

# QoE-based transmission strategies for multi-user wireless information and power transfer<sup>☆</sup>

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## Abstract

One solution to the problem of supplying energy to wireless networks is wireless power transfer. One such technology – electromagnetic radiation enabled wireless power transfer – will change traditional wireless networks. In this paper, we investigate a transmission strategy for multi-user wireless information and power transfer. We consider a multi-user multiple-input multiple-output (MIMO) channel that includes one base station (BS) and two user terminals (UT) consisting of one energy harvesting (EH) receiver and one information decoding (ID) receiver. Our system provides transmission strategies that can be executed and implemented in practical scenarios. The paper then analyzes the *rate–energy* (R–E) pair of our strategies and compares them to those of the theoretical optimal strategy. We furthermore propose a QoE-based mode selection algorithm by mapping the R–E pair to the utility functions.

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*Keywords:* Wireless power transfer; Multi-user multi-input multi-output (MIMO); Transmission strategy; *Rate–energy* region; Quality of experience (QoE)

## 1. Introduction

Over the last decade with the proliferation of networks based on wireless communications most electronic devices have become portable. Such devices, however, operate using their own batteries, which must be charged periodically via a cable. For these reasons, wireless power transfer is a promising approach to prolong the lifetime of energy-constrained wireless networks.

Wireless power transfer can be categorized as using either non-radiative or radiative techniques. The near-field technique, however, has a short-range limitation (up to only 4 cm) as well as coordination problems, and thus cannot ensure the wireless charging of mobile devices in the far-field. Among other far-field techniques, a new solution could be radio-frequency (RF) signals radiated by transmitters. Such a solution would also

be compatible in the existing wireless communications without major changes since it operates in the same frequency band [1]. Until recently, there have been issues concerning the limits, imposed by the Federal Communications Commission (FCC), of the receive power, and the low RF-to-DC conversion efficiency. Therefore, RF-based wireless power transfer is suitable for low-power applications (e.g., sensor networks), but can also be applied to some scenarios if high-efficiency rectifiers are developed or dedicated power sources are implemented.

On the other hand, the received RF signal can be harvested by what is known as a rectenna—a rectifying antenna at the receiver. The average harvested power at the receiver is proportional to the conversion efficiency and signal power [2]. In cases where both the energy harvesting (EH) and information decoding (ID) receivers are present, transmission strategies cannot be the same as the case where only the information decoding receivers are present. Prior work derived an optimal transmission strategy under a transmit power constraint to achieve different tradeoffs for the maximal achievable rate and harvested energy pair, which are bounded by a so-called *rate–energy* (R–E) region in a simplified three-node wireless broadcasting system [3]. In practical scenarios, however, this may not be easy to implement because most of the energy harvesting receivers are low-power devices such as sensors.

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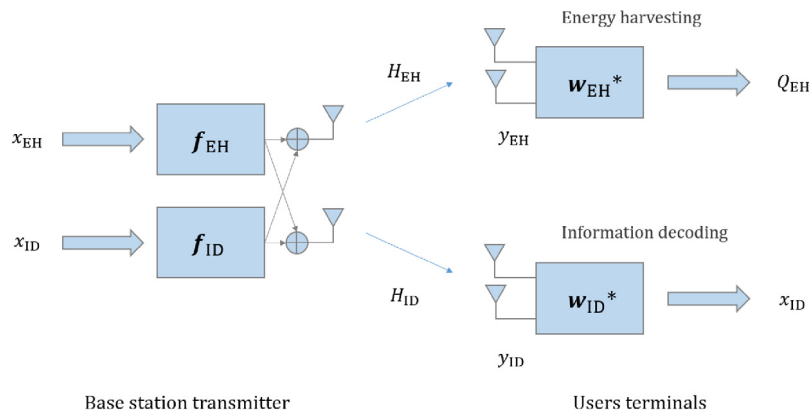


Fig. 1. Two-user MIMO system model.

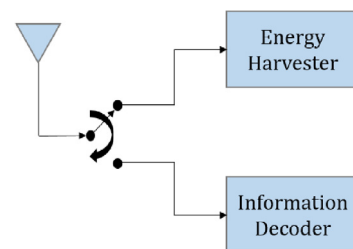
Owing the computation complexity, the low-power devices are unable to execute the spatial multiplexing multiple-input multiple-output (MIMO) technique at the receiver.

The goal of this paper is to investigate appropriate and practical transmission strategies for wireless systems such as sensor networks and the Internet of Things (IoT) environments. Consider a three-node system shown in Fig. 1, where we assume different messages for each user unlike prior work in [3]. Thanks to this assumption, it is ensured that the BS needs not to reconnect to UTs but simply modulate the appropriate messages for each receiver mode. In addition, it is possible that the BS is able to control the power of each data stream to achieve the specific R–E pair. Since the original problem has more unknown parameters than the number of equations, we first transform it into an easier problem by applying maximal-ratio combining (MRC) and obtain the solution set. We also use a quality of an experience (QoE)-based solution selection method to serve users that demand a different objective, rate, or energy. Finally, we confirm by numerical evaluations that our strategy achieves the acceptable performances against the previous optimal strategy with the given constraints.

**Notation:**  $(\cdot)^*$  and  $\mathbb{E}[\cdot]$  stand for conjugate transpose and statistical expectation respectively. The distribution of a complex Gaussian random vector with mean  $\mu$  and covariance matrix  $\Omega$  is denoted by  $\mathcal{CN}(\mu, \Omega)$ , and  $\sim$  stands for “distributed as.”  $\mathbb{C}^{x \times y}$  denotes the space of  $x \times y$  matrices with complex entries.  $\|x\|$  denotes the Euclidean norm of the vector  $x$ .  $\text{null}(X)$  denotes the null space of a matrix  $X$ . Hermitian matrix of matrix  $X$  are denoted by  $\Sigma = X^*X$ .

## 2. System model

Consider a three-node multi-user multiple-input multiple-output (MIMO) system as illustrated in Fig. 1. We assume each user terminal can, for its purpose, decode information or charge from harvest energies. For this assumption, the UT needs the practical receiver designs called *time switching* (TS) in [2]. For the TS scheme, each receiver is able to switch between EH and ID mode, as shown in Fig. 2. This assumption is reasonable because current practical circuits for harvesting energy from RF signals are unable to reuse them to decode information.

Fig. 2. The receiver design of *time switching* scheme.

We consider a two-user MIMO system, which includes one BS and two UTs, consisting of one EH receiver and one ID receiver, as shown in Fig. 1. It is assumed that the transmitter is equipped with  $M$  antennas, and that the EH receiver and the ID receiver are equipped with  $N_{EH}$  and  $N_{ID}$  receiving antennas, respectively. It is assumed that the transmitter and both the EH and ID receivers operate at the same frequency band. Assuming a narrow-band transmission over Rayleigh fading channels, we model the baseband equivalent channels from the transmitter to the EH receiver and the ID receiver by matrices  $\mathbf{H}_{EH} \in \mathbb{C}^{N_{EH} \times M}$  and  $\mathbf{H}_{ID} \in \mathbb{C}^{N_{ID} \times M}$ , respectively. It is assumed that at each fading state,  $\mathbf{H}_{EH}$  and  $\mathbf{H}_{ID}$  are both known at the transmitter, and are separately known at the corresponding receiver.

We use two split streams at the BS to transmit suitable signals depending on each receiver mode. The symbols  $x_{ID}$  and  $x_{EH}$  are the signals transmitted to the ID and EH receiver, respectively. Hence, the BS easily adjusts signals when the UT switches a receiver mode without disconnecting.  $x_{EH}$  is an arbitrary random signal over the symbol intervals with zero mean and unit variance, while  $x_{ID}$  is independent over the symbol intervals and  $x_{ID} \sim \mathcal{CN}(0, 1)$ . Assuming that a spatial multiplexing technique is inexecutable, we use the beamforming technique instead. Let  $\mathbf{f}_{EH}, \mathbf{f}_{ID}$  and  $\mathbf{w}_{EH}, \mathbf{w}_{ID}$  denote the transmit beamformers and the combining vectors for the receivers.  $\mathbf{f}_{EH}, \mathbf{f}_{ID}$  are beamforming vectors of size  $M \times 1$  and  $\mathbf{w}_{EH}, \mathbf{w}_{ID}$  are combining vectors of size  $N_{EH} \times 1, N_{ID} \times 1$ , respectively. In addition, we assume that there is an average power constraint at the BS across all transmitting antennas denoted by  $P$  and that the BS can adjust the power ratio of the two streams denoted by  $\alpha$ . Given the assumption above, the power of each stream at the BS is denoted by  $P_{EH} = (1 - \alpha)P, P_{ID} = \alpha P$ ,

( $0 \leq \alpha \leq 1$ ). The noise is assumed to be additive white Gaussian noise (AWGN),  $n \sim \mathcal{CN}(0, \sigma^2)$ .

The received signal after post processing block of the each receiver is given by

$$\begin{aligned} \mathbf{w}_{\text{EH}, \text{YEH}}^* &= \sqrt{P_{\text{EH}}} \mathbf{w}_{\text{EH}}^* \mathbf{H}_{\text{EH}} \mathbf{f}_{\text{EH}} x_{\text{EH}} \\ &\quad + \sqrt{P_{\text{ID}}} \mathbf{w}_{\text{EH}}^* \mathbf{H}_{\text{EH}} \mathbf{f}_{\text{ID}} x_{\text{ID}} + \mathbf{w}_{\text{EH}}^* \mathbf{n}_{\text{EH}} \\ \mathbf{w}_{\text{ID}, \text{YID}}^* &= \sqrt{P_{\text{EH}}} \mathbf{w}_{\text{ID}}^* \mathbf{H}_{\text{ID}} \mathbf{f}_{\text{EH}} x_{\text{EH}} \\ &\quad + \sqrt{P_{\text{ID}}} \mathbf{w}_{\text{ID}}^* \mathbf{H}_{\text{ID}} \mathbf{f}_{\text{ID}} x_{\text{ID}} + \mathbf{w}_{\text{ID}}^* \mathbf{n}_{\text{ID}}. \end{aligned}$$

Thus, the harvested energy of the EH receiver is given by

$$Q = \zeta \mathbb{E}[\|\mathbf{w}_{\text{EH}, \text{YEH}}^*\|^2].$$

For simplicity, the conversion efficiency,  $\zeta$ , is assumed to be 50%. The achievable rate of the ID receiver can be obtained from the Shannon formula.

$$R = \log_2 \left( 1 + \mathbb{E} \left[ \frac{\|\mathbf{w}_{\text{ID}, \text{YID}}^*\|^2}{\sigma^2} \right] \right)$$

### 3. Transmission strategies

#### 3.1. Solution set

In this section we focus on finding the transmission strategies to maximize the harvested energy and achievable rate simultaneously for each UT. First of all, in the case of the ID receiver, only  $x_{\text{ID}}$  needs to be decoded while  $x_{\text{EH}}$  is regarded as interference. Thus, the interference term should be either zero or of a very small value. At the same time, we attempt to maximize the  $x_{\text{ID}}$  term to obtain a high achievable rate for the ID receiver; i.e., we attempt to maximize the signal-to-interference-noise-ratio (SINR) under the zero interference constraint.

In the case of the EH receiver, we attempt to maximize the received signal to obtain high harvested energy. With respect to wireless energy transfer. It is worth noting, with that the term  $x_{\text{ID}}$  is helpful interference, which can increase the total harvested energy. Since the harvested energy is negligible owing to the background noise at the EH receiver, we assume that this term, for simplicity, can be ignored.

Based on the analysis above, we can formulate three conditions as follows.

Conditions:

- (1)  $\mathbf{w}_{\text{ID}}^* \mathbf{H}_{\text{ID}} \mathbf{f}_{\text{EH}} x_{\text{EH}} = 0$
- (2) maximize  $\mathbb{E}[\|\sqrt{P_{\text{ID}}} \mathbf{w}_{\text{ID}}^* \mathbf{H}_{\text{ID}} \mathbf{f}_{\text{ID}} x_{\text{ID}}\|^2]$
- (3) maximize  $\mathbb{E}[\|\sqrt{P_{\text{EH}}} \mathbf{w}_{\text{EH}}^* \mathbf{H}_{\text{EH}} \mathbf{f}_{\text{EH}} x_{\text{EH}} + \sqrt{P_{\text{ID}}} \mathbf{w}_{\text{EH}}^* \mathbf{H}_{\text{EH}} \mathbf{f}_{\text{ID}} x_{\text{ID}}\|^2]$ .

To reduce the number of unknowns, we assume that the maximal ratio combining (MRC) is used for the combining vectors at each receiver, given by  $\mathbf{w}_{\text{ID}} = \mathbf{H}_{\text{ID}} \mathbf{f}_{\text{ID}}$  and  $\mathbf{w}_{\text{EH}} = \mathbf{H}_{\text{EH}} \mathbf{f}_{\text{EH}}$ . This is a reasonable design for information transmission since it achieves the sum rate very close to the channel capacity under the zero-interference constraint [4–6]. MRC, however, cannot achieve the maximum harvested energy

due to the helpful interference characteristic of the EH receiver. Despite this limitation, we use MRC because it enables us to convert the equations of the conditions to be solved linearly. We can convert conditions to the following by substituting the MRC equations.

Conditions\*:

- (1)  $\mathbf{f}_{\text{ID}}^* \mathbf{H}_{\text{ID}}^* \mathbf{H}_{\text{ID}} \mathbf{f}_{\text{EH}} x_{\text{EH}} = 0$
- (2) maximize  $\mathbb{E}[\|\sqrt{P_{\text{ID}}} \mathbf{f}_{\text{ID}}^* \mathbf{H}_{\text{ID}}^* \mathbf{H}_{\text{ID}} \mathbf{f}_{\text{ID}} x_{\text{ID}}\|^2]$
- (3) maximize  $\mathbb{E}[\|\sqrt{P_{\text{EH}}} \mathbf{f}_{\text{EH}}^* \mathbf{H}_{\text{EH}}^* \mathbf{H}_{\text{EH}} \mathbf{f}_{\text{EH}} x_{\text{EH}} + \sqrt{P_{\text{ID}}} \mathbf{f}_{\text{EH}}^* \mathbf{H}_{\text{EH}}^* \mathbf{H}_{\text{EH}} \mathbf{f}_{\text{ID}} x_{\text{ID}}\|^2]$ .

In the case of Conditions\* (1), the signal  $x_{\text{EH}}$  can be treated as a constant. In the case of Conditions\* (2) and (3), the expectations of  $x_{\text{EH}}$  and  $x_{\text{ID}}$  are one. In the case of Conditions\* (3), the expectation term including  $x_{\text{EH}} \times x_{\text{ID}}$ , is zero since two random signals are independent of each other. Thus, we express the Condition\* as follows.

Conditions\*\*:

1.  $\mathbf{f}_{\text{ID}}^* \Sigma_{\text{ID}} \mathbf{f}_{\text{EH}} = 0$
2. maximize  $\|\sqrt{P_{\text{ID}}} \mathbf{f}_{\text{ID}}^* \Sigma_{\text{ID}} \mathbf{f}_{\text{ID}}\|^2$
3. maximize  $\|\sqrt{P_{\text{EH}}} \mathbf{f}_{\text{EH}}^* \Sigma_{\text{EH}} \mathbf{f}_{\text{EH}} + \sqrt{P_{\text{ID}}} \mathbf{f}_{\text{EH}}^* \Sigma_{\text{EH}} \mathbf{f}_{\text{ID}}\|^2$ .

We are now able to calculate the transmit beamforming vectors  $\mathbf{f}_{\text{EH}}$  and  $\mathbf{f}_{\text{ID}}$  satisfying the conditions.

- *Solution 1*: Let the principal eigenvector of  $\Sigma_{\text{ID}}$  be  $\mathbf{v}(1, \text{ID})$ . To satisfy Condition\*\* (2),  $\mathbf{f}_{\text{ID}}$  is determined as  $\mathbf{f}_{\text{ID}} = \mathbf{v}(1, \text{ID})$ . Given  $\mathbf{f}_{\text{ID}} = \mathbf{v}(1, \text{ID})$ , it follows that the pre-coder of the ID receiver  $\mathbf{f}_{\text{EH}}$  can be formulated as  $\mathbf{f}_{\text{EH}} = \text{null}(\mathbf{f}_{\text{ID}}^* \Sigma_{\text{ID}})$ .
- *Solution 2*: Let the principal eigenvector of  $\Sigma_{\text{EH}}$  be  $\mathbf{v}(1, \text{EH})$ . To satisfy Condition\*\* (2),  $\mathbf{f}_{\text{EH}}$  is determined as  $\mathbf{f}_{\text{EH}} = \mathbf{v}(1, \text{EH})$ . Given  $\mathbf{f}_{\text{ID}} = \mathbf{v}(1, \text{ID})$ , it follows that the pre-coder of the ID receiver  $\mathbf{f}_{\text{ID}}$  can be formulated as  $\mathbf{f}_{\text{ID}} = \text{null}(\mathbf{f}_{\text{EH}}^* \Sigma_{\text{ID}})$ .

Therefore, when the ratio of two transmit powers is fixed, we can achieve two solutions. *Solution 1* maximizes the achievable rate for the ID receiver while *Solution 2* maximizes the harvested energy for the EH receiver. By changing  $\alpha$ , which is the ratio of the power of the two streams, the solution sets can be constructed as  $S = \{s_1, s_2, \dots, s_n\}$ , where each  $s_i = (R_i, E_i)$ ,  $i \in \{1, \dots, n\}$  is achieved by the corresponding beamforming vector. Selecting the best strategy, however, is not quite straightforward since neither solution can attain superiority over the other. In addition, two quantities,  $R$  and  $E$  are not comparable in the same domain since a different system environment may demand different objectives.

#### 3.2. QoE-based solution selection method

We propose here a QoE-based solution selection method by mapping the data rate and battery charge rate of each users to the utility function. This can be thought of as a regularization process by putting the different quantities on the same axis.

For video or voice services, the subjective satisfaction of the user is measured by QoE rather than other objective metrics such as the quality of service (QoS) [7]. By nature, QoE,

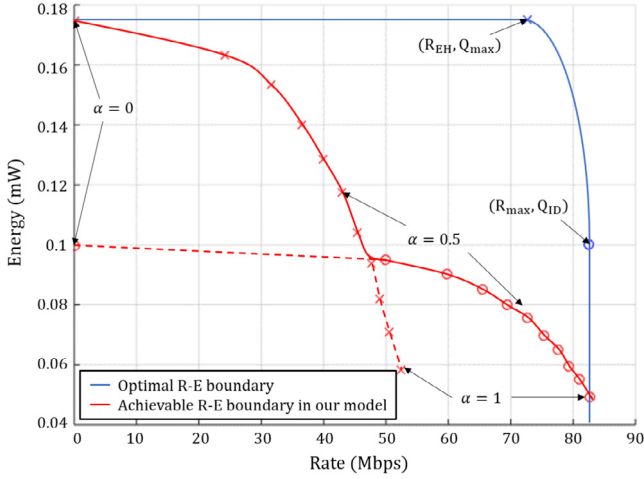


Fig. 3. Rate and energy values for the solution sets in the R–E region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which is affected by technical and environmental factors as well as user characteristics, varies from person to person. However, here we show a simple case scenario in this specific parametric environment. We first consider a utility function of the ID receiver,  $U_{ID,i}$ , as a sigmoidal utility function that is compatible for real-time services including video streaming [8]. The sigmoidal utility function is given by

$$U_{ID,i}(x) = c_i \left( \frac{1}{1 + e^{-a_i(x-b_i)}} + d_i \right),$$

where  $c_i$  and  $d_i$  are used for the normalization of the function and  $x$  is the rate in a unit of Mbps.

For the battery charge rate, the level of satisfaction, (a.k.a. *utility*) upon the battery charge rate (0% – 100%) is modeled by a concave function. Note that this concept has never been proposed in previous works, but this makes sense since people tend to be “more” satisfied with the same amount of harvested energy when the battery charge rate is low.

$$U_{EH,i}(x) = c_i(\log(a_i x + b_i) + d_i).$$

We normalize the utility function such that  $U_{ID,i}(0) = 0$ ,  $U_{ID,i}(M_i) = 1$ ,  $U_{EH,i}(0) = 0$  and  $U_{EH,i}(100) = 1$ , where  $M_i$  is the maximum transmission data rate of user  $i$ . Let the initial battery state of the ID receiver be  $B_0$  and the energy-to-charge rate conversion ratio be  $\zeta$ . By considering the sensitivity characterized by each user, we adopt the new condition variable  $0 \leq \lambda \leq 1$ . The total QoE  $U_{T,i}$  for Solution  $s^*$  is given as

$$U_{T,i}(R_i, E_i) = \lambda \cdot U_{ID,i}(R_i) + (1 - \lambda) \cdot U_{EH,i}(B_0 + \zeta \cdot E_i).$$

We, therefore, select the solution  $s_*$  that can maximize the total QoE for each system configuration.

$$s^* = \underset{s \in S}{\operatorname{argmax}} U_{T,i}(R_i, E_i).$$

#### 4. Simulations and results

In Fig. 3, an example of the R–E region is shown for a two-user MIMO system. It is assumed that  $M = N_{EH} = N_{ID} = 2$ .

Table 1  
Parameters for each utility function.

Receiver	Type	$a_i$	$b_i$	$c_i$	$d_i$
ID	Sigmoid	0.0604	49.6535	1.1711	−0.0474
EH	Concave	1000	1	0.2	0

The transmit power is assumed to be  $P = 1$  W or 30 dBm. The distances from the transmitter to the EH and ID receivers are assumed to be 1 m and 10 m, respectively. Assuming the pathloss exponent to be 4, the signal attenuation can be calculated by 40 dB for 1 m and 80 dB for 10 m. Therefore, the average signal power at the EH and ID receivers are −10 dBm and −50 dBm, respectively. Furthermore, the bandwidth is assumed to be 10 MHz, while the receiver thermal noise is assumed to be −140 dBm/Hz. As a result, considering all the aforementioned factors, the average SNR at the ID receiver is equal to 20 dB or 100 W with a unit-norm noise, and the average signal power at the EH receiver is 50  $\mu$ W. The utility function parameters of each receiver are given in Table 1 and the utility functions of each user are shown in Fig. 4.

The blue line in Fig. 3 shows the optimal R–E boundary by the optimal strategy adjusted to the system parameters. The red line in Fig. 3 represents the achievable R–E boundary by Solution 1 (o mark) and Solution 2 (x mark) for a transmission power ratio  $\alpha$  from 0 to 1. As can be observed from the figure that the achievable R–E boundary is under the optimal R–E boundary. In particular, in the case of  $\alpha = 0$  or 1, our transmission strategies obtain the same values as those of the optimal methods,  $R_{\max} = 82.59$  Mbps and  $Q_{\max} = 0.17$  mW. It is natural that our transmission strategies have lower R–E values (approximately 54% ~ 62%) than the optimal covariance method for simultaneous transmission owing to the power splitting at the transmitter. Despite the loss of performance, our transmission strategies have the advantages of not only controlling each data stream, but also having lower computational complexity. The optimal strategy uses its own algorithm to solve the Lagrangian dual problem, which includes the iterative singular vector decomposition (SVD) process, whereas our strategy does not execute the SVD process iteratively. This means the optimal strategy requires a much longer than ours. Solution 1 maximizes the achievable rate for the ID receiver while Solution 2 maximizes the harvested energy for the EH receiver. To achieve the best solution along the achievable R–E boundaries, which is the red line in Fig. 3, the total QoE score is calculated. Note that the parameters of each utility function is selected by rule of thumb, which can be changed by other analyses or experiments. Then, the solution that maximizes the total QoE is selected, which means it maximizes the satisfactoriness of the total system. For the above configuration, the most frequently chosen method is Solution 2 with a power ratio of  $\alpha = 0.6$ . This result can be changed in various ways by using different users’ characteristic parameters.

#### 5. Conclusion

In this paper, we considered the beamforming design for a wireless communication system with both an energy harvesting

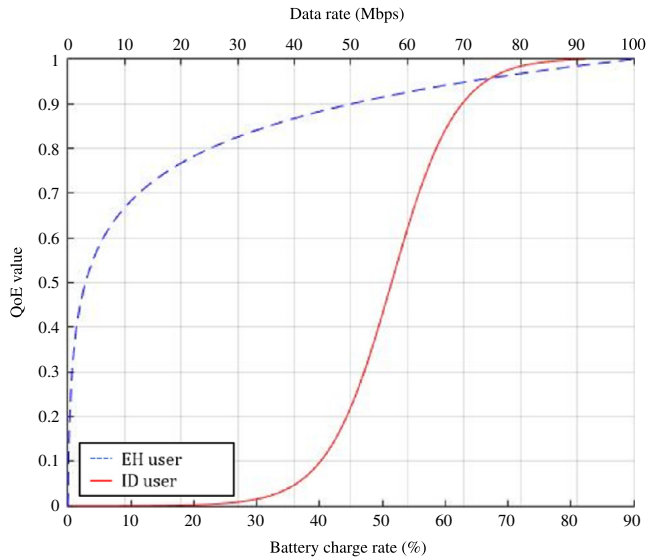


Fig. 4. Sigmoidal utility function of QoE value (data rate) for ID user and concave utility function of QoE value (battery charge rate) for EH user.

receiver and an information decoding receiver for sensor networks or IoT environments. Under a simplified system setup, we formulated a problem to find the transmission strategy for maximizing the R–E pair. By means of MRC, we transformed the original problem into an eigenvalue problem and obtained the solution set. Then we suggested a QoE-based solution selection method for the user’s satisfaction. The performance of the proposed design was confirmed through numerical simulations. Future research includes a beamforming design

for the more general cases with multiple transmitters and an algorithm to search for suitable max-QoE parameter  $\lambda$ .

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