Where's My Free Lunch?
Investigating the Bitcoin Arbitrage Premium

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Abstract. The purpose of this thesis is to investigate the history of the Bitcoin arbitrage premium to see if the possibility of 'risk-free' gains existed previously and whether or not the opportunity is still present today. It investigates market structure and price discrepancies in $147B of trading volume across 53 different exchanges between July 2010 and February 2017. This paper aggregates exchange trading into five minute buckets of transaction volume in order to see what exchange volume could have been successfully arbitraged within the context of two cases. The first requires trades to close within the same 5-minute interval and the second requires a 10-minute delay before the position is closed. It finds that the monthly average spreads of these cases have fallen below 3% in 2017 from nearly 10% in 2010. Once exchange fees are included, these spreads fall below 2% on average.

1 Introduction to Bitcoin

1.1 Structure Overview

Bitcoin is a decentralized peer-to-peer crypto-currency that was invented by an anonymous programmer or team of programmers identified only as Satoshi Nakamoto. Nakamoto introduced the concept of Bitcoin to a cryptography mailing list on October 31, 2008 in a white paper titled *Bitcoin: A Peer-to-Peer Electronic Cash System*. This paper stated that the primary purpose of Bitcoin is to act as an anonymous fiat currency that can be transferred via the blockchain with little to no fees. Critically, this process is conducted without reliance on a central banking system and is both permanent and verifiable. Instead of a middleman confirming the legitimacy of a transaction, the market participants themselves fulfill the role.

There are two major components to the whole Bitcoin system. Bitcoin, the currency, is created when an algorithm solves a cryptographic problem and transactions are then recorded in the blockchain. The Bitcoin blockchain is the ledger that contains the entire history of every Bitcoin transaction. Satoshi Nakamoto mined the 'genesis block,' the first block of the blockchain, on January 3, 2009, and created the Bitcoin Network along with it.

1.2 Mining

The Puzzle

Bitcoin is created when computers 'mine' the currency by solving a cryptographic puzzle. When a solution to the puzzle for a block is found, bitcoins are created as a reward. This encryption function takes in a single input to create one, unique output in the form of a hash. A hash is a value of fixed length usually in hexadecimal format. Specifically, miners use a twice applied SHA256 hash function to generate a 64 digit number. The block is mined when this number falls below the current 'target.' Typically knowing the desired output of a puzzle

helps the solver narrow down potential keys. However, SHA256 is a one-way hash function, so the knowledge of the proper output is not helpful beyond verifying that your answer is correct.

Imagine the input of this function as an empty text box. No matter how many characters are typed into this box, the output will be 64 digits. Miners add the previous block's hash, the hash of the current block's transaction, and one value they can change freely called the 'nonce.' When multiple transactions are contained within a block, Merkle trees (hash trees) are formed by passing paired transactions through the hash function until only one hash remains. An example is shown below in Figure 1. Algorithms guess millions of times a second until the correct hash is generated and the block is mined. The goal of the miner is to find the specific input that confirms the block before anyone else. The first miner to discover and report this input to the network 'wins' the block. This creates bitcoins and allows the miner to collect a small transaction fee. The size of the fee is dependent on the transaction volume included in the block and the quantity of bitcoins produced is based on a figure called the 'difficulty.'
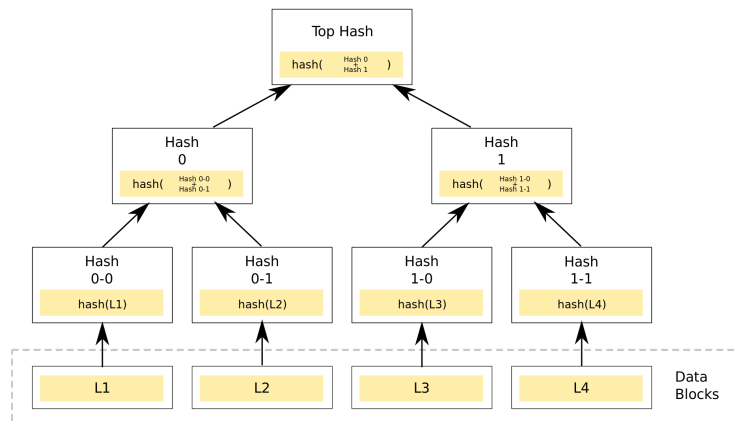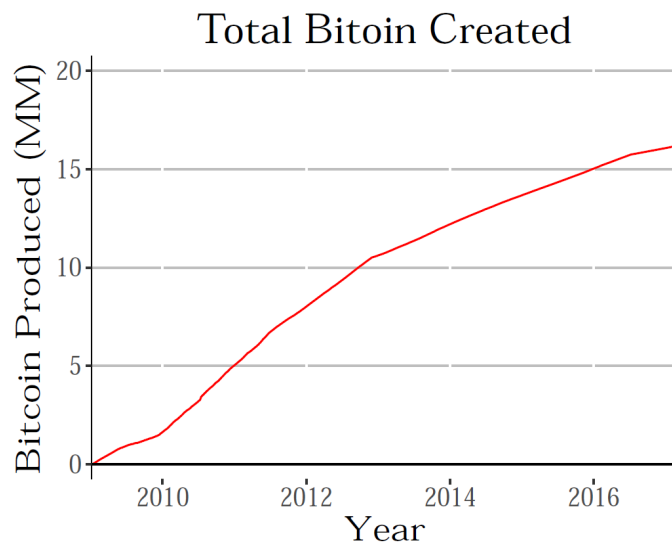

Fig. 1: Merkle Tree. Source: Göthberg, David[4]

Fig. 2: Bitcoin Produced. Source: Blockchain.info[2]

1.3 Difficulty

As intended by Satoshi Nakamoto, only 21 million bitcoins will ever be produced. Therefore, the network must manage how quickly bitcoins are being created. If miners are performing well, solving blocks quickly and generating a large quantity of bitcoins in a short period, the process needs to slow down. After every 2,016 bitcoins produced, the network takes a snapshot of mining performance to see if the difficulty needs to change. If it was mined in under 14 days, an average of under 10 minutes per bitcoin produced, the difficulty rises, the target of the cryptographic puzzle falls, and the mining process becomes harder. If the average is above 10 minutes per bitcoin, the difficulty falls, the target is increased, and mining is a bit easier. As the computation power of miners increase, so does the difficulty. Originally, these algorithms were run on a computer's central processing unit (CPU), but miners discovered that its graphics processing unit (GPU) was a better resource. GPUs typically contain a larger number of arithmetic logic units (ALUs) that make it significantly better suited for large amounts of mathematical labor. As a result of increased

competition, the difficulty has risen 195 times in its history compared to only 35 instances in which it has fallen.
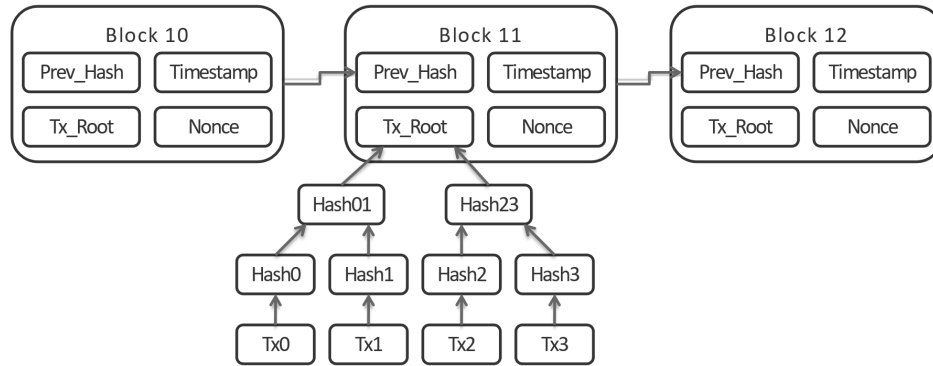

Fig. 3: Blockchain Example. Source: Wander, Matthäus[7]

1.4 Blockchain

Once a block has been mined, it is appended to the blockchain. The blockchain is the complete history of every transaction mined and transferred. These blocks consist of five primary parts: the block number in the chain, the hash of the previous block, the nonce, the transaction data, and the hash of the next block in the sequence. This public ledger is the verification component of Bitcoin and employs a concept called 'Proof-of-Work.' At its core concept, proof-of-work is intended to be strenuous or computationally difficult to create, but very quick and simple to verify. For a block to be appended to the chain, algorithms guess millions of times to find the proper nonce that produces a hash below the target. To verify this block, you simply have to test this one value. With a network as large as Bitcoin, you could theoretically create as many versions of the blockchain as you want. However, for every change made, you must recompute the proper nonces for every proceeding transaction in the hopes of fooling the network. Fortunately, this process is very time consuming and the likelihood of fooling the network is close to zero. Every resulting hash will be different than the original

chain and, as a result, will not be accepted by other participants. To combat discrepancies, the network has a consensus of participants that shows what chain everyone holds as valid. The majority determines the official blockchain.

In the early days of Bitcoin, to gain exposure to the currency, you had to either mine the bitcoins yourself or purchase them from an individual. As demand for market efficiency grew, exchanges began to surface.

1.5 Exchanges

In under a decade, there have been over fifty different exchanges that offered Bitcoin-to-US Dollar (BTC/USD) pairs trading with institutions ranging from titans like BTC-e with millions in daily dollar volume to small firms such as HitBTC with a volume of only a few hundred bitcoins traded a month. Because bitcoins themselves are perfectly uniform and precisely equivalent to each other, the price conversion to USD should be nearly identical across exchanges. However, price discrepancies across exchanges persisted for extended periods of time.

The vast majority of bitcoin exchanges only allowed trading on their exchange from their dedicated, exchange-specific account. There were no partnerships between exchanges to consolidate accounts and increase market efficiency so the entire market remained fragmented. In order to trade on several different exchanges, you must create an account with each exchange and deposit US dollars in that account. Any bitcoins purchased on that exchange are stored in a 'wallet' on that exchange, but can be transferred to other wallets via the blockchain. A wallet is the Bitcoin equivalent to a bank account. It holds bitcoins and gives an address from which you can send or receive bitcoins. Unsurprisingly, investment in firms to bridge the gaps between exchanges and to provide liquidity did not take long. Venture capital firms like F-Prime Capital and Andreessen Horowitz began investing in firms like TradeBlock that seek to provide access to multiple exchanges for institutional trading.

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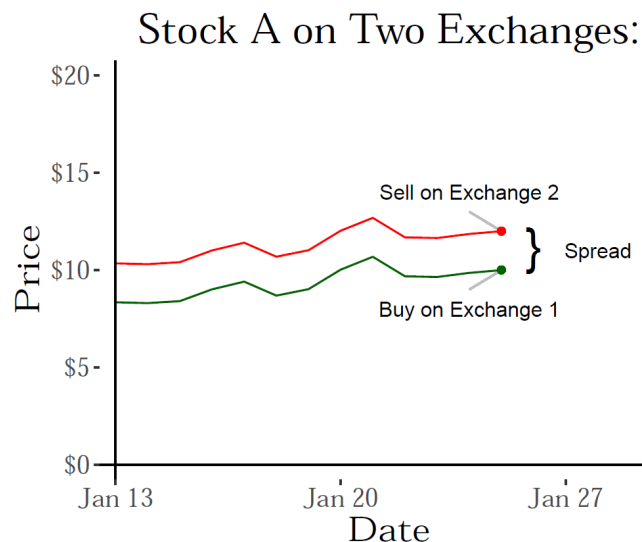
Fig. 4: Arbitrage Example

1.6 Arbitrage

According to the law of one price, a good must sell for the same price in all locations. If this is violated, it presents the opportunity to capture the difference. By definition, arbitrage is the practice of exploiting price differences across two or more markets to profit on the spread between the prices. Suppose I notice that Stock A is traded on Exchange 1 at $10 per share and on Exchange 2 at $12 per share. I can purchase Stock A on Exchange 1 and then instantaneously sell it on Exchange 2 at a 20% profit. The goal of arbitrage is to capture a profit with no risk.

When I initially examined historical prices, I found price discrepancies across multiple exchanges over the years that hinted at the potential opportunity for arbitrage. However, prices alone do not necessarily mean that the trades needed to capture the gains actually existed. In order to determine whether or not the opportunity for traders to capitalize on this free money, bitcoins had to have been traded at these prices simultaneously for successful arbitrage. Without the necessary volume, these discrepancies cannot be arbitraged.

2   Data

In an ideal world, I would have had access to the full order book of each exchange in the history of Bitcoin. From this information, I would be able to construct the true market of limit orders at which bitcoins could have been purchased or sold and show the erosion of liquidity as you purchase or sell on this market. However, this data is not available for the vast majority of exchanges. The next best option was to accumulate transactions from each exchange and analyze transactions that occurred simultaneously. I pulled data using application program interfaces (APIs) offered by exchanges to scrape historical transaction data. Most of these were call RESTful APIs that use URLs to communicate parameters like product identifiers such as BTC/USD and transaction ranges. When you attempt to reach this URL, you are issuing a request to their servers for data. A sample URL for GDAX is:

"https://api.gdax.com/products/BTC-USD/trades?after=14159882"

This request returns batches of data in a format called JavaScript Object Notation (JSON) that can be collected to form the exchange's transaction history. Unfortunately, this only works for the exchanges still operating.

[{"time":"2017-04-05T05:48:58.182Z","trade_id":14159881,"price":"1138.90000000","size":"0.23498090","side":"sell"}]

Fig. 5: JSON Data Example

While many exchanges have come and gone over the past decade, their price data remains available thanks to Bitcoincharts.com. The website integrates each exchange's Market API and requires them to provide their completed transactions and a current market depth. Over time, they have stored each exchange's historical data and made the repository publicly available. While not all exchanges formed a partnership with Bitcoin Charts, nearly 30 million separate transactions were recorded between the earliest trades in April 2009 and February 2017.

Notable absences include transactions for GDAX (formerly Coinbase) prior to December 2014 despite operating since June 2012. These trades were also missing from their API so I assume the exchange upgraded their API at that time and lost the data. OKCoin's BTC/USD pairing is missing as well and is unattainable due to their 600 most recent trades look-back restriction. Allcoin, Lake, Livecoin, BTC-X, and SpaceBTC impose similar restrictions ranging from the most recent 1,000 trades to no access entirely. Bitfinex also removed access to past transaction data in 2017.
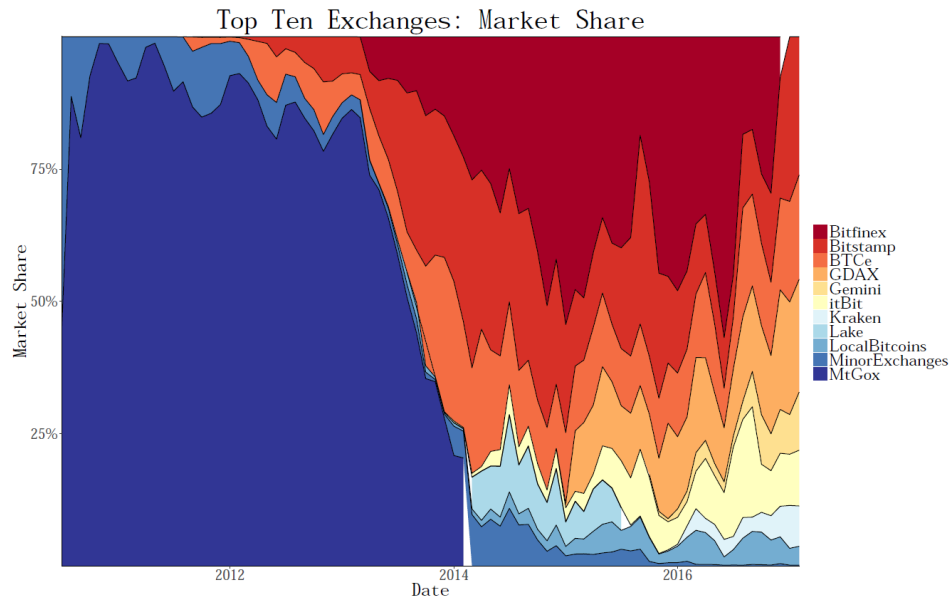
Fig. 6: Top 10 Exchanges by Dollar Volume: Market Share

The plot above shows the top ten exchanges by dollar volume and their market share across time from the data collected. Mt. Gox was by far and away the most dominant exchange, at times holding over 90% of the market share. The small white triangles mark the disappearance of an exchange's data from the graph. In February 2014, Mt. Gox announced 850,000 bitcoins were missing and likely stolen (over $450 million value). As a result, the exchange suspended

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trading and began liquidation proceedings in April 2014. The fall of Mt. Gox rattled the markets due to its reputation as the most trusted exchange at the center of Bitcoin pairs trading. The market has no longer been dominated by a single exchange as BTC-e, Bitstamp, Bitfinex, and GDAX have surged in volume. While there are typically between ten and twelve exchanges operating each month, the top five encompass most of the market share with fluctuations month-to-month. The missing data from the disappearance of Lake and Bitstamp are the result of restrictions imposed by their APIs.

3 Process

Fig. 7: BTC/USD Monthly Dollar Volume

All trade data was cleaned into the four uniform columns: a timestamp to denote the execution time, the price, the amount of bitcoin traded, and the exchange identifier.

In order to analyze these trades, I partitioned the data into monthly transaction repositories each containing all available trades across every exchange.

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This resulting dataset is the entire available market of BTC/USD paired transactions for the month.

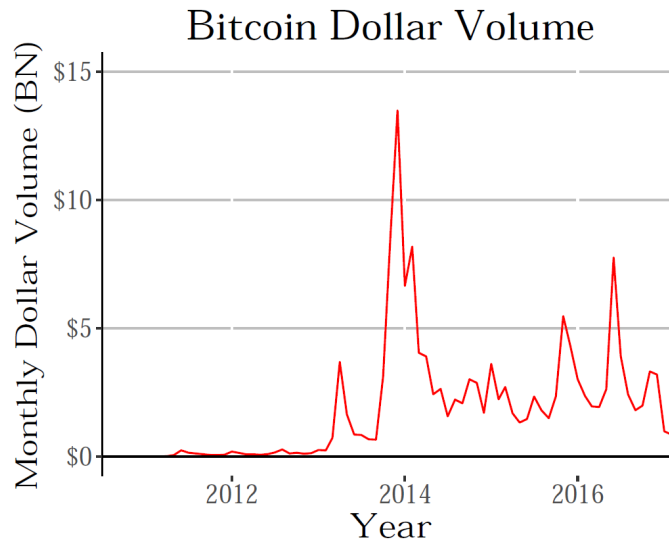| Trade Time	Price	BTC	Exchange
9/13/2011 13:53	$5.80	1	Bitstamp
9/13/2011 13:53	$5.83	3	Bitstamp
9/13/2011 13:53	$5.90	1	BTC-e
9/13/2011 13:53	$6.00	20	BTC-e

Trade Time	Price	BTC	Exchange
9/13/2011 13:55	$5.82	4	Bitstamp
9/13/2011 13:55	$6.00	21	BTC-e

Fig. 8: Trade Bucketing

Due to a lack of access to large scale computational resources, I bucketed the activity of each exchange into discrete five minute increments. Each record denotes the volume traded on that specific exchange within the last five minutes and a volume weighted average price. The process of selecting successful arbitrage opportunity is as follows:

For each month, I maintained a table of available trades that holds the entire month's activity sorted by price so that the most desirable long candidates are evaluated first. I assigned a unique identifier to each activity bucket, a position status, a trade status, and available volume. The position status denotes whether or not I had previously bought/sold (b or s) bitcoins from this bucket. I did this to avoid taking part in both sides of the transaction. The trade status referred to whether a block had been previously traded (0), partially traded (1), fully traded (2), or is without available arbitrage candidates (9). Available volume simply denoted the amount of bitcoin available to be traded and it was adjusted whenever volume was drawn from that block.

From my list of available trades, I calculated a table of buy candidates after each transaction that maintained all blocks of activity. These had not already been fully traded (2), previously included in the close of a different trade block (s), and was not yet been determined to be without arbitrage candidates (9). I drew the long component of the arbitrage trade from this list of candidates. To find a trade block to close out the long, I formed a list of sell candidates in a

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similar fashion. To be included, the block must be from the same timescale, must not have previously been traded as a long position (b), and must have available volume. The highest price was chosen from this list and I subtracted the volume used. If the long had more bitcoin traded than the sell, the long was given the partially traded designation (1) with the amount sold removed from its available volume and the sell was marked as fully traded (2) and amount available was set to zero. In this case, the long block was drawn again as a potential candidate to sell the remaining volume to next highest trade block in sell candidates.

Every block of activity was considered as a candidate for arbitrage. For each record of the dataset, I pulled all trade blocks from other exchanges within the same five minute window. The goal was to be able to purchase and sell the bitcoins back into USD as quickly as possible to realize the difference.

3.1   Margin

For bitcoins to be properly arbitraged, the trader needs to be able to instantly capture the spread with equal long and short positions instantaneously. However, implementing this in the Bitcoin marketplace requires margin as you are selling bitcoins on an exchange without bitcoins present in that account's inventory. While margin has existed on an exchange-to-exchange basis, its structure is not the same as in the equity markets. Margin is not provided by the institution, but rather by other market participants. As a result, interest rates on margin are dynamic and vary on market conditions. In an attempt to simulate a long only case without margin, I created a second case in which I instituted a trade delay of 10 minutes, the average time it takes to transfer bitcoins from one exchange wallet to another. This allows the program to initiate a trade at time t and the trade must be closed between $t + 10$ minutes and $t + 15$ minutes. I will refer to this as the Case 2 later on.

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3.2 Settlement

Cash settlement restrictions require time for capital to be transferred to the institution prior to trading as a way for the exchange to ensure you have the capital to transact. Timeframes vary, but the standard waiting period for financial institutions is three days. This is quite critical when examining a market such as bitcoin where multiple accounts are required for each exchange each with their own cash inventories. As a result, the time it takes to reinvest capital is increased and the efficiency of the strategy falls.

3.3 Case 1: Same-Period Transactions

The theoretical arbitrageur of this case is forced to enter and close a trade within the same five-minute time interval. Returns displayed in the figure below are calculated as the average return on capital over continuous 1 [Red], 2 [Blue], and 3 [Black] day windows across the entire month and multiplied by 30, 15, and 10 respectively. As cash settlement directly impacts the turnover of your account, it is crucial to see how increased settlement windows harm returns. The differences between the red (1 day settlement) and the black (3 day settlement) are immense. Over time, monthly returns have fallen except for a period of significant volatility during the collapse of Mt. Gox. Despite incredible spreads during the beginning of trading, there was only a small amount of trading on other exchanges which resulted in a relatively small amount of profits. The dollar value of proceeds from these transactions are shown in Figure 15.

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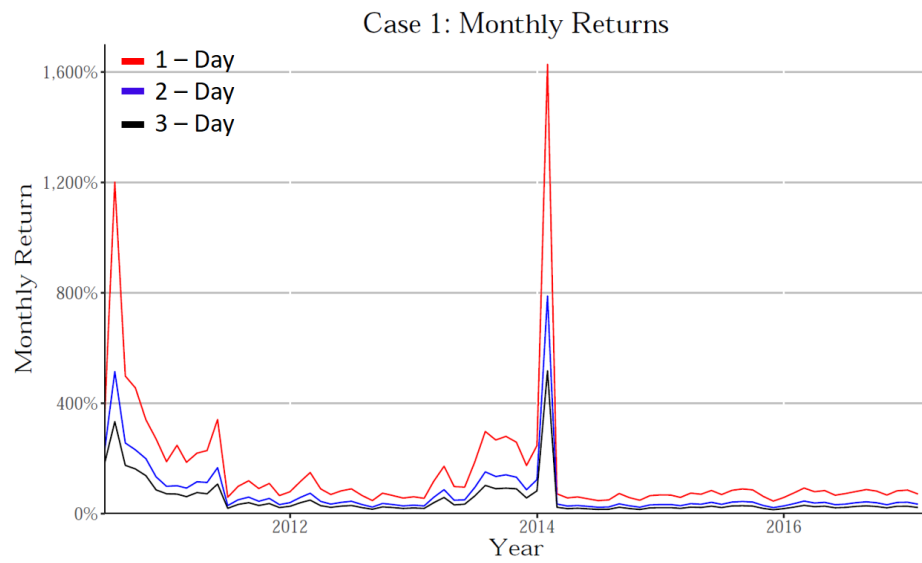
Fig. 9: Case 1: Monthly Returns (Red: Average 1-Day, Blue: 2-Day, Black: 3-Day Return Windows)
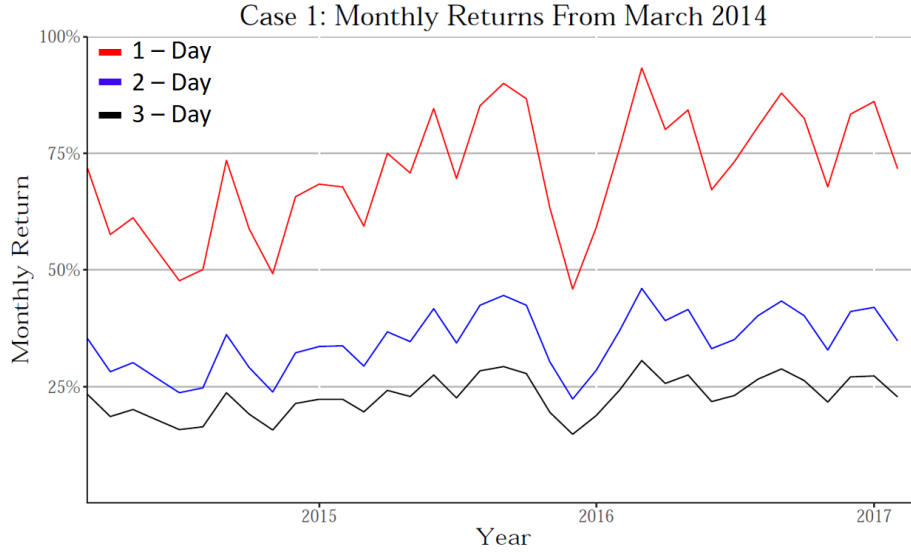
Fig. 10: Case 1: Monthly Returns After Mt. Gox (Red: Average 1-Day, Blue: 2-Day, Black: 3-Day Return Windows)

3.4 Case 2: Delayed Case

In an effort to make the statistics more robust, I imposed a trade delay on any assumed positions that required a designated waiting period to account for transactional delay. This was an effort to simulate the time it takes for bitcoins to be transferred between exchange accounts. For a long-initiated trade to close, there must be sufficient dollar volume on the over-priced exchange after a 10 minute delay and I allowed for a five minute close window similar to the previous case. The purpose of this case was to be a more realistic expectation of what a trader could have acted on. The ten minute delay to close the trade was instituted as a simulation of the time to transfer bitcoin between wallets on separate exchanges. Similar to Case 1, monthly spreads have fallen over time as the exchange market has become more competitive. As in the previous case, monthly returns are calculated as the average return on capital over 1 (red), 2 (blue), and 3 (black) day settlement periods across the entire month multiplied

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by 30, 15, and 10 respectively. In times of large price volatility, this case greatly outperformed the first. However, this is likely due to large price swings occurring over the delay period and the ability to correctly choose the winning direction. Excluding the return spikes at the beginning of the trading period and at the time of the Mt. Gox implosion, results are significantly closer to the results of the first.
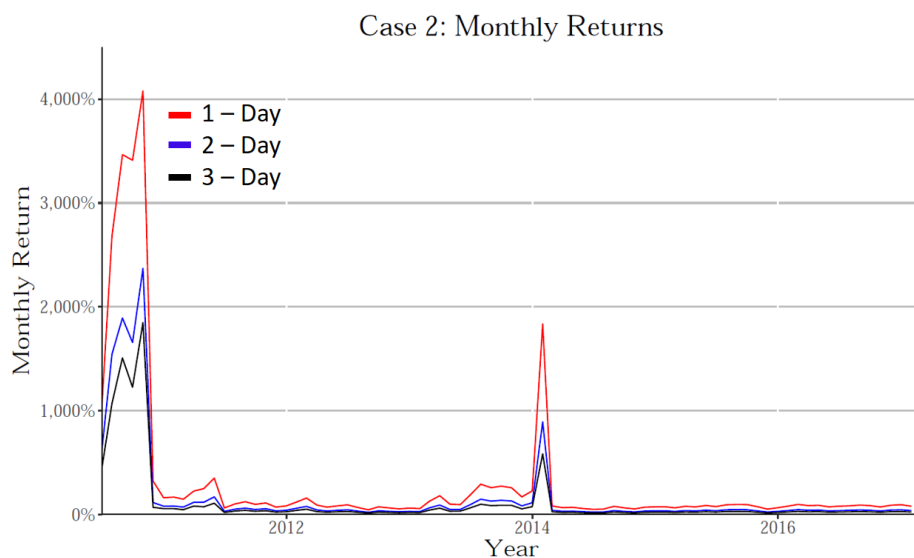
Fig. 11: Case 2: Monthly Returns (Red: Average 1-Day, Blue: 2-Day, Black: 3-Day Return Windows)
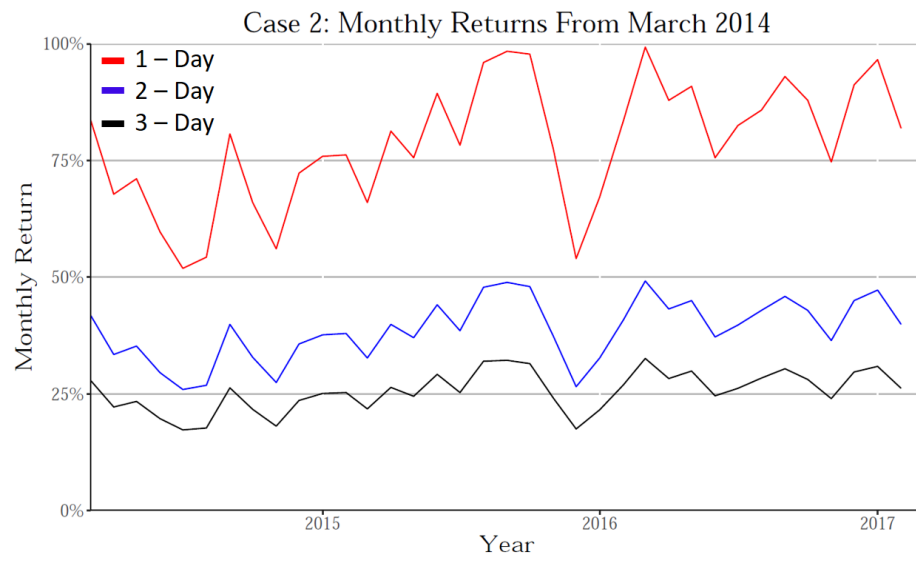
Fig. 12: Case 2: Monthly Returns After Mt. Gox (Red: Average 1-Day, Blue: 2-Day, Black: 3-Day Return Windows)
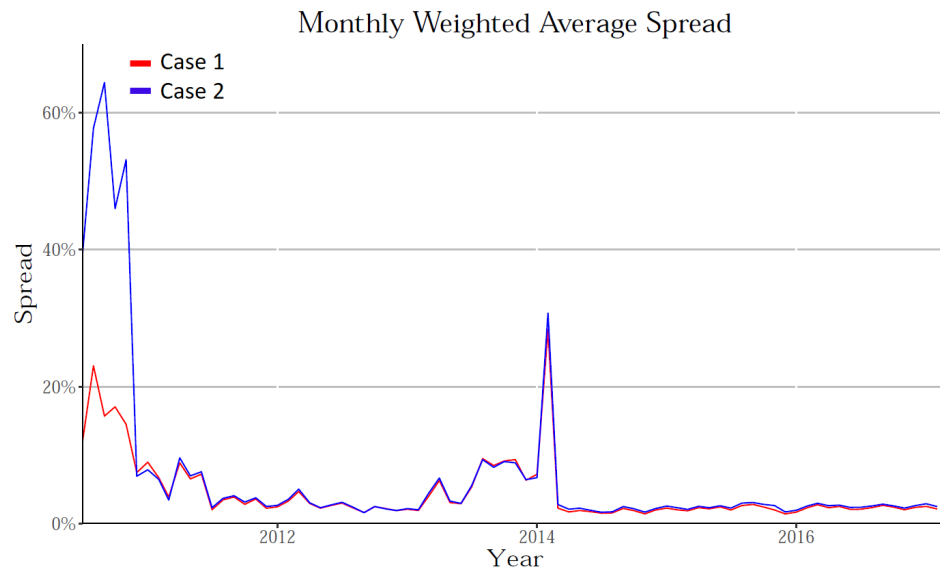
Fig. 13: Monthly Weight Average Spreads (Red: Case 1, Blue: Case 2)
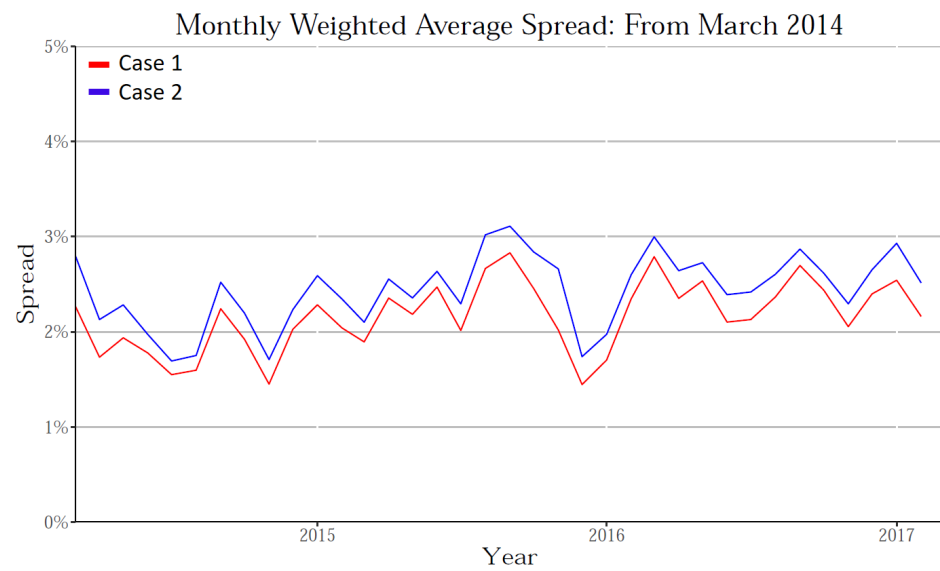
Fig. 14: Monthly Weight Average Spreads After Mt. Gox (Red: Case 1, Blue: Case 2)

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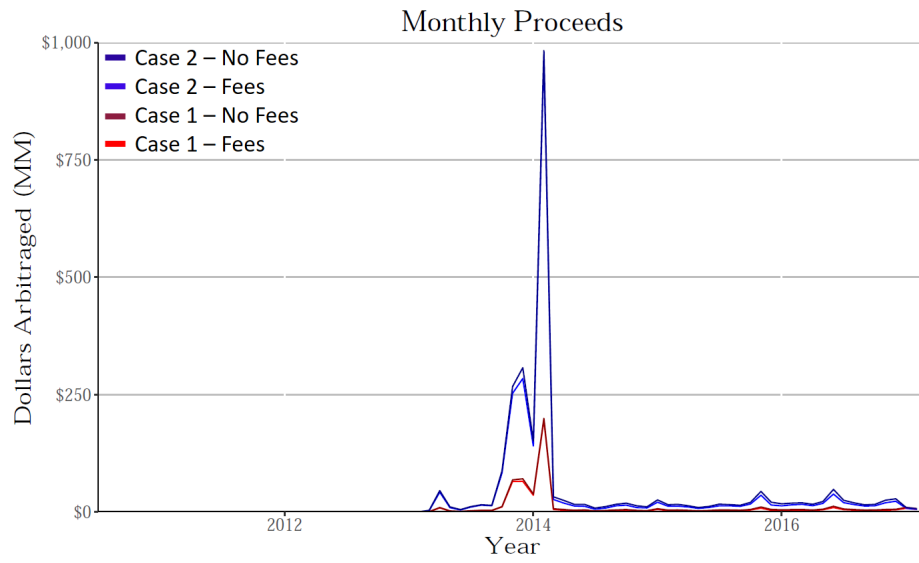
Fig. 15: Monthly Proceeds (Red: Case 1, Blue: Case 2)
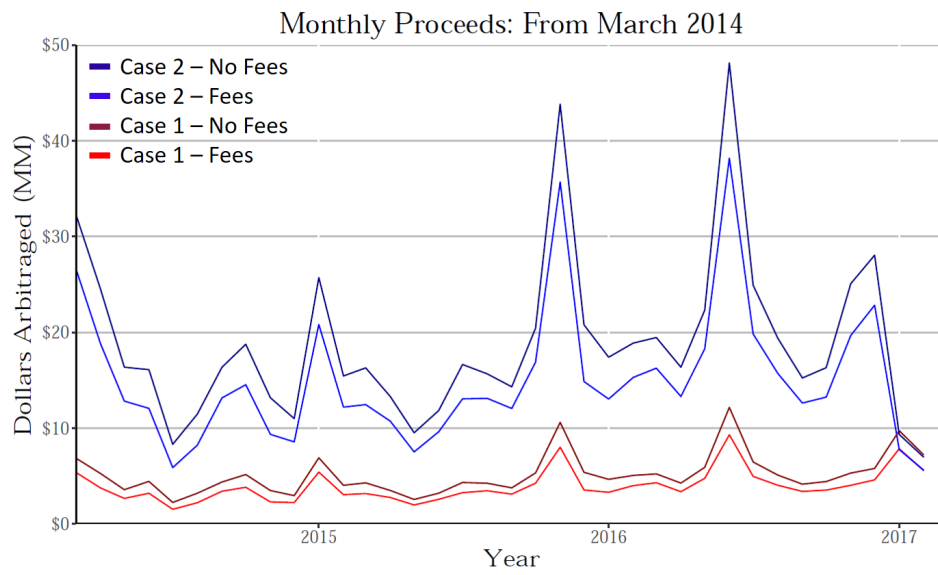
Fig. 16: Monthly Proceeds After Mt. Gox (Red: Case 1, Blue: Case 2)

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3.5 Conclusion

Both cases suffered from look ahead bias in that arbitraged positions were perfectly matched to available liquidity in accompanying exchanges at the best prices. Properly avoiding over-purchasing or over-selling bitcoins is very difficult without a full order book. A major drawback is the lack of cost to trade. Fees vary from exchange to exchange with many only charging for taking liquidity from the market. This means that you are only charged a fee if you 'hit,' or transact on an open order in the market and are known as 'taker' fees. Considering the nature of arbitrage, the arbitrageur is likely the taker and will incur the fee. I incorporated this into the proceeds graphs with the lighter line representing the figure with fees and the darker without. As with the previous example, I display the numbers after the fall of Mt. Gox to show the impact of change in market structure. It's also worth noting that despite a near 20% average spread in prices at the beginning of trading, there was virtually no volume and, as a result, proceeds were non-existent. However, if you had perfectly arbitraged the market, taking part in each of the transactions in Case 1, you would have netted $596MM or $536MM after taker fees.

I have found that while it appears the opportunity to arbitrage bitcoin prices across exchanges has been possible, the monthly returns are quite volatile. As exchanges continue to even out market share and trading volume rises, the price discrepancies fade and the markets become more efficient. Average spreads in prices were near 10% in 2013, but have fallen to under 3% in 2017. Once you factor in the costs to trade (margin, taker, and transfer fees), these small price discrepancies fall below 2% and lose their initial appeal.

In addition to these low spreads, this strategy requires a lot of legwork. The ambitious arbitrageur would have to set up accounts on each exchange, raise capital to be maintained in each account, and create an algorithm to trade with each exchange's API. The capital would sit until favorable trades appear and the return on capital would not be nearly as efficient as the returns calculated

in the cases above. The exact amount of cash was always used which is not a realistic expectation for live trading. After taking all of this into account, I came to the conclusion that you could have potentially arbitraged BTC/USD pairings successfully in previous years, but the maturity of the marketplace has eliminated a large amount of the discrepancies.

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4 Appendix

4.1 Full Exchange List

Exchange	Start Date	End Date	Trans.(k)	Avg. Monthly Trans.(k)	Dollar Volume(k)	Monthly Dollar Volume(k)	Volume(k)	Monthly Volume(k)	Avg. Trade Size	Avg. Trade Value
Bitfinex	03/31/2013	12/08/2016	10,117.25	224.83	$ 10,118,549.88	$ 224,856.66	25,647.21	569.94	2.53	$ 1,000.13
Bitstamp	09/13/2011	02/28/2017	10,690.84	164.47	$ 7,358,348.40	$ 113,205.36	18,693.78	287.60	1.75	$ 688.29
BTC-e	08/14/2011	02/28/2017	29,598.99	448.47	$ 5,528,481.45	$ 83,764.87	14,222.56	215.49	0.48	$ 186.78
Mt. Gox	07/17/2010	02/25/2014	8,295.81	192.93	$ 3,657,889.26	$ 85,067.19	55,575.35	1292.45	6.70	$ 440.93
GDAX	12/01/2014	02/28/2017	13,289.24	511.12	$ 2,516,415.09	$ 96,785.2	5,615.10	215.97	0.42	$ 189.36
itBit	08/25/2013	02/28/2017	902.76	21.49	$ 1,780,524.17	$ 42,393.43	3,882.46	92.44	4.30	$ 1,972.32
LocalBitcoins	03/11/2013	02/28/2017	2,016.94	42.91	$ 831,078.66	$ 17,682.52	1,865.28	39.69	0.92	$ 412.05
Lake	03/01/2014	07/19/2015	3,581.33	223.83	$ 779,595.99	$ 48,724.75	2,110.32	131.90	0.59	$ 217.68
Gemini	10/08/2015	02/28/2017	456.13	28.51	$ 514,260.94	$ 32,141.31	768.06	48.00	1.68	$ 1,127.45
Kraken	01/07/2014	02/28/2017	698.49	18.88	$ 421,100.69	$ 11,381.1	617.45	16.69	0.88	$ 602.87
ICBIT	03/18/2012	05/23/2014	7.92	0.30	$ 251,299.14	$ 9,665.35	400.09	15.39	50.54	$ 31,745.72
HitBTC	12/27/2013	02/28/2017	1,017.86	26.79	$ 181,856.34	$ 4,785.69	400.28	10.53	0.39	$ 178.66
ANX	08/20/2013	10/10/2015	640.83	24.65	$ 162,411.7	$ 6,246.6	460.12	17.70	0.72	$ 253.44
1Coin	03/09/2014	04/04/2015	764.73	58.83	$ 98,900.51	$ 7,607.73	231.76	17.83	0.30	$ 129.33
CampBX	07/05/2011	10/19/2016	290.50	4.61	$ 56,275.22	$ 893.26	666.80	10.58	2.30	$ 193.72
Bitfloor	05/23/2012	04/17/2013	200.21	18.20	$ 21,480.36	$ 1,952.76	417.03	37.91	2.08	$ 107.29
CEX-IO	07/18/2014	09/29/2015	376.02	26.86	$ 16,707.88	$ 1,193.42	56.71	4.05	0.15	$ 44.43

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Exchange	Start Date	End Date	Trans.(k)	Avg. Monthly Trans.(k)	Dollar Volume(k)	Monthly Dollar Volume(k)	Volume(k)	Monthly Volume(k)	Avg. Trade Size	Avg. Trade Value
RockTradingCo	11/12/2011	02/28/2017	81.87	1.30	$ 11,544.36	$ 183.24	26.06	0.41	0.32	$ 141.0
CoinTrader	12/21/2013	01/31/2016	25.84	1.03	$ 11,074.74	$ 442.99	28.87	1.15	1.12	$ 428.66
TradeHill	06/08/2011	02/13/2012	159.16	19.89	$ 6,690.68	$ 836.33	1184.92	148.11	7.44	$ 42.04
BitBay	05/16/2014	02/28/2017	81.16	2.46	$ 4,466.22	$ 135.34	10.04	0.30	0.12	$ 55.03
BitKonan	07/02/2013	02/28/2017	107.93	2.51	$ 3,889.13	$ 90.44	12.00	0.28	0.11	$ 36.03
EXMO	04/14/2016	12/14/2016	33.06	4.13	$ 3,742.78	$ 467.85	5.96	0.75	0.18	$ 113.21
Ripple	02/10/2013	11/04/2014	51.70	0.29	$ 3,159.31	$ 17.75	7.36	0.04	0.14	$ 61.11
Crytr	05/27/2013	07/16/2014	19.39	1.38	$ 1,749.95	$ 125.0	5.48	0.39	0.28	$ 90.26
Bitcurex	04/20/2016	10/14/2016	3.28	0.55	$ 1,435.36	$ 239.23	2.58	0.43	0.79	$ 437.48
CryptoX	11/10/2011	11/19/2012	19.95	1.66	$ 1,369.1	$ 114.09	222.17	18.51	11.14	$ 68.63
BTCex	02/04/2011	07/22/2012	10.28	0.60	$ 1,275.38	$ 75.02	261.26	15.37	25.41	$ 124.06
Justcoin	10/25/2013	10/29/2014	20.06	1.67	$ 1,237.47	$ 103.12	2.08	0.17	0.10	$ 61.7
Vircurex	12/25/2011	02/22/2017	74.77	1.21	$ 989.86	$ 15.97	8.49	0.14	0.11	$ 13.24
Intersango	07/21/2011	10/20/2012	23.28	1.55	$ 950.7	$ 63.38	164.13	10.94	7.05	$ 40.84
BTC24	05/14/2012	04/13/2013	5.66	0.51	$ 616.53	$ 56.05	15.95	1.45	2.82	$ 108.91
Bitcoin7	06/14/2011	10/05/2011	5.49	1.37	$ 605.75	$ 151.44	53.01	13.25	9.65	$ 110.3
ExchangeBitcoins	06/15/2011	10/16/2011	31.82	7.96	$ 485.13	$ 121.28	67.80	16.95	2.13	$ 15.24
bitme	07/08/2012	03/28/2013	3.74	0.47	$ 416.62	$ 52.08	23.98	3.00	6.42	$ 111.52
FBTC	06/25/2013	10/20/2013	1.05	0.26	$ 392.3	$ 98.08	3.99	1.00	3.80	$ 373.98
BitBox	05/07/2013	09/25/2013	1.12	0.28	$ 305.63	$ 76.41	2.75	0.69	2.45	$ 271.67
BitcoinMarketPP	04/25/2010	06/05/2011	2.89	0.21	$ 233.07	$ 16.65	745.92	53.28	258.19	$ 80.68
bitmarket	05/18/2011	12/20/2012	2.87	0.15	$ 199.54	$ 10.5	18.06	0.95	6.30	$ 69.6

Exchange	Start Date	End Date	Trans.(k)	Avg. Monthly Trans.(k)	Dollar Volume(k)	Monthly Dollar Volume(k)	Volume(k)	Monthly Volume(k)	Avg. Trade Size	Avg. Trade Value
TradeHillLR	06/10/2011	02/13/2012	2.34	0.29	$ 105.99	$ 13.25	14.07	1.76	6.02	$ 45.35
Ruxum	06/30/2011	09/12/2012	2.04	0.14	$ 89.93	$ 6.0	9.56	0.64	4.69	$ 44.09
BitcoinMarketLR	06/04/2010	08/03/2011	0.37	0.03	$ 34.93	$ 2.5	356.95	25.50	956.97	$ 93.66
BTCTree	05/02/2012	07/11/2012	0.58	0.29	$ 31.17	$ 15.59	5.23	2.62	9.05	$ 53.93
BitcoinMarketLR	12/31/2010	08/19/2011	0.44	0.05	$ 25.31	$ 3.16	18.75	2.34	42.92	$ 57.92
Bitcoin2Cash	04/01/2011	01/21/2012	0.37	0.04	$ 15.79	$ 1.75	5.18	0.58	14.15	$ 43.13
LibertyBit	01/29/2013	06/08/2013	0.08	0.02	$ 15.39	$ 3.08	0.35	0.07	4.18	$ 185.39
BitcoinMarketBM	02/04/2011	08/06/2011	0.23	0.04	$ 13.12	$ 2.19	1.41	0.24	6.13	$ 57.05
BitcoinMarketMB	05/21/2011	08/19/2011	0.14	0.05	$ 12.11	$ 4.04	0.63	0.21	4.64	$ 89.04
Global	09/26/2011	10/07/2011	0.14	0.14	$ 5.21	$ 5.21	1.03	1.03	7.59	$ 38.28
IMCEX	07/17/2011	10/14/2012	0.78	0.05	$ 4.39	$ 0.29	0.91	0.06	1.16	$ 5.63
WeExchange	06/01/2012	11/26/2013	0.16	0.01	$ 3.81	$ 0.22	0.57	0.03	3.49	$ 23.38
Bitalo	03/03/2014	08/05/2014	0.01	0.00	$ 2.0	$ 0.4	0.00	0.00	0.34	$ 285.99
IBWT	09/28/2014	11/04/2015	0.022	0.00	$ 1.42	$ 0.10	0.01	0.00	0.24	$ 64.52

4.2 Case 1 Monthly Statistics

Date	Weighted Average Spread	Amount Bought(k)	Amount Sold(k)	Total Volume(k)	BTC Volume(k)	Proceeds(k)	Trades
2010-7-01	11.89%	$0.05	$0.06	$0.12	1.11	$0.01	15
2010-8-01	23.07%	$0.29	$0.38	$0.67	5.68	$0.09	27
2010-9-01	15.73%	$0.17	$0.20	$0.37	3.17	$0.03	13
2010-10-01	17.07%	$2.99	$3.60	$6.59	35.24	$0.61	50
2010-11-01	14.53%	$1.81	$2.12	$3.92	7.27	$0.31	22
2010-12-01	7.48%	$0.12	$0.13	$0.25	0.53	$0.01	4
2011-1-01	8.99%	$1.02	$1.12	$2.15	2.76	$0.10	24
2011-2-01	6.73%	$8.34	$8.94	$17.28	9.15	$0.60	94
2011-3-01	3.91%	$3.57	$3.72	$7.29	3.96	$0.15	50
2011-4-01	8.90%	$13.91	$15.27	$29.18	9.46	$1.36	267
2011-5-01	6.55%	$58.31	$62.40	$120.70	8.73	$4.09	855
2011-6-01	7.25%	$756.72	$815.85	$1,572.57	45.10	$59.13	4,598
2011-7-01	2.06%	$1,235.18	$1,261.21	$2,496.39	88.88	$26.03	7,111
2011-8-01	3.49%	$858.27	$889.34	$1,747.60	87.24	$31.07	7,532
2011-9-01	3.91%	$923.36	$960.94	$1,884.30	167.43	$37.58	7,272
2011-10-01	2.85%	$707.55	$728.29	$1,435.84	205.62	$20.73	6,616
2011-11-01	3.62%	$600.58	$623.12	$1,223.70	234.20	$22.54	6,094
2011-12-01	2.28%	$698.96	$715.27	$1,414.24	207.32	$16.31	5,623
2012-1-01	2.48%	$1,264.22	$1,296.33	$2,560.55	208.81	$32.11	7,004
2012-2-01	3.33%	$824.09	$852.43	$1,676.52	162.00	$28.35	6,100
2012-3-01	4.71%	$629.28	$660.41	$1,289.69	134.23	$31.13	4,573

Continued on next page

Date	Weighted Average Spread	Amount Bought(k)	Amount Sold(k)	Total Volume(k)	BTC Volume(k)	Proceeds(k)	Trades
2012-4-01	2.97%	$820.86	$845.95	$1,666.81	169.54	$25.10	4,597
2012-5-01	2.28%	$827.92	$847.23	$1,675.15	166.93	$19.31	4,681
2012-6-01	2.69%	$1,301.82	$1,337.77	$2,639.58	220.70	$35.95	7,054
2012-7-01	3.02%	$1,637.25	$1,688.31	$3,325.56	213.89	$51.06	8,455
2012-8-01	2.32%	$2,915.02	$2,984.18	$5,899.20	269.18	$69.17	10,222
2012-9-01	1.64%	$1,463.52	$1,487.94	$2,951.46	128.37	$24.43	6,791
2012-10-01	2.50%	$1,967.33	$2,017.70	$3,985.03	170.17	$50.37	7,985
2012-11-01	2.23%	$1,689.37	$1,727.82	$3,417.19	150.37	$38.45	6,937
2012-12-01	1.93%	$1,809.59	$1,845.13	$3,654.71	138.06	$35.54	6,293
2013-1-01	2.12%	$3,312.58	$3,384.48	$6,697.07	207.62	$71.90	7,840
2013-2-01	1.95%	$5,062.86	$5,163.30	$10,226.16	197.27	$100.45	9,132
2013-3-01	3.96%	$17,237.38	$17,948.03	$35,185.41	302.66	$710.65	14,057
2013-4-01	6.32%	$140,920.64	$150,425.01	$29,1345.64	1,237.91	$9,504.37	20,243
2013-5-01	3.10%	$70,530.48	$72,787.60	$143,318.08	636.07	$225,7.13	18,224
2013-6-01	2.93%	$38,581.76	$39,745.29	$78,327.05	369.24	$1,163.53	16,901
2013-7-01	5.36%	$45,030.41	$47,581.47	$92,611.88	546.92	$2,551.06	19,077
2013-8-01	9.52%	$32,362.64	$35,767.40	$68,130.03	306.79	$3,404.76	18,475
2013-9-01	8.50%	$36,674.89	$40,082.25	$76,757.14	297.67	$3,407.37	17,959
2013-10-01	9.18%	$112,676.81	$124,063.23	$236,740.05	733.73	$11,386.42	19,071
2013-11-01	9.37%	$661,782.02	$730,192.39	$1,391,974.41	1,303.78	$68,410.37	21,124
2013-12-01	6.37%	$1,038,827.59	$1,109,521.48	$2,148,349.07	1,403.73	$70,693.88	24,196
2014-1-01	7.22%	$489,748.35	$527,866.33	$1,017,614.67	595.64	$38,117.98	26,715
2014-2-01	28.33%	$504,315.09	$703,702.66	$1,208,017.75	1,113.56	$199,387.58	25,053

Date	Weighted Average Spread	Amount Bought(k)	Amount Sold(k)	Total Volume(k)	BTC Volume(k)	Proceeds(k)	Trades
2014-3-01	2.28%	$294,395.84	$301,263.34	$595,659.18	513.56	$6,867.50	26,902
2014-4-01	1.73%	$298,050.32	$303,308.57	$601,358.88	660.95	$5,258.25	26,646
2014-5-01	1.94%	$180,746.44	$184,316.65	$365,063.09	360.58	$3,570.21	29,748
2014-6-01	1.78%	$244,904.47	$249,336.99	$494,241.46	400.68	$4,432.52	31,154
2014-7-01	1.55%	$142,036.41	$144,272.77	$286,309.18	232.00	$2,236.37	32,050
2014-8-01	1.60%	$197,359.50	$200,561.84	$397,921.34	382.18	$3,202.34	36,632
2014-9-01	2.24%	$190,473.33	$194,842.24	$385,315.57	444.96	$4,368.91	35,781
2014-10-01	1.92%	$262,796.91	$267,946.48	$530,743.39	745.42	$5,149.57	40,372
2014-11-01	1.45%	$236,358.27	$239,838.17	$476,196.45	629.88	$3,479.90	34,516
2014-12-01	2.03%	$142,463.70	$145,410.33	$287,874.03	421.48	$2,946.63	38,201
2015-1-01	2.28%	$295,159.00	$302,056.08	$597,215.08	1,258.95	$6,897.07	42,228
2015-2-01	2.04%	$193,263.46	$197,290.61	$390,554.07	827.80	$4,027.15	38,122
2015-3-01	1.89%	$221,817.60	$226,100.58	$447,918.18	829.48	$4,282.98	41,646
2015-4-01	2.35%	$144,616.81	$148,104.21	$292,721.03	622.77	$3,487.40	35,115
2015-5-01	2.18%	$114,222.51	$116,772.49	$230,995.00	482.32	$2,549.98	35,925
2015-6-01	2.47%	$126,443.31	$129,646.22	$256,089.53	530.58	$3,202.91	34,671
2015-7-01	2.01%	$210,112.25	$214,432.18	$424,544.43	754.08	$4,319.93	36,957
2015-8-01	2.67%	$154,905.08	$159,147.09	$314,052.16	642.08	$4,242.01	34,817
2015-9-01	2.83%	$129,088.28	$132,848.06	$261,936.34	554.40	$3,759.78	34,297
2015-10-01	2.45%	$211,390.51	$216,709.70	$428,100.21	772.65	$5,319.19	30,047
2015-11-01	2.02%	$514,042.07	$524,640.17	$1,038,682.25	1,410.73	$10,598.10	29,192
2015-12-01	1.45%	$366,520.84	$371,901.06	$738,421.90	872.35	$5,380.22	29,291
2016-1-01	1.70%	$268,429.14	$273,080.50	$541,509.63	664.92	$4,651.36	28,666

Date	Weighted Average Spread	Amount Bought(k)	Amount Sold(k)	Total Volume(k)	BTC Volume(k)	Proceeds(k)	Trades
2016-2-01	2.35%	$210,437.22	$215,494.30	$425,931.52	522.65	$5,057.08	25,861
2016-3-01	2.79%	$181,944.04	$187,163.09	$369,107.13	440.00	$5,219.06	27,362
2016-4-01	2.35%	$176,750.72	$181,006.97	$357,757.69	405.39	$4,256.25	27,272
2016-5-01	2.53%	$227,005.93	$232,909.91	$459,915.83	484.08	$5,903.98	32,250
2016-6-01	2.10%	$566,363.16	$578,526.06	$1,144,889.23	878.39	$12,162.90	34,572
2016-7-01	2.13%	$296,888.19	$303,346.69	$600,234.87	453.15	$6,458.50	34,246
2016-8-01	2.37%	$210,258.04	$215,353.50	$425,611.54	365.26	$5,095.46	32,476
2016-9-01	2.70%	$149,596.70	$153,742.48	$303,339.18	248.19	$4,145.77	32,232
2016-10-01	2.44%	$176,868.36	$181,288.44	$358,156.80	273.58	$4,420.08	31,205
2016-11-01	2.05%	$252,870.44	$258,175.06	$511,045.50	350.83	$5,304.62	32,396
2016-12-01	2.40%	$235,434.48	$241,219.88	$476,654.37	284.85	$5,785.40	31,734
2017-1-01	2.54%	$373,002.70	$382,731.73	$755,734.43	413.18	$9,729.040	29,222
2017-2-01	2.16%	$325,574.01	$332,765.71	$658,339.72	309.47	$7,191.70	27,137

4.3 Case 2 Monthly Statistics

Date	Weighted Average Spread	Amount Bought(k)	Amount Sold(k)	Total Volume(k)	BTC Volume(k)	Proceeds(k)	Trades
2010-7-01	39.16%	$0.38	$0.62	$1.00	7.08	$0.24	15
2010-8-01	57.73%	$2.82	$6.67	$9.49	56.78	$3.85	26
2010-9-01	64.4%	$2.02	$5.68	$7.70	34.70	$3.66	12
2010-10-01	46.00%	$17.83	$33.01	$50.83	163.34	$15.18	41
2010-11-01	53.15%	$15.60	$33.30	$48.91	70.50	$17.70	21
2010-12-01	6.95%	$1.01	$1.09	$2.10	4.67	$0.08	4
2011-1-01	7.88%	$8.61	$9.35	$17.96	25.55	$0.74	39
2011-2-01	6.48%	$73.06	$78.13	$151.19	79.83	$5.07	126
2011-3-01	3.47%	$26.45	$27.40	$53.85	30.80	$0.95	96
2011-4-01	9.63%	$111.46	$123.33	$234.80	75.28	$11.87	366
2011-5-01	7.00%	$513.28	$551.90	$1,065.18	79.30	$38.62	1,114
2011-6-01	7.60%	$5,855.26	$6,336.59	$12,191.85	350.68	$481.33	5,337
2011-7-01	2.35%	$9,858.17	$10,095.91	$19,954.08	711.70	$237.74	8,063
2011-8-01	3.72%	$6,554.12	$6,807.26	$13,361.38	664.21	$253.14	8,511
2011-9-01	4.10%	$7,131.36	$7,436.37	$14,567.72	1,297.83	$305.01	8,089
2011-10-01	3.17%	$5,344.42	$5,519.28	$10,863.70	1,552.38	$174.86	7,271
2011-11-01	3.80%	$4,620.38	$4,802.82	$9,423.20	1,809.25	$182.45	6,829
2011-12-01	2.53%	$5,330.77	$5,469.07	$10,799.84	1,587.09	$138.30	6,573
2012-1-01	2.69%	$9,539.28	$9,803.19	$19,342.47	1,578.87	$263.92	7,886
2012-2-01	3.58%	$6,340.93	$6,576.68	$12,917.61	1,255.37	$235.76	7,027
2012-3-01	5.06%	$5,294.83	$5,577.16	$10,871.99	1,133.70	$282.33	5,562

Date	Weighted Average Spread	Amount Bought(k)	Amount Sold(k)	Total Volume(k)	BTC Volume(k)	Proceeds(k)	Trades
2012-4-01	3.07%	$7,137.30	$7,363.09	$14,500.39	1,475.75	$225.78	5,512
2012-5-01	2.35%	$7,105.42	$7,276.35	$14,381.77	1,433.93	$170.93	5,761
2012-6-01	2.77%	$11,040.82	$11,355.24	$22,396.06	1,873.56	$314.42	8,472
2012-7-01	3.14%	$13,920.29	$14,372.26	$28,292.55	1,817.67	$451.97	9,850
2012-8-01	2.43%	$23,416.07	$23,998.04	$47,414.10	2,171.33	$581.97	11,352
2012-9-01	1.63%	$12,309.70	$12,513.67	$24,823.38	1,078.54	$203.97	7,753
2012-10-01	2.53%	$16,283.71	$16,705.81	$32,989.52	1,412.07	$422.09	9,009
2012-11-01	2.18%	$14,086.52	$14,400.58	$28,487.09	1,252.89	$314.06	7,855
2012-12-01	1.94%	$15,448.10	$15,753.26	$31,201.36	1,179.80	$305.16	7,371
2013-1-01	2.22%	$27,237.77	$27,856.15	$55,093.91	1,716.08	$618.38	8,868
2013-2-01	2.05%	$22,608.70	$23,082.37	$45,691.07	886.21	$473.66	10,001
2013-3-01	4.39%	$76,246.20	$79,746.71	$155,992.91	1,343.25	$3,500.51	14,560
2013-4-01	6.68%	$635,711.18	$681,223.23	$1,316,934.40	5,604.42	$45,512.05	20,172
2013-5-01	3.31%	$315,045.81	$325,846.30	$640,892.11	2,840.79	$10,800.50	18,054
2013-6-01	2.98%	$166,335.56	$171,449.60	$337,785.17	1,596.00	$5,114.04	16,645
2013-7-01	5.57%	$194,334.04	$205,787.65	$400,121.69	2,355.55	$11,453.60	18,929
2013-8-01	9.36%	$148,651.01	$163,997.21	$312,648.22	1,411.24	$15,346.20	18,304
2013-9-01	8.25%	$157,132.09	$171,263.02	$328,395.11	1,277.26	$14,130.94	17,622
2013-10-01	9.08%	$878,688.17	$966,488.35	$1,845,176.52	5,748.42	$87,800.19	18,409
2013-11-01	8.9%	$2,735,273.72	$3,002,416.91	$5,737,690.63	6,077.15	$267,143.20	20,695
2013-12-01	6.45%	$4,462,577.09	$4,770,003.98	$9,232,581.07	6,048.62	$307,426.90	23,489
2014-1-01	6.73%	$2,097,695.36	$2,249,064.59	$4,346,759.94	2,551.48	$151,369.23	26,090
2014-2-01	30.74%	$2,214,635.93	$3,197,678.84	$5,412,314.77	5,070.22	$983,042.92	25,541

Date	Weighted Average Spread	Amount Bought(k)	Amount Sold(k)	Total Volume(k)	BTC Volume(k)	Proceeds(k)	Trades
2014-3-01	2.81%	$1,116,561.18	$1,148,880.59	$2,265,441.77	1,951.71	$32,319.40	27,451
2014-4-01	2.13%	$1,126,684.37	$1,151,193.67	$2,277,878.05	2,505.72	$24,509.30	26,468
2014-5-01	2.28%	$700,339.20	$716,700.69	$1,417,039.89	1,403.71	$16,361.49	28,757
2014-6-01	1.97%	$800,327.02	$816,429.99	$1,616,757.01	1,312.32	$16,102.97	30,361
2014-7-01	1.69%	$482,059.58	$490364.21	$972,423.79	788.01	$8,304.63	31,100
2014-8-01	1.75%	$642,986.00	$654,448.86	$1,297,434.86	1,242.81	$11,462.86	35,665
2014-9-01	2.52%	$632,182.39	$648,533.61	$1,280,716.00	1,476.91	$16,351.21	35,095
2014-10-01	2.20%	$835,055.33	$853,812.57	$1,688,867.90	2,366.51	$18,757.24	39,486
2014-11-01	1.71%	$757,546.31	$770,714.43	$1,528,260.74	2,022.87	$13,168.12	33,805
2014-12-01	2.23%	$481,319.77	$492,313.65	$973,633.43	1,425.81	$10,993.88	36,625
2015-1-01	2.59%	$967,256.24	$992,973.19	$1,960,229.43	4,126.76	$25,716.95	41,096
2015-2-01	2.35%	$643,013.28	$658,456.65	$1,301,469.93	2,758.12	$15,443.37	36,552
2015-3-01	2.10%	$759,012.92	$775,303.41	$1,534,316.33	2,838.27	$16,290.49	40,820
2015-4-01	2.55%	$507,115.29	$520,410.32	$1,027,525.61	2,183.79	$13,295.02	34,202
2015-5-01	2.36%	$394,171.29	$403,681.18	$797,852.47	1,665.43	$9,509.88	34,567
2015-6-01	2.64%	$437,422.50	$449,260.77	$886,683.27	1,836.58	$11,838.27	33,447
2015-7-01	2.29%	$708,859.95	$725,502.57	$1,434,362.52	2,548.01	$16,642.62	35,478
2015-8-01	3.02%	$503,269.65	$518,936.31	$1,022,205.96	2,076.45	$15,666.66	33,434
2015-9-01	3.11%	$446,022.94	$460,337.28	$906,360.23	1,916.98	$14,314.34	32,895
2015-10-01	2.84%	$699,622.60	$720,062.25	$1,419,684.86	2,567.71	$20,439.65	28,967
2015-11-01	2.66%	$1,602,735.92	$1,646,554.56	$3,249,290.48	4,427.36	$43,818.65	27,986
2015-12-01	1.74%	$1,174,224.91	$1,195,007.37	$2,369,232.28	2,797.26	$20,782.45	27,949
2016-1-01	1.97%	$864,378.68	$881,780.56	$1,746,159.24	2,142.12	$17,401.88	27,221

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Date	Weighted Average Spread	Amount Bought(k)	Amount Sold(k)	Total Volume(k)	BTC Volume(k)	Proceeds(k)	Trades
2016-2-01	2.60%	$707,112.63	$725,989.03	$1,433,101.66	1,759.86	$18,876.40	24,752
2016-3-01	3.00%	$629,719.29	$649,176.98	$1,278,896.27	1,522.82	$19,457.69	26,277
2016-4-01	2.64%	$602,771.07	$619,130.27	$1,221,901.35	1,385.53	$16,359.20	26,136
2016-5-01	2.73%	$796,248.12	$818,564.89	$1,614,813.01	1,697.79	$22,316.77	31,115
2016-6-01	2.39%	$1,965,245.56	$2,013,374.32	$3,978,619.88	3,052.34	$48,128.76	33,065
2016-7-01	2.42%	$1,005,228.27	$1,030,140.02	$2,035,368.29	1,535.91	$24,911.75	32,615
2016-8-01	2.60%	$725,032.26	$744,422.50	$1,469,454.77	1,258.33	$19,390.24	30,729
2016-9-01	2.87%	$515,841.32	$531,076.23	$1,046,917.54	856.12	$15,234.91	31,032
2016-10-01	2.62%	$607,047.54	$623,358.19	$1,230,405.73	939.95	$16,310.65	30,203
2016-11-01	2.29%	$1,068,096.22	$1,093,175.55	$2,161,271.77	1,482.53	$25,079.32	30,896
2016-12-01	2.65%	$1,029,434.07	$1,057,483.34	$2,086,917.41	1,247.23	$28,049.28	30,419
2017-1-01	2.93%	$309,237.62	$318,570.85	$627,808.47	343.58	$9,333.23	25,906
2017-2-01	2.51%	$269,753.44	$276,709.10	$546,462.54	256.67	$6,955.67	24,227