Connectivity Costs and Price Efficiency: An event study

Alex Frino[a], Ognjen Kovacevic[b*], Vito Mollica[b], Robert I. Webb[c]

[a] School of Accounting, Economics and Finance, Faculty of Business, University of Wollongong, Wollongong, NSW, Australia

[b] Macquarie Business School, Department of Applied Finance, Macquarie University, Sydney, NSW, Australia

[c]McIntire School of Commerce, University of Virginia, Charlottesville, Virginia, U.S.

Abstract

This paper investigates the impact of changes in the speed and pricing of direct market access on market efficiency, as measured by frequency, duration, and profitability of arbitrage strategies. To this end, two natural experiments on the EUREX exchange are identified: an exchange-wide improvement in technology reducing message latency, and a reduction in direct exchange access fee and analyze their impact on trading of Euro Stoxx 50 Index futures and the Xtrackers Euro Stoxx 50 Ucits ETF. A decrease in the frequency and duration of arbitrages following both events is observed, in addition to a reduction in arbitrage profits in the period after the reduction of the direct access fee. The results confirm the beneficial impact of speed of trading on the efficiency of financial markets, and support the theoretical predictions of Foucault et al. (2017) and Biais et al. (2015). In addition, alternative market efficiency measurements - midquote return autocorrelation and variance ratios - show statistically significant improvements following both events, providing robustness to the presented results.

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*Corresponding author, Macquarie Business School, 99 Talavera Rd, North Ryde NSW 2113, Australia. Email: ognjen.kovacevic@hdr.mq.edu.au

1. INTRODUCTION

Regulators are concerned that speed advantage is a channel that HFT exploit in order to extract rents from the market.[1] A recent FCA study (Aquilina, Budish, & O'Neill, 2020) finds that latency arbitrages resulting from the speed arms race, while having a small effect per transaction, have a significant collective impact on liquidity, and produce a yearly "latency-arbitrage tax" of around $4.8 billion through stale quote sniping activities.[2] However, the tax observed by Aquilina et al. (2020) can be seen as remuneration to investors keeping the market prices in check, in line with Grossman & Stiglitz (1980), instead of a tax on trading activity. Grossman & Stiglitz (1980), posit the only way to keep competitive markets in an "equilibrium degree of disequilibrium" is by adequately compensating informed traders for engaging in costly arbitrage activities and thus impounding information into prices.

This paper investigates whether technological improvements enabling faster, and cheaper direct market access reduce misalignment in prices. Specifically, the occurrence, duration, and profitability of arbitrage opportunities arising from price discrepancies between an ETF and a futures contract with the same underlying is investigated. The analysis tests predictions of Foucault, Kozhan, & Tham (2017) and Biais, Foucault, & Moinas (2015). Foucault et al. (2017) posit that technological improvements enabling faster trading reduce the duration of arbitrage opportunities; in turn, Biais et al. (2015) note that trade informativeness is positively correlated with the level of fast trading and negatively with the cost of being fast.

Two events around technological improvements and changes in direct access fees implemented by Eurex exchange are identified. First, in the period spanning December 3, 2012 to June 10, 2013 Eurex rolled out a redesigned trading architecture with the aim of increasing throughput rates and reducing trading latency. In order to accommodate higher throughput of the

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[1] The interest in HFT practices is not confined to the regulators. The media and the general public also exerted a significant pressure on the HFT industry. A notable example is Flash Boys, a book by Michael Lewis (2014) which put HFT under a spotlight, intensified the already present regulatory scrutiny over HFT practices (Bullock, 2014), and had an impact reaching as far as delaying the IPO of Virtu, one of the largest HFT companies (Massoudi, 2014).

[2] It is worth noting that recent years have seen a decline in profitability of HFT companies due to lower volatility and traded volumes (Meyer, Bullock, & Rennison, 2018). This is also evidenced by a trend of consolidation in the industry resulting in a number of high profile mergers and acquisitions (see Rennison, 2017; Meyer, 2017; Stafford, 2017; McCrank, 2018).

new system, Eurex required its traders to increase the bandwidth of their connection, leading to an overall increase in speed of direct exchange access for all participants. As predicted by theory, this should lead to a decrease in arbitrage opportunities. Second, on February 1, 2014, Eurex reduced the direct exchange access fee for a subset of traders not in its colocation facility. The theory expects that with more traders accessing the exchange at higher speed, there will be less arbitrage opportunities, and lower daily arbitrage profits.

Three measures of arbitrage are estimated: arbitrage frequency, duration, and profits in order to proxy for the informativeness of prices. These metrics are estimated for the most traded Eurex futures contract, Euro Stoxx 50 Index futures (FESX), and the Xtrackers Euro Stoxx 50 Ucits ETF (ETF), both tracking the Euro Stoxx 50 Index.[3]

Reported results corroborate extant literature. The analysis finds that technological improvements enabling faster exchange access around the first event make the price series of two instruments more aligned and reduce the frequency and duration of arbitrage strategies. This is in line with the predictions of Foucault et al. (2017) and Biais et al. (2015), and with empirical findings of Chaboud, Chiquoine, Hjalmarsson, & Vega (2014). The results, however, do not show a reduction in profitability of arbitrages following the first event. Reported findings differ to those of Frino et al. (2017), which might be explained by the fact they were analyzing an event affecting HFT only, while this paper looks at an exchange wide improvement in speed of access. Reduction in price for direct exchange access for a subset of traders provides support for Biais et al. (2015) predictions, as evidenced by coefficient estimates for Event 2. With decreased costs of connectivity, traders opt for higher connection speed subscriptions resulting in a more efficient market, as indicated by a reduction in frequency, duration, and profitability of arbitrages. Consistent with Budish, Cramton, & Shim (2015) and Frino et al. (2017), frequency of arbitrage opportunities and volatility are positively correlated.

The robustness of presented results is tested by analyzing the behavior of traditional measurements of market efficiency, midquote return autocorrelation and variance ratios, and a statistically significant improvement in market efficiency following each of the events is observed.

[3] The Euro Stoxx 50 Index tracks the performance of the fifty largest and most liquid stocks in the Eurozone

This paper is organized as follows. Section 2 provides an overview of the related literature. Section 3 describes the events and data. Section 4 describes the methodology. Section 5 reports results of the main analysis and the robustness tests. Section 6 concludes.

2. LITERATURE REVIEW

Direct access to the exchange and its market data is one of the crucial factors in determining the success of trading strategies. That speed matters, and that delays in execution are costly is nothing new, however. Demsetz (1968) first introduced the idea of significance of the cost of waiting in determination of spreads. In turn, the importance of technological upgrades reducing the latency with which information is received, processed, and orders are submitted is also not confined to 21st century: as noted by Easley, Hendershott, & Ramadorai (2014) NYSE's 1980 trading platform upgrade resulted in a significant reduction in transaction costs.

High-frequency trading arms race with the goal of shaving fractions of a second off of connectivity speed has led to a proliferation in the number of scientific papers attempting to model the newly established setting and empirically analyzing its impact on different aspects of market quality.[4] Most recently, Aquilina et al., (2020) investigate latency arbitrage using a novel and more detailed dataset containing information on message data unsuccessfully attempting to trade or cancel a limit order. They note that latency arbitrage races are frequent, fast, and account for a significant portion of the total trading volume and estimate that elimination of the races would lead to a 17% reduction in the cost of trading, corresponding to an annual global value of $4.8 billion.[5] While their results point towards a negative aspect of HFT activity, and highlight the downside of the current market setting, extant academic research notes significant positive aspects of low latency trading. Overall, the theoretical research notes faster trading makes prices more informative, at the cost of higher adverse information, however, it could also lead to permanent price imbalances due to a crowding out effect. Notably, Biais et al. (2015), and Aït-Sahalia & Saglam (2013) provide theoretical insights into positive aspects of higher HFT activity and its

[4] See Jones (2013), Goldstein, Kumar, & Graves (2014), and Menkveld (2016) for a detailed overview of literature that discusses the market impact of AT/HFT

[5] It should be noted that the both global and UK annual estimates ($4.8 billion and £60 million, respectively) are extrapolated from the average latency-arbitrage tax estimated at 0.42 basis points per share traded and computed on the sample of UK equity data spanning 44 trading days between August 17 and October 16, 2015.

beneficial effects on liquidity of the markets. Biais et al. (2015) propose a model in which the fast and slow traders trade in a fragmented market based on their heterogeneous private valuations and private information they possess.[6] They predict that with a larger fraction of fast traders in the market, the informational content and price impact of the trades will be larger as well. Biais et al. (2015) note that an increase in the cost of being fast produces a drop in the level of fast trading, and stemming from it, a drop in the informational content of trades.[7] Aït-Sahalia & Saglam (2013) model a fully dynamically optimizing HFT market maker enjoying a latency advantage and placing orders based on order flow predictions.[8] The model predicts that for a monopolistic HFT market maker, a decrease in latency leads to higher profits and resulting higher liquidity provision, due to lower costs of managing the inventory.[9] In addition, the model envisions similar beneficial impact on liquidity and lower frequency traders' costs even when HFT competition is introduced, concluding that the HFT can improve liquidity, efficiency, price discovery, and help with easing market fragmentation.

Foucault et al. (2017) predict a mixed impact of HFT activity. They posit that arbitrages can either be beneficial and add liquidity to the market – in case of transient demand/supply shocks – or be "toxic" – stemming from picking off of stale quotes – and result in an increase in adverse selection and subsequent increase in spreads. Their model predicts that illiquidity is higher when there is a higher fraction of toxic arbitrageurs and when it is likelier their arbitrage attempts manage to pick off the stale quotes (with higher likelihood that toxic arbitrages terminate with an arbitrageur's trade). The negative aspects of HFT activity have their positive side: a more toxic mix of arbitrages, leads to shorter arbitrage opportunities – liquidity providers update their quotes

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[6] Fast institutions are able to instantly scan the fragmented markets for lucrative quotes, while slow ones take more time to do so (and potentially end up not trading at all)

[7] Biais et al. (2015) also note that increases in the fraction of fast traders exert a negative externality on the market by increasing adverse selection, which not taken into consideration when making decisions on investments in fast technology, leading to an overinvestment. Their model, however, does not analyze the decision of the market maker who can also invest in speed in order to scout the fragmented markets for information.

[8] They note that the HFTs primarily act as market makers that do not take directional bets, but trade small volume on each trade and carry low inventory, hence their model envisioning HFT market makers trading with

[9] In addition, they note that lower latency leads to higher HFT-order cancellation rates, which is, however, not seen as a negative trait in normal times. They do predict, however, that the HFTs' provision of liquidity decreases during volatile times which is problematic in light of liquidity need during volatile times.

faster, which in turn forces the arbitrageurs to be faster as well. Therefore, any technological change resulting in relatively faster arbitrageurs reduces the duration of arbitrage opportunities, but, in addition, reduces liquidity as well. Foucault, Hombert, & Rosu (2016) posit it is the informativeness of news that determines a stock's liquidity: stocks having more informative news will be more liquid in spite of attracting a higher share of high frequency speculators. This follows from the ability of dealers to better predict long-term price changes, compensating for the increased probability of short-term losses to the more informed speculator.[10] Kozhan & Tham (2012) point to negative aspects of HFT competition. They argue that arbitrage opportunities exist due to traders facing the risk of uncertain execution in the presence of competition. They posit exploiting arbitrage can be risky as traders might not be able to take the positions necessary to complete the strategy in the presence of competition. This crowding out effect, therefore, leads to arbitrageurs inflicting negative externalities on each other and ultimately can result in persistent mispricing.

Empirical evidence highlights both positive and negative aspects of low latency trading. The general conclusion is that a decrease in latency improves market quality by allowing investors to react faster to news stemming from the order flow, but also can lead to cases where faster investors pick off the slower ones leading to a reduction in liquidity due to increased adverse selection costs. Boehmer et al. (2018), Brogaard et al. (2015) both note a reduction in spreads resulting from faster trading. Boehmer et al. (2018) analyze the impact of Algorithmic Trading on market quality on an intraday comprehensive sample of over 21000 companies between 2001 and 2011, using the introduction of colocation services as an exogenous instrument. In addition to liquidity improvements and higher price efficiency, as measured by autocorrelation of intraday returns, fast trading also leads to higher volatility.[11] Overall, Boehmer et al. (2018) note a positive net effect of AT on buy side institutional investors, as measured by a reduction in execution

[10] Foucault et al. (2016) model the impact of speed of trading on profitability of a speculator's trading strategies. They conclude speed is crucial to profitability of trading strategies and predict a fast speculator will overperform a slow one in terms of expected profits of their trading strategies by trading more aggressively on short-term signals, while being less aggressive with trades in the long run. In turn, Scholtus et al. (2014) empirically find that even small delays in execution result in significant decreases in performance of trading strategies centered around macroeconomic news announcements.

[11] Further testing of volatility behavior shows that increases in volatility are related to higher noise levels (negative volatility), in addition to variations in price resulting from incorporation of new information, and that on days with higher volatility induced by AT, liquidity decreases, both considered to be unwanted effects of AT.

shortfall. Riordan & Storkenmaier (2012) analyze liquidity and price discovery impact of a 2007 improvement in Xetra's trading system that significantly reduced system latency. They find decreases in both quoted and effective spread resulting from the upgrade, and after decomposing the effective spread into realized and adverse components, they observe that the driver of improved liquidity is a decrease in the adverse component of the spread.[12] In addition, they observe a doubling in price discovery share of quotes post technological update, showing that the automated quoting activity positively impacts the process of impounding information into markets. Brogaard et al. (2015) investigate the 2012 speed upgrade at NASDAQ OMX Stockholm equity market where the existing subscribers are given an option to receive a boost in connection speed for an additional fee. Identifying the latency sensitive traders based on their revealed preference to upgrade, the study finds that it is primarily the market makers who upgraded, resulting in an improvement in Effective Spread, Best Depth, and Depth levels away from the best quotes. Opposite to the findings of Riordan & Storkenmaier (2012), after decomposing Effective Spread into Realized and Adverse spread (Price impact), they find that the Effective spread improvement is mainly driven by a reduction in the realized spread while only a minor increase in the adverse spread is observed. Frino et al. (2014) investigate the effects of the introduction of co-location by the ASX in 2012. They identify a growth in HFT activity and resulting improvements in liquidity, and traded volumes in 90-day, and 3 and 10-year Australian Government Bond Futures stemming from the ability of traders to faster communicate their orders to the market when co-located.

Brogaard & Garriott (2019) analyze the growth of Alpha a newcomer Canadian exchange and point to the importance of HFT in an exchange's development. They find that the presence of passive HFT's improves liquidity in the market, leading to the convergence of spreads on the newly established Alpha to the ones existing on the incumbent – Toronto Stock exchange, while aggressive HFT entry, contrary to extant theory, does not lead to identifiable harm to market

[12] Different to Boehmer et al. (2018), whose findings pertain to medium and large cap stocks, observed liquidity improvements are concentrated in the small and medium sized stocks. Riordan & Storkenmaier (2012) posit these results can be explained by minimum tick size or entrance of new liquidity providers, while the increase in realized spread demonstrates a lack of competition between liquidity suppliers.

liquidity.[13] Brogaard & Garriott (2019) highlight the importance of competition in liquidity provision – four HFT firms must join the market for the spreads on Alpha to decrease to the level of TSX, and conclude that wider electronic access to markets is beneficial for market liquidity.

On the other hand, Hendershott & Moulton (2011) and Scholtus et al. (2014) find evidence of negative impact of HFT. Hendershott & Moulton (2011) observe an increase in both quoted and effective spread caused by an increase in adverse selection following 2006 technological improvements on NYSE resulting in a significant reduction in execution times of market orders. Scholtus et al. (2014) observe a widening of the spreads and an increase in volatility caused by higher AT activity at best quotes when trading around macroeconomic news announcements.

Frino et al. (2017) and Chaboud et al. (2014) investigate the relationship between HFT and arbitrage and find mixed evidence HFT activity market impact. Frino et al. (2017) use the number of connections to the ASX colocation facility as a proxy for HFT competition and focus on the impact of its increase on arbitrage opportunities instead of liquidity effects. Across the first two years of the ASX colocation facility implementation, they find that average daily frequency, duration, and profits of arbitrages, between the S&P/ASX200 futures contract and the ETF tracking the same index, all increase with higher HFT competition. In addition, they observe greater frequency and profitability of arbitrages during periods of higher volatility and turnover. Conversely, Chaboud et al. (2014) observe that higher AT activity leads to a reduction in frequency of triangular arbitrages in the foreign exchange market and an improvement in market efficiency, as measured by autocorrelation of high frequency returns. They attribute the decrease in arbitrage opportunities to successful sniping strategies of the AT, while they posit the increase in efficiency stems from AT liquidity provision.

3. DATA AND EVENT

We analyze the impact of changes in speed and cost of direct market access on the frequency, duration, and profitability of arbitrage opportunities. To this end, the analysis inspects the relationship between Euro Stoxx 50 Index futures (FESX), the most traded Eurex Exchange

[13] They divide the high-speed traders based on their trading strategies: passive (using limit orders) and aggressive (primarily using marketable orders).

futures contract, and the aggregate feed of the Xtrackers Euro Stoxx 50 Ucits ETF (ETF), both tracking the EURO Stoxx 50 Index.

Euro Stoxx 50 Index futures contracts are continuously traded on Eurex Monday – Friday 01:10 a.m. to 10:00 p.m. (CET); maturing contract ceases to trade at 12:00 CET on the third Friday of the maturity month (March, June, September, and December). The contract is cash settled, the notional value of the contract being equal to the value of the Euro Stoxx 50 Index futures multiplied by 10 Euros, with minimum quote price change equal to 1 index point. Xtrackers Euro Stoxx 50 Ucits ETF tracks the performance of the Euro Stoxx 50 Index, replicating the index at an approximately 1/100 ratio. The ETF shares are traded at Xetra and other MTPs across Europe Monday – Friday from 9:00 a.m. to 5:30 p.m. CET and are denominated in Euros.

We identify two changes in Eurex Exchange's trading architecture and direct exchange access pricing. On December 3, 2012, Eurex Exchange launched their new trading architecture designed to reduce transaction latency and increase message throughput rates (Eurex Exchange, 2012a). A gradual product migration phase was implemented in the period from December 3 to June 10, 2013, during which the products were transferred from the old to the new trading system. Euro Stoxx 50 Index futures were transferred on the last day of that period, June 10, 2013 which marks the first event date in the sample (Eurex Exchange, 2012a, 2012c, 2013a).[14] As noted in Eurex Exchange (2012a, 2012b), given the higher system throughput of the new trading architecture, the requirements for participants' bandwidth also increased, contributing to the overall increase in the speed at which the exchange operated.[15,16] As noted in Biais et al. (2015) and Foucault et al. (2017), technological upgrades resulting in decreased latency with which the traders are able to submit their orders should lead to more informed prices, and therefore, less arbitrage opportunities.

[14] In the product migration period, the exchange operated using both, the old and the new trading systems (products not yet transferred being traded using the old platform), while following the transfer, trading participants had to migrate to the new platform in order to trade.

[15] Eurex operates a Tier system of direct exchange access, by which fees traders pay depend on the elected bandwidth, but also of the country from which the trader connects. The change in the trading architecture redesigned the previously existing country groups and imposed higher bandwidth requirements on the traders.

[16] Eurex Exchange (2012a) notes several other benefits of the new system, including functionality enhancements aiding strategy and spread trading and improved trading interface standardization, reducing the efforts for future software updates while leveraging on connectivity and co-location concepts.

On February 1, 2014, Eurex decreased the direct exchange access fee for a group of its non-co-located traders (Eurex Exchange, 2013b). In effect, the decrease in the price of non-colocation connections should result in speeding up of traders that are generally exploited by the arbitrageurs. Similar to Event 1, this should lead to less arbitrage opportunities, and lower daily arbitrage profits.

Data are sourced from Refinitiv's Datascope Select trade and quote database; futures data refer to the chain of nearest to maturity contracts, while for the ETF data, we use the TRTH consolidated tape which aggregates data from all the MTPs and displays best bid and ask quotes and traded volumes. Our sample periods span 300 trading days around the events – June 10, 2013 and February 1, 2014 – 150 trading days pre- and post-changes in the speed of direct exchange access or its pricing. We eliminate two days around contract expiry from the sample in order to remove any irregularities arising from the rolling over of the contract (see Frino & McKenzie, 2002), and focus on the overlapping trading period between the two securities, removing 30 minutes at the beginning and the end of the trading day leaving us with a 9:30 a.m. to 5:00 p.m. trading day.

METHOD

4.1. Regression Specification

We estimate the impact of changes in connectivity speed and/or fees on arbitrage opportunities between the futures and the ETF as follows:

$$arb_t = \beta_1 + \beta_2 D_t + \beta_3 log\left(\frac{1}{DolVol_t}\right) + \beta_4 Volatility_t + \beta_5 IndRet_{t-1} \quad (1)$$

where arb_t takes the value of one of the 3 arbitrage metrics on day *t*: frequency, duration, and profits; and D_t takes the value of 1 in the period of 150 trading days after the event (June 10, 2013 and February 1, 2014) and 0 – 150 trading days prior to the event. Following Frino et al. (2017), we control for logarithm of the inverse of FESX daily dollar volume, FESX midquote volatility on day *t* (both volume and volatility calculated within the 9:30 a.m. to 5:00 p.m. interval), and the lag of the EURO STOXX50 Index daily log return.

4.2. Measurement of Arbitrage Opportunities

As noted in Budish et al. (2015) and Frino et al. (2017), correlated securities move in near lockstep at lower frequencies of sampling. However, when sampling at higher frequencies, the breakdowns in correlation occur, allowing quick arbitrageurs to profit. Figure 1 depicts the price progression of the FESX and the ETF tracking the index. In line with the observations in the literature, we find high correlation and almost parallel movements in the two price paths at lower frequencies. At the same time, when zoomed in to a finer trading interval, we note that, while the underlying relationship is still present, breakdowns exist creating arbitrage opportunities.

<INSERT FIGURE 1>

Three measures of spread between the FESX and ETF are defined in order to establish and quantify arbitrage opportunities: Immediate, Bid, and Ask spread, defined as:

$$\begin{aligned} S_i^{Immediate} &= MQ_{i,FESX} - 100MQ_{i,ETF} \\ S_i^{Bid} &= Bid_{i,FESX} - 100Ask_{i,ETF} \\ S_i^{Ask} &= Ask_{i,FESX} - 100Bid_{i,ETF} \end{aligned} \tag{2}$$

where $MQ_{i,FESX}$ and $MQ_{i,ETF}$ are midquote price levels, $Bid_{i,FESX}$ and $Bid_{i,ETF}$ are the outstanding bid quotes, and $Ask_{i,FESX}$ and $Ask_{i,ETF}$ are the outstanding ask quotes of the futures and ETF respectively at an intraday point *i*. The ETF quotes are multiplied by 100 in order to account for the price difference between the two instruments, as the ETF replicates the index at a 1/100 ratio.

Due to the frequent updates in quotes of each instrument, changes in the immediate spread alone cannot be used to make investment strategies and create arbitrage position. For this reason, basis spread—an average of the immediate spread over a period prior to the current bid or ask update—is computed as a more stable measure of spread. The interval used for averaging needs to be long enough for the prices to converge, while including only information relevant to the current update. The *convergence time* parameter (r_t) is set as the time required for the returns of the FESX and ETF to reach a correlation of 0.9, estimated using the returns from the previous 20 trading days.[17]

[17] Unlike Frino et al. (2017), this analysis does not use a binary search method to find the time for which the correlation between the two instruments equals 0.9, leading to higher accuracy (the binary search method they use is less computationally intensive, but does not guarantee the solution is a global minimum). In addition, similar to their approach, all trading days needing more than 2000 s to reach a correlation of 0.9 between the two instruments are excluded (this leads to exclusion of a total of 10 trading days from the sample).

Basis spread $\bar{S}$ at time *i* is defined as the time weighted spread in the interval r_t prior to the current quote update. It is calculated as:

$$\bar{S}_i = \sum_{j=0}^{N} \frac{S_j^{Immediate} \times (t_{j+1} - t_j)}{r_t} \quad (3)$$

Where N represents the total number of updates in the interval and $S_{j=0}^{Immediate}$ is the value of the immediate spread at the beginning of the interval.

In order to determine an arbitrage opportunity, we observe the relationship between the basis, bid and ask spread at time *i*. Absent arbitrage, the following should hold:

$$S_i^{Bid} < \bar{S}_i < S_i^{Ask} \quad (4)$$

Sudden changes in FESX or ETF quotes, however, might lead to a departure from this relationship a create arbitrage opportunities. Decreases in ETF quotes or increases in the FESX large enough to put Equation (4) out of balance so that $\bar{S}_i < S_i^{Bid} < S_i^{Ask}$ enable an arbitrageur to profit by taking a short position in futures and a long position in ETF.[18] The arbitrage opportunity ends when balance is restored, and the relationship reverts to (4). The time interval between the moment the arbitrage opportunity arises due to a sudden change in quotes (say time *i*) and when the equilibrium relationship is restored (time *l*) is the duration of arbitrage: $duration\ of\ arbitrage = l - i$.[19]

The expected dollar profits per arbitrage are a product of the initial mispricing in the two instruments (π), and the FESX and ETF volume available for creating the long-short portfolio (V) at the time the mispricing occurs. π and V can be found as follows:

$$\pi_i = \begin{cases} S_i^{Bid} - \bar{S}_i, if\ \bar{S}_i < S_i^{Bid} \Rightarrow short\ position\ in\ FESX, long\ in\ ETF \\ \bar{S}_i - S_i^{Ask}, if\ \ \bar{S}_i > S_i^{Ask} \Rightarrow long\ position\ in\ FESX, short\ n\ ETF \end{cases} \quad (5)$$

[18] Alternatively, increases in the ETF value, or a decline in FESX quotes can lead to $S_i^{Bid} < S_i^{Ask} < \bar{S}_i$ providing for an arbitrage portfolio composed of futures contracts funded by shorting ETF shares.

[19] As in Frino et al. (2017), all occurrences where the relationship in Equation (4) is not re-established within an interval equal to r_t are labelled as “bad-arb” and are excluded from our sample.

$$V_i = \begin{cases} 10 \times Min\left(Vol_{i,FESX}^{Bid}, \dfrac{Vol_{i,ETF}^{Ask}}{1000}\right), if\ \bar{S_i} < S_i^{Bid} \\ 10 \times Min\left(Vol_{i,FESX}^{Ask}, \dfrac{Vol_{i,ETF}^{Bid}}{1000}\right), if\ \ \bar{S_i} > S_i^{Ask} \end{cases}$$

where the outstanding ETF volume at best bid/ask is scaled by 1000 to reflect the same value as the futures contract, and 10 reflects the multiplier of each index point in Euros.

The variables of interest: daily arbitrage profits and daily arbitrage duration are found by aggregating the duration and profit of arbitrages on a daily basis. Daily arbitrage frequency is estimated by counting unique arbitrage occurrences within the course of a day.

4. RESULTS

5.1. Descriptive Statistics

Tables 1 and 2 report the summary statistics of the two instruments. Panels A in both tables refer to the 30-month sample covering both events, 1 July 2012 – 31 December 2014, and Panels B through E describe the averages of trading values in an interval of 150 trading days pre and post each of the events under analysis: June 10, 2013 and February 1, 2014. Statistics on the average daily bid-ask spread and dollar depth at best available quotes, message traffic, number of trades, traded dollar volume, and volatility are reported.[20]

It can be observed that the futures contract is significantly more active than the ETF. FESX spread is almost 3 times narrower than the ETF one, average dollar depth is around 35 times larger, and FESX best quotes are updated around 6 times more often than the ETF. Futures contract is much more traded than the ETF, with around 500 times more trades, and 5000 times higher dollar traded value. In addition, volatility of the futures contract is around 25% lower on aggregate, but the gap between the two is narrowing with time which is to be expected given that both instruments track the same index. In addition, when looking at the trading activity behavior across the event

[20] Bid-ask spread is the difference between the best available ask and bid; best dollar depth is the dollar value of the contracts/shares available for trade at both sides of the market; message traffic is the count of daily quoting activity; number of trades is the count of individual executed trades; dollar traded volume is the sum of daily traded volume expressed in dollars; and volatility is calculated as the difference in logarithm values of highest and lowest daily midquote. Spread and depth are calculated as simple daily averages. All values are estimated on an intraday sample between 9:30am and 5 pm.

windows in Panels B and C it can be noted that there is an upward trend in trading and quoting activity of the ETF with increases in message traffic, number of trades, and traded volume.

<INSERT TABLE 1>

<INSERT TABLE 2>

5.2. Main Results

Table 3 reports the regression coefficient and p-value estimates based on Equation (1) for 3 of the analyzed metrics across two investigated events. Panels A, B, and C present results relative to arbitrage frequency, duration, and profits between FESX and the ETF, respectively.

Biais et al. (2015) model notes a decrease in the cost of being fast produces an increase in the level of fast trading, while a larger fraction of fast traders in the market results in a larger informational content and price impact of trades. In addition, Foucault et al. (2017) posit that speed-increasing technological changes impact arbitrage opportunities by reducing their duration.

The estimates for all of the analyzed metrics around Events 1 and 2 are in line with Biais et al. (2015) and Foucault et al. (2017) predictions. Technology upgrades decreasing latency for all participants market wide, as around Event 1, lead to more informative and synchronized price series which is evidenced by a reduction in arbitrage frequency and duration. in line with predictions of Biais et al. (2015), a reduction in connectivity fees for a subset of traders outside of the colocation facility around Event 2, produces similar results as seen following the upgrade in trading technology, but in addition leads to a decrease in arbitrage profits.

Our findings are in line with those of Chaboud et al. (2014) who also find a reduction in arbitrage frequency caused by an increase in HFT activity. A positive relationship between existence of arbitrage opportunities and volatility is observed, in line with Budish et al. (2015).

<INSERT TABLE 3>

5.3. Robustness Testing

We test the robustness of our results by analyzing the efficiency of the prices of the FESX futures contract around the two events. To this end, we reestimate equation (1) with two informational efficiency measures as dependent variables: autocorrelations and variance ratios. As in Hendershott & Jones (2005), autocorrelation of midquote returns is calculated as:

$$Autocorrelation_l = \left|Corr\left(r_{l,t}, r_{l,t-1}\right)\right| \quad (6)$$

where $r_{i,t}$ is the t^{th} midquote return of length *l* in a given trading day. Given the absolute value in equation (6), any positive value of the autocorrelation metric is indicative of a deviation of the midquote return series from a random walk, and thus points towards market inefficiency. Decreases in the metric, and trending towards a value of 0 would be pointing to an improvement in the efficiency of prices.

In addition to 0 correlation in returns across non overlapping periods, an efficient market is also characterized by the variance of returns being a linear in the sampling interval. As per Lo & Mackinlay (1988) comparing the variance estimates across different sampling periods (adjusted to a common unit of time) tests if a price series follows a random walk and if a market is efficient. Variance ratio is computed as in Foley & Putniņš (2016):

$$VarianceRatio_{jk} = \left|\frac{\sigma_{jk}^2}{j\sigma_k^2} - 1\right| \quad (7)$$

where σ_k^2 and σ_{jk}^2 are variances of k second, and jk second midquote returns for a given day, respectively. If the price series follows a random walk, the value of the variance ratio metric should be equal to 0. Due to the absolute value in equation (7), any departure from a random walk would result in the value of variance ratio being greated than 0.

Table 4 reports results of autocorrelation and variance rations regressions calculated with *l=10* seconds period and variance rations with a *(j,jk)* combination of (*10* seconds, *60* seconds). Reported coefficient estimates corroborate the results—following the implementation of technological improvements enabling faster direct access to the market, and a reduction in the cost of direct market access connectivity—an improvement in the efficiency of prices is observed. This is evidenced by a decrease in autocorrelation of midquote returns and variance ratio following events 1 and 2. These results imply that there is less price predictability and that the price process is closer to a random walk, pointing towards improved efficiency.

<INSERT TABLE 4>

Finally, as in Foley & Putniņš (2016), we combine the information contained in autocorrelation measurements with $l \in \{10\ seconds, 30\ seconds, 60\ seconds\}$, and variance ratios with combinations (j, jk) of (1 second, 10 seconds), (10 seconds, 60 seconds), and (1 minute, 5 minutes) into a single metric, autocorrelation factor and variance ratio factor, by computing their first principal component. Coefficient estimates of regressions with autocorreltion and variance ratio factors as dependent variables are reported in Table 5 and provide further support for our main results.

<INSERT TABLE 5>

5. CONCLUSION

We investigate how exchange-wide technological improvements reducing message latency, and reductions in direct exchange access fees impacts frequency, duration, and profitability of arbitrage strategies. The analysis demonstrates decreases in latency of trading due to technological improvements and reductions in direct market access fee allowing for more traders to obtain the ability of fast trading lead to overall improvement of price informativeness and reductions in the frequency and duration of arbitrages. In addition, a reduction in arbitrage profits in the period after the reduction of the direct access fee is documented. The results of the analysis confirm theoretical predictions of Foucault et al. (2017) and Biais et al. (2015). The robustness of our findings is supported by observed, statistically significant, improvements in market efficiency following the two events.

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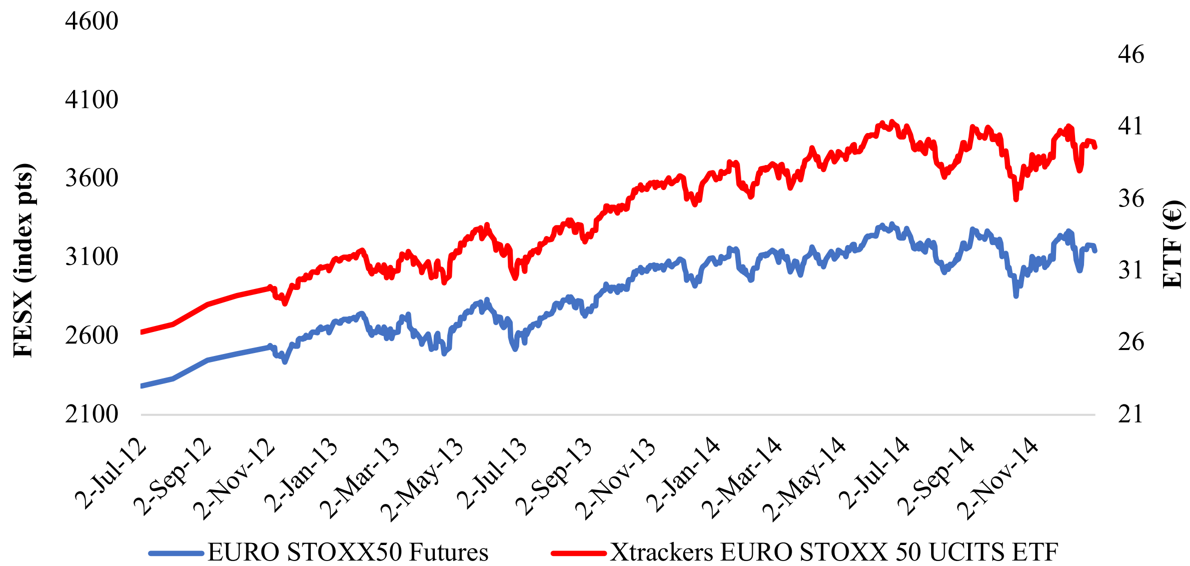
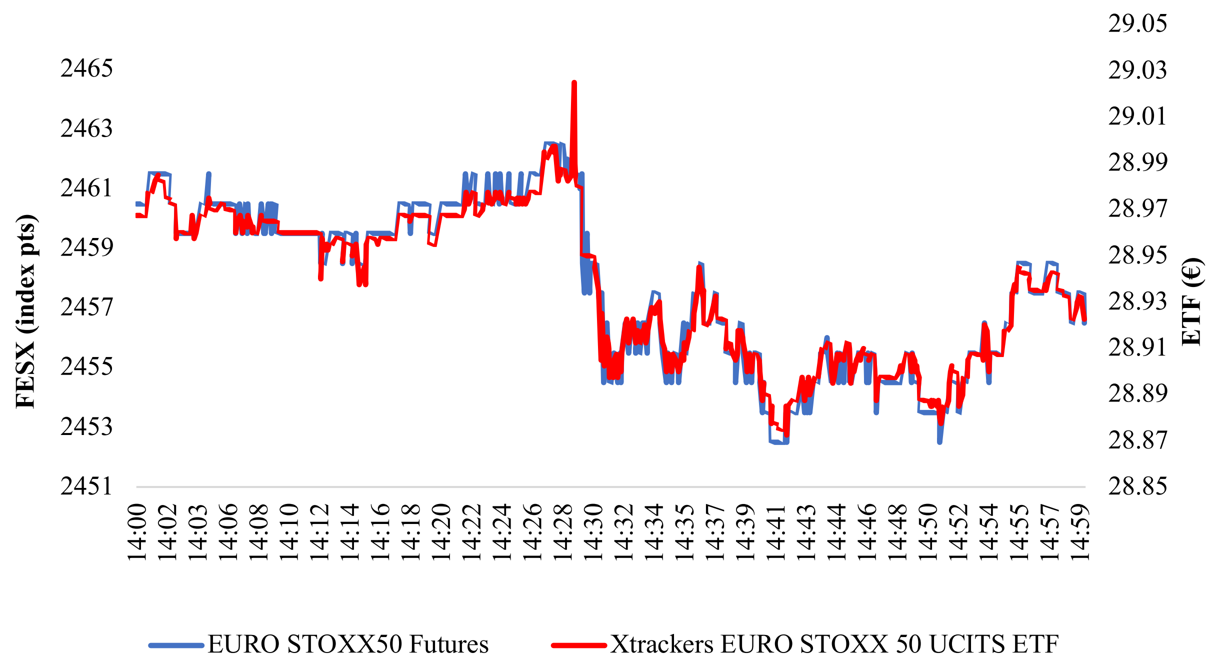
Figure 1

A: March 2012 – January 2014



B: 2:00 PM – 3:00 PM, November 15, 2012



Note: This Figure depicts price paths of the FESX futures contract and ETF tracking the Stoxx50 Index. Panel A illustrates the price path of FESX and the ETF over the sample period spanning March 2012–January 2014. Panel B depicts the price path of the two instruments over a randomly chosen one-hour trading interval.

Table 1

Summary Statistics

		Bid-Ask Spread		Depth (in $10000)		# Message Traffic (in '000)	
		FESX (index pts)	ETF (cents)	FESX	ETF	FESX	ETF
Panel A: Full Sample - 1 July 2012 – 31 Dec 2014							
Mean		1.007	2.8201	3508.3635	99.2841	122.4942	20.2211
Standard Deviation		0.0061	0.7668	930.6826	29.3146	151.1801	23.7573
Q1		1.003	2.3085	2911.6311	79.0189	67.325	6.27
Median		1.0052	2.6834	3368.7079	97.9225	74.479	9.101
Q3		1.0086	3.0604	3989.1211	114.9767	82.968	26.274
Panel B: Event 1 - 150 trading days pre and post June 10, 2013							
Mean	Before	1.0059	2.5047	3724.3561	90.1191	74.8418	7.0574
	After	1.0055	2.4556	3831.9927	106.4198	64.3499	6.536
Standard Deviation	Before	0.0049	0.4391	938.2488	26.1211	9.7184	2.5388
	After	0.0041	0.501	1158.3534	29.1115	9.9398	2.0771
Panel C: Event 2 - 150 trading days pre and post February 1, 2014							
Mean	Before	1.0051	2.4984	3956.5589	106.3467	64.0296	6.6348
	After	1.0105	2.794	3584.6657	113.5575	273.9133	32.311
Standard Deviation	Before	0.0037	0.5514	1029.3545	29.1854	9.7449	2.2834
	After	0.0084	0.4624	620.5579	34.22	249.3344	18.337

Note: This Table reports summary statistics describing the trading in the Euro Stoxx 50 Index futures and Xtrackers Euro Stoxx 50 Ucits ETF. The sample period extends 30 months of trading, July 1, 2012 to December 31, 2014. Panel A reports summary statistics across the entire sample, while Panels B and C provide insight into behavior 150 trading days pre and post June 10, 2013 and February 1, 2014 respectively (Events 1 and 2). Bid-ask spread is the difference between the best available ask and bid, best dollar depth is the dollar value of the contracts/shares available for trade at both sides of the market, and message traffic is the count of daily quoting activity. All values are estimated on an intraday sample between 9:30am and 5 pm.

Table 2

Summary Statistics cont'd

		# Trades		Traded Volume (in $ million)		Volatility (in %)	
		FESX	ETF	FESX	ETF	FESX	ETF
Panel A: Full Sample - 1 July 2012 – 31 Dec 2014							
Mean		25321.6508	49.9328	18870.8916	3.3357	1.2008	1.5601
Standard Deviation		10393.8897	53.3339	7929.2447	3.7315	0.6231	1.7191
Q1		18771	27	13688.3416	1.2395	0.7818	0.8329
Median		23174.5	40	17069.7592	2.2526	1.0638	1.1433
Q3		29287	54	22371.5312	4.0962	1.4465	1.6168
Panel B: Event 1 - 150 trading days pre and post June 10, 2013							
Mean	Before	25257.9867	44.6867	17693.0876	3.4698	1.1936	1.3821
	After	20724.4	63.6667	16602.8217	2.8404	1.018	1.3425
Standard Deviation	Before	8236.5914	23.3696	6476.5884	3.883	0.5666	0.7365
	After	6348.0643	81.1883	6168.9955	3.0604	0.4496	1.4082
Panel C: Event 2 - 150 trading days pre and post February 1, 2014							
Mean	Before	20709.7	68.3933	16599.4882	3.0612	1.036	1.3654
	After	24194.5	50.84	19564.1391	3.6214	1.0536	1.2054
Standard Deviation	Before	6509.3669	86.0278	6313.1983	3.1644	0.5011	1.427
	After	7627.7721	51.4128	7548.2803	3.8327	0.4466	0.9846

Note: This Table reports summary statistics describing the trading in the Euro Stoxx 50 Index futures and Xtrackers Euro Stoxx 50 Ucits ETF. The sample period extends 30 months of trading, July 1, 2012 to December 31, 2014. Panel A reports summary statistics across the entire sample, while Panels B and C provide insight into behavior 150 trading days pre and post June 10, 2013 and February 1, 2014 respectively (Events 1 and 2). Number of trades is the count of individual executed trades, dollar traded volume is the sum of daily traded volume expressed in dollars, and variance is the daily midquote variance. Spread and depth are calculated as simple daily averages. All values are estimated on an intraday sample between 9:30am and 5 pm.

Table 3

Regression results

	Event 1		Event 2	
	Coefficient Estimate	*p-value*	*Coefficient Estimate*	*p-value*
Panel A: Arbitrage Frequency				
Intercept	-167.8228	0.0003	-165.3124	0.0000
Event	-6.7154	0.0062	-8.6025	0.0000
Log 1/Futures Volume	-14.5426	0.0000	-13.9036	0.0000
Futures Volatility	0.0226	0.1336	0.0223	0.0474
Lag Index Return	-81.5419	0.5080	-8.1780	0.9335
R squared	0.1346		0.1908	
Panel B: Arbitrage Duration (in seconds)				
Intercept	21.2454	0.7609	-77.5731	0.1149
Event	-6.3902	0.0886	-17.1780	0.0000
Log 1/Futures Volume	-0.1628	0.9754	-7.4327	0.0485
Futures Volatility	0.0290	0.2103	0.0185	0.2353
Lag Index Return	346.1156	0.0682	42.0910	0.7580
R squared	0.0267		0.1565	
Panel C: Arbitrage Profits				
Intercept	9746.9337	0.6264	5718.8772	0.7846
Event	1257.8788	0.2417	-2009.4140	0.0558
Log 1/Futures Volume	660.3768	0.6622	249.7442	0.8759
Futures Volatility	2.5229	0.7035	1.1496	0.8628
Lag Index Return	64537.4888	0.2348	66595.0096	0.2531
R squared	0.0114		0.0176	

Note: This table reports results of the equation:

$$arb_t = \beta_1 + \beta_2 D_t + \beta_3 log\left(\frac{1}{DolVol_t}\right) + \beta_4 Volatility_t + \beta_5 IndRet_{t-1}$$

arb_t is the value of one of the 3 arbitrage metrics on day *t*: frequency, duration, and profits (reported in Panels A, B, and C, respectively); $Event_t$ takes the value of 1 after the event and 0 in the period before the event. $DolVol_t$ is the daily dollar volume of FESX futures contract, $Volatility_t$ is FESX midquote volatility on day *t* (both volume and volatility calculated within the 9:30 a.m. to 5:00 p.m. interval), and $IndRet_{t-1}$ is the lag of the EURO STOXX50 Index daily log return. Two events are identified: (1) a technological improvement decreasing the latency of trading and requiring traders to increase the speed with which they connect to the exchange. Euro Stoxx 50 Index futures began trading on the new architecture on June 10, 2013 and (2) a reduction in the cost of direct exchange access for a subset of traders effective February 1, 2014.

Table 4

Robustness Testing – Midquote Return Autocorrelation and Variance Ratio results

	Event 1		Event 2	
	Coefficient Estimate	*p-value*	*Coefficient Estimate*	*p-value*
Panel A: Midquote Return Autocorrelation (10 seconds)				
Intercept	0.2719	0.0003	0.1322	0.0793
Event	-0.0106	0.0144	-0.0118	0.0045
Log 1/Futures Volume	-0.0084	0.1390	0.0017	0.7785
Futures Volatility	-0.0001	0.0000	-0.0001	0.0000
Lag Index Return	0.7337	0.0009	0.7836	0.0007
R squared	0.1560		0.1712	
Panel B: Variance Ratio (10 seconds, 60 seconds)				
Intercept	0.7358	0.0000	0.5497	0.0005
Event	-0.0263	0.0036	-0.0237	0.0064
Log 1/Futures Volume	-0.0315	0.0078	-0.0194	0.1159
Futures Volatility	-0.0003	0.0000	-0.0003	0.0000
Lag Index Return	1.6262	0.0004	1.9643	0.0001
R squared	0.2219		0.2228	

Note: This table reports results of the equation:

$$Efficiency_t = \beta_1 + \beta_2 D_t + \beta_3 log\left(\frac{1}{DolVol_t}\right) + \beta_4 Volatility_t + \beta_5 IndRet_{t-1}$$

$Efficiency_t$ takes the value of midquote return autocorrelation or variance ratio (reported in Panels A and B, respectively); $Event_t$ takes the value of 1 after the event and 0 in the period before the event. $DolVol_t$ is the daily dollar volume of FESX futures contract, $Volatility_t$ is FESX midquote volatility on day t (both volume and volatility calculated within the 9:30 a.m. to 5:00 p.m. interval), and $IndRet_{t-1}$ is the lag of the EURO STOXX50 Index daily log return.

Two events are identified: (1) a technological improvement decreasing the latency of trading and requiring traders to increase the speed with which they connect to the exchange. Euro Stoxx 50 Index futures began trading on the new architecture on June 10, 2013 and (2) a reduction in the cost of direct exchange access for a subset of traders effective February 1, 2014.

Table 5

Robustness Testing – Midquote Return Autocorrelation and Variance Ratio Factors

	Event 1		Event 2	
	Coefficient Estimate	*p-value*	*Coefficient Estimate*	*p-value*
Panel A: Midquote Return Autocorrelation Factor				
Intercept	5.2575	0.0021	3.3685	0.0546
Event	-0.3218	0.0013	-0.1663	0.0834
Log 1/Futures Volume	-0.3519	0.0075	-0.2307	0.0924
Futures Volatility	-0.0034	0.0000	-0.0037	0.0000
Lag Index Return	16.2921	0.0013	24.0969	0.0000
R squared	0.2033		0.2436	
Panel B: Variance Ratio Factor				
Intercept	0.8932	0.5918	-2.3224	0.1669
Event	-0.2964	0.0026	-0.1727	0.0613
Log 1/Futures Volume	-0.0175	0.8917	0.2054	0.1186
Futures Volatility	-0.0039	0.0000	-0.0037	0.0000
Lag Index Return	17.5566	0.0004	26.6168	0.0000
R squared	0.2002		0.2093	

Note: This table reports results of the equation:

$$Efficiency_t = \beta_1 + \beta_2 D_t + \beta_3 log\left(\frac{1}{DolVol_t}\right) + \beta_4 Volatility_t + \beta_5 IndRet_{t-1}$$

$Efficiency_t$ takes the value of midquote return autocorrelation factor or variance ratio factor (reported in Panels A and B, respectively); $Event_t$ takes the value of 1 after the event and 0 in the period before the event. $DolVol_t$ is the daily dollar volume of FESX futures contract, $Volatility_t$ is FESX midquote volatility on day *t* (both volume and volatility calculated within the 9:30 a.m. to 5:00 p.m. interval), and $IndRet_{t-1}$ is the lag of the EURO STOXX50 Index daily log return. Autocorrelation factor is calculated by taking the first principal component of three autocorrelation measures based on 10 second, 30 second, and 60 second intervals. Variance ratio factor is calculated by taking the first principal component of three variance ratios computed comparing (1 second, 10 seconds), (10 seconds, 60 seconds), and (1 minute, 5 minutes) periods. Two events are identified: (1) a technological improvement decreasing the latency of trading and requiring traders to increase the speed with which they connect to the exchange. Euro Stoxx 50 Index futures began trading on the new architecture on June 10, 2013 and (2) a reduction in the cost of direct exchange access for a subset of traders effective February 1, 2014.