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Wish or reality? On the exploitability of triangular arbitrage in cryptocurrency markets

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ABSTRACT

This study investigates the efficiency of cryptocurrency markets by examining the presence and exploitability of arbitrage opportunities. Using high-frequency data from the Binance Exchange, we implement a triangular arbitrage strategy, considering Bitcoin, Litecoin, and the U.S. Dollar. We find 4,879 possible arbitrage opportunities. Although these findings suggest potential inefficiencies, transaction costs and limited trading volumes in the order book eliminate their profitability. Consequently, centralized cryptocurrency markets exhibit a high degree of efficiency. Moreover, our results suggest that the mere number of triangular arbitrage opportunities is not a reliable indicator of market inefficiency.

1. Introduction

In recent years, the market for cryptocurrencies has experienced a tremendous growth. Binance, the largest cryptocurrency exchange (Disli et al., 2022), handled over 300 billion transactions in 2022, with an average daily trading volume exceeding 65 billion U.S. Dollar (Binance, 2024). Due to the increasing scale of these markets, ensuring consistent and contradiction-free pricing across assets is a relevant issue. In financial markets, arbitrage mechanisms enforce pricing coherence by eliminating discrepancies between the prices of similar assets. In the relatively new and rapidly growing environment of cryptocurrency markets, the question arises whether such self-correcting mechanisms effectively operate.

In our study, we investigate whether arbitrage opportunities exist in cryptocurrency markets and assess to what extent market participants can exploit them under real-world conditions. To explore this, we implement a triangular arbitrage trading strategy on the Binance Exchange. This strategy has long been employed in traditional currency markets to secure riskless trading returns (Fenn et al., 2009). However, due to the rise of automated trading systems and increasing market efficiency, such opportunities have significantly diminished in foreign exchange markets over time (Ito et al., 2020). We focus on the U.S. Dollar, Bitcoin, and Litecoin, identifying potential triangular arbitrage opportunities. Thus, we analyse how the exchange rates of two cryptocurrencies and the U.S. Dollar are related to each other. By using Bitcoin as the most recognized cryptocurrency and Litecoin as one of its first substitutes (Miglietti et al., 2019), we are in line with existing literature that especially examines those two cryptocurrencies (e.g. Tu and Xue, 2019; Tiwari et al., 2019; Miglietti et al., 2019; Sapkota and Grobys, 2021).

Unlike most previous studies, our paper goes beyond the mere identification of arbitrage possibilities. We conduct an in-depth analysis of the duration of these opportunities and their practical exploitability. Specifically, we examine how factors like transaction costs, latency issues, and order book depth limit the extent to which identified arbitrage opportunities can be leveraged. While

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textbook cases suggest that triangular arbitrage offers theoretically unlimited profit potential, in reality, these constraints have a restricting character. We raise the question of whether the identified arbitrage opportunities can truly be exploited and, therefore, serve as an indication of potential inefficiencies in this particular market segment.

We make several contributions to the literature on cryptocurrency market efficiency. First, we create a highly granular, high-frequency dataset consisting of bid and ask quotes for the three exchange rates. These quotes are directly obtained from the Binance Exchange through the Binance Websocket. In high-frequency trading, latency plays a crucial role in determining the viability of arbitrage strategies. Although the exact location of Binance's servers is not publicly known, it is assumed that they are based in Japan. Our latency measurements support this assumption. In an initial run with a server located in Europe, we measure an 80-millisecond latency, which we reduce to 4 milliseconds by using a server in Japan. Consequently, we opt for a Tokyo-based server for the analysis. Over the course of a randomly selected week, we collect 30.9 million quotes in total.

Second, during the examined week, we identify a total of 4,879 potential triangular arbitrage opportunities. However, the majority of these offered only marginal returns, with most ranging between 0 percent and 0.025 percent. Taking real transaction fees on the Binance Exchange into account, the profitability of most of these opportunities is effectively eliminated. For regular traders, a small subset of 18 opportunities remains profitable after accounting for transaction costs. For example, traders could realize a total of 2 percent if these opportunities are taken immediately. In a best-case scenario, this sum of relative returns increases to 3 percent. The depth of the order book further restricts the quantities that could be traded. Since the average tradable amount is 4,070.86 U.S. Dollar for the 18 opportunities, this results in marginal arbitrage profits between 12.43 U.S. Dollar and 17.73 U.S. Dollar for the entire week. Therefore, we conclude that cryptocurrency markets exhibit a high degree of efficiency. Our results also suggest that the mere number of triangular arbitrage opportunities is not a reliable indicator of market inefficiency, as many of these opportunities are unprofitable to be exploited in practice.

Third, there is a time lag between the observed and realized prices. Hence, slippage[1] is a critical issue for the implementation of triangular arbitrage strategies. Under the condition that the expected value of the arbitrage trades should be profitable, we estimate the execution time for a trade in our high-frequency data. Results suggest that a trader needs to execute the triangular arbitrage strategy in not more than 146 milliseconds to be profitable. Otherwise, the slippage risk would exceed the profitability of arbitrage trades.

The reminder of the study proceeds as follows: Section 2 reviews the related literature and details our research question. Section 3 describes the data and methodology used. Section 4 presents and discusses our results, and Section 5 concludes.

2. Related literature

Cryptocurrencies such as Bitcoin and others have seen huge price explosions in the past (Bouri et al., 2019). Such new, promising market segments are intended to generate rapid, risk-free returns. For example, Makarov and Schoar (2020) find profitable arbitrage on different cryptocurrency exchanges across countries and, therefore, suggest that a lack of regulation supports those price deviations. Those findings are confirmed by Crépellière et al. (2023). However, examining a longer period, they point out a significant decline in risk-free arbitrage opportunities for market participants over time. They suggest, that increased institutional involvement and retail trader attention lead to higher informed activity in this market segment. In addition, using different specifications of statistical arbitrage, Fischer et al. (2019) and Leung and Nguyen (2019) observe significant returns for their strategies. Besides these strategies, triangular arbitrage is another method to exploit inefficiencies in currency markets. Triangular arbitrage capitalizes on discrepancies between three different trading pairs or currencies (Aiba et al., 2002). This strategy has been extensively studied in foreign exchange markets by, for example, Aiba and Hatano (2006), Fenn et al. (2009), and Akram et al. (2008), who investigate how these pricing inefficiencies arise and diminish in traditional markets. More recently, research has turned to examining arbitrage in decentralized cryptocurrency markets. Wang et al. (2022) implement a cyclical arbitrage strategy on Uniswap, where trades occur via smart contracts rather than through a traditional order book, and where converting cryptocurrencies into fiat money is not feasible. In addition, Bewaji et al. (2021) explore various arbitrage strategies and find that the exchange platform itself plays a critical role in identifying price asymmetries. However, both studies leave open the question of why those are not being exploited and omit key real-world factors, such as transaction costs for traders and the risk of slippage, which can significantly impact the feasibility and profitability of arbitrage strategies in practice. By incorporating these considerations, our study aims to provide a more comprehensive understanding of arbitrage opportunities in cryptocurrency markets.

Arbitrage-free trading is one condition for efficient markets. Moreover, it is a fundamental requirement for a consistent pricing[2] system. Vice versa, the efficiency of a market segment also implies whether arbitrage opportunities could be observed and potentially exploited by market participants. Given that the markets for cryptocurrencies are unregulated, this question is of particular relevance. The semi-strong form of the efficient market hypothesis (EMH) states that the prices of securities fully and immediately reflect all publicly available information (Fama, 1970). Consequently, there is no systematic mispricing in an efficient market, and risk-free

[1] Slippage means the price change between the time a trader identifies or places a market order and the settled price. This is specifically relevant for volatile assets and illiquid market segments.

[2] Recent literature examines the pricing of cryptocurrencies. For example, trading volume and volatility in cryptocurrency markets are subject to seasonal patterns (Kaiser, 2019). Therefore, there is a growing literature explaining these returns. For example, in line with Fama and French (1992), Liu et al. (2022) construct a cryptocurrency market, size and momentum factor to explain the returns through a standard asset-pricing model. Alternative approaches exist, like Liu and Tsyvinski (2021) suggesting that network effects, such as user adoption, are additional value drivers. Moreover, the interaction of investors and traders on social platforms contributes to the price increases of meme stocks and cryptocurrencies (Aloosh et al., 2022).

Table 1
Tradable quantities for an exemplary triangular arbitrage opportunity.

Return	BtcUsdtAskQty	LtcBtcAskQty	LtcUsdtBidQty	Time
0.015490622	1.15597	22.841	21.144	23:07:49.896938
0.015490622	1.15597	22.841	36.998	23:07:49.897050
0.015490622	1.15597	22.841	41.399	23:07:49.897150
0.015490622	1.15597	22.841	59.519	23:07:49.897276
0.015490622	1.15597	22.841	59.519	23:07:49.897374
0.015490622	1.15597	22.841	43.665	23:07:49.897474
0.015490622	1.15597	54.008	43.665	23:07:49.897624
0.015490622	1.15597	22.841	43.665	23:07:49.898155

Notes: This table shows tradable quantities of the triangular arbitrage strategy ($USD \rightarrow BTC \rightarrow LTC \rightarrow USD$) and the corresponding return. The return, without including transaction costs, is presented in percent. BtcUsdtAskQty means the ask quantity of the exchange pair of Bitcoin and U.S. Dollar; LtcBtcAskQty means the ask quantity of the exchange pair of Litecoin and Bitcoin; and LtcUsdtBidQty means the bid quantity of the exchange pair of Litecoin and U.S. Dollar.

exploitation through arbitrage is not possible. In contrast, literature exhibits inefficiencies in cryptocurrency markets. Joo et al. (2020) show that information is not immediately priced, and Aloosh and Ouzan (2020) find evidence of a small-price bias, whereby investors react more strongly to news when the price of a cryptocurrency is low. However, there are several studies suggesting that cryptocurrency markets are, to a certain degree, efficient (e.g. Wang and Chong, 2021; Vidal-Tomas and Ibanez, 2018; Alvarez-Ramirez and Rodriguez, 2021). This development is strengthened by the introduction of Bitcoin futures (Köchling et al., 2019). Moreover, Burggraf and Rudolf (2021) conclude in their analysis of low-volatility anomalies for cryptocurrencies that the markets are more efficient than previously assumed. An additional perspective views cryptocurrency markets through the lens of an adaptive market hypothesis, where market efficiency is not static but instead varies. For example, Chu et al. (2019), Al-Yahyaee et al. (2020), and Khuntia and Pattanayak (2021) find that cryptocurrencies exhibit different levels of efficiency over time.

3. Methodology and data

According to Fenn et al. (2009), a triangular arbitrage opportunity can be quantified through an exchange rate product and is given as:

$$Y(t) = \prod_{i=1}^{3} r_{\mathrm{i}}(t), \tag{3.1}$$

where $r_i(t)$ represents the respective exchange rate and $Y(t)$ the exchange rate product at time t. A profitable triangular arbitrage opportunity exists if $Y(t) > 1$. We consider the three currencies for the triangular trading strategy: U.S. Dollar (USD), Bitcoin (BTC), and Litecoin (LTC). The triangular arbitrage sequence is $USD \rightarrow BTC \rightarrow LTC \rightarrow USD$. Starting with an initial amount of X_S in U.S. Dollar, this is converted into Bitcoin, then into Litecoin, and finally back into an end amount X_E in U.S. Dollar. The trading strategy is profitable if $X_E > X_S$. As the market tends to be more efficient, the difference $X_E - X_S$ diverges towards zero. For the considered sequence of the three trading pairs, the rate product is given as:

$$Y(t) = \frac{1}{BTC/USDT_{\mathrm{Ask}}(t)} \cdot \frac{1}{LTC/BTC_{\mathrm{Ask}}(t)} \cdot LTC/USDT_{\mathrm{Bid}}(t), \tag{3.2}$$

where $Y(t)$ is the exchange rate product at time t. The trading strategy exploits the arbitrage opportunity if $Y(t) > 1$.

We collect high-frequency data from the order book of the Binance Exchange between the 06/03/2024 and the 06/09/2024.[3] Using a websocket connection containing real-time order book data, we gather the best-ask and best-bid prices for the three trading pairs, as well as the quantities offered and demanded at these prices. Additionally, time and latency data are collected. We calculate the exchange rate product and the corresponding return percentage for each data point separately. To measure the duration, the period between the moment when the exchange rate product exceeds 1 and the moment it falls back below 1 is recorded. The latency is measured as the temporal difference between the actual time of the change and the time when the corresponding message was received. The final data set contains 30.9 million exchange rate products. It is important to note, that each change in one of the variables, for example, a change in ask-quantities, leads to the calculation of a new exchange rate product. Under this assumption, a triangular arbitrage opportunity can therefore comprise multiple rate products. Table 1 illustrates such a case. While the return percentage stays the same, the quantities are changing rapidly due to high market volatility. To address this issue, we clustered the data associated with each arbitrage opportunity.

Since there could be a deviation between the observed and the actually settled price, we assume the absence of slippage. We further assume, that a trader only trades those quantities for which there are supply/demand quantities in the order book at the

[3] Beginning at 0:00 AM GMT and ending at 0:00 PM GMT.

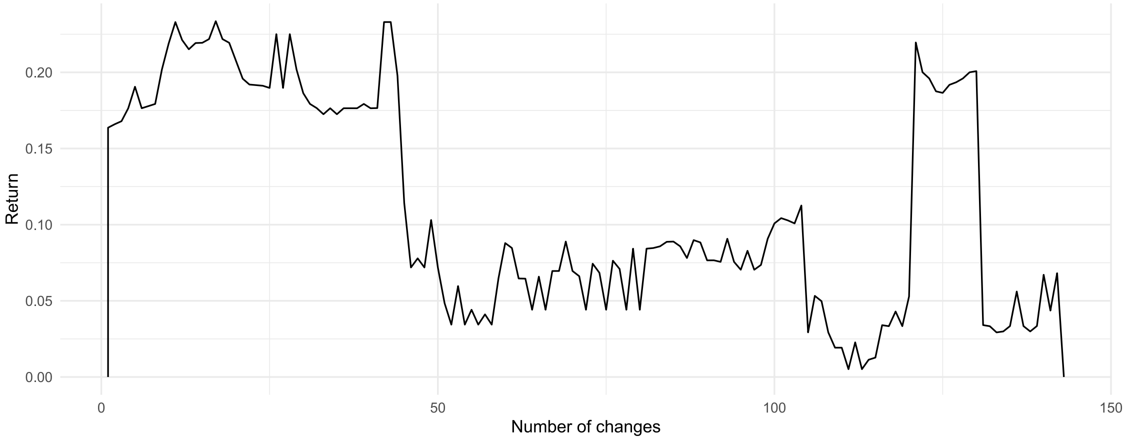

Fig. 1. Yield curve within an arbitrage opportunity: This figure shows the number of profitable possible trades during a triangular arbitrage opportunity. The vertical axis displays the return without including transaction costs for one potential trade. The return is presented in percent. The horizontal axis displays the number of changes during the profitable arbitrage opportunity.

underlying ask and bid prices. Under this assumption, the lowest quantity offered/demanded is relevant in each case, as this is the limiting factor. The maximum tradable value $MaxUSD(t)$ is defined as:

$$\text{MaxUSD(t)} = \min \begin{pmatrix} \text{BTC/USDT}_{\text{Ask\_Qty}}(\text{t}) \times \text{BTC/USDT}_{\text{Ask}}(\text{t}), \\ \text{LTC/BTC}_{\text{Ask\_Qty}}(\text{t}) \times \text{LTC/BTC}_{\text{Ask}}(\text{t}) \times \text{BTC/USDT}_{\text{Ask}}(\text{t}), \\ \text{LTC/USDT}_{\text{Bid\_Qty}}(\text{t}) \times \text{LTC/USDT}_{\text{Bid}}(\text{t}) \end{pmatrix} \tag{3.3}$$

4. Results

Before testing whether there are inefficiencies in the cryptocurrency market, we have to uniquely define the emergence of an arbitrage opportunity. The most obvious approach is that a triangular arbitrage opportunity occurs when the exchange rate product rises above the threshold of 1 and falls back below 1. As a result, the achievable return during this period is continuously positive. Since high-frequency exchange rates are subject to volatility, different levels of returns and tradable quantities can occur within this time period. Therefore, a second approach is to consider every change in the rate product and define it as an individual opportunity. This results in significantly more executable trades. Fig. 1 shows the temporal development of returns within a triangular arbitrage opportunity with a total duration of approximately 1.9 seconds. In the absence of transaction costs, an infinitely fast trader could execute every change in the exchange rate product, resulting in over 140 possible trades. However, since the exchange rates change over a fraction of a millisecond and the duration cannot be determined in advance, realistically, no trader is fast enough to take advantage of these opportunities. The majority of traders will therefore exploit the opportunity only once when the expected return exceeds the transaction costs by a certain margin. For the following analysis, we follow the first approach and count the initial passing of the threshold as one arbitrage opportunity.

Fig. 2 displays the development of the rate product over the observed period. Assuming an efficient market, the value of the exchange rate product should be 1 or just below this threshold (Fenn et al., 2009). Our findings show that, for the majority of the time, the exchange rate product remains below 1. During these periods, it is not possible to profit from a triangular arbitrage trading strategy. However, there are profitable instances when the exchange rate product exceeds the threshold of 1. This suggests that the cryptocurrency markets contain inefficiencies that can theoretically be exploited by arbitrage traders.

Table 2 presents the number of arbitrage opportunities by return (Panel A), duration (Panel B), and tradable quantity (Panel C). We identify 4,879 potential triangular arbitrage opportunities. The majority (4,337 observations) have a return between 0 percent and 0.025 percent. But we find three observations with a return larger than 0.5 percent. Simultaneously, approximately 65 percent of these arbitrage opportunities are very short and last one second or less, while 767 observations (15.72 percent) exhibit a relatively long duration of more than 5 seconds. This observation aligns with (Fenn et al., 2009), who find similar values for the forex market. Therefore, the time to react is an inherent factor for the success of the trading strategy.

Binance offers different trading fee levels depending on how much volume a market participant trades per month. They are called VIP levels, and VIP 9 indicates the lowest transaction costs, while a regular trader has to pay the highest fees. Table 3 illustrates the number of profitable triangular arbitrage opportunities after considering transaction costs. Not all the 4,879 observed triangular arbitrage opportunities are profitable, as the transaction costs reduce the potential return. 96.93 percent of the triangular arbitrage opportunities are not even profitable for VIP 9 traders. This finding is in line with Wang et al. (2022), who find that a large proportion of cryptocurrency arbitrage opportunities are not exploited. Consequently, this is due to the fact that these are not profitable for market participants paying regular trading fees. However, when considering transaction costs for a VIP 9 trader, there

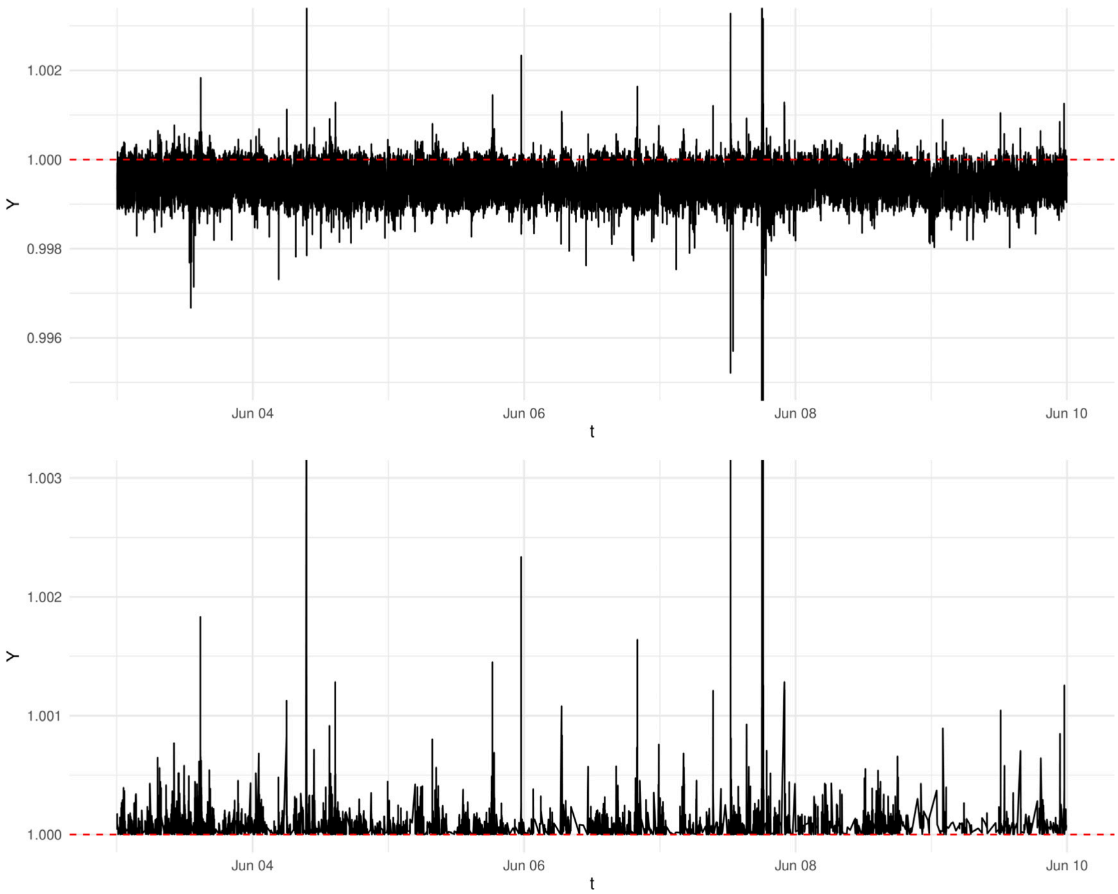

Fig. 2. Exchange rate product over time: Those figures show the development of the exchange rate product ($USD \rightarrow BTC \rightarrow LTC \rightarrow USD$) over the examination period. The vertical axis displays the exchange rate product, and the horizontal axis displays the time. The upper figure presents all exchange rate products. All products above the red line reflect a profitable triangular arbitrage opportunity without including transaction costs. The lower figure displays only the profitable arbitrage opportunities without including transaction costs. The period starts on the 06/03/2024 and ends on the 06/09/2024.

are still 150 opportunities with a return greater than the transaction costs. The lower the VIP level, the fewer arbitrage opportunities are profitable. As a consequence, 18 trading opportunities remain for a regular investor.

Transaction costs are accounted for based on the Binance spot trading fees. The transaction fees on the Binance exchange are determined by the 30-day trading volume, the balance of Binance Coins (BNB), as well as the selected order type. Consequently, a triangular arbitrage opportunity is profitable only when the achievable return exceeds the transaction costs. To analyse the profitability of triangular arbitrage opportunities for traders, we have to define the exact moment of execution. We consider four different cases, including the first, the best profit, the highest tradable value, and the average execution opportunity leading to different levels of return. The first case assumes that the trader exploits the arbitrage opportunity if the exchange rate product passes over the threshold of 1 and the return rises above the transaction costs. The second case assumes that the trader could realize the maximum profit in each triangular arbitrage trade. This value can be achieved in reality by specifying a certain return level that must be reached at least for the trade to be executed. The next case assumes that the trader realizes the highest tradable quantity for a given return. For the average arbitrage opportunity, we consider the mean return (reduced by the transaction costs) and the mean quantity during the arbitrage period. Table 4 illustrates the distribution of returns after considering transaction costs (Panel A) for a regular trader (highest transaction fees) and a VIP 9 trader (lowest transaction fees). If traders exploit the arbitrage opportunity at the first moment when the return exceeds the transaction fees, they archive a sum of returns of 2.01 percent during the week. Investors exploiting the best return opportunity could increase their return to 2.97 percent. As mentioned earlier, in practice, traders will only trade those quantities for which there are supply/demand quantities in the order book at the underlying ask and bid prices. This limits the possible net profits to 12.43 U.S. Dollar or 17.73 U.S. Dollar, respectively. Panel B displays the tradable value of the four cases. The majority of arbitrage opportunities range between a tradable value of 0 U.S. Dollar and 500 U.S. Dollar. The sum of initial quantities (10,650.26 U.S. Dollar) under the first strategy is substantially lower than the amount achieved when traders follow the highest tradable value strategy to maximize trading volume (17,947.96 U.S. Dollar), while the average traded amount is 4,070.86 U.S. Dollar. In addition, we find more profitable triangular arbitrage opportunities for a VIP 9 trader with higher corresponding quantities. Consequently, they could archive higher net returns, up to a maximum of 170.76 U.S.

Table 2
Number of arbitrage opportunities by return, duration, and value.

	Frequency	Rel. frequency	Total	Rel. total
Panel A: Return				
0.000–0.025	4,337	88.89	4,337	88.89
0.025–0.050	371	7.60	4,708	96.50
0.050–0.075	85	1.74	4,793	98.24
0.075–0.100	26	0.53	4,819	98.77
0.100–0.200	41	0.84	4,860	99.61
0.200–0.300	9	0.18	4,869	99.80
0.300–0.400	5	0.10	4,874	99.90
0.400–0.500	2	0.04	4,876	99.94
>0.500	3	0.06	4,879	100.00
Panel B: Duration				
0.000–0.500	2,825	57.90	2,825	57.90
0.500–1.000	322	6.60	3,147	64.50
1.000–2.000	440	9.02	3,587	73.52
2.000–3.000	223	4.57	3,810	78.09
3.000–4.000	167	3.42	3,977	81.51
4.000–5.000	135	2.77	4,112	84.28
>5.000	767	15.72	4,879	100.00
Panel C: Tradable value				
0–1,000	1,636	33.53	1,636	33.53
1,000–2,000	1,044	21.40	2,680	54.93
2,000–3,000	936	19.18	3,616	74.11
3,000–4,000	435	8.92	4,051	83.03
4,000–5,000	396	8.12	4,447	91.15
5,000–10,000	392	8.03	4,839	99.18
>10,000	40	0.82	4,879	100.00

Notes: This table shows summary statistics of the return, the duration, and the tradable value of the triangular arbitrage opportunities. Panel A displays the number of arbitrage opportunities by return without transaction costs. The return is presented in percent. Panel B displays the number of arbitrage opportunities by duration. The duration is presented in seconds. Panel C displays the number of arbitrage opportunities by tradable value. The tradable value is presented in U.S. Dollar.

Table 3
Number of profitable arbitrage opportunities by Binance VIP level.

VIP level	30-Day trade volume	and/or	BNB balance	Transaction costs	Rel. frequency	Total
/	/	/	/	/	96.93	4,729
VIP 9	≥4,000	and	≥5,500	0.0540	3.07	150
VIP 8	≥2,000	and	≥4,500	0.0675	2.07	101
VIP 7	≥800	and	≥3,000	0.0810	1.62	79
VIP 6	≥400	and	≥1,750	0.0945	1.27	62
VIP 5	≥150	and	≥1,000	0.1080	1.09	53
VIP 4	≥100	and	≥500	0.1215	0.94	46
VIP 3	≥20	and	≥250	0.1350	0.78	38
VIP 2	≥5	and	≥100	0.2250	0.37	18
VIP 1	≥1	and	≥25	0.2250	0.37	18
Regular	<1	or	≥0	0.2250	0.37	18

Notes: This table shows the number of profitable triangular arbitrage opportunities, including transaction costs. The "30-Day trade volume" is presented in million U.S. Dollar. The "BNB balance" (Binance Coin) is presented in Binance Coins. The "Transaction costs" are presented in percent. The "Rel. frequency" is displayed in percent, and "Total" is the absolute number of arbitrage opportunities.

Dollar. However, if we relate this finding to the condition that those market participants need at least a trading turnover of 4 billion U.S. dollars per month, the possible profit is negligible. In summary, our results indicate that transaction costs and order book depth restrict possible profits in such a way that market participants could not archive a risk-free return on cryptocurrency markets.

Since the trading quantity of the three exchange rates is a crucial factor for the profitability of the triangular arbitrage, we further identify the "bottleneck" of our strategy. Table 5 presents the relative number of exchange rates as the limiting factor. We find that for a VIP 9 trader, the cross-rate of Bitcoin and Litecoin ($BTC \rightarrow LTC$) reduces the possible profits of the trading strategy in around half of the cases. If the arbitrage opportunity is exploited immediately, the most liquid trading pair, U.S. Dollar and Bitcoin ($USD \rightarrow BTC$), limits the quantity of our strategy in 10 percent of the opportunities. In contrast, the results for traders with the highest fees, on the other hand, are not unambiguous. The two Litecoin exchange rates ($BTC \rightarrow LTC$ and $LTC \rightarrow USD$) limit the arbitrage opportunities. However, this finding is strongly influenced by outliers due to the small number of observations. In summary, this finding reflects the characteristics of foreign exchange markets for traditional currencies.[4]

Table 4
Number of profitable arbitrage opportunities by return and value.

	Regular				VIP 9			
	First	Best profit	Highest value	Average	First	Best profit	Highest value	Average
Panel A: Return								
0.000–0.025	6	5	3	3	86	68	58	58
0.025–0.050	1	2	1	1	26	24	18	22
0.050–0.075	2	1	2	2	18	18	13	7
0.075–0.100	2	1	1	0	7	10	4	9
0.100–0.200	5	6	4	3	7	17	7	8
0.200–0.300	0	0	0	1	4	6	4	3
0.300–0.400	1	1	1	0	2	4	4	4
0.400–0.500	0	1	1	0	0	0	0	0
>0.500	1	1	0	0	0	3	2	0
∑ Total return	2.01	2.97	1.66	0.90	6.21	10.83	6.98	5.89
Panel B: Value								
0–500	12	12	7	7	101	100	62	67
500–1,000	2	3	0	2	15	14	5	17
1,000–1,500	1	0	0	1	4	7	4	5
1,500–2,000	1	3	3	0	4	7	8	7
2,000–3,000	2	0	1	0	13	10	12	8
3,000–4,000	0	0	1	0	4	4	3	1
4,000–5,000	0	0	0	0	1	1	2	2
5,000–10,000	0	0	1	0	6	5	8	2
>10,000	0	0	0	0	2	2	6	2
∑ Total tradable value	10,650.26	9,257.36	17,947.96	4,070.86	188,505.13	179,800.77	254,966.18	123,588.79
Panel C: Total net profit								
	12.43	17.73	30.42	4.77	82.72	100.48	170.76	50.53

Notes: This table presents profitable arbitrage opportunities after subtracting transaction costs. Panel A displays the number of profitable opportunities by return. The return is presented in percent. Panel B displays the number of profitable arbitrage opportunities by tradable value. The value is presented in U.S. Dollar. The column "First" assumes that the trader exploits the triangular arbitrage opportunity immediately if the exchange rate product passes the threshold of 1 and the return is higher than the transaction costs; the column "Best profit" assumes that the trade is realized at the maximum return by the corresponding tradable value; the column "Highest value" assumes that the trade is realized at the maximum tradable value by the corresponding return; and the column "Average" assumes the means of return and tradable value during an arbitrage opportunity. Panel C displays the total net profit in U.S. Dollar during the examined week.

Table 5
Quantities by trading pairs.

	Regular				VIP 9			
	Trading value	$USD \rightarrow BTC$	$BTC \rightarrow LTC$	$LTC \rightarrow USD$	Trading value	$USD \rightarrow BTC$	$BTC \rightarrow LTC$	$LTC \rightarrow USD$
Panel A: First								
Total	10,650.26	451,624.21	365,133.72	25,768.32	188,505.13	35,863,109.19	1,041,792.30	595,830.92
Average per day	1,521.47	64,517.74	52,161.96	3,681.19	26,929.30	5,123,301.31	148,827.47	85,118.70
Rel. Amount		22.22	44.44	33.33		10.67	50.67	38.67
Panel B: Best profit								
Total	9,257.36	393,741.86	345,506.23	17,085.52	179,800.77	34,876,736.82	1,017,469.32	576,552.09
Average per day	1,322.48	56,248.84	49,358.03	2,440.79	25,685.82	4,982,390.97	145,352.76	82,364.58
Rel. Amount		16.67	33.33	50.00		14.00	45.33	40.67
Panel C: Highest value								
Total	17,947.97	290,463.55	332,273.82	24,029.92	254,966.18	34,549,980.87	848,097.84	503,110.71
Average per day	2,564.00	41,494.79	47,467.69	3,432.85	36,423.74	4,935,711.55	121,156.83	71,872.96
Rel. amount		0.00	41.67	66.67		4.55	53.64	41.82
Panel D: Average								
Total	4,070.86	159,681.01	162,992.96	11,565.93	123,588.79	26,517,295.01	555,177.72	394,512.36
Average per day	581.55	22,811.57	23,284.71	1,652.28	17,655.54	3,788,185.00	79,311.10	56,358.91
Rel. Amount		0.00	50.00	50.00		5.41	53.15	41.44

Notes: This table presents the trading pair quantities of the profitable arbitrage opportunities after subtracting transaction costs. "Total" means the U.S. Dollar amount of the sum of the quantities for every trading. "Rel. Amount" means the percentage of cases when the appropriate quantity of the trading pair limits the profit of the arbitrage opportunity. Panel A "First" assumes that the trader exploits the triangular arbitrage opportunity immediately if the exchange rate product passes the threshold of 1 and the return is higher than the transaction costs; Panel B "Best profit" assumes that the trade is realized at the maximum return by the corresponding tradable value; Panel C "Highest value" assumes that the trade is realized at the maximum tradable value by the corresponding return; and Panel D "Average" assumes the means of return and tradable value during an arbitrage opportunity.

[4] Triangular arbitrage involves exchange rates (with respect to the USD) and cross-rates (exchange rate of one currency with respect to another one but not the USD). For example, trading EUR and JPY with respect to the USD is more relevant than the EUR with the JPY directly.

An important concern is that the time to identify and execute the arbitrage opportunity exceeds the time period when it is profitable. When collecting the data, it takes an average of 4 milliseconds to identify a triangular arbitrage opportunity. However, executing the trades involves an additional latency. As mentioned earlier, the maximum return cannot be achieved over the entire duration of the arbitrage opportunity. Instead, the achievable return fluctuates during phases with high volatility. Therefore, for a practical assessment of these opportunities, the entire duration of the arbitrage opportunity cannot be considered. Rather, the relevant duration is the period during which the return exceeds the transaction costs. Within the 18 profitable opportunities for a trader, we identify a total of 34 phases with a return greater than the transaction costs. We assume that a trader uses the first phase, in which the return exceeds the transaction fees. This results in 18 phases, each with a specific duration and a certain achievable return. If a trader manages to trade quickly enough, they achieve a profit equal to the return minus the transaction costs. If they do not manage to trade quickly enough, we assume that they trade at the next available price. In this case, they realize a loss as the transaction costs exceed the return. The expected value for each possibility is then calculated as:

$$EV_i(T) = \begin{cases} G_i & \text{if } T \leq D_i \\ -L_i & \text{if } T > D_i, \end{cases} \tag{4.1}$$

where G_i is the possible gain, L_i is the possible loss, D_i is the duration of the arbitrage possibility i, and T the trading duration. For the total expected value $GEV(T)$ as a function of the trading duration, the following applies:

$$GEV(T) = \sum_{i=1}^{18} EV_i(T). \tag{4.2}$$

For a trading strategy to be profitable, the sum of gains must exceed the sum of losses. This means that the total expected value must be positive. Through an iteration process, the duration of T can be determined up to the point where the expected value remains positive. Consequently, a regular trader has to execute trades on average within a maximum of 146 milliseconds, based on the data. In order to reduce the risk of slippage, the strategy must be implemented that, if the arbitrage opportunity is recognized, trading should take place within these 146 milliseconds in order to avoid making a loss on average. This result emphasizes the location advantage in high-frequency trading. We interpret this finding as a potential filter criteria that allows us to distinguish between real arbitrage opportunities and those, which exist just in theory, as their slippage risk exceeds the potential profits.

5. Conclusion

By implementing a triangular arbitrage strategy under real circumstances at the Binance Exchange, we analyse 4,879 arbitrage opportunities in a highly granular, high-frequency data set covering a randomly chosen trading week. Considering practical frictions such as transaction costs, a limited order book, and latencies, we find that these arbitrage opportunities only offer marginal net profits. In relation to the necessary trading volumes, the possible trading profits seem negligible. Thus, our findings indicate that the market segment for Bitcoin, Litecoin, and the U.S. Dollar is free of arbitrage and suggest that the mere size of triangular arbitrage opportunities is a weak indicator of market efficiency, since most of these opportunities are not exploitable in a realistic setting. In addition, we propose a detailed filter criteria for the duration of arbitrage opportunities to be profitable in terms of slippage. This has practical implications for future research and traders to distinguish between real exploitable arbitrage opportunities and those which exist just in theory.

Possible limitations of our study are that we could only analyse the best bid- and ask-quotes. We did not have further information on the depth of the order book, implying potentially further trading opportunities. However, these trading opportunities can only be executed at less favourable prices. We leave this question for further research to determine whether these more unfavourable quotes lead to exploitable triangular arbitrages under realistic conditions.

Moreover, we examine a combination of a "major" cryptocurrency (Bitcoin) and a "smaller" cryptocurrency (Litecoin). By including Litecoin, we also align with the existing literature. However, it remains to be evaluated to what extent our results could be generalized to other adjustments, such as using two "major" (e.g., Bitcoin and Ethereum) or two "smaller" cryptocurrencies. Differences may arise due to the lower trading depth in Litecoin, potentially leading to fewer arbitrage opportunities. Conversely, larger order books and potentially smaller bid–ask spreads in "major" cryptocurrencies like Bitcoin and Ethereum could facilitate greater arbitrage volumes.

Furthermore, we randomly selected an examination period, that is free of extraordinary market events. An open question for future research is the existence and characteristics of triangular arbitrage in stress scenarios. It is likely that such opportunities would become more prevalent in highly volatile markets, potentially accompanied by turbulence, forced sales, or restricted capital access for arbitrageurs. Since the examination of these additional circumstances could contribute to further generalizability, we leave those questions for future research.

CRediT authorship contribution statement

Matthias Muck: Writing – review & editing, Supervision, Project administration, Conceptualization, Writing – original draft. **Thomas Schmidl:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization, Methodology, Project administration, Visualization. **Julian Wolf:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization, Project administration.

Declaration of Generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work the authors used ChatGPT, Google Gemini and DeepL in order to copy editing the original text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data availability

The authors do not have permission to share data.

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