

Research Article

Improving Energy Efficiency of Cooperative Femtocell Networks via Base Station Switching Off

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Recently, energy efficiency (EE) of cellular networks has become an important performance metric, and several techniques have been proposed to increase the EE. Among them, turning off base stations (BSs) when not needed is considered as one of the most powerful techniques due to its simple operation and effectiveness. Herein, we propose a novel BS switching-off technique for cooperative femtocell networks where multiple femtocell BSs (FBSs) simultaneously send packets to the same mobile station (MS). Unlike conventional schemes, cooperative operation of FBSs, also known as coordinated multipoint (CoMP) transmission, is considered to determine which BSs are turned off in the proposed technique. We first formulate the optimization problem to find the optimal set of FBSs to be turned off. Then, we propose a suboptimal scheme operating in a distributed manner in order to reduce the computational complexity of the optimal scheme. The suboptimal scheme is based on throughput ratio (TR) which specifies the importance of a particular FBS for the cooperative transmission. Through simulations, we show that the energy consumption can be greatly reduced with the proposed technique, compared with conventional schemes. Moreover, we show that the suboptimal scheme also achieves the near-optimal performance even without the excessive computations.

1. Introduction

In recent days, environmental pollution has become one of the biggest threats to mankind. The generation of electricity is one of the major sources of environmental pollution due to the use of fossil fuel or nuclear energy [1]. Given that the amount of electricity consumed by telecommunication systems (TSs) is considerably huge, a lot of efforts have been made to reduce the electricity usage in TSs such as the use of renewable electricity generation in base station (BS) [2, 3]. The TSs with less electricity usage, that is, green cellular networks (GCNs), will be more important in the near future because the amount of electricity consumption is expected to increase nearly 20% per year [4].

One way to reduce the electricity consumption by TSs is to improve the energy efficiency of TS. Particularly, it is crucial to increase the energy efficiency of BS, since it consumes much more electricity compared to other network

entities (more than half of total electricity consumption in TSs is caused by BSs), for example, mobile stations (MSs). For this reason, various methods have been taken into account in order to improve the energy efficiency of BS [5, 6].

Most powerful yet simple way to improve the energy efficiency of BS is to halt the operation of redundant BSs. However, the set of BSs which are switched off should not be selected randomly but it should be carefully chosen because the shutdown of BSs can severely deteriorate the performance of cellular network (CN), and it can also cause the outage of mobile services. Therefore, the shutdown of BSs has recently been the subject of extensive investigation [3, 7–14].

First, in [7, 8], the shutdown of macro BSs was considered. Specifically, in [7], the shutdown of macro BSs which are located at rural area during night time, that is, the statistical shutdown scheme where network operators manually decide which BSs to be switched off, was considered and in [8] the energy efficiency and coverage probability of macro

We assume that the set of MSs is denoted as \mathbb{M} and just represents the set of FBSs which can cooperate in data transmission to MS i ; that is, not all FBSs are able to participate in data transmission to MSs. For example, in Figure 1, only FBS 1 and FBS 2 are in \mathbb{K}_1 and hence FBS 3 cannot transmit data to MS 1. Note that a specific clustering algorithm to determine \mathbb{K}_i is not taken into account in this work; that is, any clustering algorithm can be used. Moreover, we let P_t be the transmit power of FBSs, where the transmit power control is not considered. Furthermore, the time-varying channel gain is denoted as $G_{i,j}(t)$, where i is the index of MS, j is the index of FBS, and t is the time. It should be noted that $G_{i,j}(t)$ comprises both path-loss and fast fading. In addition, the bandwidth and the noise density are denoted as W and N_0 , respectively. In this paper, we assume that only one MS can receive data at the same time (this assumption is reasonable because FBSs within close proximity are unlikely to transmit data to multiple MSs simultaneously on the same channel, due to the excessive interference among them [15]), such that the interference among cooperative transmission is not considered. In addition, the amount of interference caused by other communication entities, for example, macro BS, is modeled as I_{int} ; compare Figure 1. Finally, we assume that the power consumption of active FBS is $P_A > 0$ and that of turned-off FBS is 0.

We take into account a simple cooperative transmission scheme in which collaborating FBSs simply transmit the same signal to the target MS [15]. Then, the average throughput of MS $_i$, $R_i(\mathbb{F}_A)$, can be formulated as follows:

$$R_i(\mathbb{F}_A) = \mathbb{E} \left[\gamma_{i,t} W \log_2 \left(1 + \frac{\sum_{j \in \{\mathbb{F}_A \cap \mathbb{K}_i\}} G_{i,j}(t) P_t}{N_0 W + I_{\text{int}}} \right) \right], \quad (1)$$

where $\gamma_{i,t}$ is the indicator (given that multiple MSs cannot receive data at the same time in our system model, $\sum_{i=1}^{|\mathbb{M}|} \gamma_{i,t} = 1$) which shows whether MS $_i$ receives data at time t ; that is, $\gamma_{i,t} = 1$ when FBSs transmit data to MS $_i$ at time t and $\gamma_{i,t} = 0$ otherwise. Moreover, $\mathbb{E}[\cdot]$ is the expectation. In (1), it is worth noting that only the signal power from active FBSs is accumulated.

Moreover, the average energy consumption of CN when the set of active FBSs is \mathbb{F}_A , which we denote as $E(\mathbb{F}_A)$, can be written as follows:

$$E(\mathbb{F}_A) = P_A |\mathbb{F}_A|, \quad (2)$$

where $|\cdot|$ denotes the cardinality of the set; for example, $|\mathbb{M}|$ corresponds to the number of all MSs. Note that when none of FBSs is turned off, the average throughput of MS $_i$ and the average energy consumption of CN will become $\mathbb{E}[\gamma_{i,t} W \log_2(1 + (\sum_{j \in \mathbb{K}_i} G_{i,j}(t) P_t)/(N_0 W + I_{\text{int}}))]$ and $P_A |\mathbb{F}|$, respectively, because \mathbb{F}_A becomes \mathbb{F} .

Finally, we can derive the average traffic load of FBS $_j$, when the active set of FBSs is \mathbb{F}_A , which we denote as $U_j(\mathbb{F}_A)$, as follows:

$$U_j(\mathbb{F}_A) = \mathbb{E} \left[\sum_{i \in \mathbb{M}} R_{i,t}(\mathbb{F}_A) \mathbb{1}_{j \in \mathbb{K}_i} \mathbb{1}_{j \in \mathbb{F}_A} \right], \quad (3)$$

where $\mathbb{1}(x)$ is the indicator function whose value is 1 when x is true and 0 otherwise.

3. Problem Formulation

The optimization problem to find the optimal set of switched-off FBSs can be formulated based on our system model. The objective of the formulated problem is the minimization of the total electricity consumption of FBSs, $E(\mathbb{F}_A)$, while guaranteeing the performance degradation of CN to be less than the predefined threshold. To be more specific, we assume that the total network throughput should be larger than the predefined threshold, R_{thr} . Then, the optimization problem to find \mathbb{F}_A can be formulated as follows:

$$\begin{aligned} & \underset{\mathbb{F}_A \subset \mathbb{F}}{\text{minimize}} && E(\mathbb{F}_A) \\ & \text{s.t.} && \sum_{i \in \mathbb{M}} R_i(\mathbb{F}_A) \geq R_{\text{thr}}. \end{aligned} \quad (4)$$

It is worth noting that problem (4) is a binary programming such that it is nonconvex and the solution cannot be found within short computation time, especially, when the number of FBSs is large; that is, $|\mathbb{F}| \gg 0$. In order to solve this excessive computational complexity problem, we propose a heuristic way to find the optimal \mathbb{F}_A within polynomial time in Section 4.

Note that the optimization problem to find \mathbb{F}_A with conventional shutdown scheme, where FBSs with low traffic load are turned off, can be formulated as follows:

$$\begin{aligned} & \underset{\mathbb{F}_A \subset \mathbb{F}}{\text{minimize}} && E(\mathbb{F}_A) \\ & \text{s.t.} && \sum_{i \in \mathbb{M}} R_i(\mathbb{F}_A) \geq R_{\text{thr}} \\ & && U_a(\mathbb{F}) \geq U_b(\mathbb{F}), \quad \forall a \in \mathbb{F}_A, b \in \mathbb{F}_1. \end{aligned} \quad (5)$$

In (5), the last constraint guarantees the FBSs with low traffic load to be switched off. It should be noted that, due to this last constraint, the optimal solution of (5) can be found within polynomial time unlike optimization problem (4). To be more specific, the optimal solution can be found by turning off FBS in ascending order of traffic load until the constraint on data rate is satisfied. However, the solution will work poorly in practice when the cooperative transmission is considered, as shown in our performance evaluation.

4. Proposed Scheme

Herein, we have proposed a heuristic scheme based on TR, which indicates the contribution of certain FBS in the cooperative transmission, to solve the intractability problem of optimization problem (4). To be more specific, the TR value of FBS $_j$, which we denote as TR_j , can be defined as follows:

$$\begin{aligned} \text{TR}_j &= \sum_{i \in \mathbb{M}} \frac{\mathbb{E} \left[\gamma_{i,t} W \log_2 \left(1 + G_{i,j}(t) P_t / (N_0 W + I_{\text{int}}) \right) \right]}{R_i(\mathbb{F})}. \end{aligned} \quad (6)$$

Note that, in (6), numerator corresponds to the expected achievable data rate of MS $_i$ when FBS $_j$ is the only FBS

- (1) Set $\mathbb{F} = \mathbb{F}_A$ and $\mathbb{F}_T = \emptyset$
- (2) Calculate TR_j based on (6)
- (3) **repeat**
- (4) Turn-off FBS $_j$ after delay $D(\text{TR}_j)$
- (5) $\mathbb{F}_A = \mathbb{F}_A \setminus \{j\}$ and $\mathbb{F}_T = \mathbb{F}_T \cup \{j\}$
- (6) **until** $\sum_{i \in \mathbb{M}} R_i(\mathbb{F}_A) < R_{\text{thr}}$
- (7) $\mathbb{F}_A = \mathbb{F}_A \cup \{j\}$ and $\mathbb{F}_T = \mathbb{F}_T \setminus \{j\}$

ALGORITHM 1: FBS shutdown based on TR.

to be activated. Accordingly, if the operation of FBS $_j$ is important in view of cooperative transmission, the value of TR_j will be high. For example, if FBS $_j$ is the only FBS which transmits data to MS $_i$, then $\sum_{i \in \mathbb{M}} (\mathbb{E}[\gamma_{i,t} W \log_2(1 + G_{i,j}(t)P_t/(N_0W + I_{\text{int}}))]/R_i(\mathbb{F})) = 1$; however, if FBS $_j$ is not participating in transmission to MS $_i$, that is, $i \notin \mathbb{K}_i$, then $\sum_{i \in \mathbb{M}} (\mathbb{E}[\gamma_{i,t} W \log_2(1 + G_{i,j}(t)P_t/(N_0W + I_{\text{int}}))]/R_i(\mathbb{F})) = 0$.

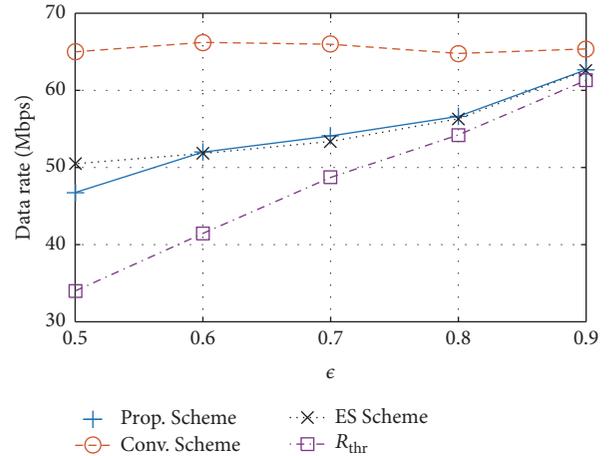
In our proposed scheme, the TR value of FBSs is used to decide which FBS to be switched off, such that FBS $_j$ with low TR_j will be turned off. More specifically, FBSs are switched off based on the ascending order of TR_j . The shutdown of FBSs can be performed in distributed manner because each FBS can calculate its own TR_j based on its own channel condition and information from central management unit (CMU) which manages the operation of FBSs. Let $D(x)$ be the increasing function of x ; for example, $D(x) = x^2$. Then, the operation of FBS $_j$ can be halted after the delay of $D(\text{TR}_j)$ and CMU can cease the shutdown of remaining active FBSs when $\sum_{i \in \mathbb{M}} R_i(\mathbb{F}_A) < R_{\text{thr}}$. The last turned-off FBS should be immediately turned on to guarantee our constraint. It is worth noting that the overhead of our proposed scheme will be negligible compared to that of the optimal scheme which can be found by directly solving (4). In summary, the overall procedures of the proposed algorithm are described in Algorithm 1.

5. Performance Evaluation

In this section, we investigate the performance of our proposed FBS shutdown scheme using simulation. In the performance evaluation, we assume that N FBSs are randomly deployed and they transmit data using CoMP to two MSs which are located at the (0, 0) and (50 m, 0); that is, $|\mathbb{M}| = 2$. The distribution of FBSs is uniform, and $10 \text{ m} < x < 40 \text{ m}$ and $-15 \text{ m} < y < 15 \text{ m}$, where (x, y) is the position of FBS; that is, FBSs are uniformly distributed within a square area. We assume that FBS whose value of x is less than 30 m belongs to set \mathbb{K}_1 and FBS whose value of x is larger than 20 m is within set \mathbb{K}_2 , such that only FBSs whose x are within $20 \text{ m} < x < 30 \text{ m}$ can transmit data to both MSs (we have used this simulation scenario with only two MSs, in order to focus on the difference between conventional switching-off scheme and our proposed scheme; performance evaluation in more general environment, where more MSs coexist, will be an interesting extension of this work). IMT-R M.2135 urban macromodel (therefore, the path-loss becomes $34.5 +$

TABLE I: Simulation parameters.

Parameters	Values
Number of MSs	2
Path-loss	$34.5 + 38 \log_{10}(d_{i,j})$ (IMT-R M.2135 urban macromodel [17])
I_{int}	-70 dBm
N_0	-174 dBm/Hz
Bandwidth (W)	10 MHz
$\gamma_{1,t}$	0.5
$\gamma_{2,t}$	0.5
Transmit power of FBS	23 dBm

FIGURE 2: Data rate versus ϵ when $|\mathbb{F}| = 10$.

$38 \log_{10}(d_{i,j})$, where $d_{i,j}$ is the distance between MS $_i$ and FBS $_j$) is used for path-loss [17]. Furthermore, we assume that $I_{\text{int}} = -70 \text{ dBm}$, $N_0 = -174 \text{ dBm/Hz}$, W is 10 MHz, $\gamma_{1,t} = \gamma_{2,t} = 0.5$, and the transmit power of FBS, P_t , is 23 dBm. In addition, we assume that the channel experiences the fast fading which is modeled as a circularly symmetric complex Gaussian random variable with mean 0 and variance 1. Simulation parameters are summarized in Table 1.

In the performance evaluation, we examine the performance of our proposed scheme based on Algorithm 1 (Prop. Scheme) and also consider the performance of optimal scheme which can be found by solving (4) with exhaustive search (ES Scheme). Moreover, the conventional shutdown scheme, in which FBSs are switched off based on their traffic load, is also taken into account (Conv. Scheme), where FBS to be shut down is randomly chosen when multiple FBSs have the same traffic load. Note that the shutdown of Conv. Scheme is adjusted such that $\sum_{i \in \mathbb{M}} R_i(\mathbb{F}_A) \geq R_{\text{thr}}$ is satisfied. Finally, in the simulation, we assume that $R_{\text{thr}} = \epsilon \sum_{i \in \mathbb{M}} R_i(\mathbb{F})$, where $0 \leq \epsilon \leq 1$, such that ϵ indicates the degree of throughput deterioration that the system can tolerate. In other words, low value of ϵ means that decreasing power consumption is more important such that more FBSs will be turned off even if the throughput of the system is decreased significantly.

In Figures 2 and 3, the data rate and power consumption ratio, by varying ϵ , are shown when the number of FBSs, $|\mathbb{F}|$,

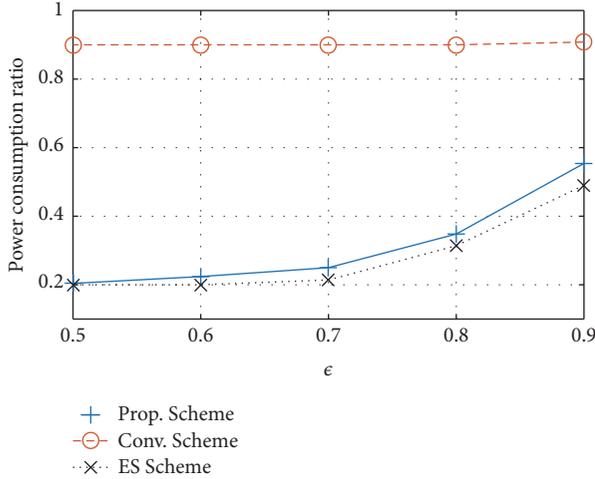


FIGURE 3: Power consumption ratio versus ϵ when $|\mathcal{F}| = 10$.

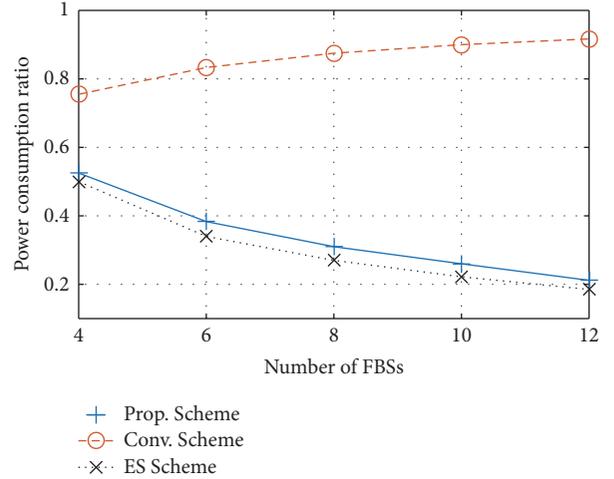


FIGURE 5: Power consumption ratio versus number of FBSs when $\epsilon = 0.7$.

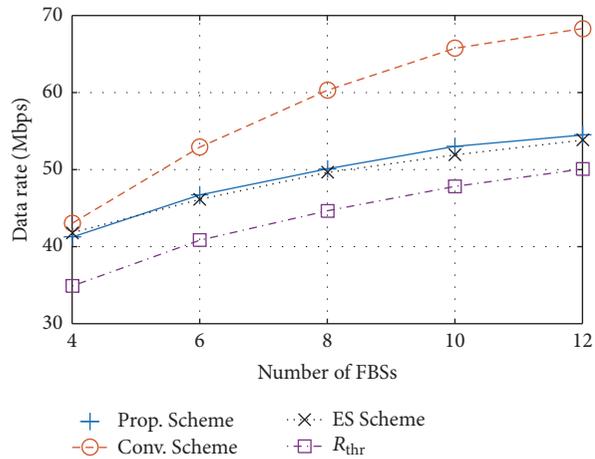


FIGURE 4: Data rate versus number of FBSs when $\epsilon = 0.7$.

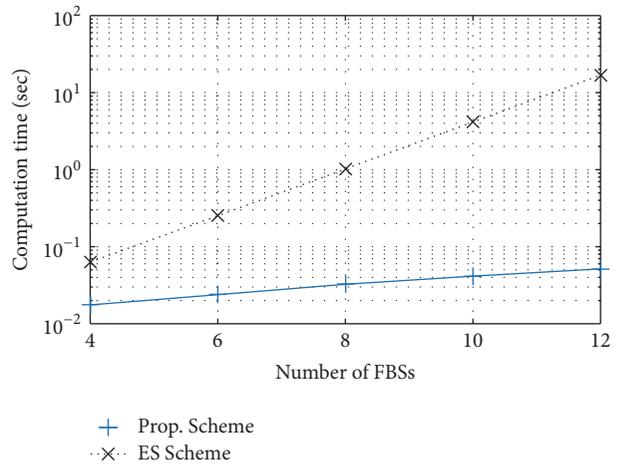


FIGURE 6: Computation time versus number of FBSs when $\epsilon = 0.7$.

is 10, where the power consumption ratio is the ratio of power consumption of the scheme and the power consumption without FBS shutdown, that is, $|\mathcal{F}_A|/|\mathcal{F}|$. For example, when the power consumption ratio is 0.5, 50% of energy can be saved. We can find that the data rate of all considered schemes is larger than R_{thr} ; that is, constraints on data rate are satisfied in all cases. However, the data rate of Prop. Scheme and ES Scheme decreases as ϵ decreases while that of Conv. Scheme remains the same because the number of FBSs to be turned off is unchanged in Conv. Scheme while that of Prop. Scheme and ES Scheme decreases greatly, as can be verified from Figure 3. Specifically, in Prop. Scheme and ES Scheme, nearly 80% of FBSs can be turned off without violating the constraint on data rate such that energy consumption can be reduced significantly, which validates the benefit of our proposed scheme. Moreover, we can verify that our proposed scheme achieves near-optimal performance in terms of power consumption.

Figures 4 and 5 show the data rate and power consumption ratio by varying the number of FBSs when ϵ is 0.7. We can observe that the data rate increases as the number

of FBSs increases because received signal power of MSs is likely to increase. It is worth noting that the data rate of all considered schemes exceeds R_{thr} ; that is, the constraint on data rate is satisfied even when $|\mathcal{F}|$ increases. Moreover, we can find that the power consumption ratio of our proposed scheme is much lower than that of Conv. Scheme, such that more energy can be saved in our proposed scheme compared to conventional FBS shutdown scheme. Particularly, we can observe that the gap between the power consumption ratio of our scheme and that of conventional scheme increases as $|\mathcal{F}|$ increases because the number of redundant FBSs is more when $|\mathcal{F}|$ is large; that is, the operation of more FBSs can be halted without hurting the data rate significantly. Therefore, we can conclude that our proposed scheme works better when the number of FBS is large. It should be noted that the power consumption ratio of Prop. Scheme and ES Scheme is almost the same; that is, the performance of our proposed scheme is nearly optimal, although Prop. Scheme is a heuristic scheme that works in distributed manner.

Finally, in Figure 6, the computation time of Prop. Scheme and ES Scheme by varying $|\mathcal{F}|$ is depicted. As can be

seen from the results, the computation time of our proposed scheme is much lower than that of ES Scheme because the number of computations required for ES Scheme increases exponentially with $|F|$. Therefore, our proposed scheme is much better to be implemented in practice, especially in large CN where large number of FBSs is considered.

6. Conclusions

In this paper, the efficient way to halt the operation of redundant FBSs in cooperative transmission was exploited. Given that existing FBS shutdown schemes are inappropriate for FBS with cooperative transmission, we proposed new scheme by formulating the optimization problem. In order to solve the excessive computational complexity problem, a heuristic scheme based on TR was devised, which can operate in distributed manner. Through simulations based on realistic parameters, it was shown that our proposed scheme achieves near-optimal performance without excessive computations, such that the power consumption of FBSs can be greatly reduced without overly degrading the data rate of CN. The consideration of more generalized system model, in which FBSs transmit with different transmit power on multiple channels, might be an interesting extension of this work.

Competing Interests

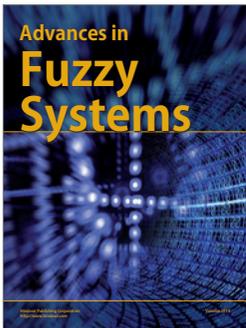
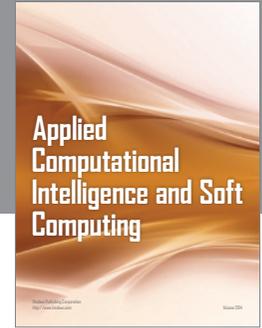
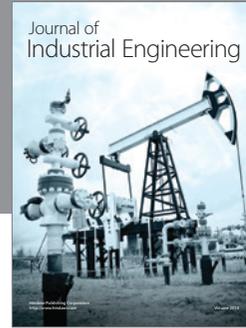
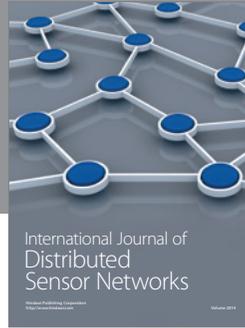
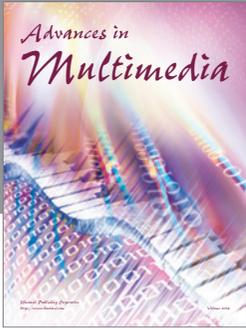
The authors declare that they have no competing interests.

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