similar rules as M approaches infinity. The bound of MSE in limit cases such as $P \rightarrow 0$ and $P \rightarrow \infty$ are similar to the case of NP Detector PD. The detection

probability of NP detector vs. the value of P , with antenna number $M=50$, as shown in Fig. 2. Mean squared error vs. the value of P , with number of antennas $M = 50$, as shown in Fig. 3.

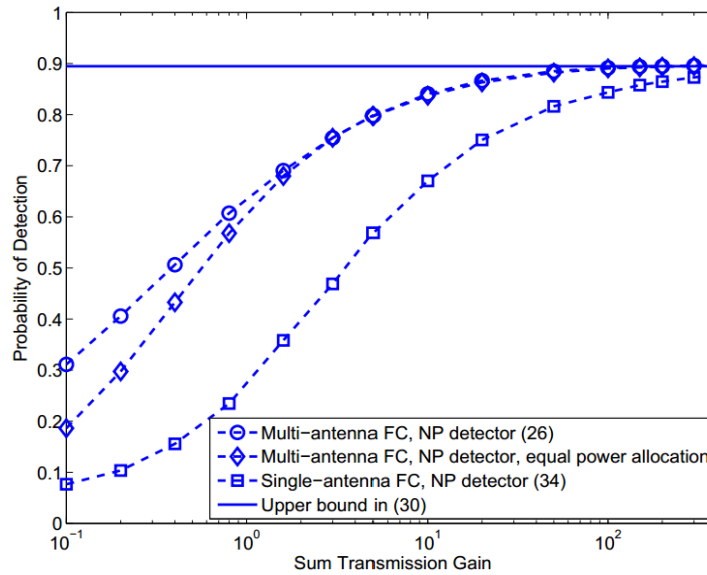


Fig. 2 Detection probability of NP detector vs. the value of P , with antenna number $M=50$ [6]

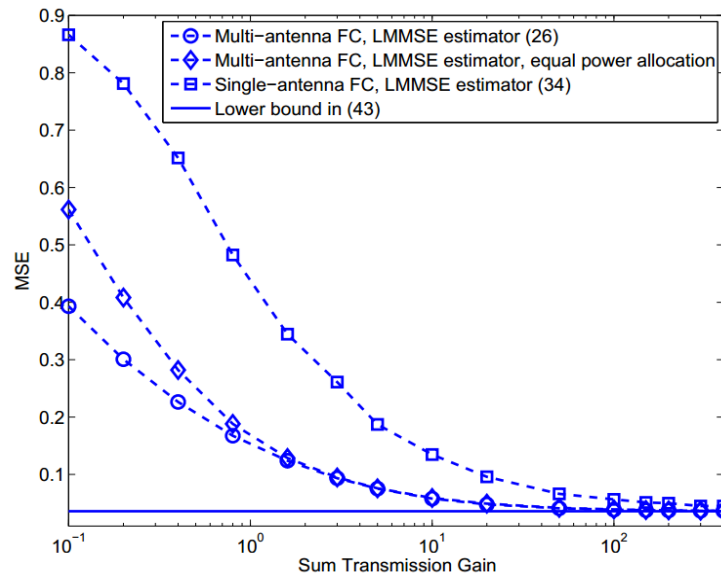


Fig. 3 Mean squared error vs. the value of P , with number of antennas $M = 50$ [6]

This paper studies the performance of detecting and estimating of a multi-antenna coherent multiple access channel sensor network. The optimal transmission gain of sensor is derived by analyzing Neyman-Pearson and energy detection. The conclusion is that the optimal transmission gain does not change due to the change of phase with the increasing number of antennas. The antennas at the fusion center can trade off with the energy efficiency of sensors, similar to the characteristics of Massive MIMO wireless communication. For the Neyman-Pearson detection and LMMSE estimation that need CSI, reducing the sensor's transmitting power proportionally to the gain of the number of antennas allows a constant level of performance to be achieved. For energy detection which does not require CSI, it is possible to keep a constant deviation factor by decreasing the power proportional to the inverse square root of the antenna count. Although Neyman-Pearson detection and LMMSE estimation illustrate improved performance with a multi-antenna fusion center at low sensor transmitting power, these advantages disappear at high transmitting power. However, the Energy Detector with numerous antennas at the fusion center provides evident advantages even when sensors operate at high power [6].

3. Conclusion

This paper discusses four innovative research in MIMO wireless systems. The first research proposes a novel channel feedback framework for MIMO WET systems, considering the energy and hardware constraints of practical ERs. It concludes that energy quantization outperforms energy comparison when the number of feedback bits per interval is enormous, while energy comparison is superior when feedback bits are limited.

The second research introduces a non-cooperative association game for massive MIMO heterogeneous networks, where users are participants and base stations are governed by the local resource assignment rules. Under heavy-loaded network conditions, the user-centric association game converges to a sheer strategy Nash equilibrium, which closely approximates the centralized global optimum. This user-centric decentralized approach converges to a Nash equilibrium with probability 1 for both proportional fairness (PF) and hard fairness (HF), making it not only easy to implement but also near-optimal in terms of system performance. The third research presents a MU-MIMO WPCN system where users and H-AP both have many antennas installed. In order to maximize the sum rate, it suggests simultaneously optimizing the transmission covariance matrices and time allocation. This new optimization method demonstrates significant performance gains compared to traditional approaches.

The fourth research derives optimal sensor transmission gains for Neyman-Pearson and energy detection in multi-antenna fusion center scenarios. It shows that the optimal gain becomes independent of phase with increase of number of antennas. For Neyman-Pearson detection and LMMSE estimation requiring CSI, constant performance can be attained if sensor transmitting power decreases proportionally with the number of antennas. For energy detection without CSI, a constant deflection coefficient can be maintained if power is decreased in inverse proportion to the square root of the number of antennas. At high transmit power, the performance advantage of multi-antenna fusion centers diminishes Neyman-Pearson detection and LMMSE estimation. However, for energy detectors, numerous antennas in the fusion center provide significant advantages even at high sensor power levels.

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