Overview of Emerging Blockchain Architectures and Platforms for Electronic Trading Exchanges.

Gareth W. Peters‡ ⋆ ∗

Guy R. Vishnia† ♢

‡ Department of Statistical Science, University College London. [*]

⋆ Associate Fellow, Oxford Mann Institute, Oxford University

∗ Associate Fellow, Systemic Risk Center, London School of Economics.

† UCL, Department of Computer Science, WC1E 6BT, London, UK

♢ ITG, 25 Ropemaker Street, EC2Y 9LY, London, UK [†]

White paper with ASTRI and Hong Kong Monetary Authority.

August 31, 2016

Key Words: Blockchain; Blockchain transaction reporting; Trade reporting; Transparency.

Overview.

Several international electronic primary financial exchanges have begun to announce they will explore the adoption of blockchain technology in their trade processing and reporting for execution and clearing. Therefore, in this work we will begin by providing an overview of the new exchange regulations appearing in different jurisdictions around the world, including EMIR, Dodd Frank, MiFID I/II, MiFIR, REMIT, Reg NMS and T2S. We will discuss some of their key features, specifically in regard to transparency reporting and trade/transaction reporting requirements.

The current status of regulatory requirements for reporting and the massive data sets such regulation will generate as well as the significant challenges faced by firms and market participants in meeting such requirements in an automated manner, is a key to the discussion in this paper. We explain different blockchain solutions based on blockchain architectures being currently developed in the market place to handle key aspects of transparency and pre and post trade reporting requirements that will be universal in applicability in both UK, Europe and U.S. regulations.

In the process of this commentary we will discuss the different emerging architectures and features that are being developed in a range of different blockchain technologies. This will include details on different forms of blockchain technology including : Permissionless blockchains, where anyone can participate in the verification process, i.e. no prior authorisation is required and a user can contribute his/her computational power, usually in return for a monetary reward. Permissioned blockchains, where verification nodes are preselected by a central authority or consortium. Public blockchains, where anyone can read and submit

[*]QRSLab details are available at http://garethpeters78.wixsite.com/garethwpeters.

[†]http://www.itg.com

transactions to the blockchain and Private blockchains, where this permission is restricted to users within an organisation or group of organisations. We detail which market participants and which blockchain architectures are emerging as possible solutions for addressing pre and post trade reporting requirements in modern electronic exchanges.

1 Brief Commentary on Modern Electronic Exchanges and Networks

In discussing how blockchain architectures can be used to facilitate exchange and transaction transparency as part of new exchange regulations it will be important to first understand the current landscape of electronic exchanges, a detailed overview of this is provided in the first three sections of Gareth W. Peters [2017].

As they discuss, there are a number of trading venues possible to modern traders. A trader can choose to execute their orders in more than one venue, and in more than one venue type. A trader can choose to target all available venues, or only a subset of these venues based on their preferences, trading cost or other motivations. In addition there are new regulations that are emerging in different jurisdictions that are changing these venue options for traders.

In this section we will briefly describe current venue types. One broad classification of such venues that is often adopted in practice (see Moloney *et al.* [2002]) is to consider the distinctions between: Regulated Markets (RMs); Multilateral Trading Facilities (MTFs); Organised Trading Facilities (OTFs); Swap Execution Facilities (SEFs); Designated Contract Markets (DCMs); Broker Crossing Networks (BCNs); Dark Pools (DPs) and Customized Liquidity Pools (CLPs) and the emerging area of Multilateral systems (MS).

Before continuing to detail different types of venues, it will be useful to explain briefly a key quantity in modern electronic exchanges, the Limit Order Book (LOB).

1.1 Limit Order Books Lit (visible) and Dark

The Limit Order Book (LOB) can be viewed as a list of the willingness of people to buy or sell a certain quantity of a certain asset at a certain price. When a buy and a sell price match, we have an execution (trade). Sizes do not have to match on a trade, and one part of the bargain can remain with residuals, see discussions in Gould *et al.* [2013], Richards *et al.* [2015], Panayi *et al.* [2015] and Panayi & Peters [2015]. In modern market places one common distinction that has arisen for different types of LOB is between lit and dark books or sometimes referred to as lit and dark liquidity.

We can look at the lit LOB as a two prices queue system, one for buy orders and one for sell orders, each position at the queue is called a level, i.e. the first in the queue on each side will be level 1, second will be level 2 etc. On each level there are also queues noting when the order was inserted to the level. This is called the depth of the level.

This data in the Lit Order books is visible to market participants usually by subscribing to a venue feed, wether directly or via a data provider such as Thompson Reuters or Bloomberg.

The formal definitions of the best bid, ask and the mid point are:

$BestBid$ = the maximum price a participant is willing to buy X amount of shares at a certain point in time.

$$BestBid = Max(P_b1...P_bk) \tag{1}$$

BestAsk the minimum price a participant is willing to sell X amount of shares at a certain point in time.

$$BestAsk = Min(P_a 1 ... P_a k) \tag{2}$$

Mid price - the midpoint between the best bid and the best ask. It does not have to fall under the tick size rules.

$$Mid = (BestAsk + BestBid)/2 \tag{3}$$

A Dark Limit Order Book (DLOB) is, as its name states, not publicly visible, i.e. the orders that reside within it are not public and no one knows at any point which entries and what sizes / prices are currently in the dark pool order book. In a DLOB there is no best Bid/Ask and volume being published, that is trading orders/interest are not disclosed to the market publicly. Only once a trade occurs in the dark pool will it be published and then visible to the public (via Boat platform for example [1]).

The Orders that reside in the DLOB are adhering to client limit prices and to queue/size priority as per venue regulations, but no one besides the sender of the order to the dark pool knows about this order until it is executed. In addition, it is also the case the removing or cancelling an order from the DLOB is also not visible to the outside world, see discussions on such venues in Degryse *et al.* [2008] and Gresse [2015].

1.2 Exchange Venues

We first note that a more comprehensive analysis of the venue types mentioned below is detailed in Gareth W. Peters [2017] and references therein.

The first and foremost exchange venue that should be discussed is known as the Primary Market or Regulated Market (RM). Under such a classification a RM can be thought of as market place that is typically managed by the market operator who does not run this market primarily as an investment activity. In such markets they typically involve non-discretionary execution systems. In this setting non-discretionary refers to the fact that they are typically execution-only services that allow clients to make their own investment decisions and provide purely a platform for them to carry out trades to fulfill their investment decisions. Examples of such RMs include the Primary Exchanges (PEs) of each country. Typically such RMs are associated with formal, organised markets, including traditional stock exchange PEs but also newer multilateral platforms.

Primary exchanges typically offer lit Limit Order Books (LOBs), which means that the best bid and ask prices and volumes (first level of the book) are published for any subscriber, and also deeper levels of the book are available for subscriptions. Levels of the book proceed in tick size, i.e. specific predefined sizes which may be different per stock based on it's traded value.

In such RMs the market is typically informed of levels of trading interest pre- and post-trade. It is well documents that such forms of electronic trading are involved in price-setting since the active and timely disclosure of trading interest supports the development of a wider price formation. As a consequence, these RMs are offering an important market function for investors and consequently many transparency rules which require the disclosure of pre-trade bid/offer prices and post-trade trade price, volume and time information are required to be satisfied.

In contrast to RMs and PEs there are numerous other types of electronic market venues that have emerged in recent years. In general prior to recent regulations for instance in Europe, known as the (Markets in Financial Instruments Directive 2004/39/EC) (MiFID),

[1] Boat Platform `https://www.theboatplatform.com/`

there was only a second type of venue which was associated with investment firms and brokers who provided discretionary execution services which were previously classified as Over the Counter (OTC) services. In such settings, they typically ran as client execution services that were bilateral between clients and a brokers proprietary order book or bilaterally between clients and a "crossed" book constructed from other clients orders. As these services became automated in nature, it removed the traditional client facing role of a broker, consequently it was perceived to also remove the fiduciary duties typically imposed on client facing investment firms with respect to best execution obligations. To address this potential issue new regulation was developed to rectify this challenge, initially with the transparency and fragmentation requirements of MiFID I, see a detailed discussion in Gareth W. Peters [2017] and references therein.

After MiFID I there was an emergence of what are known as Multilateral Trading Facilities (MTFs), opening the traditional primary exchange only execution market to competition which increased the transparency of the markets as well as making them fragmented.

An MTF is a trading system that facilitates the exchange of financial instruments between multiple parties. Multilateral trading facilities allow eligible contract participants to gather and transfer a variety of securities, especially instruments that may not have an official market. Typically an MTF is managed by either a market operator or investment fund which runs the operation as an investment service. MTF's are also typically non-discretionary execution environments. These facilities are often electronic systems controlled by approved market operators or larger investment banks. Traders will usually submit orders electronically, where a matching software engine is used to pair buyers with sellers. However, until recently there have been few requirements made regarding conduct of business regulations. These venues can be considered as a primary exchange in many ways, they offer pre and post trade transparency (publish bid-ask) and users can choose to target directly these venues. They often offer better rates and higher speed then the primary exchanges.

An OTF is any facility or system designed to bring together buying and selling interests or orders related to financial instruments, however they apply typically only to non-equities. They form a new classification of trading venue which is designed to act as a regulatory "catch all" for all organised trading that occurs away from RMs and MTFs and that is not genuinely OTC, see discussions in MaretWiki [2016] and Linklaters [2016]. These venues or electronic exchanges arose primarily after MiFID II regulations, whereas under MiFID there was only a requirement of MTF's, this will be discussed in detail below.

In the U.S. the SEF is a venue specifically developed to clear OTC swaps under a regulated platform. According to Dodd-Frank, any swap that is "made available to trade" must do so on a DCM or a SEF Commision [2016]. The SEF can be defined as "a trading system or platform in which multiple participants have the ability to execute or trade swaps by accepting bids and offers made by multiple participants in the facility or system, through any means of interstate commerce" that is not a designated contract market, see Commision [n.d.b].

The structuring and main principles of how SEFs operate was left to the Commodity Futures Trading Commision (CFTC) and the U.S. Secutiries and Exchange Commission (SEC). The main principles were established for these venues by the CFTC which proposed in December 10, 2010 a guidance on such venues and was introduced to the Federal Register on January 7, 2011, details will be discussed below.

Subsequent to the introduction of the SEF, the CFTC has continued to finalize several execution rules in May 16, 2013 which include 15 core principles Commission [2013]: Core Principles and Other Requirements for SEFs; the "made available to trade" (MAT) provision; Block trade rules; Trading and product requirements; Compliance obligations; Surveillance obligations; Operational capabilities; and Financial information and resource requirements.

These also include the requirement of registration of a SEF such that they are required under regulation to demonstrate that they meet minimum trade functionality requirements such as having a LOB, and they offer impartial access to their markets.

Systematic Internalisers (SIs) have been recently brought in under regulation to replace the traditional Broker Crossing Networks (BCNs). Whilst BCNs are privately run crossing networks which match flow of clients in order to execute. Systematic internalizers is doing the same but the crossing is against the SI operator capital and not vs. other clients. In general one can consider an SI as "*An investment firm which, on an organised, frequent systematic and substantial basis deals on own account by executing client orders outside RM, MTF or OTF*" [2].

The other versions of trading venue that are not accessible to general public with published liquidity are known as private liquidity pools, often termed dark. Dark Pools (DPs) are trading venues which offer electronically off the book block trades usually at Mid price but at the moment can also cross on the Bid and Ask. The reference price is typically taken from the primary exchange. When referring to dark pool liquidity it can be considered as the trading volume created by institutional orders executed on private exchanges and unavailable to the public. The bulk of dark pool liquidity is represented by block trades facilitated away from the central exchanges. It is also referred to as the "upstairs market", "dark liquidity" or "dark pool".

Under new regulations the dark pool universe will need to support the same order types and pricing and queue priority rules as a lit exchange, but will not publish publicly their order book hence giving no view to what orders are currently reside in the dark pool. Usually it will also require a larger minimum trading size.

In particular, trade reporting will be published with the maximum allowed delay in order to reduce market impact. The dark traded are considered to be OTC (Over the counter) and are not contributing to the electronic daily volume traded on a stock.

2 Exchange Reporting and Transparency Regulations and Directives

For a more detailed discussion on exchange regulations we refer the interested reader to Gareth W. Peters [2017] and references therein. In this section we briefly comment on some recent changes in regulation.

After the global financial crisis of 2008 there was an international push to develop an international regulatory program which was primarily driven by the G20 and enhanced at the 2009 Pittsburgh summit. With a universal focus on the core principle of increasing transparency and reporting requirements, markets have witnessed the emergence of Dodd-Frank Commission [2015], the European Market Infrastructure Regulation (EMIR) FCA [2016], Markets in Financial Instruments Directive (MiFID) I, II Commision [n.d.a] and Regulation (MiFIR) ESMA [n.d.], Securities Financing Transactions Regulation (SFTR) FIA [2015] and Money Market Statistical Reporting (MMSR) ECB [n.d.] which all contain some form of reporting obligations.

Some key examples of current regulations that pertain to recent electronic market reporting requirements, of focus in this white paper are briefly outlined below:

- European Market Infrastructure Regulation (EMIR) [short for Regulation (EU) No 648/2012 of the European Parliament and of the Council of 4 July 2012 on OTC

[2] `http://www.icmagroup.org/assets/documents/Regulatory/MiFID-Review/ICMA_MiFID2_systematic-internalisers_QA_14-July-2015.pdf`

derivatives, central counterparties and trade repositories entered in force on 16 August 2012.]. The key requirement is to increase the transparency of the over the counter (OTC) derivatives market. EMIR establishes new regulatory requirements on all types and sizes of entities that enter into any form of derivative contract. The new regulatory requirements are separated into three main categories: transaction reporting; clearing and risk mitigation.

- Markets in Financial Instruments Directive (MiFID II) with some of its key goals including to move trading of standardised derivatives on to exchanges or other organised trading venues as part of OTFs in order to capture smaller broker to broker networks. In addition it aims to significantly enhance pre and post trade transparency and transaction reporting. A particular focus on commodity and high frequency trading including potential position limits or forced reduction of positions.

- BASEL II/III with one of the aims to in the context of this paper, being to increases capital for trading book positions and introduce new liquidity rules to require larger holdings of a limited pool of assets which must also be used to satisfy likely collateral rules.

- Fundamental review of trading book which is expected to reduce or remove capital and financial accounting distinctions between trading and banking book.

- Market Abuse Directive (MAD) which currently covers disclosure of interests, reporting of suspicious transactions, maintenance of insiders lists and accepted market practices. It is now extended to also include derivatives and commodities with additional featuers relating to data sanctions and HFT activities. Can affect MTFs and OFTs as well as OTC.

- Dodd-Frank Act has one of its key objectives being to perform OTC trade standardisation and to introduce SEFs for swap market exchange trading. In addition, all derivatives trades should be cleared through CCPs, with all trades reported to trade repositories following confirmation.

- Principles for Financial Market Infrastructures (PFMI) is a new proposal brought out by the Bank of International Settlements (BIS) through the Committee on Payment and Settlement Systems (CPSS) with the goal to enact through IOSCO a more demanding international standard for payment, clearing and settlement systems, including central counterparties. The PFMI will aim to ensure that infrastructures supporting global financial markets are more robust. The principles apply to all systemically important payment systems, central securities depositories, securities settlement systems, central counterparties and trade repositories (collectively "financial market infrastructures" (FMIs)).

- Settlement Under Target2 Securities (T2S) and Central Securities Depositories Regulation (CSDR). The T2S regulation is a response by the ECB to trigger fundamental changes in the post-trade processing, far beyond the initial scope of pan-European settlement in central bank money.

- Basel III (CRD IV), AIFMD and UCITS V are all depository banking regulations but they will not be discussed in detail in this paper.

All of these regulations have a substantial aspect of market participant private and public data reporting as well as pre and post trade reporting. We will discuss key aspects that are universal to these and propose blockchain based solution architectures to address these regulatory challenges.

3 The Role of Blockchain Technology in Electronic Exchanges

There are a range different blockchain architectures and the aim of this section is to illustrate how such structures can be relevant to electronic exchange reporting under the new exchange transparency and reporting requirement regulations discussed previously in this paper.

Discussions on blockchain technology are provided in Peters & Panayi [2015] and Peters *et al.* [2015]. In general the terminology of this new field is still evolving, with many using the terms block chain (or blockchain), distributed ledger and shared ledger interchangeably. Formal definitions are unlikely to satisfy all parties but for the purposes of this report, the key terms are as follows which we briefly define below, before going into more detail on some aspects in subsequent sections.

Blockchain. A blockchain is not a databased but it can conceptually be thought of as acting like a database in the sense that it is a ledger that takes a number of records and puts them in a block (rather like collating them on to a single sheet of paper). Each block is then chained to the next block, using a cryptographic signature. This allows block chains to be used like a ledger, which can be shared and corroborated by anyone with the appropriate permissions. There are many ways to corroborate the accuracy of a ledger, but they are broadly known as consensus (the term mining is used for a variant of this process in the cryptocurrency Bitcoin). If participants in that process are preselected, the ledger is permissioned. If the process is open to everyone, the ledger is unpermissioned see discussions below. The real novelty of block chain technology is that it is more than just a database it can also set rules about a transaction (business logic) that are tied to the transaction itself. This contrasts with conventional databases, in which rules are often set at the entire database level, or in the application, but not in the transaction.

Permissionless Ledgers. In the case of an unpermissioned or permissionless ledger, such as the one utilised in Bitcoin, there is no single owner indeed, they cannot be owned. The purpose of an unpermissioned ledger is to allow anyone to contribute data to the ledger and for everyone in possession of the ledger to have identical copies. This creates censorship resistance, which means that no actor can prevent a transaction from being added to the ledger. Participants maintain the integrity of the ledger by reaching a consensus about its state. Unpermissioned ledgers can be used as a global record that cannot be edited: for declaring a last will and testament, for example, or assigning property ownership. But they also pose a challenge to institutional power structures and existing industries, and this may warrant a policy response on governance considerations.

Permissioned Ledgers. Permissioned ledgers may have one or many owners. When a new record is added, the ledgers integrity is checked by a limited consensus process. This is carried out by trusted actors government departments or banks, for example which makes maintaining a shared record much simpler that the consensus process used by unpermissioned ledgers. Permissioned block chains provide highly-verifiable data sets because the consensus process creates a digital signature, which can be seen by all parties. Requiring many government departments to validate a record could give a high degree of confidence in the records security, for example, in contrast to the current situation where departments often have to share data using other means such as physical copies. A permissioned ledger is usually faster than an unpermissioned ledger.

Distributed Ledgers. Distributed ledgers are a type of database that is spread across multiple sites, countries or institutions, and is typically public. Records are stored one after the other in a continuous ledger, rather than sorted into blocks, but they can only be added when the participants reach a quorum. A distributed ledger requires greater trust in the validators or operators of the ledger. For example, the global financial transactions system Ripple selects a list of validators (known as Unique Node Validators) from up to 200 known, unknown or partially known validators who are trusted not to collude in defrauding the actors in a transaction. This process provides a digital signature that is considered less censorship resistant than Bitcoins, but is significantly faster.

Public Blockchains. A public blockchain is a blockchain that anyone in the world can read, anyone in the world can send transactions to and expect to see them included if they are valid, and anyone in the world can participate in the consensus process the process for determining what blocks get added to the chain and what the current state is. As a substitute for centralized or quasi-centralized trust, public blockchains are secured by cryptoeconomics the combination of economic incentives and cryptographic verification using mechanisms such as proof of work or proof of stake, following a general principle that the degree to which someone can have an influence in the consensus process is proportional to the quantity of economic resources that they can bring to bear. These blockchains are generally considered to be “fully decentralized”[3].

Shared Ledgers and Consortium Blockchains. A shared ledger is a term coined by Richard Brown, formerly of IBM and now Chief Technology Officer of the Distributed Ledger Group, which typically refers to any database and application that is shared by an industry or private consortium, or that is open to the public. It is the most generic and catch-all term for this group of technologies. A shared ledger may use a distributed ledger or block chain as its underlying database, but will often layer on permissions for different types of users. As such, shared ledger represents a spectrum of possible ledger or database designs that are permissioned at some level. An industrys shared ledger may have a limited number of fixed validators who are trusted to maintain the ledger, which can offer significant benefits.

A consortium blockchain is a blockchain where the consensus process is controlled by a pre-selected set of nodes; for example, one might imagine a consortium of 15 financial institutions, each of which operates a node and of which 10 must sign every block in order for the block to be valid. The right to read the blockchain may be public, or restricted to the participants, and there are also hybrid routes such as the root hashes of the blocks being public together with an API that allows members of the public to make a limited number of queries and get back cryptographic proofs of some parts of the blockchain state. These blockchains may be considered “partially decentralized”[4].

Fully Private Blockchains. A fully private blockchain is a blockchain where write permissions are kept centralized to one organization. Read permissions may be public or restricted to an arbitrary extent. Likely applications include database management, auditing, etc internal to a single company, and so public readability may not be necessary in many

[3] `https://blog.ethereum.org/2015/08/07/on-public-and-private-blockchains/`

[4] `https://blog.ethereum.org/2015/08/07/on-public-and-private-blockchains/`

cases at all, though in other cases public auditability is desired [5].

Smart Contracts. Smart contracts are contracts whose terms are recorded in a computer language instead of legal language that can be designed to enact legal contracts or regulations. Smart contracts can be automatically executed by a computing system, such as a suitable distributed ledger system in response to changes in the ledger, in real time. The potential benefits of smart contracts include reduction in contracting, enforcement, and compliance costs; consequently it becomes economically viable to form contracts over numerous low-value transactions. The potential risks include a reliance on the computing system that executes the contract.

Multi-chain, Off-Chain, Side-Chain and Pegged-Chain Blockchains. Recently, there has been emergence of blockchain platforms and architectures which enable multiple blockchains to interact, these include variations known as multi-chain, off-chain, side-chain and pegged-chain variants of blockchain architectures, see discussions in Back *et al.* [2014].

3.0.1 A Blockchain is not exactly a Database

In terms of applications of blockchain technology, one could argue that we are still in the exploration phase. It is prudent to be cautious about claims that this technology, particularly in its ‘permissioned blockchain’ form when being used in fields as diverse as banking, insurance, accounting etc. In particular, it would be useful to explore exactly what advantages blockchains have compared to well-understood transaction recording technologies, such as databases. In fact one could think of a blockchain as a technology for creating structured repositories of information, often termed a ledger in blockchain parlance. This can be strongly linked to similar understanding of a database. For instance, when talking about a ledger for financial assets. This of course could be represented in a database table, where in the simplest form each row represents one asset type owned by one particular entity. It has a number of attributes, one per column indicating information such as the owners identifier, an identifier for the asset type and the quantity of that asset.

We can think of blockchain in the simplest form as a technology that allows for such ledgers to be managed with multiple participants. In simple forms of blockchain technology, each participant will in some cases also run “nodes” in the blockchain network which hold a copy of the database. Their role is then to transmit transactions to other nodes in a peer-to-peer fashion, these transactions from mutiple participants can occur in a blockchain typically with out requiring the trust of all the participants. This brings us to considerations such as those discussed in Peters & Panayi [2015] which consider data integrity and governance considerations via the blockchain technologies ability to offer disintermediation. So we learn that a blockchain is a technology that allows us to utilise a database with multiple non-trusting participants, which doesnt necessarily require a trusted intermediary. Versions of the blockchain architecture such as those developed in Bitcoin removed the requirement for trusted intermediaries by extending the definition of a transaction, ie. a modification to the database entry, to include a proof of authorization and a proof of validity. This relates to the data integrity protocols discussed in Peters & Panayi [2015] as several approaches can be adopted to achieve this in blockchain technologies. Upon this extended definition of a transaction, it allows the removal of intermediaries since now transactions can be independently verified and processed by every node in the network which maintains a copy of the database.

[5] `https://blog.ethereum.org/2015/08/07/on-public-and-private-blockchains/`

To move beyond this simple description and understand further the differences between blockchain and standard database technologies, we first discuss about the types and capabilities of modern databases. Depending on the nature of the data one is storing, there are five genres of databases (Redmond & Wilson [2012]):

- Relational databases, such as SQL and variants, which are based on set theory and implemented as two-dimensional tables;
- Key-value stores, which store pairs of keys and values for fast retrieval;
- Columnar databases, which store data in columns, and can have more efficient representations of sparse tables compared to relational databases;
- Document databases; and
- Graph databases, which model data as nodes and relationships.

Databases can be centralised (residing at a single site) or distributed over many sites and connected by a computer network. We will focus on the latter, given the closer proximity to the blockchain concept.

Distributed Databases and Blockchain. In several blockchain platforms emerging, they are begining to utilise connections between the blockchain ledger and some version of a distributed data base for secure off-chain data storage. It is therefore useful to recall the difference between a blockchain and a distributed database.

A distributed database is a database in which portions of the database are stored in multiple physical locations and processing is distributed among multiple database nodes.

A centralized distributed database management system (DDBMS) integrates the data logically so it can be managed as if it were all stored in the same location. The DDBMS synchronizes all the data periodically and ensures that updates and deletes performed on the data at one location will be automatically reflected in the data stored elsewhere.

Distributed databases can be homogenous or heterogeneous. In a homeogenous distributed database system, all the physical locations have the same underlying hardware and run the same operating systems and database applications. In a heterogeneous distributed database, the hardware, operating systems or database applications may be different at each of the locations.

The objective of a distributed database is to partition larger information retrieval and processing problems into smaller ones, in order to be able to solve them more efficiently. In such databases, a user does not, as a general rule, need to be aware of the database network topology or the distribution of data across the different nodes. It should also be noted that in a distributed database, the connected nodes need not be homogeneous, in terms of the data that they store (Elmasri & Navathe [2014]).

Because of the design of these databases and the replication of data across different nodes, such a database has several advantages (Elmasri & Navathe [2014] (p. 882)):

- Better reliability and availability, where localised faults do not make the system unavailable;
- Improved performance / throughput;
- Easier expansion.

In every distributed database, however, there is the issue of how modifications to the databases are propagated to the various nodes that should hold that data. The traditional approach is a 'master-slave' relationship, where updates to a master database are then propagated to the various slaves. However, this means that the master database can become a bottleneck for performance. In multi-master replication[6] modifications can be made to any copy of the data, and then propagated to the others. There is a problem in this case also, when two copies of the data get modified by different write commands simultaneously.

A blockchain could be seen as a new type of distributed database which can help prevent such conflicts. In the same way that the Bitcoin network will reject a transaction where the Bitcoin balance to be transferred has already been 'spent', a blockchain can extend the operation of distributed databases by rejecting transactions which, e.g. delete a row that has already been deleted by a previous transaction (where a modification is a deletion, followed by the creation of a new row).

A second difference between blockchains and distributed databases lies in the ability to create self-enforcing contracts that will modify the blockchain's data. Many permissioned blockchains have a built-in virtual machine, such that one can execute pieces of computer code on the network. If this virtual machine is Turing-complete, this means that the machine can potentially solve a very large set of problems, which is very useful for executing more complex transactions on the network, possibly conditional on the state of certain off-chain variables.

The proliferation of databases as data stores has spawned considerations regarding data-related aspects, such as security, confidentiality and integrity. We argue that discussions around these issues will be important for blockchain technologies too, if they are to be successful in a business enterprise setting. In the following section we discuss these security aspects in depth and comment on blockchain attributes with regard to them.

So far we can conclude that blockchains are a sensible technology when we wish to consider a set of databases that is to be shared by multiple participant contributors all of whom can modify the database directly, in an environment in which no trust is required between members of the network. Furthermore, we can see that blockchains further differentiate themselves from direct database solutions when we begin to consider transactions of multiple participants that interact or have dependencies on transactions of other blockchain member participants in non-trivial manner with each other.

A key feature of emerging blockchain technologies that is expected to facilitate their uptake over existing database solution technologies is the relative ease that transactions can be created jointly by multiple participants, without either party exposing themselves to risk. Such technologies are expected to facilitate all types of useful exchange processing and reporting functionality such as payment settlement which can in principle under such technology be performed safely over a blockchain, without requiring a trusted intermediary.

3.1 Overview of Blockchain Emerging in Electronic Exchanges

It is now the case that several major electronic exchange venues and clearing houses are exploring the capabilities of blockchain technology for trade processing. An example of this was the US stock exchange provider Nasdaq launching a blockchain prototype last fall known as Linq [7]. They can be quoted as stating that they believe that "*blockchain holds potential for 99% reduced settlement time and risk exposure in capital markets.*"

As of Dec. 30, 2015 Linq blockchain ledger was used successfully to complete and record a private securities transaction which represented the first of its kind using blockchain tech-

[6] http://www.multichain.com/blog/2015/07/bitcoin-vs-blockchain-debate/

[7] http://ir.nasdaq.com/releasedetail.cfm?ReleaseID=948326

nology. This transaction marked a real demonstration of this conceptual technology in real use case and therefore represents a major advance in the application of blockchain technology for private companies.

In creating this "transaction" under Linq the issuer was able to digitally represent a record of ownership, while significantly reducing settlement time and eliminating the need for paper stock certificates. Furthermore, elements of trade reporting are starting to be considered in applications like Linq. For instance, in addition to its equity management function, Nasdaq Linq also provides issuers and investors an ability to complete and execute subscription documents online. Other applications of Linq include the use of blockchain for trade settlement transactions in public electronic exchanges. It is argued by Nasdaq that "*blockchain technology has the potential to assist in expediting trade clearing and settlement from the current equity market standards of three days to as little as ten minutes. This technology could allow issuers to significantly lower the risk and the administrative burden of what is largely a manual and multi-step process today*".[8]

Various other important use cases are being explore with payment systems, credit card systems, banking systems and exchanges. Below we mention 10 major stock and commodities exchanges have so far publicly announced their intention to explore blockchain technologies.

There are also industry working groups being initiated such as the Post-Trade Distributed Ledger (PTDL) Group which was an initiative launched in 2015 by a number of banks, clearing houses and exchanges. It currently has around 37 financial institutions as members, with its organization committee being composed of CME Group, Euroclear, HSBC, the London Stock Exchange and UniCredit with additional active members such as LCH.Clearnet, Societe Generale and UBS [9].

Furthermore, there was a recent unveiling of the Global Blockchain Council (GBC) which is a 46-member consortium of startups, financial firms and technology companies that was established to review the technology and its impact, [10]. This consortium includes Dubai Trade, Dubai Gold and Commodities Exchange, Emirates, Moe Levin and Dubai Department of Economic Development and falls under the strategic direction of UAE leadership. It is quoated by HE Mohammed Al Gergawi , Vice Chairman and Manging Director of Dubai Future Foundation that "*...blockchain technology, which is expected to have a market value of USD 290 Billion by 2019, will contribute massively in elevating the level of the smart services provided to citizens from cost, time and efficiency perspectives...*"[11].

The following core exchange groups are looking at ways to adopt blockchain technology[12]:

- *Australian Securities Exchange (ASX)*. ASX group have reportedly invested more than $10m in industry startup Digital Asset Holdings in January as part of its R&D efforts towards blockchain iniatives. ASX has also publicly revealed that it would aim to develop a new post-trade settlement system to be developed by Digital Asset using a distributed ledger architecture.

- *CME Group*. This group was one of the initial founders of the "Post-Trade Distributed Ledger Working Group" via its investment arm, CME Ventures. It has been reported that CME Group has contributed to funding rounds raised by distributed ledger startup Ripple, blockchain investment conglomerate Digital Currency Group and Digital Asset Holdings.

[8] http://ir.nasdaq.com/releasedetail.cfm?ReleaseID=948326
[9] http://www.coindesk.com/ptdl-group-37-members-post-trade-ledgers/
[10] http://www.coindesk.com/dubai-government-backs-expansive-blockchain-tech-research-effort/
[11] https://menaherald.com/en/2016/06/12/global-blockchain-council-meeting-introduces-seven-pilot-proj
[12] http://www.coindesk.com/10-stock-exchanges-blockchain/

- *Deutsche Borse*. This group operates the primary stoch exchange in Frankfurt, Germany. This group also participated in the funding round of Digital Asset Holdings with $60m funding.

- *Dubai Multi Commodities Centre*. This is part of the GBC developed in the UAE. The DMCC is a special economic zone and commodities center that oversees trading of precious metals and other tangible goods. The new initiatives starting from this GBC and the DMCC include:

  - "FlexiDesk" which is the first pilot project of the GBC which involves cooperation between BitOasis and DMCC to find practical applications for Blockchain technology. The project is aimed at facilitating DMCCs transactions in line with Dubai Plan 2021 by accelerating services and achieving high efficiency at lower costs.; and
  - "Trade Flow" which is the second project by DMCC that will provide digital financial transaction services using Blockchain technology. The project will also help significantly reduce costs, increase operations security, unify transactions procedures.

- *Japan Exchange Group (JPX)*. This group announced its interest in blockchain technologies with the news it had formally partnered with IBM as a user of its Blockchain-as-a-Service (BaaS) offering. The initial reports are that the JPX group is studying proof-of-concept for blockchain technologies use in creating new systems for the trading of low-liquidity assets. Further collaborations in this regard are also taking place with JPX and Nomura Research Institute who are investigating how such technologies may apply to securities markets.

- *Korea Securities Exchange*. The KSE announced it would aim to launch an over-the-counter trading platform using blockchain technology.

- *London Stock Exchange (LSE)*. This group was also one of the founders of the previously mentioned Post-Trade Distributed Ledger Working Group. It has been actively linked with startup R3. In addition, LSE is one of the initial clients of IBMs Blockchain-as-a-Service (BaaS) offering alongside Kouvola Innovation and Japan Exchange Group.

- *Nasdaq*. This group was the first US stock market operator to take a blockchain proof-of-concept live when it debuted its private shares trading platform, Linq, in 2015. It also has a partnership with the blockchain solutions provider Chain. Further developments from Nasdaq include working to develop a trial with the Nasdaq OMX Tallinn Stock Exchange in Estonia.

- *New York Stock Exchange (NYSE)*. This group have made two important announcements publicy about blockchain technologies. The NYSE invested in bitcoin services firm Coinbase as part of its $75m Series C funding round. In addition the NYSE are in the process of launching a bitcoin pricing index, a competitor to CoinDesks Bitcoin Price Index (BPI).

- *TMX Group*. This group runs the Toronto Stock Exchange and has actively explored avenues with smart contracts and recently hired Anthony Di Iorio, one of the co-founders of the Ethereum project, as its first chief digital officer.

We see that blockchain technologies are expected to make a significant impact on several aspects of automation in electronic exchanges, below we discuss a few important cases that pertain to satisfying the regulatory standards on transaction transparency and pre and post trade reporting.

3.2 Existing Blockchain Platforms Relevant to Pre and Post Trade Transaction Reporting

Below we discuss a few emerging blockchain platforms that are being widely considered as discussed previously by different market participants. We discuss Ethereum Ethereum.org [2016], Enigma mit.edu [2016], Blockchain as a Service (BaaS) microsoft.com [2016] , Hyper Ledger project Hyperledger.org [2016] , Lykke Lykke.com [2016] and MultiChain MultiChain [n.d.]

3.2.1 Ethereum

Initially purposed in a white paper by Vitalik Buterin in late 2013, Ethereum is an open platform which allows users to build Smart Contracts on decentralized applications. It is an initiative that is developed by the Ethereum Foundation, which is a Swiss non profit organization. [13] [14] Wood [2014]

Ethereum platform has developed it's own propriety language, known as Solidity. This language is purpose built for Smart contract design and combines on the Ethereum platform with a decentralised virtual machine known as Ethereum Virtual Machine (EVM). However, the name Etherium derives from the platforms adoption of unit of currency in the platform known as Ether, it's own cryptocurrency for use in the platform, see discussions in Peters *et al.* [2015]. Ethers are used to pay for computational resource in the EVM. The base unit of ether is called Wei, and it goes up in a metric system up until the Ether, which value is 1,000,000,000,000,000,000 Wei. There are numerous ways to obtain Ether such as: Mining; Buying Ether via other currencies; and Buying Ether using Mist Ethereum GUI Wallet.

To understand the extent of Ethereum considered potential, in 2014 it was Crowd funded and raised over 18 million dollars in less then a month, which created a bit more then 60 Million Ether tokens. it is currently the sixth highest funded crowdfunding project. [15]

Ethereum Virtual Machine (EVM)

The EVM represents a runtime environment for smart contracts in Ethereum. It runs code in complete isolation, i.e. the executed code has no access to the network, file system or other processes. Smart contracts even have limited access to other smart contracts. Contracts are compiled to byte code by the EVM compiler, and uploaded to the blockchain.

In the heart of the Ethereum system sites the Ethereum Virtual Machine (EVM) which can execute code of arbitrary algorithmic complexity. This makes Ethereum Turing complete (can be used to simulate any single-taped Turing machine). Developers can write code in existing languages like JavaScript and python that will run on the EVM.

Solidity

Solidity is one of two programming languages that have been specifically designed to target the EVM. It's syntax is similar to JavaScript, and it is used to write Smart Contracts on EVM. It is currently available as an extension for on Microsoft Visual Studio Platform [16]

[13] Ethereum Project `https://www.ethereum.org/`

[14] Ethereum white paper `http://vbuterin.com/ethereum.html`

[15] `https://en.wikipedia.org/wiki/List_of_highest_funded_crowdfunding_projects`

[16] `https://visualstudiogallery.msdn.microsoft.com/96221853-33c4-4531-bdd5-d2ea5acc4799`

and on consensys platform [17]

Ethereum and the DAO project
Ethereum had been used in the last couple of years as the platform for decentralized applications. The most know is probably the DAO [18] which aims to provide a new decentralized business model.

The DAO was crowd-funded in May 2016 and raised 160 Million dollars held in the Ether cryptocurrency. It was the biggest crowd-fund in history. In June 2016 the DAO was hacked and around 45 Millions dollars worth of Ether were stolen [19]. In order to restore stability to Ethereum the DAO code was forked, which as a result Ethereum was broken into two separate active cryptocurrencies. There is also recently the Ethereum homestead release which is the blockchain application tool.

3.2.2 Enigma

Enigma is a new Decentralized Computation cloud platform from MIT with guaranteed privacy Zyskind *et al.* [2015]. Enigma offers privacy by distribution of data between nodes where no node has access to the data in full. Computation is run on the nodes without the need to reveal the full information to other nodes. Since data is not replicated on each node it gives the platform the ability to scale horizontally.

Key features of Enigma: the two main features that Enigma offers users as a blockchain platform are each critical for the applications we are studying in this paper, they include - Privacy and Scalability.

In terms of privacy, this is achieved in Enigma through its use of a secure multi party computation model. In this framework, queries are done in a distributed way without a governing trusted third party being required. Furthermore, the computation is split between different nodes and no single node has access to the other nodes data. Each node only sees part of the data which has no value or meaning on its own.

With respect to scalability, this is achieved by the fact that data is not being replicated to every node in the network. The computation is being done on a small subset of nodes which hold different parts of the data. This enables Enigma to run more demanding computations and require significantly less storage requirements.

One of the possible application for Enigma is as a Distributed Personal Data Stores which fits our usage case for personal trader data information, see discussion in Enigma document Section 8.7 where it states: "*Store and share data with third parties while maintaining control and ownership. Set specific policies for each service with private contracts. Identity is truly protected since the decision to share data is Always reversible - services have no access to raw data, all they can do is run secure computation*".

At the time of writing it is possible to register to Beta test of the platform which is not open yet [20].

Enigma Design: the framework of Enigma off loads private and intensive computation work from an existing Blockchain to an off-chain network. It also provides a scalable Turing complete scripting language for handling private contracts (with private information). An

[17] https://consensys.net/
[18] https://daohub.org/
[19] http://vessenes.com/deconstructing-thedao-attack-a-brief-code-tour/
[20] Enigma paper http://wwww.mit.edu.ac/enigma_full.pdf

Interpreter will break down the execution of this private contract which in addition to privacy also improves the run time of the code.

Through the use of off-chain processing and storage it is possible for Enigma to solve data capacity problems, it enforces the privacy of computation by allowing each node to execute code without leaking data to the other nodes, and solves scalability problems when heavy computation is needed on the chain. Enigma performs the heavy computation on the off-chain and broadcast the results to the Blockchain.

The off-chain storage creates a distributed database, where every node has a distinct view of the data. It is possible to store large public data in the off-chain and link it to the blockchain. The distribution is based on a Kademlia DHT protocol which was modified for Enigma.

Distributed Hash Table (DHT): a distributed hash table (DHT) provides a look-up service similar to a Key-Value hash table, but does so in a decentralized distributed manner. The Key-Value pair can be stored in any participating node and the Key-Value mapping is then maintained by all nodes. This allows a DHT to scale on a very large number of nodes. DHT, which was in part originally motivated by peer-to-peer (P2P) systems can be used to build complex infrastructures like distributed file systems, P2P file sharing and content distribution. There are three key properties of a DHT which include, see discussion in :

- *Autonomy and decentralization*: all the nodes construct the system without any centralized governance.
- *Fault tolerance*: the system will continue to w0rk as usual when nodes are added/removed or suffer a from a failure.
- *Scalability*: the system can scale up to millions of nodes and continue to work as normal.

In Enigma, the blockchain acts an interface between the off-chain DHT architecture which stores references to data in a decentralized manner and the actual data of interest, which is first encrypted on the client side before storage and access protocols are enacted in the blockchain or on off-chain distributed data-bases. However, since the Engima blockchain does not replicate the data over all nodes in the network, instead only requiring a small subset of such nodes to perform each computation over different parts of the data, this allows for efficiency gains. The off-chain storage of data occurs with off-chain nodes constructing a distributed database.

In Zyskind *et al.* [2015] they explain how Enigma offers a combination of off-chain storage and blockchain storage for data. In this structure, each node will have a specific unique view of what they term 'shares' in the total data (a portion of the total data) as well as the encrypted data, where the share is set up in such a manner to guarantee privacy preservation and fault tolerance. In addition, this architecture also allows for large public data storage that may be linked to the blockchain and un-encrypted for all participants to access. The manner that this is achieve in a network architecture is known as Kademlia DHT (see **?**) with enhancements for the Enigma use case.

3.2.3 Blockchain-as-a-Service (BaaS)

Blockchain-as-a-Service (Baas) is a new addition to the fast changing blockchain ecosystem. BaaS lets developers build applications with Blockchain capabilities without the need to directly manage and handle the storage, middleware and other core functionalities. Microsoft, IBM and very soon Amazon are all big industry names who provide BaaS which runs on their Platform-as-a-Service (PaaS).

Microsoft Azure BaaS Platform: as part of **Microsoft Azure** cloud service, Microsoft offers now a BaaS solution which lets the user develop, test and deploy Blockchain applications [21]

This service opens the Ethereum protocol to a wider variety of users and developers. The BasS solution is tied very well to the Microsoft Ecosystem and development products and offers the distributed ledger protocol of Ethereum as a secure and efficient platform to build applications. In addition it also has a built in smart contract extension to the visual studio environment like Solidity. [22] In June 2016 Microsoft released Project Bletchley which expands the blockchain capabilities in the areas of security, middleware, and BI.

IBM Bluemix PaaS and Hyperledger BaaS : in lign with other large technology companies, IBM also now offers BaaS solutions which run on IBM **Bluemix** PaaS [23]. The IBM solution provides convenient ways to test an IBM Blockchain network on the cloud and is built on top of the Linux Foundations's Hyperledger Project open source code which IBM contributes to.

IBM Blockchain building blocks [24] consist of Blockchain network, creation and storage of digital records using chiancode and creating transaction sign chaincode where it is claimed that "*IBM Cloud sets the essential standard for tamper-proof, secure blockchain networks, enabling you to meet crucial regulatory and data protection standards*".

3.2.4 Hyperledger Project

The Hyperledger Project [25] is a collaborative cross industry initiative started by the Linux Foundation in December 2015. The Linux Foundation (LF) is a non-profit technology trade association which is chartered to promote, protect and advance Linux and collaborative development. In this regard they are a significant driver of joint industry innovations in blockchain technologies. The aim of their hyperledger initiative is to crate advances blockchain technology with the main goal being to develop cross industry ledgers in order to change the way transactions are done globally. Some major companies like IBM, Accenture, Intel, JP Morgan and the CME group are heavily engaged in this project.

The project aims to bring together numerous independent efforts to develop open protocols and standards, by providing a modular framework that supports different components for different uses. In this universe of blockchains, many can co-exist and maintain their own versions of featurs such as: consensus and storage models, and services for identity, access control, and contracts.

3.2.5 Lykke Blockchain Project

Richard Olsson's Lykke project is another new initiative thats taking shape in the blockchain universe, which in the founders words aims to "*...build an efficient marketplace with immediate settlement*"[26]. Initially it will provide a trading platform for currencies, clearly building

[21] Blockchain as a Service `https://azure.microsoft.com/en-us/solutions/blockchain/`

[22] Solidity extension `https://visualstudiogallery.msdn.microsoft.com/96221853-33c4-4531-bdd5-d2ea5acc4799`

[23] `http://www.ibm.com/blockchain/bluemix.html`

[24] `http://www.ibm.com/blockchain/for_developers.html`

[25] `https://www.hyperledger.org/`

[26] `https://www.leaprate.com/2015/09/richard-olsen-of-oanda-fame-on-his-new-startup-lykke-leaprate-in`

upon the experience of the founder and former chairman of Canadian foreign exchange company OANDA, Richard Olsen. Lykke is described as a global marketplace for multiple assets and financial instrument built on the Bitcoin blockchain. The aim of this service is to utilise "*the Bitcoin blockchain as a global notary service to record and settle all types of transactions*"[27].

The guidelines on the functionality of the Lykke 'exchange' [28] include description of how to establish trading on LykkeX, detailing the market structure, the instrument types traded, the trading methods, the registration of OTC-trades, order types and order functionalities such as insertion, modification and deletion of trades in a Lykke LOB.

In addition to trading platforms, the Lykke blockchain project is proposing Lykke City which involves a community made of Lykke Citizens or Inhabitants, whereby one can become a Lykke Citizen by registering on the website and provide KYC details including a mobile phone number, a photo and a copy of ID or passport. Such a registered citizen is then granted to obtain a number of rights such as the ability to form teams and democratic autonomic organizations, to vote for projects, initiatives and submissions, as well as the ability to receive, send and trade Lykke coins. To support the Lykke economy, the Lykke Corp. has mentioned maintaining a minimum of US$0.004 per Lykke coin until the end of 2016.

3.2.6 MultiChain

MultiChain[29] is an off the shelf private Blockchain Platform, which allow users to design deploy and operate distributed ledgers in a fast and easy way. MultiChain is developed by Coin Sciences LTD, a privately held company, and aims to be open source platform under the GPLv3 license[30] once it gets to Beta phase (plan 2016). MultiChain was forked from the Bitcoin Core [31] which means that the majority of Bitcoin documentation is applicable to MultiChain, and on top of that MultiChain adds the following features:

- *Off the shelf private Blockchains*: Easy and fast to develop and deploy.
- *Permission Management*: Controlled network which is controlled by one or more administrators.
- *Multi-Network*: Can connect to more then one network on a single server.

For developers it offers several tools and libraries inducing wrappers for the JSON-RPC libraries in C#, Javascript, PHP , Ruby and Python and a web based blockchain activity browsing tool.

4 Conclusions

This White-paper servers as an introduction to the modern electronic exchange markets and the latest regulatory changes and requirements that developed in recent years, and how Blockchain technology can play its part in the evolving process. It has given a review of different trading venue types and operations, such as Lit, MTFs and Dark pools, as well as the Limit Order Book Model which is the backbone of most exchanges. It gives a

[27] `https://lykke.com/exchange.php`
[28] `https://lykke.com/lykkex_rulebook.php`
[29] `http://www.multichain.com/download/MultiChain-White-Paper.pdf`
[30] `https://www.gnu.org/licenses/gpl-3.0.en.html`
[31] `https://bitcoin.org/en/download`

short summary of the regulations which effected the electronic markets in the last years. It then explains in more detail the role of Blockchain technology in regard to electronic markets and regulations, with specifics on the different types of ledgers such as permissioned, permisonless, distributed and controlled ledgers, and smart contracts. It also discusses the difference between blockchain and database technology. In the end it gives a survey of current blockchain platforms and their key attributes that are applicable to transaction pre and post trade reporting under new exchange regulations. We believe that blockchain, with some of the platforms introduced in this paper, will take a major role in the coming future of electronic markets in order to meet regulations and control processes being developed to manage risk and transparency in electronic exchanges.

References

Back, Adam, Corallo, Matt, Dashjr, Luke, Friedenbach, Mark, Maxwell, Gregory, Miller, Andrew, Poelstra, Andrew, Timón, Jorge, & Wuille, Pieter. 2014. Enabling blockchain innovations with pegged sidechains. *URL: http://www.opensciencereview.com/papers/123/enablingblockchain-innovations-with-pegged-sidechains.*

Commision, Eurepean. *Investment Services and regulated markets (MiFID 1 & MiFID 2).*

Commision, U.S Commodity Futures Trading. *Designated Contract Markets (DCMs).*

Commision, U.S Commodity Futures Trading. 2016. *Swaps Execution Facilities (SEFs).*

Commission, U.S. Commodity Futures Trading. 2013. Core Principles and Other Requirements for Swap Execution Facilities. *Commodity Futures Trading Commision available at* `http://www.cftc.gov/idc/groups/public/@newsroom/documents/file/federalregister051613b.pdf`.

Commission, U.S. Commodity Futures Trading. 2015. Dodd Frank Act. *U. C. F. T. Commision available at* `http://www.cftc.gov/LawRegulation/DoddFrankAct/index.htm`.

Degryse, Hans, Van Achter, Mark, & Wuyts, Gunther. 2008. Shedding light on dark liquidity pools.

ECB. *Money Market Statistical Reporting.*

Elmasri, Ramez, & Navathe, Shamkant B. 2014. *Fundamentals of database systems.* Pearson.

ESMA. *MiFID (II) and MiFIR.*

Ethereum.org. 2016. *Ethereum.* [Online; accessed 24-August-2016].

FCA. 2016. *EMIR.*

FIA. 2015. *Securities Financing Transaction Regulation (SFTR) and its impact on Commodities Markets.*

Gareth W. Peters, Guy R. Vishnia. 2017. *Blockchain Architectures for Electronic Exchange Reporting Requirements: EMIR, Dodd Frank, MiFID I/II, MiFIR, REMIT, Reg NMS and T2S.*

Gould, Martin D, Porter, Mason A, Williams, Stacy, McDonald, Mark, Fenn, Daniel J, & Howison, Sam D. 2013. Limit order books. *Quantitative Finance*, **13**(11), 1709–1742.

Gresse, Carole. 2015. Effects of lit and dark market fragmentation on liquidity. *Available at SSRN 1918473*.

Hyperledger.org. 2016. *Hyperledger*. [Online; accessed 24-August-2016].

Linklaters. 2016. *Organised Trading Facilitie*.

Lykke.com. 2016. *Lykke*. [Online; accessed 24-August-2016].

MaretWiki. 2016. *Organized Trading Facility*. [Online; accessed 24-August-2016].

microsoft.com. 2016. *Azure BaaS*. [Online; accessed 24-August-2016].

mit.edu. 2016. *Enigma*. [Online; accessed 24-August-2016].

Moloney, Niamh, *et al.* 2002. *EC securities regulation*. Oxford University Press Oxford.

MultiChain. *MultiChain*.

Panayi, Efstathios, & Peters, Gareth W. 2015. Stochastic simulation framework for the limit order book using liquidity-motivated agents. *International Journal of Financial Engineering*, **2**(02), 1550013.

Panayi, Efstathios, Peters, Gareth W, & Kosmidis, Ioannis. 2015. Liquidity commonality does not imply liquidity resilience commonality: a functional characterisation for ultra-high frequency cross-sectional LOB data. *Quantitative Finance*, **15**(10), 1737–1758.

Peters, Gareth William, & Panayi, Efstathios. 2015. Understanding Modern Banking Ledgers through Blockchain Technologies: Future of Transaction Processing and Smart Contracts on the Internet of Money. *Available at SSRN 2692487*.

Peters, Gareth William, Panayi, Efstathios, & Chapelle, Ariane. 2015. Trends in crypto-currencies and blockchain technologies: A monetary theory and regulation perspective. *Available at SSRN 2646618*.

Redmond, Eric, & Wilson, Jim R. 2012. *Seven databases in seven weeks: a guide to modern databases and the NoSQL movement*. Pragmatic Bookshelf.

Richards, Kylie-Anne, Peters, Gareth W, & Dunsmuir, William. 2015. Heavy-tailed features and dependence in limit order book volume profiles in futures markets. *International Journal of Financial Engineering*, **2**(03), 1550033.

Wood, Gavin. 2014. Ethereum: A secure decentralised generalised transaction ledger. *Ethereum Project Yellow Paper*.

Zyskind, Guy, Nathan, Oz, & Pentland, Alex. 2015. Enigma: Decentralized computation platform with guaranteed privacy. *arXiv preprint arXiv:1506.03471*.