Simultaneous Wireless Information and Energy Transfer for MIMO Relay Channel with Antenna Switching

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Abstract—In this paper, we investigate a new technique for simultaneous wireless information and energy transfer in multiple-input multiple-output relay channels. The proposed technique exploits the array configuration at the relay node and uses the antenna elements either for conventional decoding or for rectifying (rectennas). In order to keep the complexity low, a dynamic antenna switching between decoding/rectifying is proposed based on the principles of the generalized selection combiner (GSC); the \( L \) strongest paths are allocated for decoding while the remaining channel paths for rectifying (and vice versa). The optimal \( L \) as well as the allocation strategy that minimizes the outage probability are investigated via theoretical and numerical results. In addition, two performance bounds that provide the optimal performance without the limitation of GSC are proposed by solving a linear programming and a binary knapsack problem, respectively.

Index Terms—RF energy harvesting, MIMO relay channel, generalized selection combiner, Zero-forcing, optimization.

I. INTRODUCTION

Recently, there is a lot of interest to integrate energy harvesting technologies into communication networks. Energy harvesting is a new paradigm and allows the nodes to recharge their batteries from the environment. Several studies consider conventional renewable energy resources (solar/wind energy) and investigate optimal resource allocation techniques for different objective functions and network topologies i.e., [1], [2]. However, the intermittent and unpredictable nature of these energy sources makes energy harvesting critical for applications where quality-of-service (QoS) is of paramount importance.

An energy harvesting technology that overcomes the above limitations, is the radio-frequency (RF) energy harvesting where the nodes can charge their batteries from the electromagnetic radiation [3]. RF energy transfer can be fully-controlled and therefore can be used for scenarios with strict QoS constraints as well for applications where conventional harvesting technologies cannot be applied. The fundamental element for the implementation of the RF energy transfer is the rectifying antenna (rectenna); it mainly consists of an antenna that collects the RF waves and a diode-based rectifying circuit that converts the RF signal to DC voltage. Although, information theoretic studies assume that the same signal can be used for both decoding and rectifying [4], this simultaneous transfer is not possible due to practical limitations.

In [5], the authors investigate two practical techniques for simultaneous wireless information and energy transfer a) “time switching” (TS), where the receiver switches between decoding information and harvesting energy and b) “power splitting” (PS), where the receiver splits the received signal in two parts for decoding information and harvesting energy, respectively. Both techniques have been applied in different network topologies and contexts i.e., [6], [7]. The work in [6] discusses optimal TS policies for a point-to-point transmission with/without channel state information (CSI). In [7], the authors study a multi-user multiple-input single-output (MISO) interference channel, where the receivers are characterized by both QoS and RF-PS energy harvesting constraints; an optimization problem that minimizes the total transmitted power is discussed. On the other hand, the integration of the RF energy harvesting technology into cooperative networks is a research topic of increasing interest. In [8], the authors derive the outage probability for a decode-and-forward (DF) cooperative network, when the relay applies TS and is equipped with a battery. The work in [9] deals with an Amplify-and-Forward relay channel and studies the performance for both TS and PS, when the relay is battery-free. In addition, the work in [10] discusses the problem of relay selection for a cooperative network with both QoS and RF energy transfer requirements.

Although the current literature is based on the TS and PS techniques, their practical implementation is not an easy task. TS requires a strict synchronization process or a non-continuous information transmission, while PS requires appropriate power split circuits that increase the complexity of the hardware. In this work, we investigate a new technique for joint wireless information and energy transfer. Typically, a single rectenna is not sufficient to ensure reliable device operation; therefore rectenna array configurations are used to generate DC power for reliable device operation [11].

Inspired by this approach, we propose an antenna switching between decoding/rectifying in order to achieve simultaneous information/energy transfer. The proposed technique does not require any additional hardware or any synchronization process and therefore it is attractive for practical multiple-input multiple-output (MIMO) implementations. This tech-
unique is applied to a battery-free MIMO relay channel and low-complexity antenna switching mechanisms that use the principles of the generalized selection combiner (GSC) are investigated. Specifically, we assume that the L antennas with the strongest channel paths are used for decoding, while the rest of the antennas are used for rectifying (and vice-versa). The outage probability of the proposed schemes is derived in closed form and compared to two theoretical bounds corresponding to a) PS with CSI and b) optimal antenna splitting with CSI; these bounds are provided by solving a feasibility linear program (LP) and a binary knapsack problem, respectively.

This paper is organized as follows. Section II introduces the system model and the basic notation. In Section III, we present the proposed GSC-based schemes as well as the considered bounds. Simulation results and comparisons are given in Section IV, and finally, conclusions are drawn in Section V.

Notation: All boldface letters indicate vectors (lower case) or matrices (upper case). The superscripts (·)T, (·)H, (·)−1, denote the transpose, the conjugate transpose, and the matrix inverse respectively. ||z|| denotes the Euclidean norm of a complex vector z and |A|_{i,j} denotes the (i, j)-th element of the matrix A.

II. SYSTEM MODEL

We assume a basic MIMO relay channel consisting of a single-antenna source, S, a multi-antenna DF relay, R, and a single-antenna destination, D. A direct link is not available and communication can be established only via the relaying path [8], [9]. The relay node cannot receive/transmit data simultaneously (half-duplex) and is equipped with N antennas that form the set $I = \{1, 2, \ldots, N\}$. In addition, it is battery-free and has RF energy harvesting capabilities; this means that it harvests energy from the received signal and uses it for relaying [9], [12]. In contrast to the existing RF energy transfer techniques (e.g. TS, PS), we exploit the multi-antenna configuration at the relay node and we assume that each antenna can be used either for information decoding or for rectification. Specifically, the output of each antenna can be connected to one of two different RF combining circuits (RFCC): a) RFCC I is used for combining the channel paths that will be used for data decoding (e.g. diversity combiner), b) RFCC II is used for combining the channel paths that will be used for RF-to-DC conversion. All wireless links exhibit independent fading and Additive White Gaussian Noise (AWGN) with zero mean and unit variance. The fading is assumed to be frequency non-selective Rayleigh block fading with unit variance. A global channel knowledge is assumed at the receivers which enables coherent detection as well as beamforming transmission at the relay node; an instantaneous feedback channel from D can ensure the knowledge of the $R \rightarrow D$ link. The source node transmits with a spectral efficiency $r_0$ in bits per channel use (BPCU) and a constant power $P$. Time is considered to be slotted and the duration of one slot is equal to one time unit; due to the normalized slot duration, the measures of energy and power become identical and therefore are used equivalently throughout the paper. Fig. 1 schematically presents the proposed antenna split.

Communication is performed in two orthogonal time slots due to the half-duplex limitation and the principles of the DF relaying scheme. In the first time slot, the source transmits and the relay node uses the antenna set $U \subseteq I$ via RFCC I and the remaining antennas (complement set $U^C$) via RFCC II; the assignment of the antennas to the RFCC circuits is discussed in the next section. In the second time slot, given that the relay has successfully decoded the source signal, the relay transmits towards the destination by using all the energy harvested by the rectification process; relaying transmission is based on MISO beamforming and uses all the N antennas. The first phase of the DF protocol is characterized by the following equations

$$\gamma_{R_i} = P \sum_{i \in U} |h_{S,i}|^2,$$

(1)

$$\gamma_{R_E} = P \sum_{i \in U^C} |h_{S,i}|^2,$$

(2)

$$P_R = \eta \gamma_{R_E},$$

(3)

where $h_{S,i}$ denotes the channel from S to the i-th relay’s antenna, $\gamma_{R_i}$ denotes the combined signal-to-noise ratio (SNR) at the output of the RFCC I, $\gamma_{R_E}$ denotes the combined power (SNR for the non-interference case) at the output of RFCC II, $P_R$ is the energy harvested that is available for relaying and $\eta \in [0, 1]$ represents the RF-to-DC conversion efficiency. Unless otherwise specified, we assume that the channels $h_{S,i}$ are ordered as $|h_{S,1}|^2 \geq |h_{S,2}|^2 \geq \ldots \geq |h_{S,N}|^2$ (e.g., the i-th antenna has the i-th strongest path). It is worth noting that RF harvesting from the AWGN is negligible. In the second time slot, the relay node transmits with a power $P_R$ by using a beamforming strategy (achieving MISO capacity); this second time slot is characterized by

$$y_D = ||\mathbf{h}_{R,D}||x + n,$$

(4)

$$\gamma_D = P_R ||\mathbf{h}_{R,D}||^2,$$

(5)

where $y_D$ denotes the received signal at D, $x$ is the relaying signal with unit variance, $n$ is the AWGN term, $\mathbf{h}_{R,D} \in \mathbb{C}^{N \times 1}$ is the channel vector for the $R \rightarrow D$ link and $\gamma_D$ is the SNR at D.

A. Outage probability

The performance criterion of interest is the outage probability, which is the probability that the instantaneous capacity cannot support the target spectral efficiency $r_0$. If $C(x) = \ldots$
0.5 \log_2 (1 + x) \text{ denotes the instantaneous Shannon capacity of one hop, where } x \text{ corresponds to the SNR, the outage probability for the considered scheme becomes}

\[ P_{\text{out}} = 1 - P_\alpha P_\beta, \]

where \( P_\alpha = \mathbb{P}\{C(\gamma_{Ri}) > r_0\} \) and \( P_\beta = \mathbb{P}\{C(\gamma_D) > r_0\} \) denote the success probability for the first and the second hop, respectively.

### III. antenna assignment policies

In this section, we study the antenna switching between decoding/rectifying and we investigate some antenna assignment techniques that split the relay’s antennas to the circuits RFCC I and RFCC II, respectively.

#### A. PS-based optimal scheme (Bound I)

The PS-based optimal scheme (PSOS) assumes that each antenna can be used for both decoding/rectifying based on the PS strategy; this means that \( \alpha_i \times 100\% \) of the received energy at the \( i \)-th antenna is used from RFCC I (information) and \( (1 - \alpha_i) \times 100\% \) from RFCC II (harvesting) where \( 0 \leq \alpha_i \leq 1 \).

The implementation of this scheme requires that each antenna simultaneously is connected to both circuits and corresponds to a high complexity. It is used as a useful performance upper bound in order to evaluate the proposed GSC-based schemes. The knowledge of the \( \mathbf{h}_{R,D} \) channel is used in order to identify the required harvested energy that ensures a non-outage in the second relaying hop (\( R \xrightarrow{} D \) link). The PSOS scheme requires the solution of the following LP feasibility problem that is solved every communication frame (two time slots) [14, Sec. 4.1.1]:

\[
\begin{align*}
\min_{\alpha_i} \quad & 0 \\
\text{subject to} \quad & \sum_{i \in \mathcal{I}} \alpha_i |h_{S,i}|^2 \geq U_1 \\
& \sum_{i \in \mathcal{I}} (1 - \alpha_i) |h_{S,i}|^2 \geq U_2 \\
& 0 \leq \alpha_i \leq 1, \forall i \in \mathcal{I}.
\end{align*}
\]

where \( U_1 = \frac{2^{2\gamma_0} - 1}{\beta} \) and \( U_2 = \frac{2^{2\gamma_0} - 1}{\eta P[|\mathbf{h}_{R,D}|^2]} \).

The first constraint ensures successful decoding in the first hop with \( C(P \sum_{i \in \mathcal{I}} \alpha_i |h_{S,i}|^2) \geq r_0 \Rightarrow \sum_{i \in \mathcal{I}} \alpha_i |h_{S,i}|^2 \geq U_1 \).

The second constraint ensures that the harvested energy is sufficient in order to ensure decoding in the second hop e.g., \( C(P||\mathbf{h}_{R,D}||^2 \sum_{i \in \mathcal{I}} (1 - \alpha_i) |h_{S,i}|^2) \geq r_0 \Rightarrow \sum_{i \in \mathcal{I}} (1 - \alpha_i) |h_{S,i}|^2 \geq U_2 \).

The above LP feasibility problem can be solved with standard convex optimization solvers such as CVX [14]; if the constraints are infeasible, the optimization problem gives a solution \( x^* = \infty \) and the system is in outage.

#### B. Binary knapsack optimal scheme (Bound II)

The binary knapsack optimal scheme (BKOS) respects the limitation that each antenna can be used either for data decoding or energy harvesting. In this case, the antenna assignment feasibility problem in (7) can be written as

\[
U_1 \leq \sum_{i \in \mathcal{I}} \alpha_i |h_{S,i}|^2 \leq U_3, \quad \alpha_i \in \{0, 1\}
\]

where \( U_3 = \sum_{i \in \mathcal{I}} |h_{S,i}|^2 - U_2 \). This problem can be reformulated as:

\[
\begin{align*}
\max & \quad \sum_{i \in \mathcal{I}} \alpha_i w_i \\
\text{subject to} \quad & \sum_{i \in \mathcal{I}} \alpha_i w_i \leq U_3, \\
& \alpha_i \in \{0, 1\},
\end{align*}
\]

where \( w_i = |h_{S,i}|^2 \) with \( i \in \mathcal{I} \). Formulation (9) explicitly respects the upper bound of the binary feasibility problem (8). The lower bound is satisfied if \( \sum_{i \in \mathcal{I}} \alpha_i w_i \geq U_1 \), where \( a^* \) is the optimal solution of the above problem; otherwise, problem (8) is infeasible and the system is in outage and cannot support the required spectral efficiency.

Problem (9), is a special case of the binary knapsack problem with equal values and weights, called the subset-sum problem. This problem is known to be NP-complete and hence there is no known algorithm that solves it in polynomial-time [15]. However, several algorithms have been proposed in the literature that solve the binary knapsack problems in pseudo-polynomial time by using dynamic programming [16] (e.g., kp01(1) function in MATLAB). It is obvious that the BKOS scheme requires the solution of a binary knapsack problem for each communication frame which has high computational complexity; hence, it is used as a theoretical bound which is tighter than the bound provided by the PS-based optimal scheme (respects the fundamental antenna switching between decoding/rectifying).

#### C. GSC-based assignment schemes

All the previous schemes solve an optimization problem at each transmission frame; these schemes are characterized by high complexity and hence are mainly used for providing useful performance bounds. Here, we study low complexity
solutions based on the principles of the GSC. More specifically, we assume that the relay node assigns its $N$ antennas into the two RFCC circuits based on the strength of the associated channel paths; this means that the $L$ antennas with the strongest channel paths are connected to the RFCC I and the rest $(N-L)$ antennas to the RFCC II (and vice versa). This strategy exploits the GSC technique that mainly exists in conventional multiple-antenna receivers and provides a low-complexity mechanism for the antenna assignment. We distinguish two basic GSC-based assignment schemes:

1) GSC-Information: The GSC-Information (GSI) scheme prioritizes the RFCC I circuit and allocates the $L$ strongest channel paths to the diversity combiner for data decoding, and the rest $(N-L)$ channel paths to the RFCC II so that

$$ U = \{1, 2, \ldots, L\}, \quad U^C = \{L + 1, \ldots, N\}. \quad (10) $$

This scheme is more appropriate for high conversion efficiencies $\eta$, where the diversity gain of the first hop becomes the bottleneck of the end-to-end (e2e) performance. In this case, the RFCC I circuit behaves as a standard $L$-branch GSC and therefore the random variable $\gamma_R / P$ corresponds to the sum of the $L$ largest independent and identically distributed (i.i.d.) exponential random variables with unit variance among $N$ ones. The cumulative distribution function (CDF) of the random variable $\gamma_R$ can be calculated by using order statistics tools and is equal to [17]

$$ F_{\gamma_R}(x) = \frac{N!}{(N-L)!L!} \left\{ 1 - \exp \left( -\frac{x}{P} \right) \sum_{k=0}^{L-1} \frac{1}{k!} \left( \frac{x}{P} \right)^k ight. 
+ \sum_{l=1}^{N-L} (-1)^{L+l-1} \left( \frac{(N-L)!}{(N-L-l)!} \right) \left( \frac{L}{l} \right)^{L-1} 
\times \left[ \left( 1 + \frac{l}{L} \right)^{-1} \left( 1 - \exp \left( -\left( 1 + \frac{l}{L} \right) \frac{x}{P} \right) \right) - \sum_{m=0}^{L-2} \left( \frac{l}{L} \right)^m \left( 1 - \exp \left( -\frac{x}{P} \right) \sum_{k=0}^{m} \frac{1}{k!} \left( \frac{x}{P} \right)^k \right) \right] \left\} \right\} \quad (11) $$

The circuit RFCC II combines the $(N-L)$ weakest channel branches and therefore the statistic of the random variable $P_R$ can be calculated by using the following moment-generating function (MGF)-based methodology [17]:

1) By using the classical result by Sukhatme that converts the sum of correlated random variables to the sum of independent random variables [18, Section 3.3.1], the MGF of the random variable $P_R$ becomes

$$ \mathcal{M}_{P_R}(s) = \prod_{k=L+1}^{N} \left( 1 - \frac{s(k-L)\eta P}{k} \right)^{-1}. \quad (12) $$

2) Based on (12) and by using the fundamental relation between MGF and Laplacian transform, the CDF of $P_R$ can be calculated by

$$ F_{P_R}(x) = \mathcal{L}_s^{-1}(s^{-1} \mathcal{M}_{P_R}(s)), \quad \text{(13)} $$

where $\mathcal{L}_s^{-1}(\cdot)$ denotes the inverse Laplace transform.

On the other hand, the random variable $Y = |\mathbf{h}_{R,D}|^2$ follows a Chi-Square distribution with $2K$ DoF; its probability density function (PDF) and the associated CDF are given by

$$ f_Y(N, x) = \frac{1}{(N-1)!} x^{-(N-1)} \exp(-x), \quad \text{(14)} $$

$$ F_Y(N, x) = \frac{\gamma(N, x)}{\Gamma(N)}, \quad \text{(15)} $$

where $\gamma(a, x) = \int_0^x t^{a-1} \exp(-t)dt$ denotes the lower incomplete gamma function and $\Gamma(x) = (x-1)!$ denotes the Gamma function. The outage probability of the GSI scheme is given by (6) with

$$ P_\alpha = \mathbb{P}\{C(\gamma_R) \geq r_0\} $$

$$ = 1 - F_{\gamma_R}(2^{2r_0} - 1), $$

$$ P_\beta = \mathbb{P}\{C(P_R) | |\mathbf{h}_{R,D}|^2 \geq r_0\} $$

$$ = 1 - \int_0^\infty F_{P_R}(\frac{2^{2r_0} - 1}{y}) \cdot f_Y(y)dy. \quad \text{(17)} $$

The probability in (17) can be calculated numerically; however for specific values of $N, L$ we can provide closed-form expressions (we present some illustrative examples in the following discussion).

2) GSC-Energy: The GSC-Energy (GSE) scheme is similar to the GSI scheme but prioritizes the RFCC II circuit; it allocates the antennas with the strongest $L$ channel paths to the RFCC II (rectifying) while it allocates the rest $(N-L)$ to the diversity combiner RFCC I so that

$$ U = \{L + 1, \ldots, N\}, \quad U^C = \{1, 2, \ldots, L\}. \quad (18) $$

The GSE scheme is more appropriate for low energy efficiencies $\eta$, where the energy harvested, which is used for transmission at the second hop, becomes the bottleneck of the e2e path. The outage probability of the GSE scheme can be calculated by using the same methodology with the GSI scheme; in this case the CDF of the random variables are used with the inverse order since the $L$ strongest paths are used for generating $P_R$.

3) Illustrative examples with $N = 3, L = 1$: In order to give intuition into the above analysis, we present some illustrative examples for both GSI and GSE schemes. Specifically, GSI scheme: The success probabilities for the two relaying branches are given by

$$ P_\alpha = 1 - \left[ 1 - \exp(-Q_1) \right]^L, \quad \text{(19)} $$

$$ P_\beta = 3\sqrt{6Q_2^2} K_3(\sqrt{6Q_2}) - 6\sqrt{2Q_2^2} K_3(2\sqrt{2Q_2}), \quad \text{(20)} $$

where $Q_1 = \frac{2^{2r_0} - 1}{\eta}$, $Q_2 = 6\sqrt{2Q_2^2}$ and $K_v(\cdot)$ denotes the second kind modified Bessel function of order $v$. For high SNR’s
(e.g., transmitted power $P$), the associated diversity gain of the system is dominated by the weakest relaying branch; therefore, the diversity of the system becomes

$$d^* = \min\{d_1, d_2\} = \min\{3, 2\} = 2,$$

where $d_1 = -\lim_{P \to 0} \frac{\log(1-P)}{\log P} = 3$ and $d_2 = -\lim_{P \to 0} \frac{\log(1-P)}{\log P} = 2$ denote the diversity gain for the first and second relaying hop, respectively. This result shows that the considered antenna-based strategy sacrifices one diversity degree in order to achieve simultaneous wireless information and power transfer at the MIMO relay.

GSE scheme: In a similar way, we have

$$P_\alpha = 4 \exp\left(-\frac{3Q_1}{2}\right) - 3 \exp\left(-2Q_1\right)$$

$$P_\beta = 3Q_2^2 K_3(2\sqrt{Q_2}) + \sqrt{2}K_3(2\sqrt{2Q_2}) - \frac{\sqrt{2}}{2}K_3(2\sqrt{3Q_2})$$

with a diversity gain equal to $d^* = \min\{d_1, d_2\} = \min\{2, 3\} = 2$; therefore the GSE scheme also sacrifices one diversity degree in order to ensure energy transfer at the MIMO relay.

4) Optimal GSCI/GSCE scheme: The GSCI/GSCE schemes are characterized by a simple antenna assignment strategy that exploits the strength of the diversity branches at the relay reception side. However, the parameter $L$ as well as the prioritized circuit (GSCI/GSCE) should be decided in an optimal way in order to achieve the best possible performance. This decision is taken during the initialization (set-up) period of the system and only depends on the average statistics of the propagation channel as well as the efficiency of the RF-to-DC circuit. The optimal decision corresponds to the following optimization problem:

$$\{L^*, m^*\} = \arg\min_{L,m} P_{\text{out}}^{(m)}(L),$$

subject to $L = 1, \ldots, K,$

$$m = \{\text{GSCI, GSCE}\}.$$

The solution of the above optimization problem requires exhaustive search to identify the best combination $\{L, m\}$; based on the previous analysis, we need to compare $2(N-1)$ outage probabilities $P_{\text{out}}$ and thus the associated complexity remains low.

IV. NUMERICAL RESULTS

Computer simulation are carried-out in order to evaluate the performance of the proposed schemes. Fig. 2 plots the outage probability versus $P$ for the different proposed schemes (GSCI, GSCE, BKOS, PSOS); the simulation setup is $r_0 = 2$ BPCU, $N = 3$ antennas, $L = \{1, 2\}$ and $\eta = 1$. The first observation is that the GSCI scheme outperforms GSCE scheme for both configurations (i.e., 3.5 dB for $L = 2$). This result shows that diversity gain becomes more important than energy harvesting due to the high conversion efficiency $\eta$. In addition, it can be seen that the GSCI scheme with $L = 1$ is the optimal GSC-based strategy and achieves a diversity gain equal to two; a channel diversity degree is sacrificed in order to support RF energy harvesting. Regarding the proposed bounds, we plot the performance of the BKOS and the PSOS schemes. It can be seen, that the PSOS scheme outperforms the practical BKOS (due to the PS strategy) with a gain of 2.5 dB at high SNRs, while it has a gain of about 5 dB against GSCI with $L = 1$ for an outage probability $10^{-4}$. The same figure also depicts the analytical outage probabilities for the proposed GSC-based schemes, which perfectly match with the numerical results and validate our analysis.

Fig. 3 plots the outage probability performance of the proposed schemes for a simulation setup with a poor converting efficiency e.g., $\eta = 0.1$ (the other simulation parameters are
the same with the previous example). In this case, it can be seen that the GSCE scheme significantly outperforms the GSCI scheme; GSCI with $L = 1$ gives the best performance with a gain $5$ dB against the associated GSCI scheme. Due to the poor converting efficiency, the power available for the relaying transmission becomes the bottleneck of the e2e transmission; the allocation of the strongest path for energy harvesting is the appropriate strategy in order to minimize the outage probability. The other curves are inline with the previous observations and validate our main remarks.

V. CONCLUSION

This paper has investigated a new technique for joint wireless information and energy transfer in MIMO relay channels. In contrast to conventional approaches (i.e., TS, PS), the proposed technique exploits the array configuration at the relay node and dynamically switches the antenna elements between conventional decoding and rectifying. We proposed a low complexity GSC-based switching that allocates the $L$ strongest channel paths for decoding and the rest for rectifying (and vice versa). The achieved outage probability has been derived in closed form for different configurations and two appropriate theoretical bounds have been investigated by using optimization theory tools. We have shown that the appropriate allocation depends on the channel conditions and mainly on the conversion efficiency.

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