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(54) **METHODS AND SYSTEMS FOR IMPLEMENTING MARKET MAKING STRATEGIES AT LOW LATENCY**

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(21) Appl. No.: **17/673,343**

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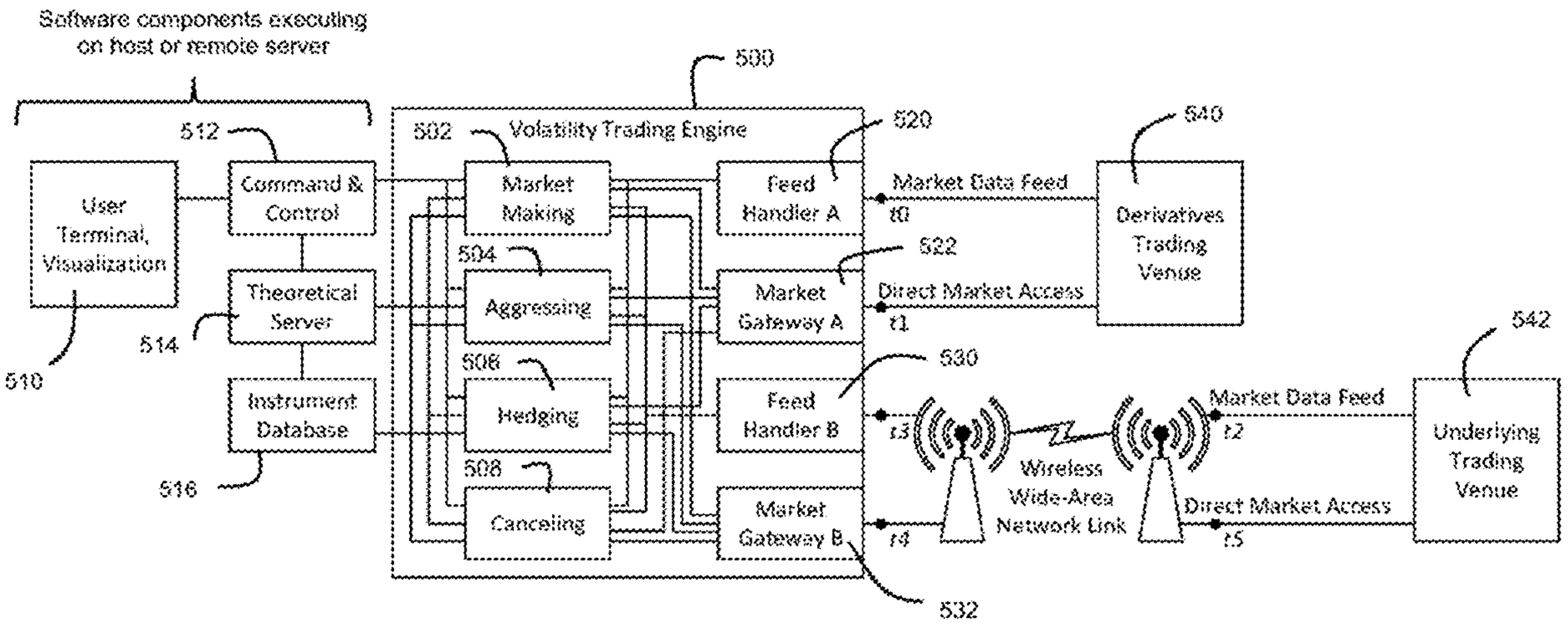
G06Q 30/02	(2006.01)

(52) **U.S. Cl.**

CPC ***G06Q 40/04*** (2013.01); ***G06Q 30/0201*** (2013.01); ***G06Q 40/06*** (2013.01)

(57) **ABSTRACT**

Disclosed herein are automated trading engine embodiments that operate on market data and re-engineer trading logic to operate on computational resources that are capable of providing highly parallelized and pipelined processing operations to improve tick to trade latency. As an example, logic resources for the automated trading engine can implement multiple market making strategies that post and cancel quotes on markets. Examples of market making strategies that can be implemented by the automated trading engine include basic market making, joining market making, and bettering market making. Further still, the market making strategies can be driven by low latency derivative pricing.



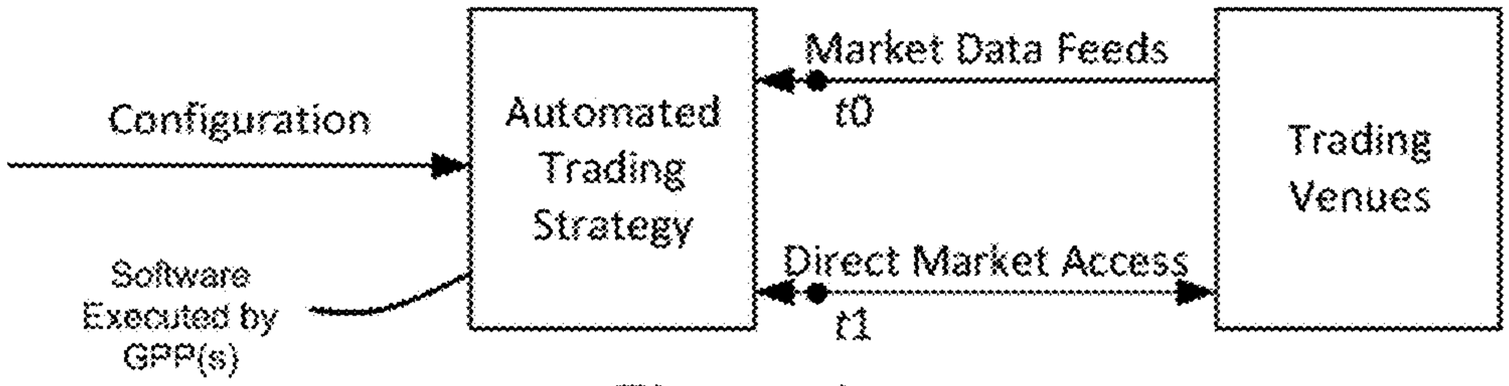


Figure 1

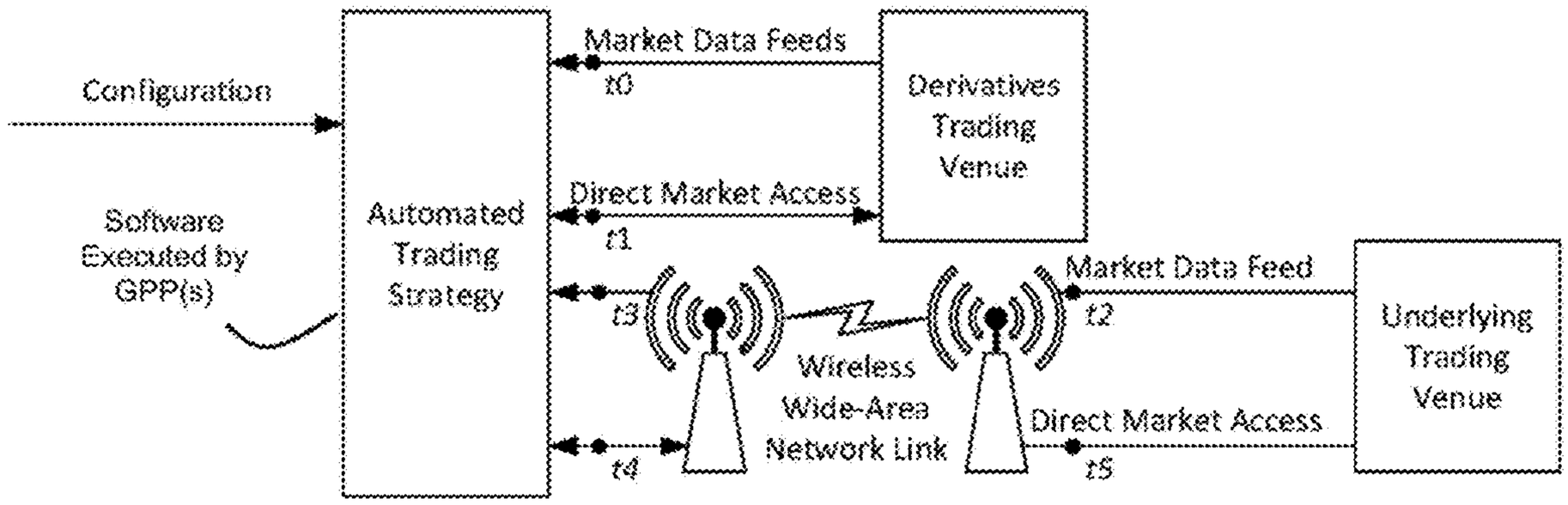


Figure 2

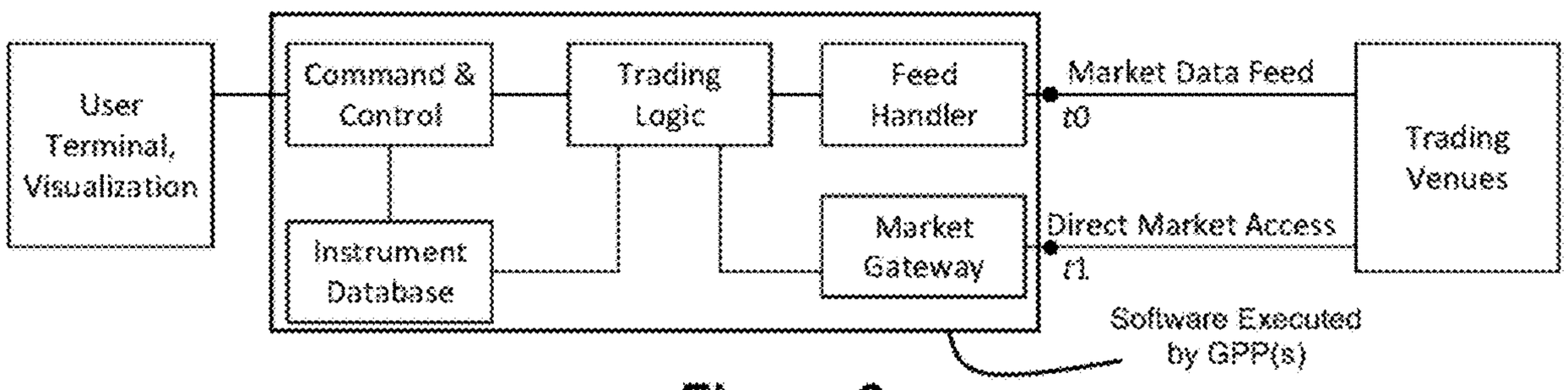


Figure 3

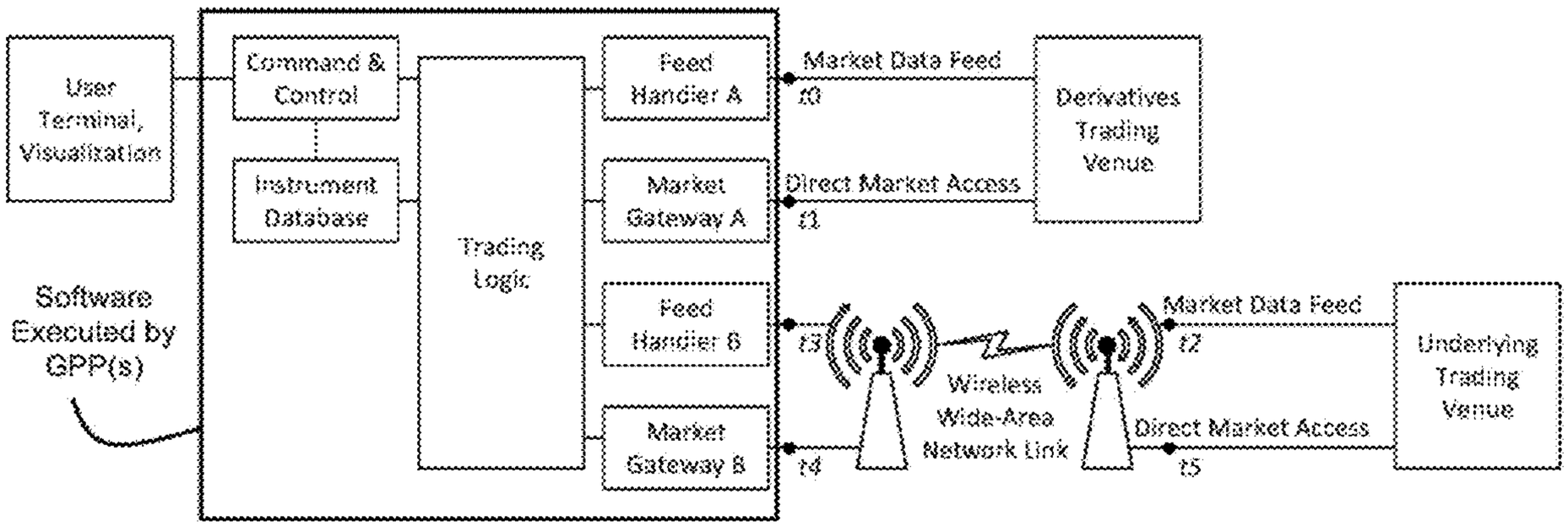


Figure 4

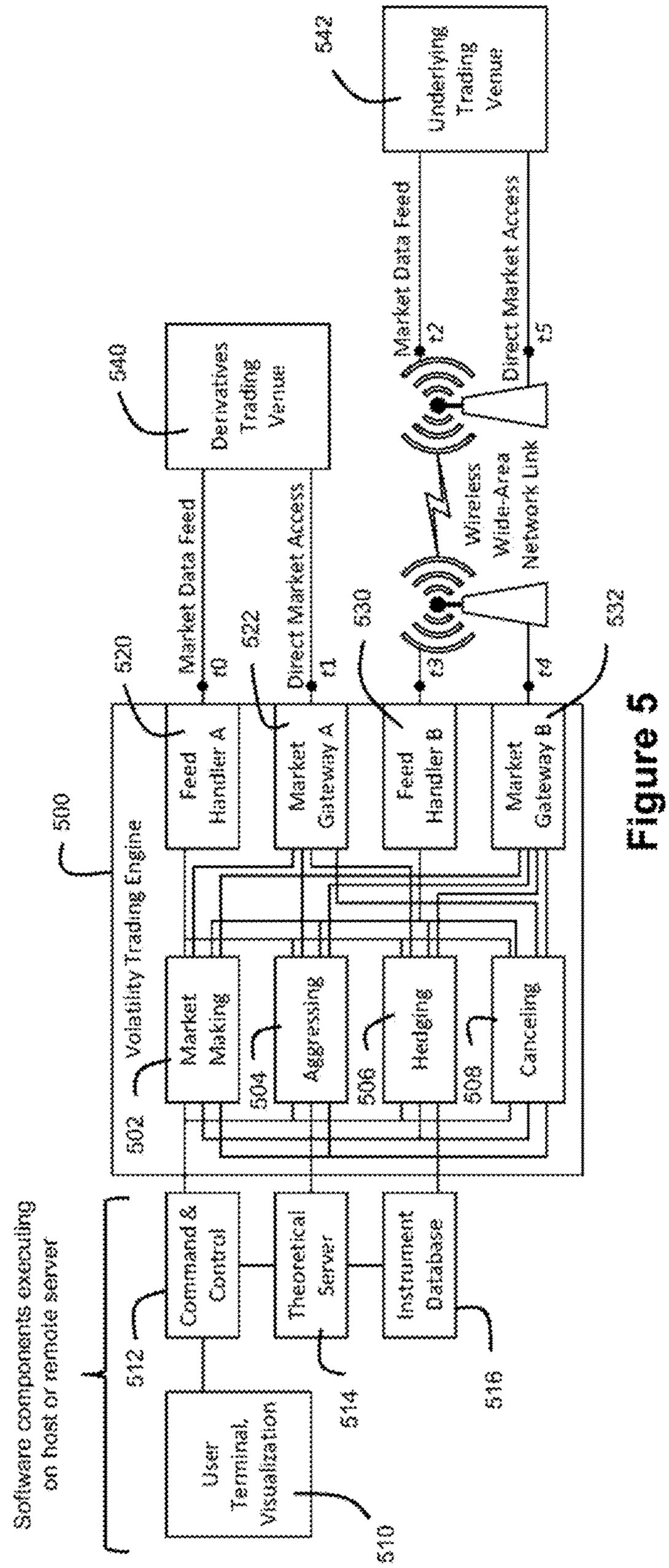

542
Underlying Trading Venue
Market Data Feed
t2
Direct Market Access
t5
540
Derivatives Trading Venue
Wireless Wide-Area Network Link
Market Data Feed
t0
522
Direct Market Access
t1
530
t3
t4
532
520
Feed Handler A
Market Gateway A
Feed Handler B
Market Gateway B
500
Volatility Trading Engine
502
Market Making
504
Aggressing
506
Hedging
508
Canceling
Software components executing on host or remote server
512
Command & Control
User Terminal, Visualization
514
Theoretical Server
516
Instrument Database
510

Figure 5

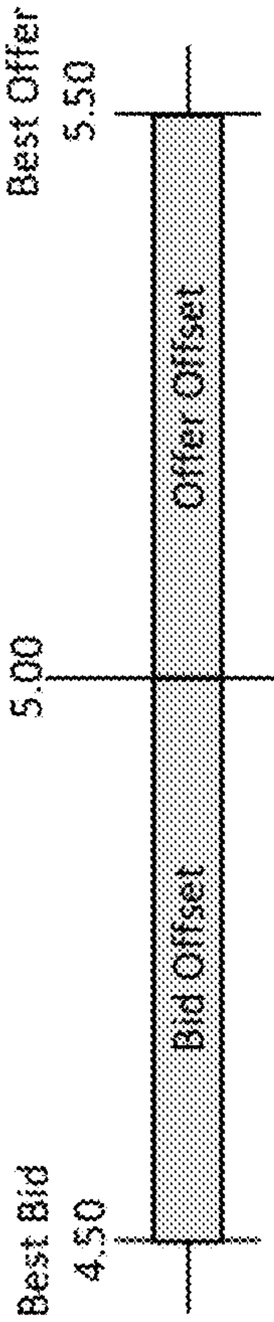


Figure 6A

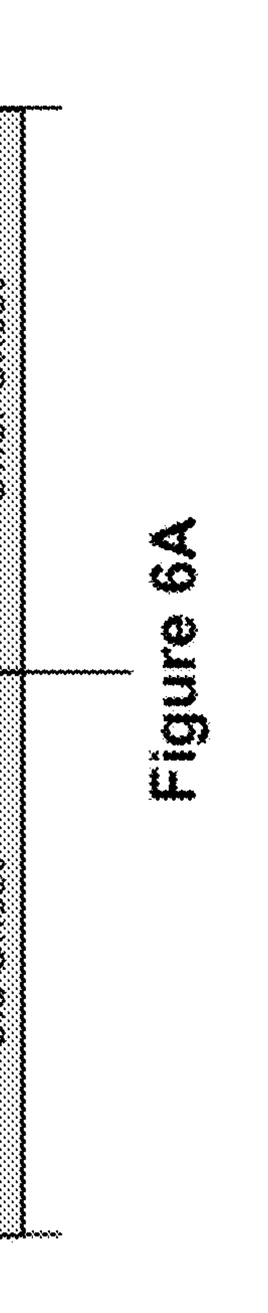


Figure 6B

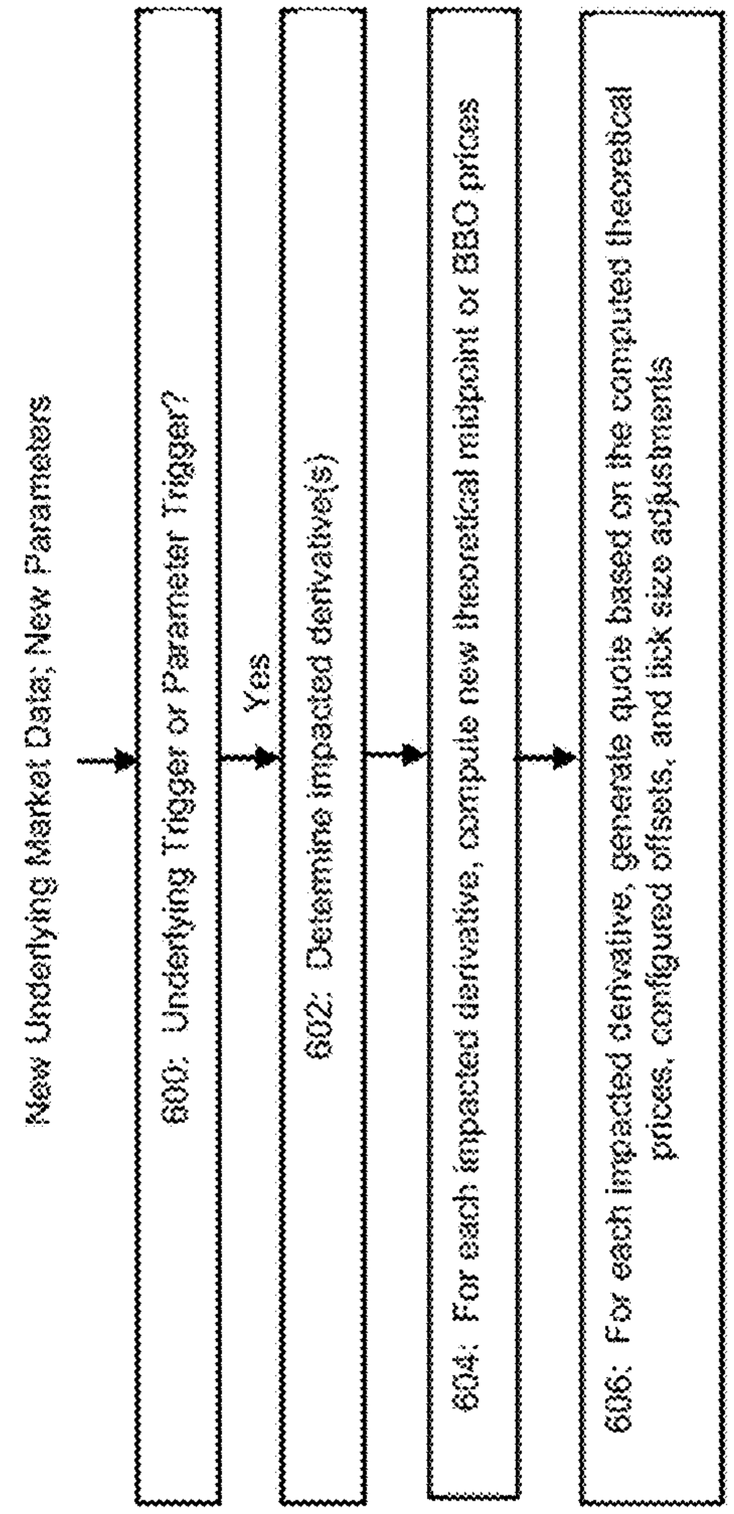


Figure 6C

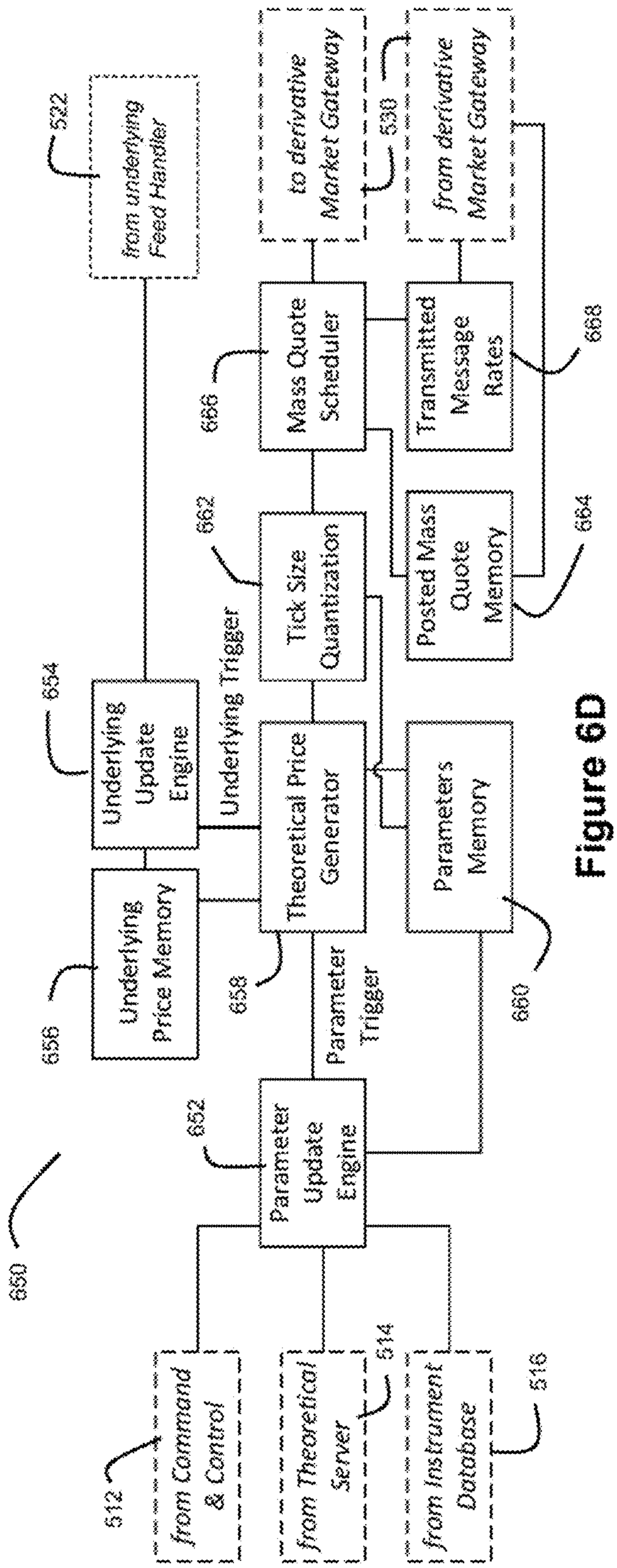

650
652
Parameter Update Engine
654
Underlying Update Engine
656
Underlying Price Memory
658
Theoretical Price Generator
660
Parameters Memory
662
Tick Size Quantization
664
Posted Mass Quote Memory
666
Mass Quote Scheduler
668
Transmitted Message Rates
Underlying Trigger
Parameter Trigger
512
from Command & Control
514
from Theoretical Server
516
from Instrument Database
522
from underlying Feed Handler
530
to derivative Market Gateway
from derivative Market Gateway

Figure 6D

$$T = T_{ref} + (\delta \times \Delta_{underlying})$$

Figure 7A

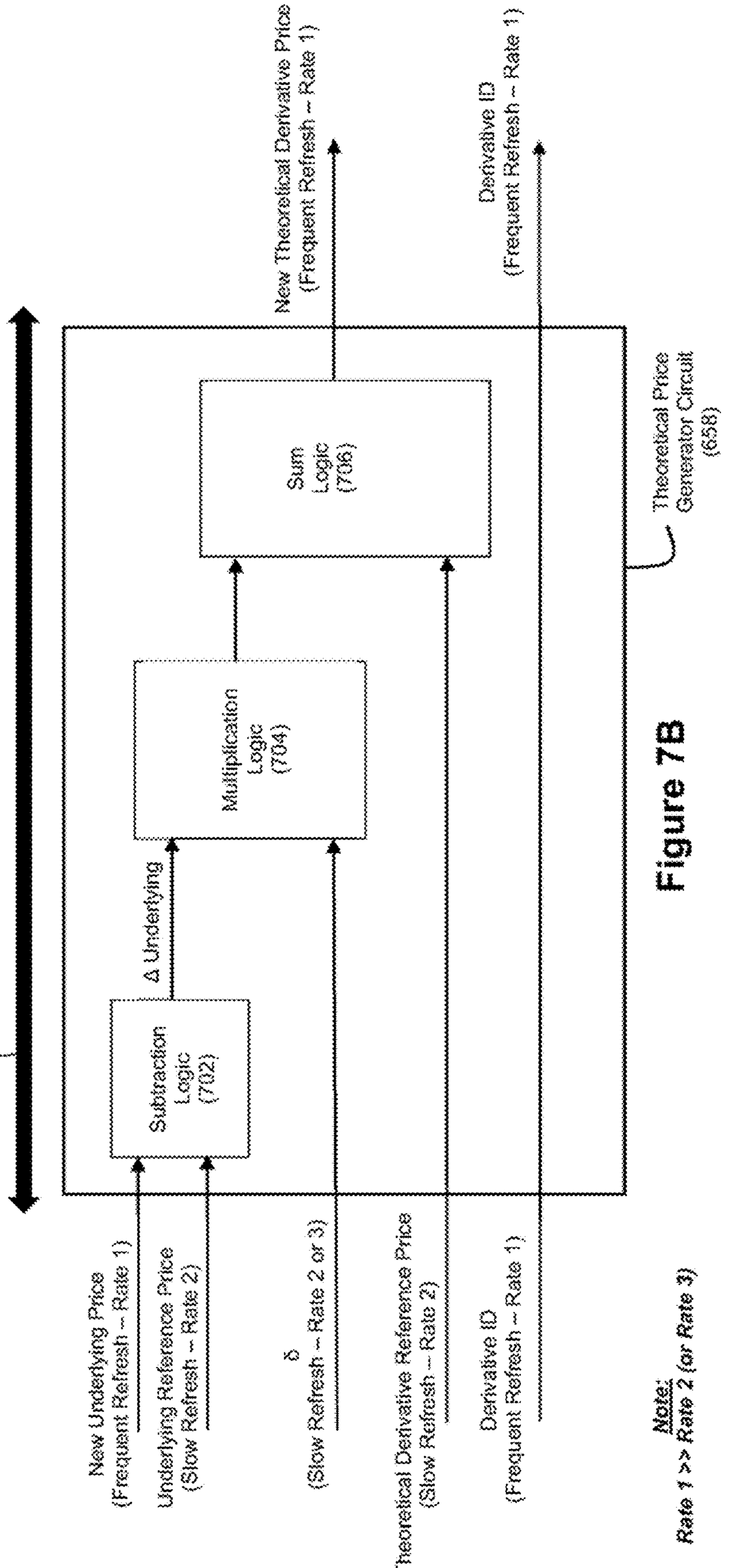


Figure 7B

Note:
Rate 1 >> Rate 2 (or Rate 3)

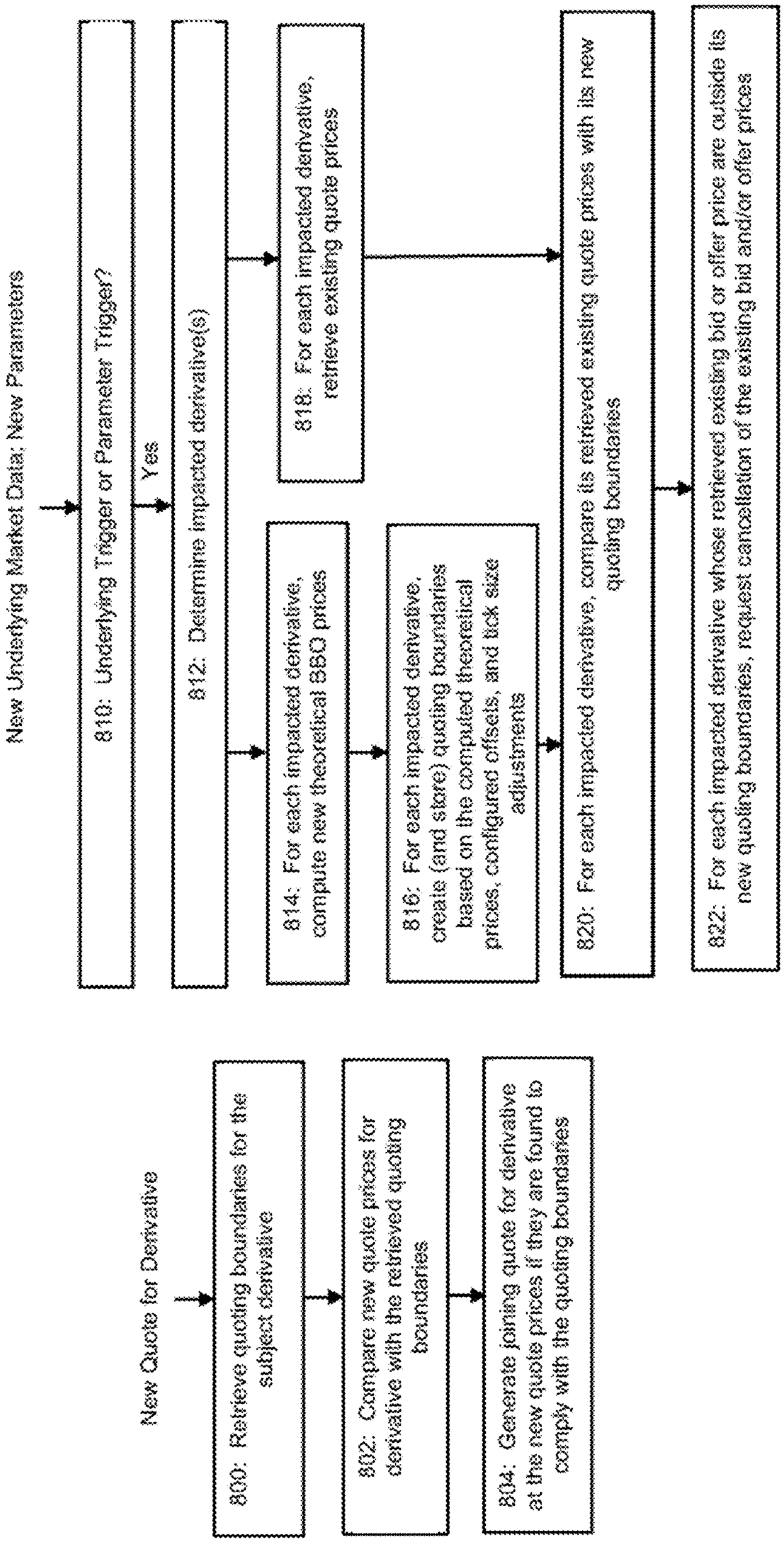

New Underlying Market Data; New Parameters
810: Underlying Trigger or Parameter Trigger?
Yes
812: Determine impacted derivative(s)
814: For each impacted derivative, compute new theoretical BBO prices
816: For each impacted derivative, create (and store) quoting boundaries based on the computed theoretical prices, configured offsets, and tick size adjustments
818: For each impacted derivative, retrieve existing quote prices
820: For each impacted derivative, compare its retrieved existing quote prices with its new quoting boundaries
822: For each impacted derivative whose retrieved existing bid or offer price are outside its new quoting boundaries, request cancellation of the existing bid and/or offer prices
New Quote for Derivative
800: Retrieve quoting boundaries for the subject derivative
802: Compare new quote prices for derivative with the retrieved quoting boundaries
804: Generate joining quote for derivative at the new quote prices if they are found to comply with the quoting boundaries

Figure 8A

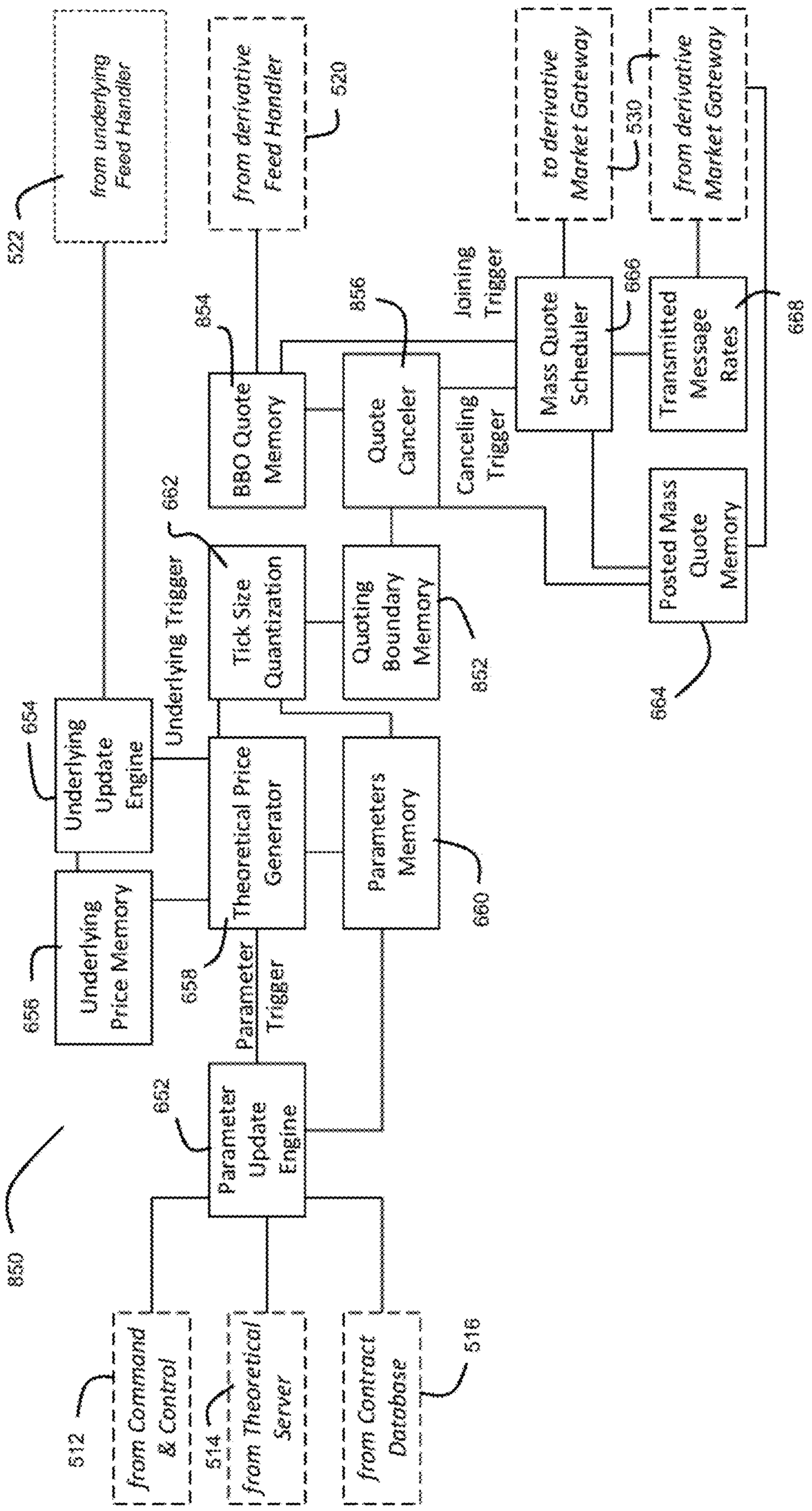

850
852
854
856
858
860
862
864
866
868
520
522
530
612
614
616
652
654
656
658
664
666
668
Underlying Update Engine
Underlying Price Memory
Theoretical Price Generator
Parameters Memory
Parameter Update Engine
Parameter Trigger
Underlying Trigger
Tick Size Quantization
Quoting Boundary Memory
BBO Quote Memory
Quote Canceler
Canceling Trigger
Joining Trigger
Mass Quote Scheduler
Posted Mass Quote Memory
Transmitted Message Rates
from underlying Feed Handler
from derivative Feed Handler
to derivative Market Gateway
from derivative Market Gateway
from Command & Control
from Theoretical Server
from Contract Database

Figure 8B

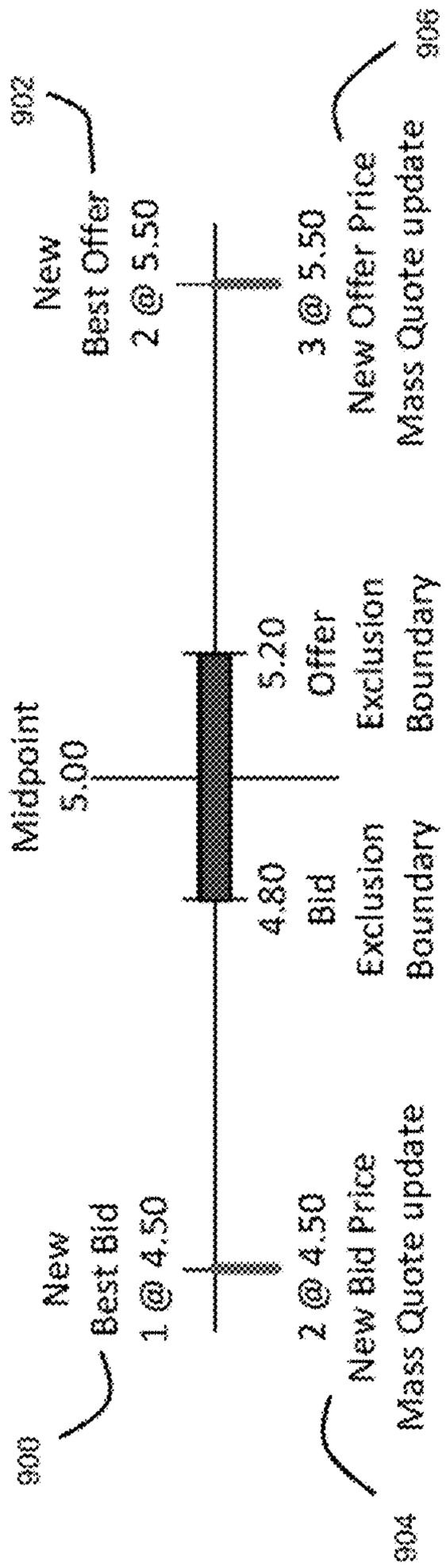

902
New
Best Offer
2 @ 5.50
3 @ 5.50
New Offer Price
Mass Quote update
906
Midpoint
5.00
5.20
Offer
Exclusion
Boundary
4.80
Bid
Exclusion
Boundary
908
New
Best Bid
1 @ 4.50
2 @ 4.50
New Bid Price
Mass Quote update
904

Figure 9

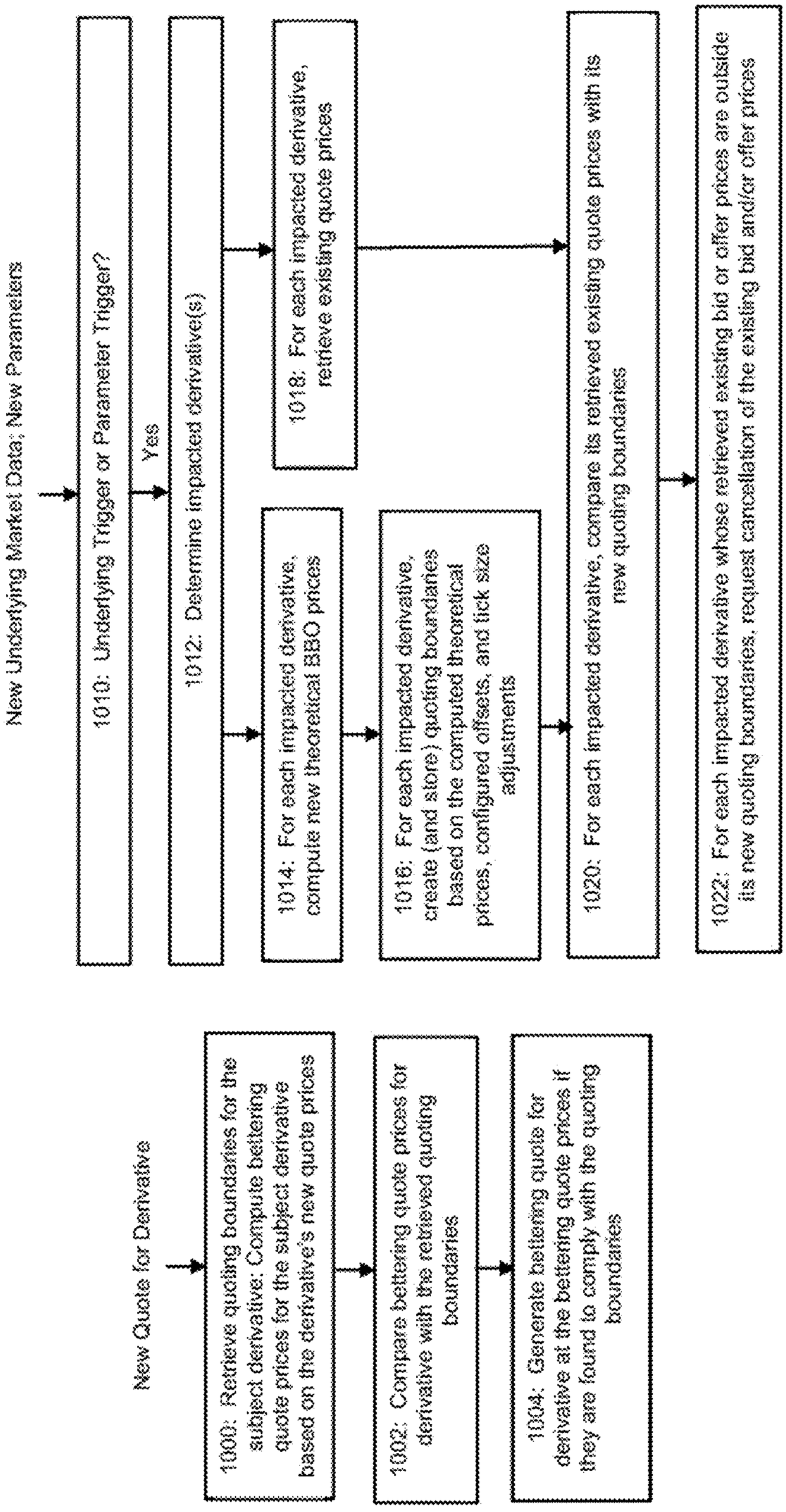

New Underlying Market Data; New Parameters
1010: Underlying Trigger or Parameter Trigger?
Yes
1012: Determine impacted derivative(s)
1014: For each impacted derivative, compute new theoretical BBO prices
1016: For each impacted derivative, create (and store) quoting boundaries based on the computed theoretical prices, configured offsets, and tick size adjustments
1018: For each impacted derivative, retrieve existing quote prices with its
1020: For each impacted derivative, compare its retrieved existing quote prices with its new quoting boundaries
1022: For each impacted derivative whose retrieved existing bid or offer prices are outside its new quoting boundaries, request cancellation of the existing bid and/or offer prices
New Quote for Derivative
1000: Retrieve quoting boundaries for the subject derivative; Compute bettering quote prices for the subject derivative based on the derivative's new quote prices
1002: Compare bettering quote prices for derivative with the retrieved quoting boundaries
1004: Generate bettering quote for derivative at the bettering quote prices if they are found to comply with the quoting boundaries

Figure 10A

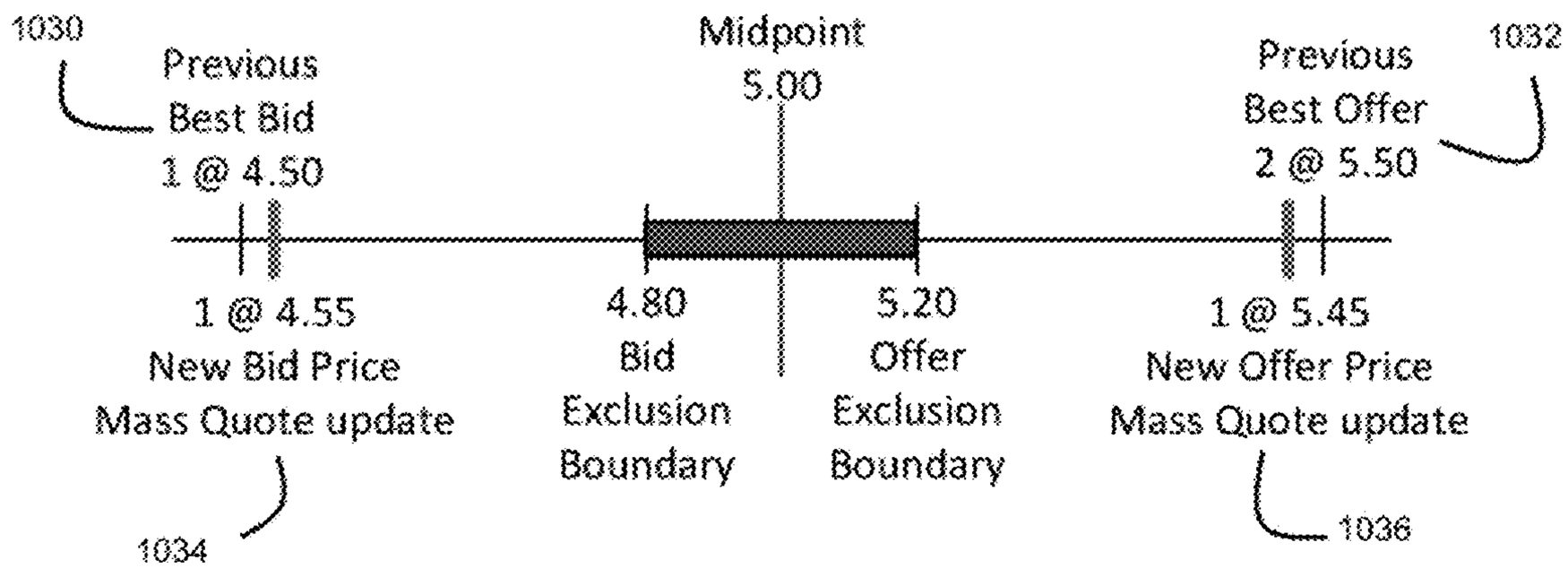

1030
Previous
Best Bid
1 @ 4.50
1 @ 4.55
New Bid Price
Mass Quote update
1034
Midpoint
5.00
4.80
Bid
Exclusion
Boundary
5.20
Offer
Exclusion
Boundary
1032
Previous
Best Offer
2 @ 5.50
1 @ 5.45
New Offer Price
Mass Quote update
1036

Figure 10B

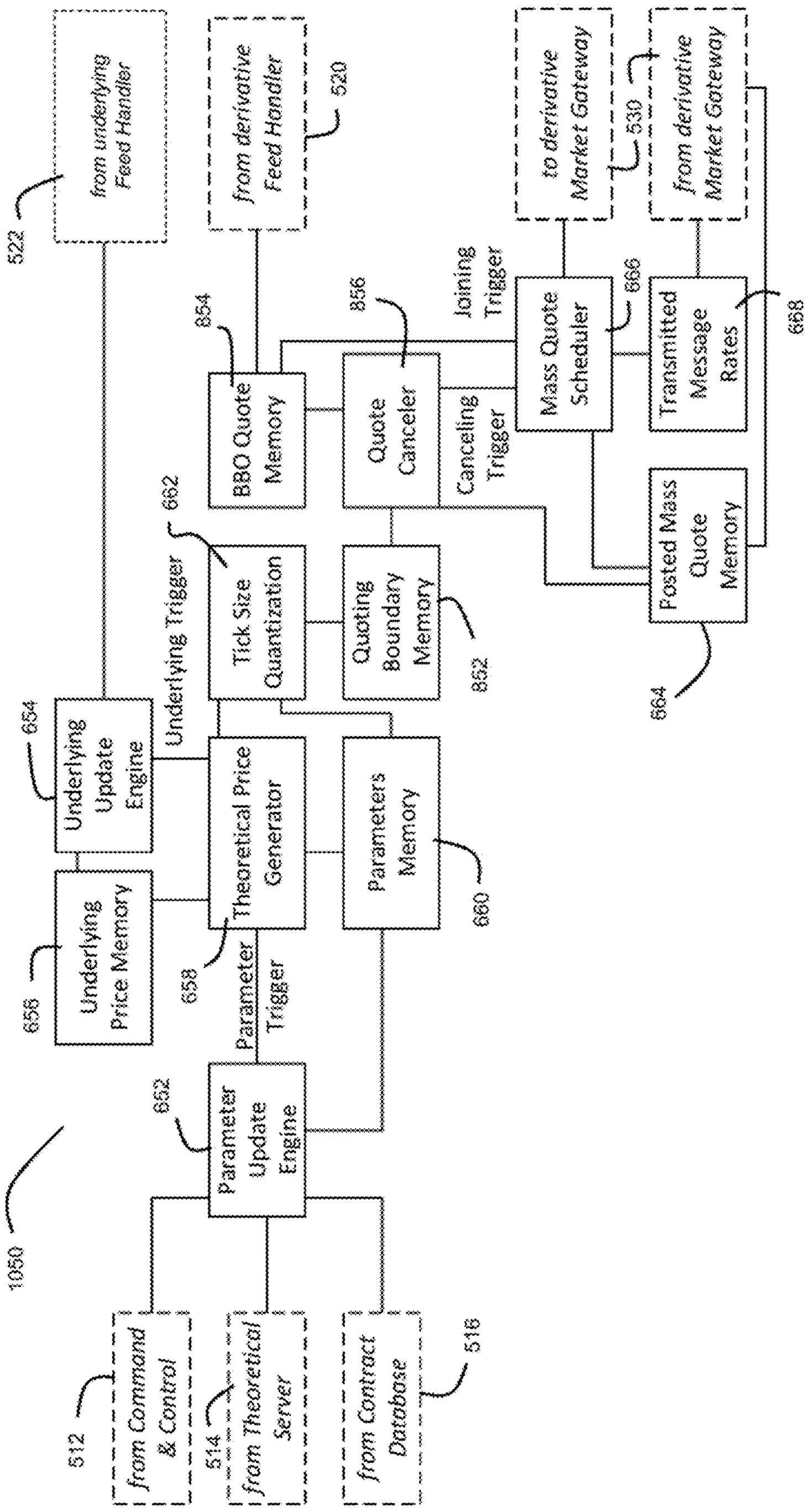

from underlying Feed Handler
522
from derivative Feed Handler
520
854
856
Joining Trigger
to derivative Market Gateway
539
from derivative Market Gateway
666
668
Underlying Update Engine
654
Underlying Trigger
662
BBO Quote Memory
Quote Canceler
Canceling Trigger
Mass Quote Scheduler
Transmitted Message Rates
Underlying Price Memory
656
Theoretical Price Generator
658
Tick Size Quantization
Quoting Boundary Memory
852
Parameters Memory
660
Posted Mass Quote Memory
664
Parameter Trigger
Parameter Update Engine
652
1050
from Command & Control
512
from Theoretical Server
514
from Contract Database
516

Figure 10C

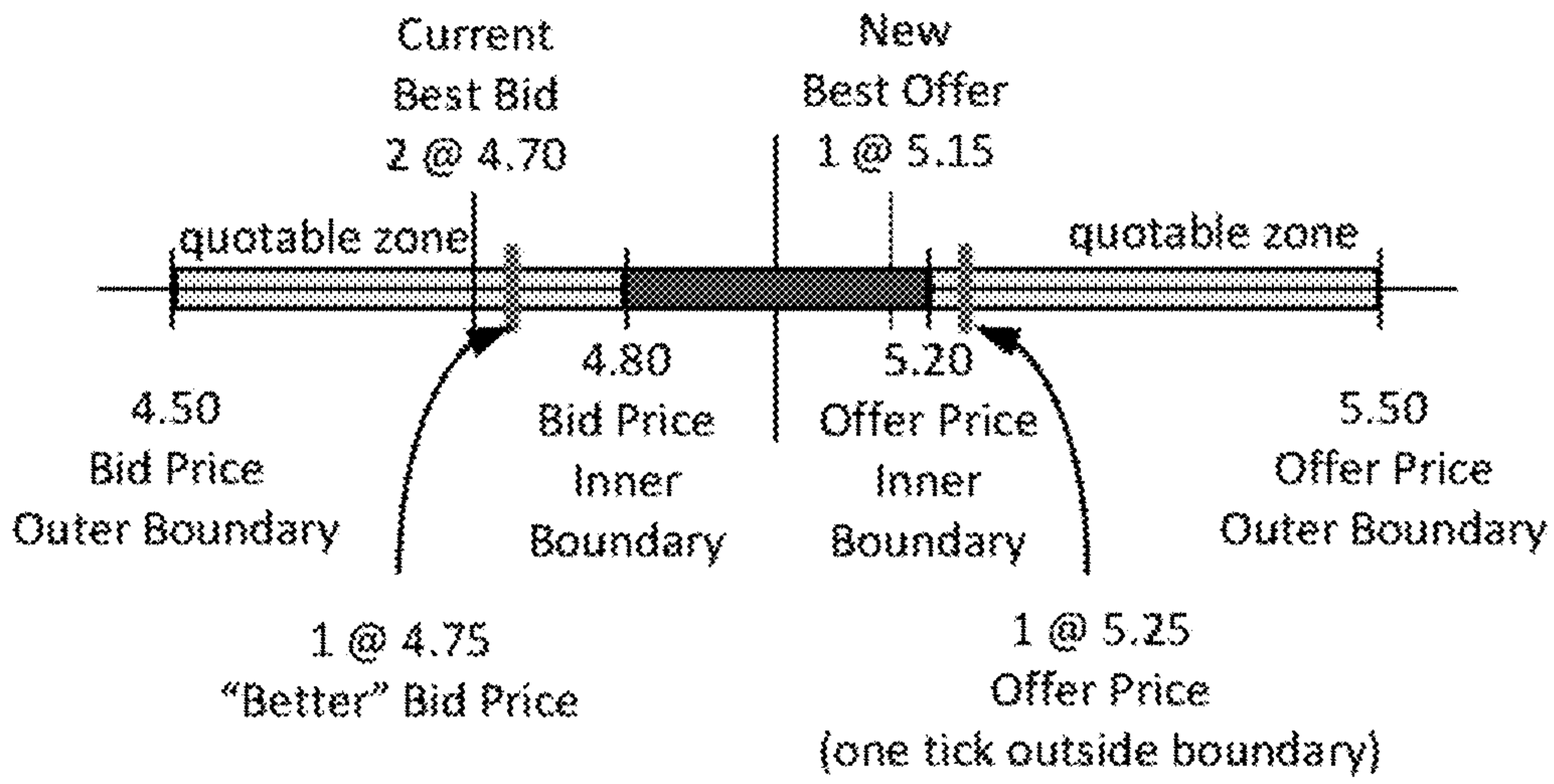


Figure 11

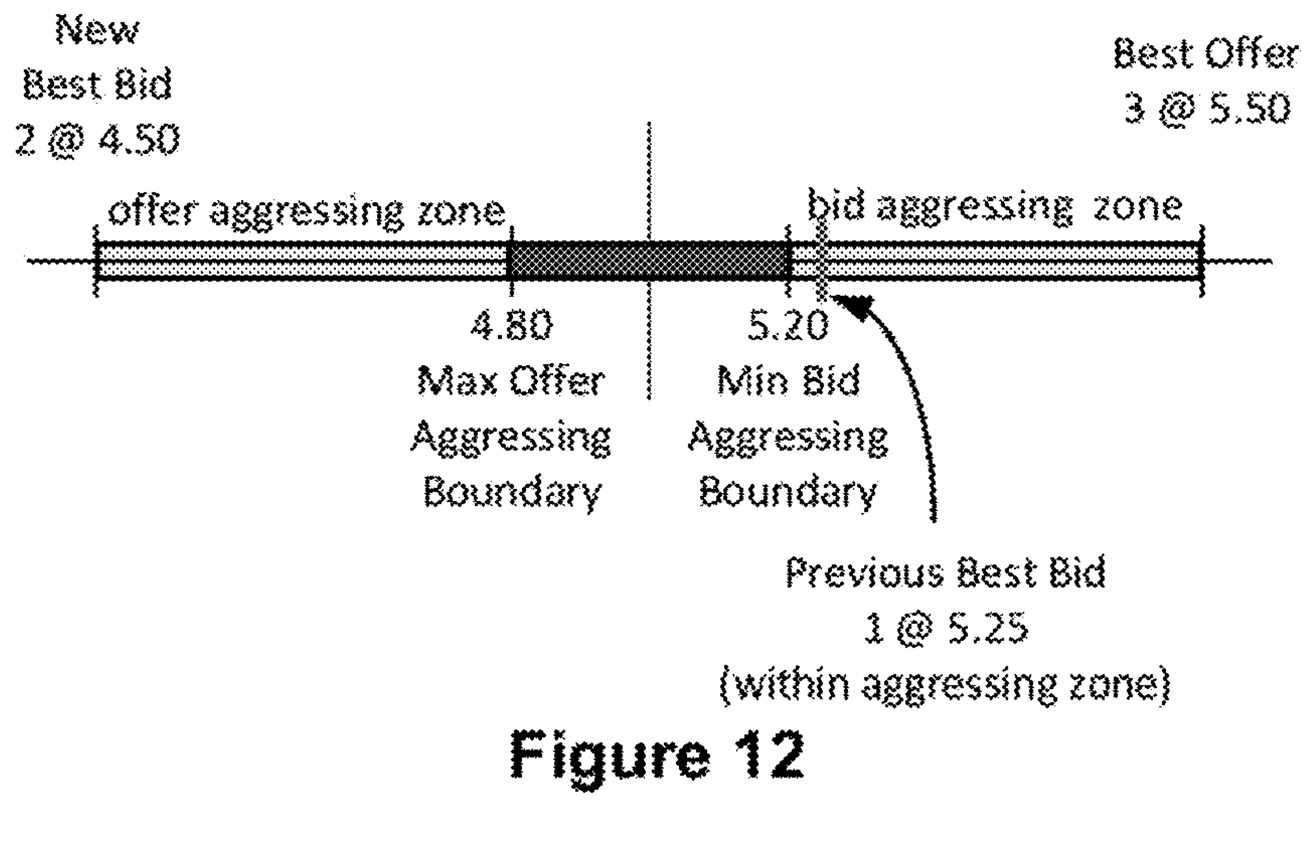


Figure 12

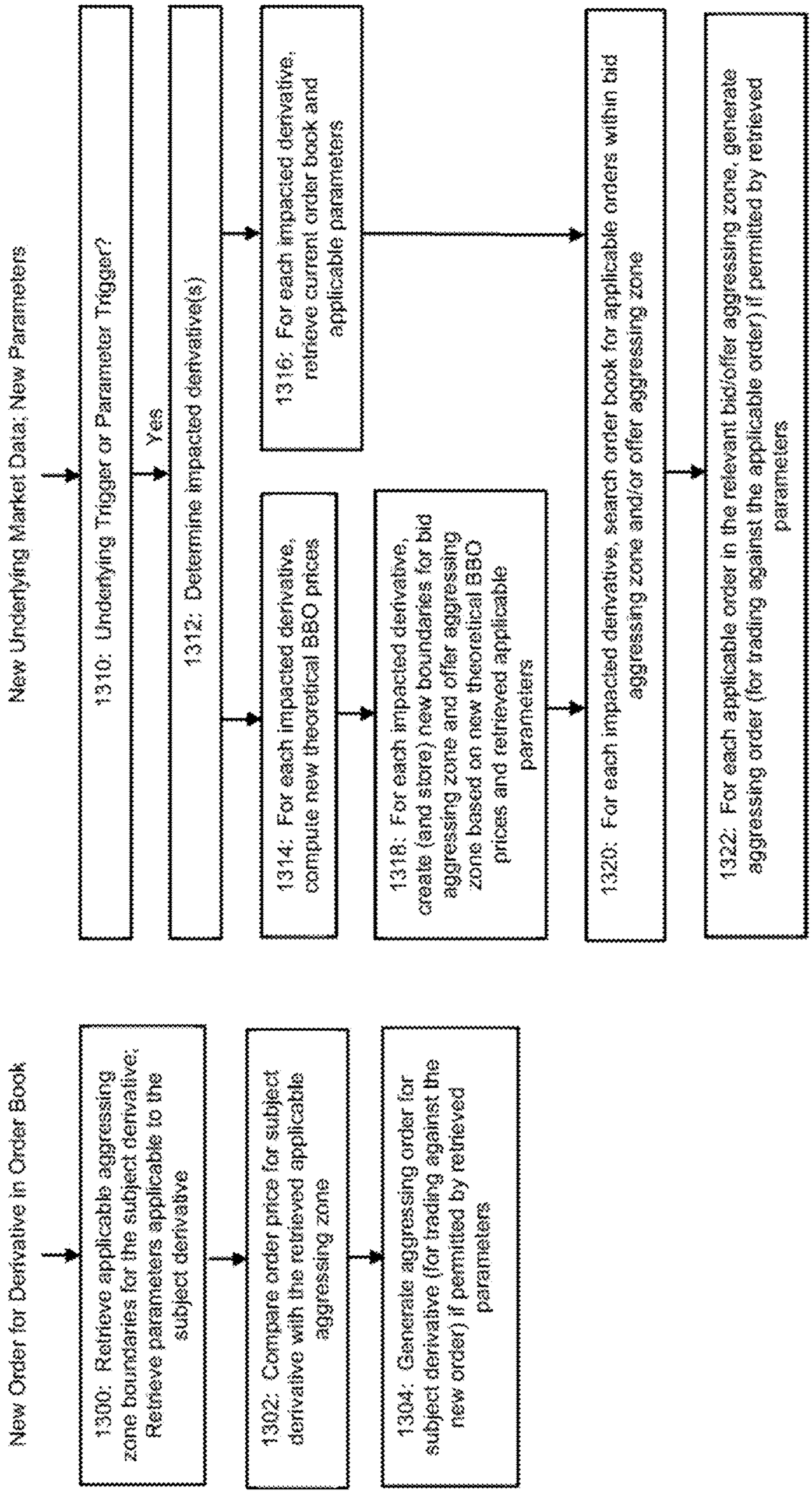

New Underlying Market Data; New Parameters
1310: Underlying Trigger or Parameter Trigger?
Yes
1312: Determine impacted derivative(s)
1316: For each impacted derivative, retrieve current order book and applicable parameters
1314: For each impacted derivative, compute new theoretical BBO prices
1318: For each impacted derivative, create (and store) new boundaries for bid aggressing zone and offer aggressing zone based on new theoretical BBO prices and retrieved applicable parameters
1320: For each impacted derivative, search order book for applicable orders within bid aggressing zone and/or offer aggressing zone
1322: For each applicable order in the relevant bid/offer aggressing zone, generate aggressing order (for trading against the applicable order) if permitted by retrieved parameters
New Order for Derivative in Order Book
1300: Retrieve applicable aggressing zone boundaries for the subject derivative; Retrieve parameters applicable to the subject derivative
1302: Compare order price for subject derivative with the retrieved applicable aggressing zone
1304: Generate aggressing order for subject derivative (for trading against the new order) if permitted by retrieved parameters

Figure 13A

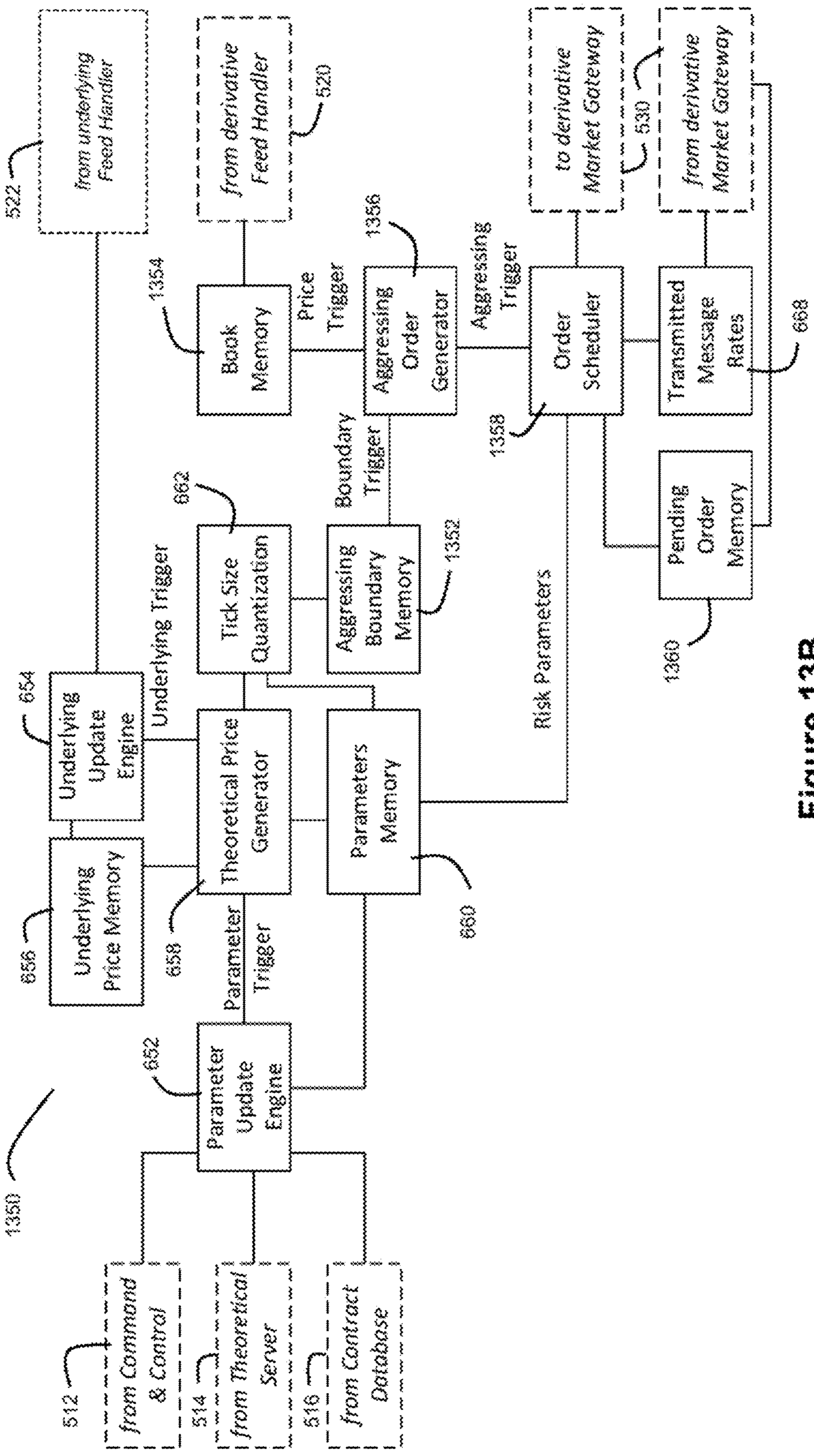

522
from underlying Feed Handler
520
from derivative Feed Handler
530
to derivative Market Gateway
from derivative Market Gateway
1354
Book Memory
Price Trigger
1356
Aggressing Order Generator
Aggressing Trigger
Order Scheduler
Transmitted Message Rates
668
1358
654
Underlying Update Engine
Underlying Trigger
662
Tick Size Quantization
Boundary Trigger
Aggressing Boundary Memory
1352
Risk Parameters
Pending Order Memory
1360
656
Underlying Price Memory
658
Theoretical Price Generator
Parameter Trigger
Parameters Memory
660
1350
652
Parameter Update Engine
512
from Command & Control
514
from Theoretical Server
516
from Contract Database

Figure 13B

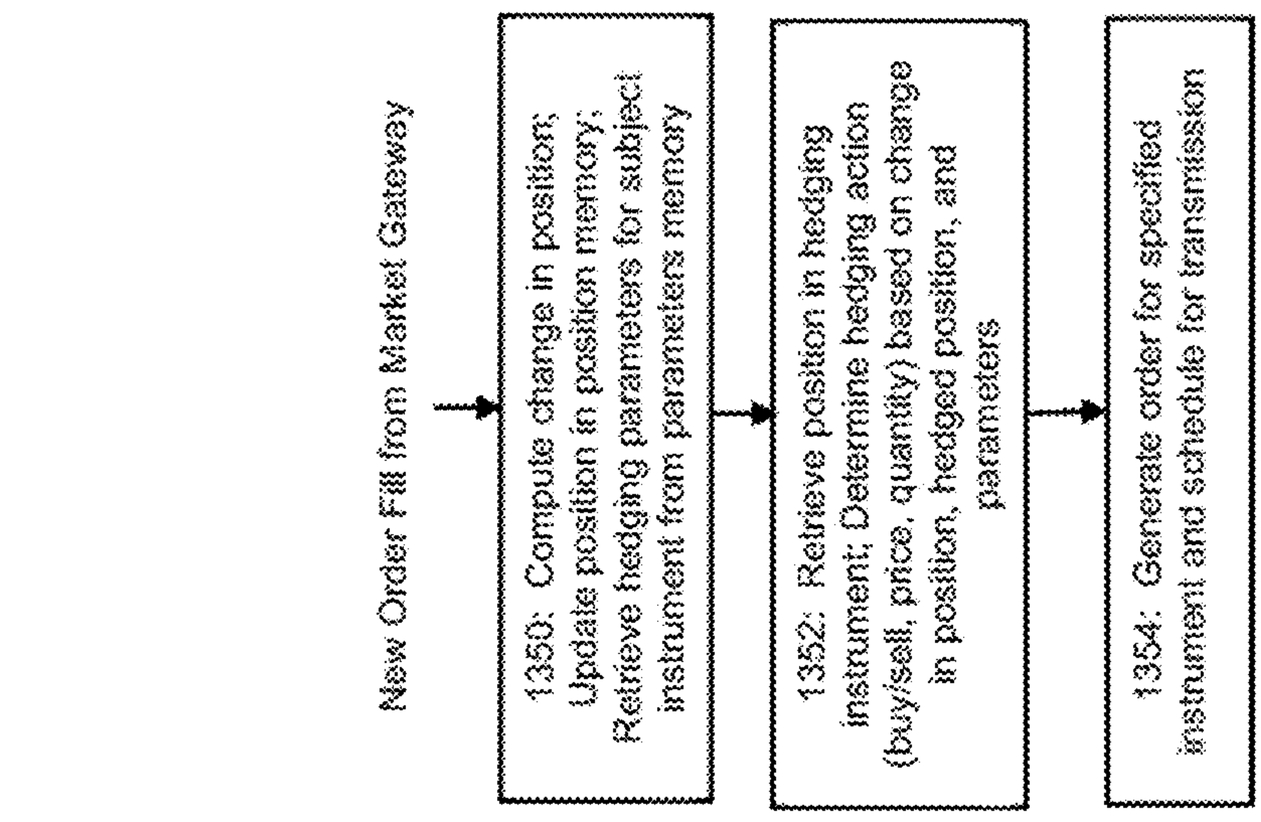

New Order Fill from Market Gateway
1350: Compute change in position; Update position in position memory; Retrieve hedging parameters for subject instrument from parameters memory
1352: Retrieve position in hedging instrument; Determine hedging action (buy/sell, price, quantity) based on change in position, hedged position, and parameters
1354: Generate order for specified instrument and schedule for transmission

Figure 13C

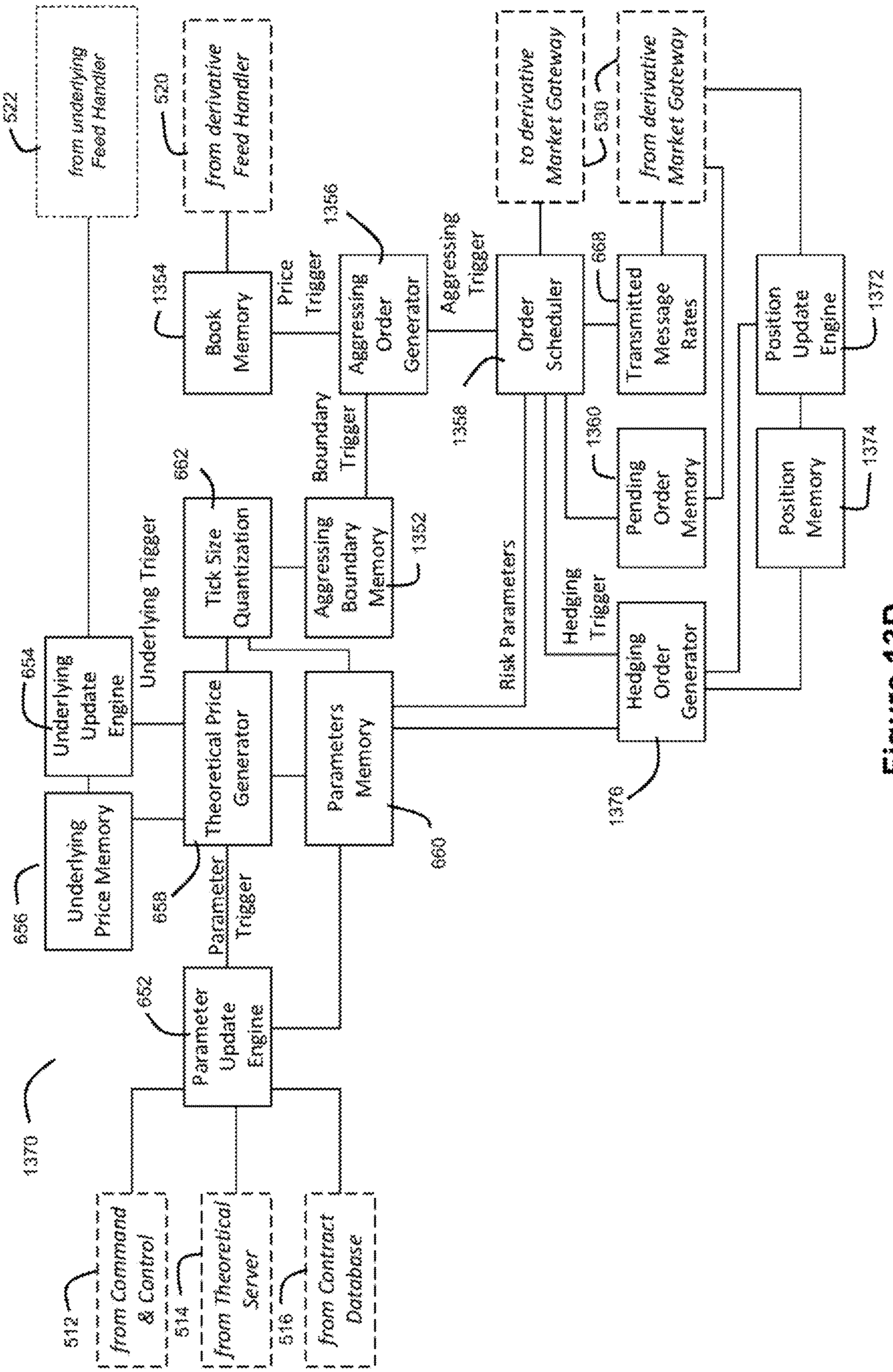

522
from underlying Feed Handler
520
from derivative Feed Handler
1354
Book Memory
Price Trigger
1356
Aggressing Order Generator
Aggressing Trigger
to derivative Market Gateway
530
from derivative Market Gateway
668
Order Scheduler
Transmitted Message Rates
Position Update Engine
1372
Boundary Trigger
1358
662
Tick Size Quantization
Aggressing Boundary Memory
1352
Risk Parameters
Hedging Trigger
1360
Pending Order Memory
Position Memory
1374
654
Underlying Update Engine
Underlying Trigger
Hedging Order Generator
1376
656
Underlying Price Memory
Theoretical Price Generator
Parameters Memory
660
658
Parameter Trigger
1370
652
Parameter Update Engine
512
from Command & Control
514
from Theoretical Server
516
from Contract Database

Figure 13D

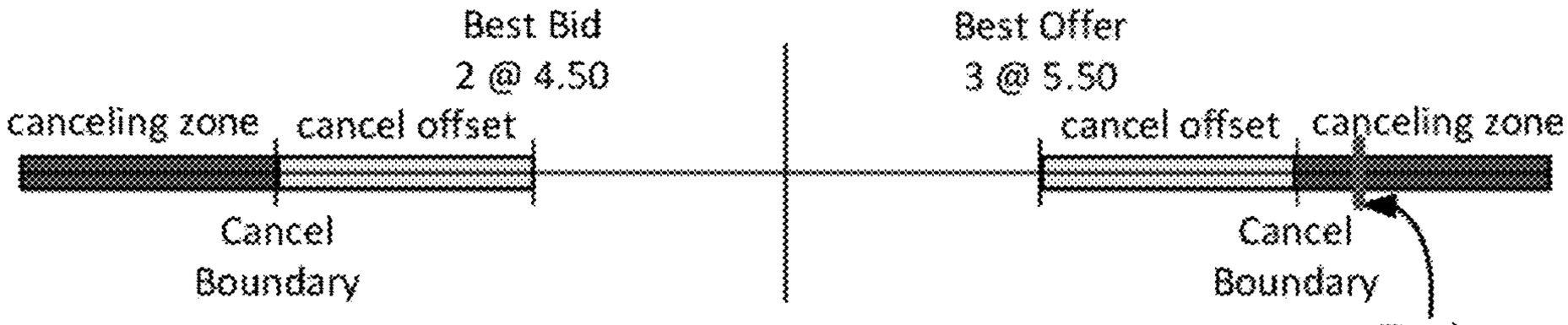


Figure 14

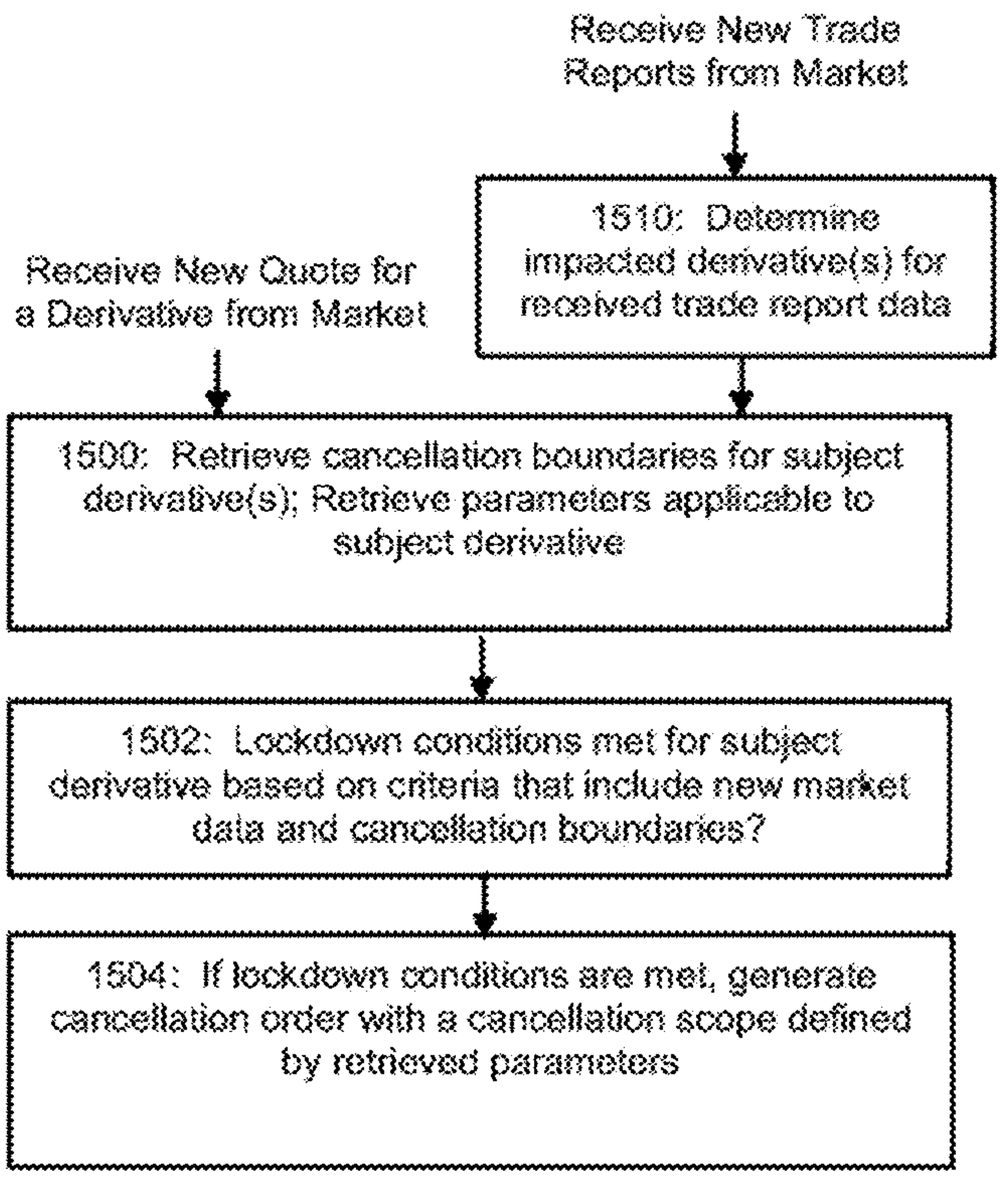


Figure 15A

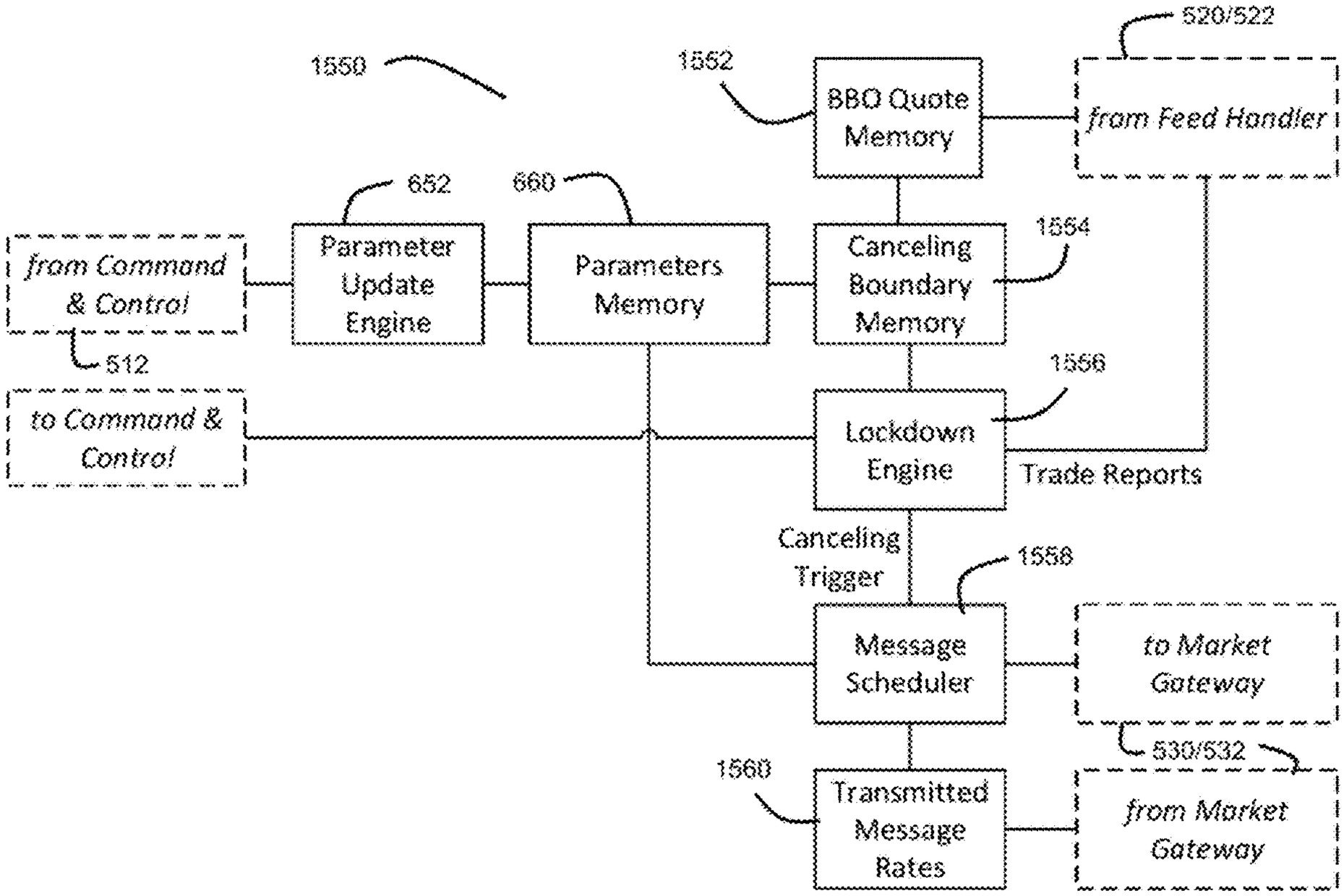

1550
1552
BBO Quote Memory
520/522
from Feed Handler
652
660
Parameter Update Engine
Parameters Memory
Canceling Boundary Memory
1554
from Command & Control
512
to Command & Control
1556
Lockdown Engine
Trade Reports
Canceling Trigger
1558
Message Scheduler
to Market Gateway
530/532
1560
Transmitted Message Rates
from Market Gateway

Figure 15B

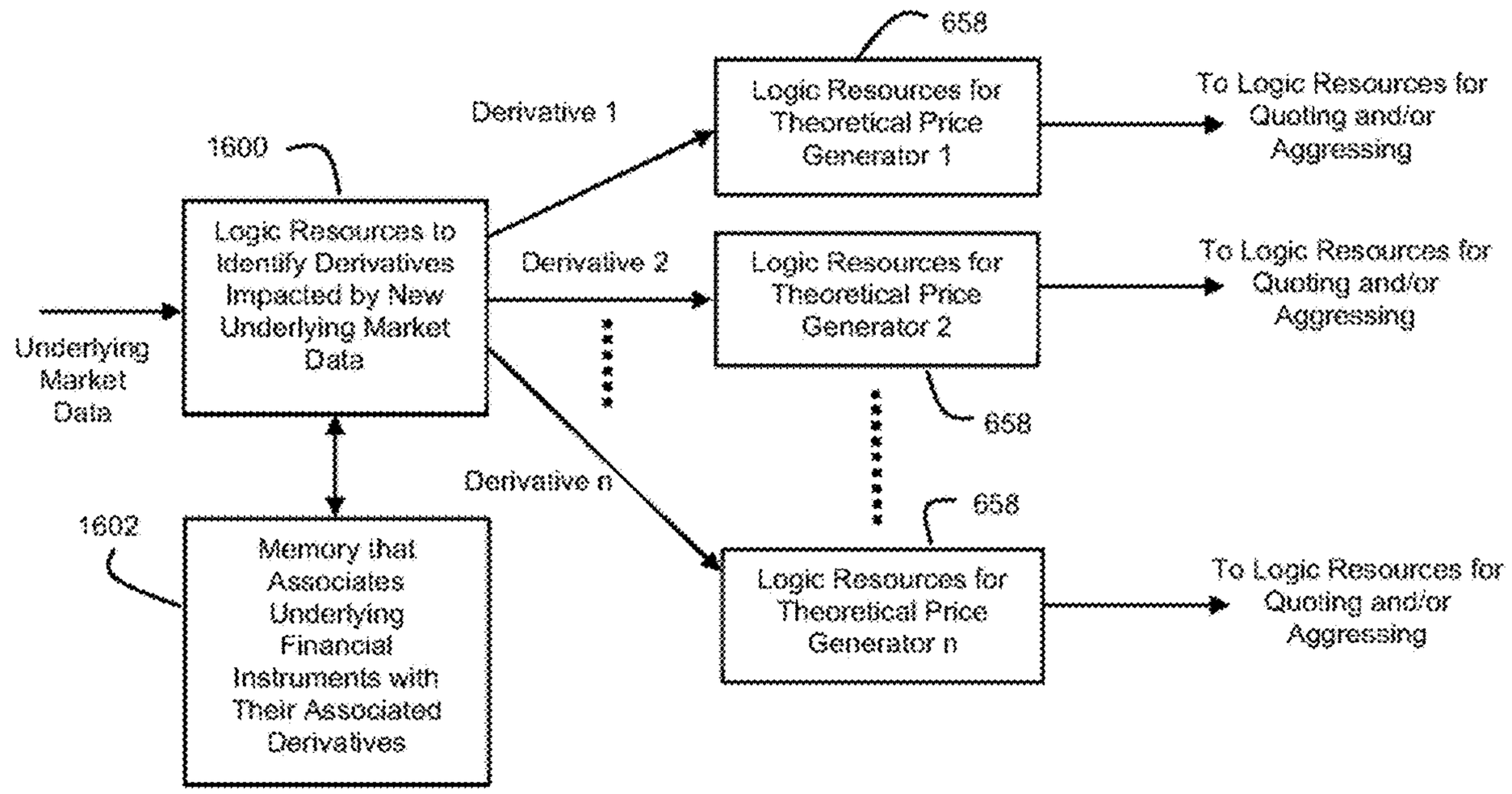

658
Logic Resources for Theoretical Price Generator 1
To Logic Resources for Quoting and/or Aggressing
Derivative 1
1600
Logic Resources to Identify Derivatives Impacted by New Underlying Market Data
Derivative 2
Logic Resources for Theoretical Price Generator 2
To Logic Resources for Quoting and/or Aggressing
Underlying Market Data
658
Derivative n
658
Logic Resources for Theoretical Price Generator n
To Logic Resources for Quoting and/or Aggressing
1602
Memory that Associates Underlying Financial Instruments with Their Associated Derivatives

Figure 16

METHODS AND SYSTEMS FOR IMPLEMENTING MARKET MAKING STRATEGIES AT LOW LATENCY

CROSS-REFERENCE AND PRIORITY CLAIM TO RELATED PATENT APPLICATIONS

[0001] This patent application claims priority to U.S. provisional patent application Ser. No. 63/149,904, filed Feb. 16, 2021, and entitled "Methods and Systems for Low Latency Automated Trading", the entire disclosure of which is incorporated herein by reference.

[0002] This patent application is related to (1) U.S. patent application Ser. No. _____, filed this same day, and entitled "Methods and Systems for Market Making at Low Latency" (said patent application being identified by Thompson Coburn Attorney Docket Number 44826-215369), (2) U.S. patent application Ser. No. _____, filed this same day, and entitled "Methods and Systems for Joining Market Making at Low Latency" (said patent application being identified by Thompson Coburn Attorney Docket Number 44826-217124), (3) U.S. patent application Ser. No. _____, filed this same day, and entitled "Methods and Systems for Bettering Market Making at Low Latency" (said patent application being identified by Thompson Coburn Attorney Docket Number 44826-217125), (4) U.S. patent application Ser. No. _____, filed this same day, and entitled "Methods and Systems for Mass Quoting at Low Latency" (said patent application being identified by Thompson Coburn Attorney Docket Number 44826-217127), (5) U.S. patent application Ser. No. _____, filed this same day, and entitled "Methods and Systems for Pricing Derivatives at Low Latency" (said patent application being identified by Thompson Coburn Attorney Docket Number 44826-217128), (6) U.S. patent application Ser. No. _____, filed this same day, and entitled "Methods and Systems for Low Latency Automated Trading Using an Aggressing Strategy" (said patent application being identified by Thompson Coburn Attorney Docket Number 44826-217129), (7) U.S. patent application Ser. No. _____, filed this same day, and entitled "Methods and Systems for Low Latency Automated Trading Using a Canceling Strategy" (said patent application being identified by Thompson Coburn Attorney Docket Number 44826-217130), (8) U.S. patent application Ser. No. _____, filed this same day, and entitled "Methods and Systems for Low Latency Automated Trading Using a Hedging Strategy" (said patent application being identified by Thompson Coburn Attorney Docket Number 44826-217131), and (9) U.S. patent application Ser. No. _____, filed this same day, and entitled "Methods and Systems for Low Latency Automated Trading" (said patent application being identified by Thompson Coburn Attorney Docket Number 44826-217132), the entire disclosures of each of which are incorporated herein by reference.

INTRODUCTION

[0003] Many financial trading strategies benefit from the ability to quickly respond to market events. This is especially true for automated strategies that trade on electronic financial markets. In some forms of trading, such as volatility trading of derivatives contracts, the speed at which an automated strategy is able to operate is a primary determiner of its likelihood of profit as well as its risk of loss.

[0004] In its most basic form, an automated trading strategy sends messages to buy and sell financial instruments to trading venues as depicted in FIG. **1**. The decisions to buy and sell are dictated by configuration information provided by a user or other component of a trading system, real-time information provided by financial market data feeds, and responses from trading venues such as acknowledgements of order reception, order rejection notifications, and "fill" reports of completed trades.

[0005] Depending upon the type of automated trading strategy, the system may receive configuration information infrequently (e.g. prior to the beginning of a trading session) or continuously (e.g. many times per second). It may trade on a single venue; it may trade the same fungible financial instruments across multiple venues; or it may trade underlying and derivatives instruments across multiple venues. It may consume real-time market data feeds from multiple markets, including markets that it is not trading upon, as well as other forms of data such as sentiment scores derived from various forms of media and "alternative data" such as consumer data collected from payments systems.

[0006] A primary measure of the speed at which an automated trading strategy functions is its "tick to trade" latency—the elapsed time from the arrival of a triggering event (i.e. "tick") at the input of the system to the transmission of a resulting message to a trading venue (i.e. "the trade"). Typically, the "tick" is new pricing information from a real-time financial market data feed. Note that it may also be a new sentiment score or receipt of a "fill" report from a trading venue. The type of responding order message sent to a trading venue depends upon the type of automated trading strategy. Tick-to-trade latency is depicted in FIG. **1** as the difference between the arrival of new pricing information on the financial market data feed at time to and the transmission of a new order message via the direct market access connection to the trading venue at time Market making is a trading strategy that continuously posts offers to both buy and sell a financial instrument with the goal of achieving an aggregate sale price higher than an aggregate buy price. This is commonly referred to as "capturing the spread" between the best offer and best bid price. Competition among market makers for these opportunities to capture the spread generally drives offer and bid prices closer together, thus narrowing the spread and reducing the profit on each market making trade. Generally, maximizing market making profits then depends upon maximizing the number of trades performed. It is largely for this reason that market making strategies were some of the first to be automated. Market making strategies that can quickly respond to changes in financial instrument prices and post new best bid and offer (BBO) prices maximize their opportunity to capture the spread on the next transaction.

[0007] The policy of the trading venue also contributes to market making strategies. When a trade occurs at a price posted by multiple market participants (which are usually market makers), the venue must define how the transaction is apportioned to the participants at that price. In a time-priority stock market, the executed shares are apportioned in the order in which the posted prices from the participants were received. One can imagine market makers lining up at a common price for the opportunity to trade at that price. Again, the speed at which a market maker responds to a change in instrument prices with new BBO prices largely determines his "queue position" in a time-priority market.

[0008] Rather than fight for queue position, some market making strategies may seek to post its BBO prices at one price increment "better than" or "inside" the posted BBO prices from other market participants. For example, if the current best bid and offer prices for an instrument are $10.04 and $10.08, respectively, then a market maker may choose to post their BBO prices at $10.05 and $10.07. By doing so, they are first in line to be traded at those prices. They also may trade against "market orders" that arrive seeking to immediately buy or sell at the best prices posted, or they may trade against various types of "hidden" orders that the trading venue provides to market participants seeking to minimize "information leakage" of their desires to buy or sell.

[0009] An alternative to time-priority matching policy is pro rata apportionment. In this case, the trading venue divides the matched orders (e.g. future option contracts) among all market participants (usually market makers) at the posted price. Such a policy may induce market making strategies to "join" the BBO prices currently posted on a market, such that its BBO prices are equal to those of other market participants. While queue position is no longer a primary consideration, market makers on pro rata markets continue to have strong incentives to act quickly.

[0010] Additional alternative matching policies exist in the marketplace, including a blend of time-priority and pro rata apportionment. Other markets may offer incentives in the form of rebates to establish best bid and offer prices. These incentives provide additional opportunities for market makers to profit with the intent of narrowing spreads.

[0011] The largest opportunities to capture the spread occur in volatile markets with concentrations of trading activity and rapidly changing prices. Not only do market makers need to be able to post new BBO prices in order to be present for the fleeting opportunities to trade, they also need to ensure that they cancel or modify their previously posted BBO prices before they create an arbitrage opportunity for a faster market participant.

[0012] Arbitrage is another example of a trading strategy that typically depends on speed, and thus it is commonly implemented as an automated trading strategy. Some trading firms may run stand-alone arbitrage strategies, or it may be operated as a complementary part of a market making strategy. An arbitrage trading strategy monitors the prices of financial instruments and identifies opportunities to immediately sell the instrument at a price higher than the price to immediately buy the instrument.

[0013] Arbitrage opportunities can be created when a market participant with a resting order or a market maker with a BBO quote is slow to respond to a change in price. For fungible financial instruments that trade across multiple markets, such as equities and equity options in the United States or spot currency pairs in the global foreign exchange (FX) markets, market arbitrage opportunities exist because the financial instrument can be bought at a lower price on one market and sold at a higher price on another market.

[0014] Latency arbitrage is closely related whereby an automated trading strategy identifies demand (e.g. incoming orders to buy), quickly trades at the current best price (e.g. buys all shares at the current best bid price), then sets the new best price with a small profit margin (e.g. sells shares to the incoming buy orders at a "tick" higher than they were purchased).

[0015] In derivatives markets, the challenges of automated market making and the potential for arbitrage opportunities are amplified for several reasons. Firstly, the price of a derivative instrument generally depends on the price of its underlying instrument. A common example of a derivative is a stock option which is a contractual right, but not the obligation, to buy (a call) or sell (a put) a stock (the underlying) at a defined price (the strike) for a period of time limited by a defined date (the expiration). Due to the large number of permutations of values for each of these parameters, it is common for many, potentially thousands, of options to be tied to a single underlying instrument. Options or their equivalents also exist for futures, foreign exchange, and a variety of credit instruments.

[0016] How to arrive at the fair value of an option contract is complex and computationally intensive. The difference between the current price of the underlying financial instrument and the strike price of the option is one consideration. Because the price of the underlying financial instrument can and will move after the option contract is traded, the volatility of the price of the underlying financial instrument is another consideration. Because the contract exists for a defined period of time, interest rates are another consideration, as well as if the contract allows the holder to exercise (buy/sell) at any time prior to the expiration (e.g. an American stock option) or only on the date of expiration (e.g. a European stock option).

[0017] Various option pricing models are known in the art or used in a proprietary manner for computing theoretical option prices. Prominent among these models are the Black-Scholes option pricing model and the iterative binomial Cox, Ross, and Rubinstein (CRR) option pricing model. While the Black-Scholes model is computationally far simpler than CRR, it makes simplistic assumptions, lacks support for American exercise, and therefore lacks of precision for many strategies in modern electronic markets. While there are known techniques in the art that dramatically increase the speed of using the CRR model—see, for example, U.S. Pat. Nos. 7,840,482 and 8,843,408—these techniques are still expected to operate 10 to 100 times too slowly for practical use in the latency-critical datapath of automated trading strategies. Even when implemented with reconfigurable logic devices and/or general purpose graphics processing units (GP-GPUs), these techniques are expected to require 1 to 10 microseconds to produce a new theoretical option price; whereas automated trading strategies are expected to require latencies of approximately 100 nanoseconds or less to be effective. Accordingly, improvements in the art are still needed for computing and updating theoretical prices for derivative instruments at sufficiently low latency to make these theoretical prices relevant and helpful for automated trading strategies.

[0018] In addition to the complexity of computing fair values and the large number of financial instruments, automated trading in derivatives markets presents additional challenges when the underlying financial instruments are traded on a different market (e.g. stocks on the New York Stock Exchange) and in a different physical location than the derivative financial instruments (e.g. stock options on the Chicago Board Options Exchange). As shown in FIG. **2**, updated prices for underlying instruments may be transmitted at time t_2 to the location of a derivatives market. An automated trading strategy receives these new prices at time t_3. In response, it computes new fair prices for all of the

derivatives instruments that it trades. These new fair prices may cause the strategy to update its BBO prices, if it is executing a market making strategy. Note that in derivatives market making, sending new BBO prices for multiple derivatives contracts commonly is referred to as "mass quoting". The market making strategy also may send mass quotes to multiple derivatives trading venues for the same fungible derivative instruments.

[0019] Note that the propagation delay of data from the underlying market to the automated trading strategy (i.e. the time elapsed from t_2 to t_3) in part determines the speed of response of the automated trading strategy. As depicted in FIG. **2**, market participants may use data networking technologies, such as "line of sight" wireless network links, to minimize the propagation delay.

[0020] New fair price values may also cause the automated trading strategy to identify an arbitrage opportunity. For example, if the strategy determines that the new fair value of the offer price is higher than the current best offer price on the market, it may buy at the current best offer and post a new best offer at the new fair value. Capturing such arbitrage opportunities is frequently termed "aggressing", and these opportunities most frequently arise in fast-moving markets. Many proprietary trading firms use a blend of market making and aggressing strategies.

[0021] While firms seek to increase their trading profits by adding aggressing algorithms to their market making algorithms, they also want to defend against the possibility of offering another market participant the opportunity to aggress against its BBO prices. Especially in the case of derivatives market making strategies, it may not be possible for an automated trading strategy to respond to a change in underlying prices by computing new fair prices and sending a message with new mass quotes for thousands of derivative instruments before another market participant is able to send a single message that successfully aggresses against one of those derivatives instruments.

[0022] For this reason, automated trading strategies frequently choose to cancel mass quotes or orders when they determine that an undue risk of adverse trades exists. Trading venues typically provide market participants the ability to cancel mass quotes and orders at various granularities. For example, a market maker may have the ability to cancel mass quotes for all contracts on a common underlying instrument (for ease of references, the financial instrument that is underlying a derivative instrument can be referred to as an "underlying"; and the derivative instrument can be referred to as a "derivative"), for all contracts on a set of underlyings in a category, or simply for all contracts. Mass quote cancellations may also cancel one side (i.e., only the bid or offer price) or both sides of the quote. Similarly, a market participant may cancel a single posted order, all resting orders, or orders for a specific group of contracts.

[0023] Another strategy used by firms to capture arbitrage opportunities and minimize risk of losses is hedging. When a firm takes a position by buying or selling a financial instrument, they may buy or sell another financial instrument that mitigates losses due to adverse price changes to their position. For example, if a firm expects the value of a stock to increase and takes a long position by buying at $10 per share, they may immediately buy a put option on the same stock at a strike price of $10. Given that the put option provides the opportunity to sell at the strike price, the firm has the opportunity to sell the stock at the price they purchased it at even if the value of the stock declines. Given that the put option was purchased "at the money" with no immediate profit possible, it likely would be an inexpensive option. For example, if the put option cost $0.30 per share to buy, the firm spent 3% in potential returns for a defense against losses.

[0024] Various combinations of financial instruments can be used for hedging, including future options and futures, stock options and stocks, stock options and stock options, futures and stocks, etc. When crafting hedging strategies, firms specify the hedging instrument and the ratio of hedging instrument to buy or sell relative to the new position.

[0025] Automated trading strategies typically define market conditions that trigger cancel actions at various granularities. For example, if the price difference between the most recent two trades of an underlying instrument is larger than a configured threshold, the strategy may choose to cancel mass quotes on all contracts tied to the underlying instrument. There may be other conditions, such as a technical outage on the trading venue for underlying instruments, that cause the strategy to cancel all mass quotes and orders for all contracts.

[0026] Many firms that engage in automated trading use a "grey box" architecture that utilizes software-based computer automation to execute trading algorithms and allows human traders to monitor and control a number of parameters in real-time, including:

[0027] Underlying instruments and derivatives to trade

[0028] Algorithms and parameters to apply to each instrument

[0029] Estimations of volatility, interest rates, and other parameters that drive fair value calculations

[0030] Risk parameters and bounds

[0031] A diagram of a conventional grey box system for automated trading on a trading venue is shown in FIG. **3**. FIG. **4** shows a corresponding conventional grey box system for automated trading where the trading includes trading on a derivatives trading venue. A first software-driven component, labeled as the User Terminal, Visualization system in FIGS. **3** and **4**, enables a human trader to perform the monitoring and control functions highlighted above. This may be used by a trader to operate a second software component, labeled as the Command and Control system in FIGS. **3** and **4**.

[0032] The Command and Control system serves as an interface hub between User Terminal, Visualization systems (likely deployed in corporate offices) to a third software component, labeled as Trading Logic in FIGS. **3** and **4**, where this Trading Logic software is deployed in colocation data centers. The systems of FIGS. **3** and **4** marshal monitoring information back to traders and operators. Likewise, the systems of FIGS. **3** and **4** pass the "grey box" parameters listed above to the Trading Logic software.

[0033] An Instrument Database tracks the universe of financial instruments available for trading, along with trading venue rules for trading them. For example, when a new publicly-traded company executes an Initial Public Offering (IPO) a new stock is added to the Instrument Database. When a publicly-traded company is delisted from an exchange, an entry for the stock on the specific exchange may be removed from the Instrument Database.

[0034] For derivatives trading strategies, the Instrument Database tracks the universe of derivatives contracts available for trading, along with trading venue rules for trading

them. Since derivatives contracts are frequently created and expire, this universe is dynamic. Furthermore, trading venues typically establish rules such as the minimum price increment for market maker quotes (i.e. the "tick size") and how various types of auctions function. This information is made available to the Command and Control system to allow users to select from a relevant menu of instrument to trade. It is also made available to the Trading Logic software to govern the generation of quotes and orders.

[0035] The Trading Logic software implements a specified algorithm or a combination of algorithms as directed by the Command and Control system. The algorithms may be drawn from the set of market making, aggressing, hedging, and canceling strategies described above. The integration of market making, aggressing, and canceling strategies for derivatives trading is commonly referred to as "volatility trading," as trading revenues increase as the frequency of asset price changes increase. Importantly, trading revenues can be independent of the direction in which asset prices move.

[0036] Volatility trading represents one of the most computationally intensive forms of automated trading due to large number of financial instruments, the need to perform fair value calculations for each derivative instrument in order to drive trading logic, and the complexity of each of those fair value calculations. Furthermore, volatility trading strategies face more risk of adverse trades from aggressing orders of other market participants. They must also keep tight risk controls on the number of outstanding aggressing orders.

[0037] In a conventional approach to automated trading, most trading firms implement in software all of the components in the automated trading systems of FIGS. **3** and **4**. These systems typically operate with tick to trade latencies of five to ten microseconds (one millionth of a second). With these types of systems, which are widely deployed for trading underlying financial instruments, the result is derivatives markets that in aggregate change prices tens to thousands of times more often due to the number of contracts linked to a single underlying. Accordingly, these conventional software-based approaches to automated trading are not adequate for automated trading of derivatives because these conventional software-based approaches are not sufficiently fast. That is to say that these conventional software-based approaches to automated trading suffer from a technical shortcoming in that they are not able to adequately take into consideration up-to-date pricing information for swiftly changing market conditions in derivatives markets.

[0038] In an alternate approach, the Feed Handler component of the system may be implemented in hardware such as a field programmable gate array (FPGA), while the other system components including the Trading Logic are implemented in software executed by one or more GPPs. Examples of FPGA-based Feed Handlers are described in U.S. Pat. Nos. 7,921,046 and 8,762,249, the entire disclosures of which are incorporated herein by reference. While the use of FPGA-based Feed Handlers constitutes a significant improvement over systems that implement the full cycle in software, such alternate approaches still suffer from relatively high tick to trade latencies due to the latency present in the software-based Trading Logic.

[0039] The inventors herein believe that a need in the art exists for automated trading strategies that operate 10 to 100 times faster than what is achievable in software running on general purpose processors (GPPs). For derivatives trading strategies, there also exists a need to compute the fair value of derivatives contracts 10 to 100 times faster than known methods in the art to compute a CRR model.

[0040] Faster methods and systems would enable automated trading strategies that maximize profitable opportunities and minimize risks of adverse trades due to mispriced quotes and orders. Without such faster methods and systems, trading firms may take steps to reduce the number of derivatives contracts they trade, post BBO prices with wider spreads, or use more conservative parameters for canceling quotes and orders. All of these steps undesirably result in reduced opportunities to trade and may eliminate incentives to trade in certain contracts or markets.

[0041] As technical solutions to the above-described technical shortcomings in the art, the inventors disclose a number of example embodiments that integrate and re-engineer the trading logic for automated trading in coordination with the feed handlers and market gateways to operate on computational resources that are capable of providing highly parallelized and pipelined processing operations to improve tick to trade latency. As examples, a field programmable gate array (FPGA) or application-specific integrated circuit (ASIC) can be used as the processing resource on which automated trading logic is deployed in order to reduce tick to trade latency. However, it should be understood that other types of processors that provide sufficient granularity of parallel operations (data-level and functional parallelism) and speed may also be used. With the availability of the massive parallelism that is available on such chips, the trading logic in coordination with the feed handlers and market gateways can then be re-engineered to take advantage of this parallelism. To do so, the feed handlers, market gateways, and trading logic can be deployed on the logic resources of the chip (which are capable of operating in parallel with other) to serve as automated trading engine. In this fashion, different logic resources of the chip can carry out different parts of the feed handlers, market gateways, and trading logic at the same time. For example, one set of logic resources for the automated trading engine can be scheduling a transmission of a quote or an order for Instrument A to a trading venue while at the same time another set of logic resources for the automated trading engine can be computing theoretical BBO prices for Instrument B. Still another set of logic resources for the automated trading engine can be evaluating multiple canceling conditions in parallel. And yet another set of logic resources for the automated trading engine can be evaluating aggressing conditions.

[0042] Furthermore, given the limitations imposed by trading venues on the number of messages per second that may be transmitted by a market participant, conventional GPP-based trading strategies must do one of the following, all of which increase tick-to-trade latencies and thus reduce trading opportunities and increase risk:

[0043] (1) perform trade decision-making and message scheduling serially on a single GPP platform

[0044] (2) perform trade decision-making in parallel on multiple GPP platforms and then multiplex messages to the trading venues through another platform that performs scheduling and aggregate risk checks

[0045] By contrast, by leveraging the parallelized logic resources of the FPGA or ASIC, the ability of the automated trading engines described herein to assess all aspects of a

trading strategy in parallel and make fine-grained scheduling decisions on the messages to be sent or queued on the network link to the trading venue allows for example embodiments of the invention to lower risk and increase potential trading opportunities.

[0046] By operation in the parallelized and pipelined manners described herein, the automated trading engines disclosed herein can be capable ingesting new market events at the maximum rate of the network interfaces to and from trading venues and produce tick to trade latencies that are less than 1 microsecond—for example tick to trade latencies of around 50 nanoseconds to 500 nanoseconds. As examples, tick to trade latencies of 100 ns, 150 ns, 200 ns, 250, ns, 300 ns, 350 ns, 400 ns, 450, ns, or 500 ns or less can be achieved. Moreover, the automated trading engines disclosed herein can operate at sustained throughputs of over 10 million messages per second. This represents a dramatic technical improvement over the above-described conventional approaches to automated trading which are believed to operate at tick to trade latencies of around five to ten microseconds.

[0047] With such a dramatic reduction in tick to trade latency, the automated trading engines disclosed herein are capable of operating with derivatives while taking into consideration changes in pricing for the financial instruments that underly such derivatives (where the pricing of such underlying financial instruments may be changing more than one million times per second). The inventors believe that such levels of responsiveness for automated trading strategies are simply not something that conventional automated trading systems are technically capable of achieving. Examples of automated trading strategies that can be used for derivatives with example embodiments disclosed herein include market making strategies (such as basic market making, joining market making, bettering market making, and/or combinations thereof), aggressing strategies, hedging strategies, and/or canceling strategies.

[0048] As additional technical solutions to the above-described technical shortcomings in the art, the inventors disclose techniques for computing theoretical fair prices of derivatives at dramatically lower latencies than other approaches known in the art. As explained above, techniques such as Black-Scholes or CRR for computing the fair market price of an option can be unduly slow due to the large numbers of iterations that are needed by these techniques to arrive at theoretical fair market prices. For example, the computational latency for computing theoretical fair market prices of a derivative using the Black-Scholes or CRR models will be on the order of one to ten microseconds. Accordingly, by the time these conventional techniques are able to arrive at a theoretical fair market price, it is almost certain that the pricing for the financial instrument underlying the derivative has changed, in which case the computed theoretical fair market price will be stale and may not accurately reflect market conditions (and a trading strategy that relies on such theoretical fair market price computations will be carrying risks that arise from potential mispricing).

[0049] To reduce the latency of computing theoretical fair market prices for derivatives, the inventors disclose a computational approach where the theoretical fair market prices for a derivative (which in turn can drive the trading strategies, BBO prices for quotes, exclusion boundaries for market making quotes, and/or aggressing boundaries for aggressing orders) are extrapolated through parallelized and pipelined computations from a feed of "coarse" theoretical fair market prices for the derivative (where these coarse theoretical fair market prices serve as reference prices for the derivative), a feed of "coarse" prices for the financial instrument underlying the derivative (where these coarse underlying prices serve as the reference prices for the underlying that are linked to the derivative's reference price), a feed of "coarse" Greek values for the derivative, and a market data feed that includes real-time pricing for the financial instrument underlying the derivative. The terminology "coarse" in this context refers to a relatively slow refresh rate of these feeds for the reference prices and Greek values relative to the refresh rate of the underlying financial instrument feed. That is, the reference prices for the derivative and the underlying and associated Greek values for the derivative are expected to refresh at a relatively low rate of around one to 100 times per second. By contrast, the market data feed of underlying financial instrument prices is expected to refresh at a much higher rate of around one million to ten million messages per second For highly traded underlying financial instruments, the refresh rate of pricing for a particular underlying financial instrument may be of similar rates to the refresh rate of the underlying market data feed itself. As such, the refresh rate for the market data feed of underlying financial instrument prices will need to be the driver for refreshing the computed theoretical fair market prices of the derivative if real-time theoretical pricing is desired for derivatives. To accomplish this, the extrapolation model for computing theoretical fair market prices of a subject derivative is designed to use a significantly smaller sequence of arithmetic operations than those used by the Black-Scholes or CRR models. In this fashion, the computational latency for computing theoretical fair market prices of a derivative will be on the order of five to fifty nanoseconds, which is sufficiently fast to keep up with the fast pace of new events in the market data feed of underlying financial instrument prices (and significantly faster than the conventional computational approaches discussed above). By keeping such a close watch over the changing theoretical fair pricing of derivatives, this inventive approach helps traders greatly reduce the uncertainty and risk of their automated trading strategies for derivatives.

[0050] As still additional technical solutions to the above-described technical shortcomings in the art, the inventors disclose techniques where parallelized computational resources implement a scheduling circuit that can be used to schedule the transmissions of quotes to trading venues. The scheduling circuit can monitor transmission metrics (e.g., transmission rates) with one or more trading venues and then compare these transmission metrics with permitted transmission metric limits with the trading venues to determine when quotes can be transmitted to trading venues for acceptance. Quotes that are awaiting transmission can be stored in a pending buffer, and should new quotes on the same financial instrument arrive at the scheduler while the previous quote on that financial instrument is queued in the pending buffer, the scheduling circuit can overwrite the previous quote with the new quote in the pending buffer to ensure that the newer, more up-to-date quote is the one that gets transmitted to the trading venue. The scheduling circuit can also accommodate various prioritization criteria when deciding how to schedule quotes for transmission to trading venues.

[0051] These and other features and advantages of the present invention will be described hereinafter to those having ordinary skill in the art.

BRIEF DESCRIPTION OF THE DRAWINGS

[0052] FIG. **1** illustrates an automated trading strategy connected to trading venues via direct market access, consuming market data feeds, and receiving configuration information.

[0053] FIG. **2** illustrates an automated trading strategy connected to a derivatives trading venue and a remote trading venue for the underlying instruments via a wireless network link.

[0054] FIG. **3** illustrates an example of a conventional automated trading system in the art.

[0055] FIG. **4** illustrates an example of a conventional automated trading system that connects to a local derivatives market and a remote market for underlying instruments.

[0056] FIG. **5** provides a block diagram of an example embodiment of a volatility trading engine that connects to a local derivatives market and a remote market for underlying instruments.

[0057] FIG. **6**A provides an example of a basic market making scenario based on a theoretical midpoint price.

[0058] FIG. **6**B provides an example of a basic market making scenario based on theoretical bid and offer prices.

[0059] FIG. **6**C provides an example of pipelined logic for carrying out basic market making.

[0060] FIG. **6**D provides a block diagram of an example basic market making circuit.

[0061] FIG. **7**A provides an example of a theoretical price calculation.

[0062] FIG. **7**B provides a block diagram of an example theoretical price generator circuit.

[0063] FIG. **8**A provides an example of pipelined logic for carrying out joining market making.

[0064] FIG. **8**B provides a block diagram of an example joining market making circuit.

[0065] FIG. **9** provides an example of a joining market making scenario.

[0066] FIG. **10**A provides an example of pipelined logic for carrying out bettering market making.

[0067] FIG. **10**B provides an example of a bettering market making scenario.

[0068] FIG. **10**C provides a block diagram of an example bettering market making circuit.

[0069] FIG. **11** provides an example of a combination market making scenario.

[0070] FIG. **12** provides an example of an aggressing scenario.

[0071] FIG. **13**A provides an example of pipelined logic for carrying out an aggressing strategy.

[0072] FIG. **13**B provides a block diagram of an example aggressing circuit.

[0073] FIG. **13**C provides an example of pipelined logic for carrying out a hedging strategy.

[0074] FIG. **13**D provides a block diagram of an example hedging circuit in combination with an aggressing circuit.

[0075] FIG. **14** provides an example of a canceling scenario.

[0076] FIG. **15**A provides an example of pipelined logic for carrying out a canceling strategy.

[0077] FIG. **15**B provides a block diagram of an example canceling circuit.

[0078] FIG. **16** shows an example of parallelized logic for computing theoretical fair prices of different derivatives in parallel.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0079] The example embodiments of the invention that are described herein implement automated trading strategies that operate at 10 to 100 times faster than the state of the art by using novel and innovative system architectures and integrated circuits for latency-critical functions. These embodiments may be used for automated trading of any financial instrument by both "buy side" and "sell side" market participants. Relevant buy side market participants include proprietary (or principal) traders who invest their own capital and asset managers (or funds) who invest capital from clients. Relevant sell side market participants include brokers, both institutional and retail, and banks.

[0080] While the automated trading techniques described herein can be used to support trading of financial instruments such as stocks, it should be understood that they are particularly useful for supporting trades in derivative financial instruments Trading derivatives, such as stock options and future options, are the most computationally intensive use cases, and the examples discussed below describe applications to automated trading of derivatives.

[0081] The automated trading strategies described herein can be deployed as an automated trading engine on a processor having parallelized computational resources.

[0082] As an example, a reconfigurable logic device such as an FPGA would be suitable for use as the processor on which the automated trading strategy is deployed. As used herein, the term "reconfigurable logic" refers to any logic technology whose form and function can be significantly altered (i.e., reconfigured) in the field post-manufacture.

[0083] This is to be contrasted with a general purpose processor (GPP), whose function can change post-manufacture, but whose form is fixed at manufacture. As used herein, the term "general-purpose processor" (or "GPP") refers to a hardware device having a fixed form and whose functionality is variable, wherein this variable functionality is defined by fetching instructions and executing those instructions, of which a conventional central processing unit (CPU) is a common example. Exemplary embodiments of GPPs include an Intel Xeon processor and an AMD Opteron processor. Furthermore, as used herein, the term "software" refers to data processing functionality that is deployed on a GPP or other processing devices, wherein software cannot be used to change or define the form of the device on which it is loaded. By contrast, the term "firmware", as used herein, refers to data processing functionality that is deployed on reconfigurable logic or other processing devices, wherein firmware may be used to change or define the form of the device on which it is loaded. With an FPGA, the firmware can take the form of a configuration file (or bit file) that defines the gate level hardware configurations for the FPGA that will implement massively parallelized processing functionality defined by the firmware. Such configuration files (bit files) can be compiled from VHDL or Verilog code prepared by a designer and maintained in a non-transitory computer-readable storage medium (such as computer memory). These configuration files (bit files) can then be

made available for loading onto an FPGA through either a local connection to the FPGA or a networked connection to an FPGA.

[0084] As another example, an ASIC would be suitable for use as the processor on which the automated trading strategy is deployed. With the ASIC, massively parallel logic resources can be hardwired into the ASIC chip to support the trading strategies described herein.

[0085] Examples of trading strategies that can be deployed in the automated trading engine include market making strategies, aggressing strategies, hedging strategies, and/or canceling strategies (including any combination thereof). More detailed examples of these trading strategies as implemented in an automated trading engine are described below.

[0086] FIG. **5** is a block diagram of an example embodiment for automated trading of derivatives by a buy side firm, commonly referred to as volatility trading. The primary element of this embodiment is an automated trading engine in the form of the Volatility Trading Engine (VTE), where the VTE performs the latency-critical functions of the automated trading platform as an integrated circuit using parallel logic resources deployed on a chip **500** such as an FPGA or ASIC as discussed above. As noted above, other forms of computing devices that provide sufficient granularity of parallel operations (data-level and functional parallelism) and speed may be used as chip **500** if desired by a practitioner. The VTE interfaces to one or more electronic financial markets, as well as other components of the automated trading platform.

[0087] The automated trading engine can leverage the parallel logic resources of the chip **500** to deploy a number of parallel instances of its computational and decision-making logic for operation in parallel with each other. For example, there can be multiple parallel instances of the Theoretical Price Generator component **658** discussed below (e.g., see FIGS. **6**D, **7**B, **8**B, **13**B, and **13**D), and these parallel instances of the Theoretical Price Generator **658** can operate on data for different derivatives at the same time. An example of this is shown by FIG. **16** where parallel instances of the logic resources **658** for computing theoretical fair prices for derivatives operate on different derivatives that have been identified as being impacted by new market data for an underlying financial instrument via logic **1600**. This type of parallelization helps the automated trading engine handle workloads that are produced when a given update (e.g., a new price for an underlying financial instrument) triggers the need to compute new theoretical prices for multiple derivatives. For example, there may be a number of different derivatives that are based on Acme stock (say, 50 derivatives). When a new price is received in the underlying market data feed for Acme stock, this can trigger the automated trading engine to compute new theoretical prices for 50 different derivatives. Rather than sequentially computing new theoretical prices for each of these 50 derivatives, the automated trading engine can deploy a number of parallel instances of the Theoretical Price Generator **658** so several of the theoretical prices for different derivatives can be computed at the same time. A practitioner can choose how many parallel instances of a given circuit component such as the Theoretical Price Generator **658** should be deployed in the automated trading engine based on any of a number of considerations. For example, the number of different messages that can be combined in a packet for transmission to a trading venue could drive the choice of how many parallel instances of a circuit component to deploy on the chip **500**. Thus, if the trading venue permits 10 messages to be combined in a single packet transmission to that trading venue, then a practitioner may find it desirable to deploy 10 parallel instances of relevant circuit components. In this scenario, if some underlying price changes only trigger the need to update (say) 5 derivatives, then some of the parallel instances of the Theoretical Price Generator **658** may be idle during operation of the automated trading engine. Similarly, if some underlying price changes trigger the need to update more than 10 derivatives, then the automated trading engine can push the workload through the parallel instances in sequenced groups. Buffers can reside on the chip **500** between the circuit components of the automated trading engine to hold the data values being passed from component to component.

[0088] Furthermore, different components of the automated trading engine can operate in a pipelined manner, in which case the automated trading engine may include one or more pipelines within it. Moreover, the logic resources that implement the various circuit components of the automated trading engine may be internally pipelined if desired by a practitioner.

[0089] Further still, the chip **500** can include on-chip memory resources in which various data items that are to be considered by the automated trading pipeline are stored for fast access by the chip's logic resources. For example, as discussed below, memory on the chip **500** can store underlying prices extracted from underlying market data (e.g., see **656** in FIGS. **6**D, **8**B, **13**B, and **13**D), pricing and configuration parameters (e.g., see **660** in FIGS. **6**D, **8**B, **13**B, **13**D, and **15**B), posted quotes (e.g., see **664** in FIGS. **6**D and **8**B), quoting boundaries for governing joining and bettering market making strategies (e.g., see **852** in FIG. **8**B), quote prices extracted from derivatives market data (e.g., see **854** in FIG. **8**B), order books from derivatives market data (e.g., see **1354** in FIGS. **13**B and **13**D), aggressing boundaries for governing aggressing strategies (e.g., see **1352** in FIGS. **13**B and **13**D), and/or canceling boundaries for governing canceling strategies (e.g., see **1554** in FIG. **15**B).

[0090] In the example embodiment of FIG. **5**, the VTE includes four configured algorithm engine components that define automated trading strategies for the automated trading engine—Market Making **502**, Aggressing **504**, Hedging **506**, and Canceling **508**. Example embodiments for implementing these automated trading strategies on the chip **500** will be discussed below. It should be understood that the VTE may employ any combination of these automated trading strategies as desired by a practitioner. Similarly, a practitioner may choose to deploy only one of these automated trading strategies on the chip **500** if desired.

Feed Handlers:

[0091] For each market that the VTE consumes real-time market data from, a Feed Handler component processes the message stream and extracts the fields required by the configured algorithm engine and market gateway components (e.g., see **520**, **522** in FIG. **5**). In an example embodiment, a Feed Handler only extracts the fields required by the configured algorithm engines and market gateways, ignoring other content in the market data feed packets and their concomitant messages. Also in an example embodiment, a Feed Handler only stores information required for it to perform its parsing function, which means the algorithm

engine and market gateway components would maintain records for any market data information they need to perform their functions.

[0092] Alternative embodiments may configure the Feed Handler components to store all market data information required by the configured algorithm engine and market gateway components. Since the algorithm engine and market gateway components all function in parallel within the VTE engine, such a Feed Handler should provide sufficient access bandwidth to the stored market data information to service simultaneous requests by multiple components without causing a component to delay processing while it waits for requested market data information to return. The example embodiment eliminates this implementation challenge by parallelizing the storage of required market data information by each algorithm engine and market gateway component that requires it.

[0093] Examples of feed handlers that can be deployed on massively parallelized computational resources such as an FPGA and produce streams of normalized market data fields are described in the above-referenced and incorporated U.S. Pat. Nos. 7,921,046 and 8,762,249.

[0094] In the example of FIG. **5**, two Feed Handler components are configured in the Volatility Trading Engine—one for a local derivatives market (Feed Handler A **520**) and one for a remote underlying market (Feed Handler B **522**). It should be understood that additional Feed Handlers may be deployed on the chip **500** if desired by a practitioner to accommodate feeds from additional trading venues. Note that underlying financial instruments may trade on the same market as the derivatives instruments (e.g. the Chicago Mercantile Exchange's Globex market for futures and future options). Furthermore, some simple derivatives trading strategies may only require market data from one market, either the underlying market or the derivatives market.

Market Gateways:

[0095] For each market that the VTE trades upon, a Market Gateway component interfaces to the market via direct market access (DMA) and sends orders to buy and sell or mass quotes to establish best bid and offer prices (e.g., see **530**, **532** in FIG. **5**). In an example embodiment, a Market Gateway establishes and maintains connectivity to the configured market according to the market's DMA protocols. For messages sent to the market, the Market Gateway formats the messages according to the market's DMA protocols, allowing internal algorithm engine components to use internal message formats that minimize the latency of passing information to and from the Message Gateway.

[0096] For messages received from the market, the Market Gateway extracts the fields required by the configured algorithm engines and market gateways, ignoring other content in the DMA protocol packets and concomitant messages. Also in an example embodiment, a Market Gateway only stores information required for it to perform its formatting and parsing functions, which means algorithm engine components would need to maintain records for any DMA information required to perform its function. DMA information for a trading strategy may include its posted best bid and offer prices and sizes (mass quote) for a given financial instrument, the list of all posted mass quotes for all derivatives on a given underlying financial instrument, the status of an order to buy or sell a given financial instrument (e.g. has a limit order been accepted by the exchange yet?), the number of mass quotes transmitted to the market in the past second or minute, the number of cancellation messages transmitted to the market in the past second or minute, and the round-trip-time (latency) of order transmission to acknowledgement from the market.

[0097] Alternative embodiments may configure the Market Gateway components to store all DMA information required by the configured algorithm engine components. Since the algorithm engine components all function in parallel within the VTE engine, such a Market Gateway should provide sufficient access bandwidth to the stored DMA information to service simultaneous requests by multiple components without causing a component to delay processing while it waits for requested DMA information to return. The example embodiment eliminates this implementation challenge by parallelizing the storage of required DMA information by each algorithm engine component that requires it.

[0098] Examples of message parsing, message generation, and order functionality for the Market Gateways that can be deployed on massively parallelized computational resources such as an FPGA and produce streams of normalized market data fields are described in the above-referenced and incorporated U.S. Pat. Nos. 7,921,046 and 8,762,249 as well as U.S. Pat. No. 10,037,568, the entire disclosure of which is incorporated herein by reference.

[0099] In the example of FIG. **5**, two Market Gateway components are configured in the Volatility Trading Engine—one for a local derivatives market (Market Gateway A **530**) and one for a remote underlying market (Market Gateway B **532**). It should be understood that additional Market Gateways may be deployed on the chip **500** if desired by a practitioner to accommodate connections with additional trading venues.

Operational Control of the VTE:

[0100] In the example embodiment of FIG. **5**, the financial instruments to trade, the algorithm to use, and the configuration parameters that dictate the algorithm engine's behavior and its configuration parameters can be defined by a user via the User Terminal Visualization component **510**. The interface provided to users may include listings of financial instruments available for trading pulled from the Instrument Database **516** and current pricing parameters from the Theoretical Server **514**. In response to user input, the Command & Control component **512** sends messages containing the configuration information to the VTE.

[0101] The example embodiment of FIG. **5** as used for derivatives trading includes a Theoretical Server **514**. The Theoretical Server **514** continuously computes pricing parameters that are used by the configured algorithm engine components of the VTE. Fair value of derivatives instruments may be computed by a number known techniques, including the Cox Ross Rubenstein (CRR) binomial model or proprietary models developed by the user. Typically, these models require input values such as a short-term interest rate. These parameters may be drawn from an external or proprietary data source. The refresh rate for the pricing generated by the Theoretical Server **514** will be relatively low due to the time it takes the Theoretical Server **514** to generate its pricing. For this reason, as discussed above, the theoretical derivative prices generated by the Theoretical Server **514** can be referred to as coarse reference theoretical

derivative prices. The Theoretical Server **514** can also track the reference underlying price that was used to compute the reference theoretical derivative price. This reference underlying price can be included as part of the pricing parameters for its subject derivative, and the VTE can use this information to facilitate computation of real-time theoretical fair prices for derivatives using the techniques discussed below. As discussed above and below, these coarse reference prices can be used by the VTE to drive low latency computation of theoretical fair prices for derivatives.

[0102] In addition to computing a fair value for each derivatives instrument, the Theoretical Server **514** can also compute parameters that describe the relationship between the prices of underlying instruments and their derivative instruments. These parameters primarily describe the magnitude of change in a derivative's price relative to a change in the price of the underlying instrument. These parameters include:

[0103] The rate of change between the derivative price relative to the underlying price (Delta),

[0104] The rate of change between the derivative price and time (Theta),

[0105] The rate of change between a derivative's Delta and the underlying price (Gamma),

[0106] The rate of change between a derivative's price and the underlying instruments implied volatility (Vega), and

[0107] The rate of change between a derivative price relative to a change in interest rates (Rho).

[0108] These parameters are commonly referred to as the "Greeks". An embodiment may compute additional parameters describing relative price changes of a derivative instrument, such as the leverage ratio of a derivative relative to the derivative's price (Lambda).

[0109] As discussed below, one or more of these Greeks (e.g., the Delta or δ) can be used to drive the real-time computation of theoretical fair prices for a derivative from the reference price and the real-time pricing changes for the financial instrument underlying the derivative.

[0110] In an example embodiment, the Theoretical Server **514** attempts to compute a full set of pricing parameters for each enabled derivative instrument for every change to user inputs or change to underlying instrument price reported by a real-time market data feed. Given the aforementioned computational complexity of doing so with sufficient precision and the frequency of updates to underlying asset prices, the Theoretical Server **514** continuously cycles through the set of enabled derivative instruments updating the set of pricing parameters using the latest user inputs and most recent underlying price information from the real-time market data feeds. If multiple changes to either user inputs or underlying price information occur during a cycle of the Theoretical Server **514**, the inputs are effectively conflated.

[0111] The Command & Control component **512** and the Theoretical Server component **514** can be implemented in software for execution by one or more GPPs on the same server that hosts chip **500**. Similarly, the Instrument Database **516** can be implemented in memory on this server. The User Terminal, Visualization Component **510** may be implemented by the same or remote server. Furthermore, if desired by a practitioner, the Command & Control component **512**, the Theoretical Server component **514**, and/or the Instrument Database **516** can be implemented on a server remote from the server that hosts chip **500**.

Market Making Strategy:

[0112] The Market Making component **502** generates and continuously updates best bid and offer prices (i.e. mass quotes) as directed by the parameter set received from the Command and Control **512**, Theoretical Server **514**, and Instrument Database **516**. The Market Making component **502** implements one or a combination of algorithms for mass quoting, as directed by the parameter set. Examples of different market making strategies that can be employed include basic market making, joining market making, bettering market making, and/or some combination thereof.

Basic Market Making

[0113] A basic market making algorithm engine generates new BBO prices for a derivative by directly using the pricing parameters from the Theoretical Server **514** and the current price of the underlying instrument to compute new theoretical BBO prices that are used to generate new quotes for posting with a trading venue.

[0114] FIG. **6**A provides an example of a basic market making scenario that uses a theoretical midpoint price and offset parameters. The theoretical midpoint price is computed using the midpoint price (the average of the bid and offer prices) for the underlying instrument. The bid price is determined by subtracting a bid offset from the theoretical midpoint price. Likewise, the offer price is determined by adding an offer offset to the theoretical midpoint price. Optionally, the bid and offer offsets may be a single offset value. The offset values are specified as a configuration parameter and serve to ensure a minimum spread (or "edge") for the BBO prices posted by the market making algorithm.

[0115] FIG. **6**B provides an example of a basic market making scenario that uses a theoretical bid and offer prices and offset parameters. The theoretical bid price is computed using the bid price for the underlying instrument. The bid price for quoting is determined by subtracting a bid offset from the theoretical bid price. Likewise, the theoretical offer price is computed using the offer price for the underlying instrument. The offer price for quoting is determined by adding an offer offset to the theoretical offer price. Optionally, the bid and offer offsets may be a single offset value. Independently computing theoretical prices for the bid and offer can help defend against erroneous values for underlying instruments due to data loss or other errors in the market data feeds.

[0116] FIG. **6**C provides an example of pipelined logic for carrying out basic market making. The operations of FIG. **6**C can be implemented via parallelized logic resources on the chip **500** so that each operation can operate concurrently with the other operations (e.g., see FIG. **16**). The pipeline of FIG. **6**C ingests and listens for new underlying market data (from one or more underlying trading venues via one or more Feed Handlers) and/or new parameters (from the system's operational control subsystem).

[0117] At step **600**, an underlying trigger is generated in response to new underlying market data (e.g., a new underlying price) for a financial instrument that underlies a derivative covered by the VTE; or a parameter trigger is generated in response to new parameter data being received from the operational control subsystem.

[0118] At step **602**, in response to the underlying trigger or parameter trigger, the pipeline determines which derivatives are impacted by the new underlying market data or new

parameter (e.g., see **1600** in FIG. **16**). This can be accomplished via a lookup in memory that links each underlying instrument with its corresponding derivative(s) (e.g., see **1602** in FIG. **16**) and a memory that links each parameter with its corresponding derivative(s). Such memory(ies) can be deployed on-chip for fast access by logic **1600** that performs step **602**. As noted above, it should be understood that a given financial instrument may underly multiple derivatives covered by the VTE. Similarly, a given control parameter may apply to multiple derivatives covered by the VTE. As such, step **602** can introduce a one-to-many fanout of workload for the pipeline.

[0119] At step **604**, the pipeline computes new theoretical fair bid and offer prices for each impacted derivative (based on the new underlying price or new parameter). These new theoretical fair bid and offer prices can be used as the BBO prices for a new quote on a subject derivative. Due to the parallelism available on chip **500**, the chip's logic resources can accommodate this one-to-many workload as discussed above by deploying multiple copies of the Theoretical Price Generator component **658** discussed below and then using different copies of the Theoretical Price Generator component **658** to compute theoretical prices for different derivatives at the same time (see FIG. **16**). Moreover, in situations where a given underlying price change or parameter change triggers a need to update a number of derivatives that is greater than the number of copies of the Theoretical Price Generator component **658** on the chip **500**, step **602** can also involve prioritizing the ordering of derivatives for processing through the parallel Theoretical Price Generator components. For example, derivatives that are closer to "being in the money' can be prioritized over derivatives that are less close to being in the money. As another example, derivatives that are more frequently traded can be prioritized over derivatives that are less frequently traded. The control parameters from the user can be used to govern such prioritizing approaches.

[0120] At step **606**, the pipeline, for each impacted derivative, generates a quote with BBO prices that are based on the subject derivative's computed theoretical fair bid and offer prices (as tick size adjusted (discussed below)) if a minimum spread requirement for the derivative is satisfied by the BBO prices. As with step **604**, chip **500** can include multiple copies of the logic resources that perform quote generation so that the pipeline can generate multiple quotes in parallel in situations where multiple derivatives are impacted by a given price or parameter update. Moreover, the ability to generate multiple quotes in parallel allows a quote scheduling component (see the Mass Quote Scheduler **666** discussed below) to consider different quotes in parallel when deciding which quotes to prioritize for transmission to a trading venue. Prioritization strategies for such scheduling can be driven by user-defined configuration parameters.

[0121] An example embodiment of a basic market making circuit **650** is shown by FIG. **6**D. The different components of the basic market making circuit of FIG. **6**D can be implemented by different sets of parallelized logic resources of the chip **500**. In this fashion, the logic resources can operated in a pipelined manner (e.g., the Mass Quote Scheduler **666** can be operating on data for Derivative A while at the same time the Theoretical Price Generator **658** is operating on subsequently received data for Derivative B).

[0122] The logic resources of the chip **500** which define the Parameter Update Engine **652** receive updated configuration parameters from Command and Control **512**, updated pricing parameters from the Theoretical Server **514**, and updated instrument parameters from the Instrument Database **516**. The Parameter Update Engine **652** stores these parameters in a Parameters Memory **660** that may also be accessed by other components of the basic market making circuit **650**. When the Parameter Update Engine **652** detects a change in any of the parameters that drive the basic market making circuit **650** (e.g., a new reference price for a derivative handled by the VTE, a new Greek value for a derivative handled by the VTE, a new derivative to be handled by the VTE, etc.), it can generate a Parameter Trigger that will drive a re-computation of theoretical fair prices for the subject derivative(s).

[0123] Real-time updates for underlying instruments are received by the Underlying Price Memory **656** and Theoretical Price Generator **658** from one or more Feed Handler components **522**. The Underlying Price Memory **656** stores the most recent pricing information for all underlying instruments of the enabled derivatives instruments.

[0124] Logic resources of the chip **500** that define an Underlying Update Engine **654** can detect whether any of the new prices for an underlying in the incoming stream from the Feed Handler **522** reflect a change in price for that underlying financial instrument. This detection can be accomplished by comparing the stored most recent price for a subject underlying as reflected in and retrieved from the Underlying Price Memory **656** with the new price for that underlying financial instrument from the Feed Handler **522**. If an underlying price change is detected, the Underlying Update Engine **654** can generate an Underlying Trigger that will drive a re-computation of theoretical fair prices for the derivatives corresponding to that underlying financial instrument.

[0125] Logic resources of the chip **500** that define a Theoretical Price Generator **658** generate new theoretical best bid and offer (BBO) prices for a derivatives contract when notified of a change to underlying instrument prices (the "underlying trigger") or a change to parameters (the "parameter trigger"). Note that an underlying trigger will cause new theoretical bid and offer prices to be generated for each enabled derivatives instrument tied to the underlying instrument. Further note that a parameter change may include enabling trading on a new derivatives instrument or new theoretical pricing parameters from the Theoretical Server.

[0126] In an example embodiment, the Theoretical Price Generator **658** generates new theoretical fair prices by implementing a circuit to compute the equation shown in FIG. **7**A. First the difference in the current underlying instrument price (from the real-time market data feed) and the reference underlying price (supplied in the pricing parameters from the Theoretical Server) is computed as $\Delta_{underlying}$. This difference is multiplied by δ, the Greek Delta value for the subject derivative that is supplied in the pricing parameters from the Theoretical Server **514**. The result is added to the reference theoretical derivative price, T_{ref}, that is also supplied in the pricing parameters from the Theoretical Server **514**, to form the new theoretical fair price, T. The reference underlying price that is used can be the same underlying price that was used to compute the reference theoretical derivative price.

[0127] In an example embodiment, a new theoretical fair price is computed independently for the best bid and best

offer prices. FIG. **7**B depicts an example embodiment for logic resources to carry out these computations in the circuit **658** (see subtraction logic **702**, multiplication logic **704**, and sum logic **706**). Alternatively, the new theoretical fair price may specify the midpoint price. The theoretical price generator circuit **658** of FIG. **7**B is capable producing a "tick to price" latency on the order of around 5 to 50 nanoseconds, which is sufficiently fast to keep up with how quickly underlying prices may change (see Rate 1 in FIG. **7**B which may be more than one million times per second). In the example of FIG. **7**B, Rate 1 is expected to be (but need not be) faster than Rate 2 (which corresponds to the refresh rate of the coarse reference prices of the underlying and derivative) and Rate 3 (which corresponds to the refresh rate of the Greek—where Rate 3 may be the same as Rate 2). In an example embodiment, the theoretical price generator circuit **658** operates on the most recently received of the current reference prices (for the derivative and its underlying instrument), Greek value, and new underlying instrument price.

[0128] The new theoretical fair prices are passed to the Tick Size Quantization circuit **662** that adjusts the theoretical fair prices by the specified offsets (see FIGS. **6**A and **6**B). This adjustment process can also ensure that the resulting theoretical fair bid and offer prices conform to the tick size rules of the market. For example, a derivatives market may specify that options contracts may only be quoted in increments of ten cents ($0.10). The market may also specify different tick sizes based on price ranges. In addition to the tick size rules for the market, the pricing parameters may specify the logic for adjusting theoretical prices. Example adjustments might be to always round theoretical prices toward or away from the midpoint price. The adjusted BBO prices then serve as the BBO prices for a new quote on the subject derivative and are passed to the Mass Quote Scheduler circuit **666**.

[0129] The Mass Quote Scheduler **666** transmits mass quote messages to the Market Gateway **530** as quickly as possible, subject to bandwidth limitations of the network connectivity to the trading venue and any rate restrictions imposed by the trading venue. Some trading venues limit the rate that a market participant may transmit various message types such as mass quotes and cancellations. When those rates are exceeded, the trading venues may reject new messages or disconnect the market participant and cancel all posted quotes and orders.

[0130] When a quote is able to be transmitted by the Mass Quote Scheduler circuit **666**, it is stored in the Posted Mass Quote memory **664**. If at a later time the quote is rejected by the trading venue or not acknowledged and accepted within a specified time period, the quote is removed from the Posted Mass Quote memory **664** and passed back to the Mass Quote Scheduler **666**. If a more recent Mass Quote update has been successfully transmitted by the Mass Quote Scheduler **666**, then no further action is taken. If not, the Mass Quote still represents the most current price for the instrument and the Mass Quote Scheduler **666** transmits the mass quote as soon as possible.

[0131] When a quote cannot be immediately transmitted by the Mass Quote Scheduler circuit **666**, the Mass Quote Scheduler **666** stores the quote in a pending buffer. The Mass Quote Scheduler **666** can sequence quotes in the pending buffer for transmission according to their order of arrival. If a new quote for the same instrument arrives from the Tick Size Quantization circuit **662** while the previous quote is still in the pending buffer, then the previous quote is replaced by the new quote (and the new quote can retain the previous quote's place in the transmission sequence). The Mass Quote Scheduler **666** drains the pending buffer by transmitting quotes stored therein as quickly as allowed by the constraints of the Market Gateway interface, e.g. link bandwidth or market rate limits.

[0132] The Mass Quote Scheduler **666** also can sequence quotes in the pending buffer according to a priority associated with the financial instrument to be quoted. The configuration parameters for the financial instrument may specify the priority explicitly or it may specify a metric that dictates the priority. Example metrics that can be used to define priority include the current trading volume for the subject instrument, the distance of the strike price for an option instrument from the current price of the underlying instrument, or the rate of price underlying price changes for the subject financial instrument. Values for these metrics can be computed and derived from market data that is available from the underlying feed handler **522** and derivatives feed handler **520** as well as reference Greeks from the Theoretical Server **514**.

[0133] If the size of the pending buffer grows beyond a specified threshold, the Mass Quote Scheduler **666** transmits a cancellation message to the trading venue. This can be done to prevent posted quotes that no longer represent fair values from being executed against by a fast-moving market participant before they are able to be updated due to message rate limitations imposed by the trading venue. The Mass Quote Scheduler **666** then retransmits current quotes for all enabled instruments. Based on parameters entered by the user via Command and Control **512**, this action occurs either immediately, after a configured wait period, or after a user enters a manual command.

Joining Market Making

[0134] Whereas basic market making sets BBO prices for quotes based on the theoretical prices derived directly from the current prices of the underlying instrument, joining market making seeks to maintain BBO quote prices equal to the current best prices for the subject derivative contract. As previously described, this strategy is commonly used for trading venues that use pro rata apportionment of executed shared among all participants at the best price.

[0135] FIG. **8**A provides an example of pipelined logic for carrying out joining market making. The operations of FIG. **8**A can be implemented via parallelized logic resources on the chip **500** so that each operation can operate concurrently with the other operations (e.g., see FIG. **16**). The pipeline of FIG. **8**A ingests and listens for (1) new quotes for derivatives (from one or more derivatives trading venues via one or more Feed Handlers **520**) and (2) new underlying market data (from one or more underlying trading venues via one or more Feed Handlers **522**) and/or new parameters (from the system's operational control subsystem). The pipeline can employ roughly two decision paths for handling these inputs—one path for deciding whether to join a market quote and one path for deciding whether market conditions indicate any existing market quotes should be canceled.

[0136] For example, when a new quote for a derivative is received, the pipeline will retrieve quoting boundaries for the subject derivative at step **800**. These quoting boundaries will control the decision-making as to whether a joining quote should be generated, as discussed below. At step **802**,

the pipeline compares the new quote pricing with the retrieved quoting boundaries. If the comparison at step **802** results in a determination that the new quote pricing complies with the retrieved quoting boundaries, then the pipeline generates a joining quote at the new quote's pricing.

[0137] When new underlying market data or new parameter(s) are received, then steps **810**, **812**, and **814** operate in a like manner as steps **600**, **602**, and **604** of FIG. **6**A (see also FIG. **16**). However, with joining market making, the computed theoretical fair bid and offer prices are used to define the quoting boundaries rather than setting the BBO prices of a new quote. Accordingly, at step **816**, the pipeline—for each derivative impacted by the new underlying price or the new parameter(s)—creates (and stores) new quoting boundaries for the subject derivative based on the computed theoretical BBO prices (as tick size adjusted). Furthermore, while these operations are being carried out, the pipeline can also retrieve the existing quote prices for each impacted derivative (step **818**) (e.g., see memory **854** in FIG. **8**B). Then, at step **820**, the pipeline—for each impacted derivative—compares the impacted derivative's retrieved existing quote prices with its newly computed quoting boundaries. If an existing quote's pricing now falls outside the new quoting boundaries, the pipeline will request cancellation of that existing quote (step **822**), which permits the VTE to quickly avoid leaving a quote on a market with stale and outdated pricing.

[0138] An example embodiment of a joining market making circuit **850** is shown by FIG. **8**B.

[0139] The current quote (the BBO prices) for derivatives contracts on the trading venue are received from a real-time market data feed for the derivatives trading venue via a Feed Handler component **520**. Updates to the current quote are stored in the BBO Quote Memory **854** and passed to the Quote Canceler **856** and Mass Quote Scheduler **666** as a joining trigger signal. In this fashion, the Quote Canceler **856** and Mass Quote Scheduler **666** are notified that there are new BBO prices for a subject derivative that should be considered for joining in the marketplace.

[0140] In the same manner as the basic market making circuit **650**, the joining market making circuit **850** includes a Parameter Update Engine **652**, Underlying Price Memory **656**, Underlying Update Engine **654**, Parameters Memory **660**, Theoretical Price Generator **658**, and Tick Size Quantization circuit **662**. These serve the same role of generating new theoretical BBO prices (quote) in response to an underlying trigger or a parameter trigger. The difference in the joining market making circuit **850** is that these prices represent the boundaries of an exclusion range of prices for the joining decision. That is, the newly computed theoretical BBO prices for a subject derivative (as adjusted to fit the tick size requirements of a subject trading venue) are used to define the exclusion zone's quoting boundaries. These new quoting boundaries are added to the Quoting Boundary Memory **852** in association with their subject derivative and are passed to the Quote Canceler circuit **856** as a boundary trigger. The joining market making circuit **850** is configured to not post new quotes for derivatives within the derivatives' exclusion boundaries. Furthermore, the joining market making circuit **850** is also configured to cancel any posted quotes for derivatives whose newly computed theoretical BBO prices (as tick-size adjusted) now fall within the exclusion boundaries for those derivatives. A logic table for this joining/canceling decision-making is below. It should be understood that the logic below applies to the bid price and offer price independently.

Trigger	Need	Test	Action
New quote price for a subject derivative is received from market	Does the new quote price for the subject derivative fall within the exclusion boundaries for the subject derivative	Compare exclusion boundaries for the subject derivative that are retrieved from Quoting Boundary Memory with the new quote prices for the subject derivative	If new quote price falls outside the retrieved exclusion boundaries, then generate a quote at the new quote price; Otherwise do not generate a new quote at the new quote price
New underlying price for the underlying instrument of a subject derivative is received from market	Compute new exclusion boundaries (based on newly computed theoretical BBO prices that take into consideration the new underlying price) for subject derivative; and compare existing quote for the subject derivative with the new exclusion boundaries	Compare BBO prices for existing quote on the subject derivative that are retrieved from the BBO Quote Memory with the new exclusion boundaries	If retrieved BBO prices fall within the new exclusion boundaries, then cancel the existing quote; Otherwise keep the existing quote
New parameter for a subject derivative is received from	Compute new exclusion boundaries (based on newly computed theoretical BBO prices	Compare BBO prices for existing quote on the subject derivative	If retrieved BBO prices fall within the new exclusion boundaries, then

-continued

Trigger	Need	Test	Action
operational control system	that take into consideration the new parameter(s)) for subject derivative; and compare existing quote for the subject derivative with the new exclusion boundaries	that are retrieved from the BBO Quote Memory with the new exclusion boundaries	cancel the existing quote; Otherwise keep the existing quote

[0141] In response to a boundary trigger or a joining trigger, the Quote Canceler circuit **856** checks to see if the new BBO prices from the market or the currently posted BBO prices for an existing quote now fall within the exclusion boundaries. If so, the Quote Canceler **856** issues a canceling trigger to the Mass Quote Scheduler **666**, which directs the Mass Quote Scheduler **666** to cancel and not join either the best bid, the best offer, or both the best bid and best offer prices for the given derivative contract.

[0142] In response to a canceling trigger, the Mass Quote Scheduler **666** immediately generates a mass quote cancelation message and attempts to transmit it to the Market Gateway **530**. In an example embodiment, cancellation actions always take precedence over mass quote update actions.

[0143] In response to a joining trigger, the Mass Quote Scheduler **666** retrieves the current posted quote values for the associated derivative contract from the Posted Mass Quote Memory **664**. If the posted quote prices differ from the received quote prices, then the Mass Quote Scheduler **666** generates a mass quote update message. Note that a coincident cancellation trigger (caused by the same market data update) may override either the best bid or best offer price in the new mass quote message if either price fell within the exclusion boundary and thus was immediately canceled. The new mass quote message would then update the price that remained outside the exclusion boundary to join the new best price on the trading venue. In the case that the coincident cancellation trigger overrides both best bid and offer prices, the action of generating a new mass quote update message is abandoned. Transmission of new mass quote messages to the Market Gateway **530** are governed as previously described in the basic market making circuit **650**.

[0144] FIG. **9** provides an example of a joining scenario. For a given derivatives contract, the most recent market data update from the trading venue reports a best bid of one lot at $4.50 (see **900**) and a best offer of two lots at $5.50 (see **902**). Per the joining logic, the circuit **850** generates a mass quote with a best bid of one lot at $4.50 (which results in there being 2 lots of the quoted best bid price of $4.50—see **904**) and a best offer of one lot at $5.50 (which results in there being 3 lots of the quoted best offer price of $5.50—see **906**). Note that while the prices are dictated by the joining logic, the number of lots (i.e. amount or size) to post on the bid and offer can be configuration parameters specified by a user that are passed to the joining market making circuit **850** via the Command and Control component **512**.

[0145] In the example of FIG. **9**, the bid and offer exclusion boundary prices generated by the Theoretical Price Generator **658** (as tick size-adjusted by **662**) are $4.80 and $5.20, respectively. If a new market update from the trading venue improved the best bid to three lots at $4.85 and two lots at $5.85, then the joining market making circuit **850** can immediately cancel the posted best bid at $4.50 and update the best offer to one lot at $4.85.

Bettering Market Making

[0146] Another market making strategy that can be implemented by the VTE is bettering market making. Bettering market making can operate nearly identically to joining market making except that the posted BBO prices for the mass quotes are offset by a specified tick increment "better than" the BBO prices on the trading venue. That is, rather than joining an existing quote on the market, the bettering market making strategy seeks to post a quote with pricing that is one or more specified tick sizes better than that existing quote.

[0147] FIG. **10**A provides an example of pipelined logic for carrying out bettering market making. The operations of FIG. **10**A can be implemented via parallelized logic resources on the chip **500** so that each operation can operate concurrently with the other operations (e.g., see FIG. **16**). Steps **1000**, **1002**, and **1004** are carried in largely the same fashion as steps **800**, **802**, and **804** of FIG. **8**A (see also FIG. **16**), except that these steps will include the computation of bettering prices for a quote candidate (e.g., one tick size better than the existing quote's pricing) and where these bettered quote prices are the ones that are compared with the quoting boundaries. Similarly, the quote cancellation decision logic of steps **1010-1022** can operate in the same manner at steps **810-822** of FIG. **8**A.

[0148] Accordingly, as shown by FIG. **10**C, an example bettering market making circuit **1050** can be configured nearly identically to the joining market making circuit **850**, with the exception that the posted BBO prices for the mass quotes are offset by a specified tick increment "better than" the BBO prices on the trading venue. This specified tick increment can be a defined number of tick increments (e.g., a single tick increment, two tick increments, etc. as desired by a user). Accordingly, the bettering market making circuit **1050** can include the same basic components as the joining market making circuit **850** shown by FIG. **8**B, but where the logic to test and set the mass quote prices (e.g., via **662** and **666**) includes the defined tick increment adjustment for generated mass quotes.

[0149] FIG. **10**B provides an example of a bettering scenario. The most recent market data update from the trading venue reports a best bid of one lot at $4.50 (see **1030**) and a best offer of two lots at $5.50 (see **1032**). The most recent parameters received from the Command and Control component **512** specify that quotes should better the market BBO by one tick increment and should post one lot sizes. The most recent parameters received from the Instrument

Database component **516** specify that the tick increment for the contract is $0.05. Per the bettering logic, the circuit **1050** generates a mass quote with a best bid of one lot at $4.55 (see **1034**) and a best offer of one lot at $5.45 (see **1036**).

[0150] As with the joining circuit **850**, the bettering circuit **1050** governs the posting of new mass quotes according to an exclusion boundary defined by theoretical price calculations. Note that the Quote Canceler logic simply adjusts its computation of a canceling trigger to determine if a new "bettered" quote price would fall within the exclusion boundary.

Combination Market Making

[0151] Note that the exclusion boundary used by the joining and bettering circuits **850/1050** may cause the VTE to post single-sided quotes that contain only a best bid or only a best offer. This can prevent the user from participating in trading opportunities that fit within their risk tolerance. In order to provide more opportunities to participate in market making trades, an example embodiment of the Market Making component **502** of the VTE can support combinations of the making, joining, and bettering logic.

[0152] FIG. **11** provides an example of the operation of combination market making logic. As with the joining and bettering cases, theoretical price calculations continuously update the bid and offer prices that define an inner exclusion boundary. In the same manner, outer exclusion boundary prices are established. In another example embodiment, these outer boundary prices are generated by applying offset parameters specified by the user to the prices generated by the Theoretical Price Generator circuit **658** (which define the inner boundary prices). The bid and offer price ranges between the inner and outer boundary prices define a quotable zone for the combination market making logic.

[0153] A combination market making circuit allows users to specify the logic to be used to generate mass quotes. Typically, this is either the joining or bettering logic. Provided that the generated prices fall within the quotable zones, the logic operates as previously described. This is depicted in the example of FIG. **11** with the posting of a best bid of one lot at $4.75 which "betters" the market best bid of two lots at $4.70.

[0154] When a price falls within an inner boundary, the combination circuit allows the user to specify an alternative to simply canceling the posted price. Specifically, the circuit allows the user to specify the number of tick increments away from the cross boundary to post the price. Typically, the user specifies that the price be posted one tick increment outside of the boundary, but within the quotable zone. This is depicted in the example of FIG. **11** where the market best offer of one lot at $5.15 falls within the inner exclusion zone, less than the offer price inner boundary. Accordingly, the logic posts a best offer of one lot at $5.25 which is one tick increment outside of the inner exclusion boundary and within the quotable zone.

[0155] Variations of making, joining, and bettering logic, and combinations thereof, may be supported by the VTE.

[0156] Furthermore, in some example embodiments of the VTE, the market making circuit **502** can controllably implement any of a plurality of the basic, joining, and bettering market making strategies (or combinations thereof). Accordingly, the VTE can be configured to control which of the market making strategies are used by the VTE based on a plurality of criteria. As an example, the criteria include derivative-specific criteria. Through such derivative-specific criteria, a trading firm can define that derivatives within Derivative Set A are subjected to a first type of market making (e.g., basic market making) while the derivatives within Derivative Set B are subjected to a second type of market making (e.g., joining market making), and so on. In this fashion, the VTE can apply different market making strategies to different derivatives. As another example, the criteria include trading venue-specific criteria. Through such trading venue-specific criteria, a trading firm can define that derivatives which are traded on Trading Venue A are subjected to a first type of market making (e.g., basic market making) while derivatives which are traded on Trading Venue B are subjected to a second type of market making (e.g., joining market making), and so on. For example, for derivatives that trade on markets that apply pro rata apportionment, a joining market making strategy may be desirable; while for derivatives that trade on markets that apply time-based apportionment, a basic market making strategy may be desirable.

Aggressing Strategy:

[0157] Aggressing strategies seek to identify mispriced limit order or mass quotes and execute against them to accumulate profits. The most common scenario that creates opportunities for an Aggressing strategy is when a limit order for a derivative contract rests on the trading venue when a substantive change to the price of the underlying price occurs (where this underlying price change is potentially on another trading venue). When this occurs, it changes the theoretical price of the derivative contract. If the market participant is slow to cancel or update the price of the resting limit order, then another fast-acting market participant has the opportunity to execute against the limit order. This allows the participant to capture a portion of the price difference between the limit order and the new fair price of the derivative contract.

[0158] An example of an aggressing scenario is shown in FIG. **12**. Initially, the best bid price of the derivative contract was $5.25, and a limit order was entered by a market participant that effectively joined the best bid (see the "Previous Best Bid" in FIG. **12**).

[0159] Subsequently, the price of the underlying instrument moved lower, causing the new fair value of the best bid to be $4.50. A fast market participant quickly computes the new fair value of $4.50 for the derivative contract, detects the mispricing of the existing bid at $5.25, and sends a limit order to sell one lot at $5.25, which trades against the resting limit order with a bid price of $5.25.

[0160] There are a number of ways for the fast market participant to capture the difference between the transaction price and the new fair price—to effectively buy one lot at a price lower than the $5.25 price at which it was able to sell. The market participant could simply "better" the new best bid by posting a quote with a $4.55 bid price. Buying at this price would result in a profit of $0.70 for the market participant. More likely, the market participant will immediately hedge their new short position at $5.25 by using one of a number of known hedging strategies.

[0161] As shown in FIG. **5**, an example embodiment of the VTE includes an aggressing circuit **504** that allows users to automate the execution of aggressing strategies.

[0162] FIG. **13**A provides an example of pipelined logic for carrying out an aggressing strategy. The operations of

FIG. **13**A can be implemented via parallelized logic resources on the chip **500** so that each operation can operate concurrently with the other operations (e.g., see FIG. **16**). The pipeline of FIG. **13**A ingests and listens for (1) new orders for derivatives in the order book and (2) new underlying market data (from one or more underlying trading venues via one or more Feed Handlers **522**) and/or new parameters (from the system's operational control subsystem). The pipeline can employ roughly two decision paths for handling these inputs—one path for deciding whether to create aggressing orders in response to new derivative orders in the order book and one path for deciding whether to create aggressing orders in response to new underlying market data or new control parameters.

[0163] For example, when a new order for a derivative is added to the order book, the pipeline will retrieve aggressing zone boundaries for the subject derivative at step **1300**. These aggressing boundaries will define a bid aggressing zone and an offer aggressing zone for the subject derivative and control whether it would be deemed advantageous to profit from the new order. At step **1300**, the pipeline can also retrieve parameters applicable to the subject derivative, which may include parameters such as a size threshold for potential aggressing orders and risk parameters for the trader.

[0164] In an example embodiment, the lower bound of the bid aggressing zone is determined by the theoretical offer price, and the upper bound of the bid aggressing zone is the maximum price allowed by the trading venue. Similarly, the upper bound of the offer aggressing zone is determined by the theoretical bid price, and the lower bound of the offer aggressing zone is the minimum price allowed by the trading venue. Note that the lower bid aggressing bound and the upper aggressing bound may also be determined from offsets to the theoretical bid and offer prices.

[0165] At step **1302**, the pipeline compares the pricing for the new order with the retrieved aggressing zone boundaries. If the comparison at step **1302** results in a determination that the new order pricing falls within the applicable retrieved aggressing zone, then the pipeline generates an aggressing order for the subject derivative (to trade against the new order) if such an aggressing order is deemed permissible in view of the retrieved parameters (e.g., compliant with size thresholds, risk parameters, etc.) (see step **1304**).

[0166] When new underlying market data or new parameter(s) are received, then steps **1310**, **1312**, and **1314** operate in a like manner as steps **600**, **602**, and **604** of FIG. **6**C (see also FIG. **16**). However, with an aggressing strategy, the computed theoretical fair bid and offer prices are used to define the aggressing zone boundaries for an impacted derivative rather than setting the BBO prices of a new quote. At step **1316**, the pipeline can also retrieve the current order book and applicable parameters for each impacted derivative (where such parameters may also include parameters that help define the bid and offer aggressing zones). Accordingly, at step **1318**, the pipeline—for each derivative impacted by the new underlying price or the new parameter(s)—creates (and stores) new bid aggressing zone boundaries and new offer aggressing zone boundaries for the subject derivative based on (1) the computed theoretical BBO prices (as tick size adjusted) and (2) the retrieved parameters. Then, at step **1320**, the pipeline—for each impacted derivative—searches the order book for applicable orders that lie within the bid aggressing zone or offer aggressing zone (as applicable). This search can be performed using parallelized logic resources so that multiple orders in the order book are tested against the relevant aggressing zones in parallel. For each applicable order in the relevant bid/offer aggressing zone, the pipeline will generate an aggressing order for the subject derivative (to trade against the applicable order) if such an aggressing order is deemed permissible in view of the retrieved parameters (e.g., compliant with size thresholds, risk parameters, etc.) (see step **1322**).

[0167] An example embodiment of an aggressing circuit **1350** is shown in FIG. **13**B. It shares many of the same components as the market making circuits **650**/**850**/**1050**, including logic resources for the Parameter Update Engine **652**, Underlying Price Memory **656**, Underlying Update Engine **654**, Theoretical Price Generator **658**, Parameters Memory **660**, and Tick Size Quantization **662**. For the aggressing circuit **1350**, the Tick Size Quantization circuit **662** uses the generated theoretical prices and parameters received from the Parameters Memory **660** to update the prices that define the bid and offer aggressing zones.

[0168] A logic table for aggressing decision-making is below.

Trigger	Need	Test	Action
New limit order for a subject derivative is added to the order book from the market	Does the new limit order fall within an applicable aggressing zone for the subject derivative?	Compare bid limit order with bid aggressing zone retrieved from the Aggressing Boundary Memory 1354 for the subject derivative; Compare offer limit order with offer aggressing zone retrieved from the Aggressing Boundary Memory 1354 for the subject derivative	If there is a resting offer in the offer aggressing zone, generate a bid order to trade against it; if there is a resting bid in the bid aggressing zone, generate an offer order to trade against it; Take appropriate additional actions to profit from the generated order
New quote for a subject derivative is	Does the new quote fall within an applicable aggressing	Compare quote's best bid price with bid aggressing zone	If the quote's best offer price is in the offer aggressing

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Trigger	Need	Test	Action
received from the market	zone for the subject derivative?	retrieved from the Aggressing Boundary Memory 1354 for the subject derivative; Compare quote's best offer price with offer aggressing zone retrieved from the Aggressing Boundary Memory 1354 for the subject derivative	zone, generate a bid order to trade against it; if the quote's best bid price is in the bid aggressing zone, generate an offer order to trade against it; Take appropriate additional actions to profit from the generated order
New price of an underlying instrument for a subject derivative is received from market	Compute new aggressing zones (based on newly computed theoretical BBO prices that take into consideration the new underlying price) for subject derivative(s); Are there orders in the order book or quotes for the subject derivative that fall within the aggressing zones?	Compare orders in order book for subject derivative with the newly computed aggressing zones; Compare quotes for subject derivative with the newly computed aggressing zones	If there is a resting offer or quote offer in the offer aggressing zone, generate a bid order to trade against it; if there is a resting bid or quote bid in the bid aggressing zone, generate an offer order to trade against it; Take appropriate additional actions to profit from the generated order

[0169] When an underlying trigger or parameter trigger results in a change in one or more prices that form the aggressing zone boundaries, a Boundary Trigger is sent to the Aggressing Order Generator **1356**.

[0170] The Book Memory **1354** maintains a depth-of-market view of the posted prices for each enabled derivative contract. In an example embodiment, the Book Memory **1354** shows the price-aggregated view of the book for all price levels that fall within or are likely to fall within the aggressing zones following a shift in price. Limiting the number of price levels maintained reduces the memory and circuit bandwidth consumed on a per derivative contract basis, and thus boosts the capacity of the aggressing circuit **1350** to operate on a larger number of enabled derivative contracts. Market data updates to the Book Memory **1354** result in a price triggers to the Aggressing Order Generator **1356**.

[0171] In response to a boundary trigger or a price trigger, the Aggressing Order Generator **1356** determines if any resting orders on the trading venue now fall within the defined aggressing zones. In addition to price values, the defined aggressing zones may include size thresholds for orders to be traded against. For example, even if a resting order's price falls within an aggressing zone, if it is an order for one lot and the minimum threshold is five lots, then an aggressing order will not be generated. If the specified aggressing conditions are met, the Aggressing Order Generator **1356** sends an aggressing trigger to the Order Scheduler **1358** with the specified action (buy or sell), price, and quantity.

[0172] In response to an aggressing trigger, the Order Scheduler **1358** determines if an aggressing order can be immediately transmitted to the trading venue. In an example embodiment, this determination as to whether a given aggressing order can be immediately transmitted to the trading venue is governed by risk parameters provided by the user, pending order status information from the Pending Order Memory **1360** (which can be on-chip memory similar in nature to Posted Mass Quotes Memory **664**), and available order entry bandwidth defined by the Transmitted Message Rate circuit **668**. Examples of risk parameters provided by a user include the maximum notional value of pending orders for all instruments, for all derivatives of a given underlying instrument, or for a single derivative contract. In an example embodiment, the user may also specify the type of aggressing order to use as another parameter. For example, a user may specify that Immediate Or Cancel (IOC) order types that instruct the trading venue to immediately execute the order upon receipt, if possible, else cancel the order and do not allow it to rest on the venue's order book. As with the market making circuits, the Transmitted Message Rates component **668** determines whether or not the VTE has exceeded its allowed transmission rate for orders.

[0173] If transmission bandwidth is available and the pending orders fall within defined risk limits, the Order Scheduler **1358** immediately transmits the aggressing order to the trading venue and adds an associated entry to the Pending Order Memory **1360**. If any of the defined conditions prevent the Order Scheduler **1358** from immediately transmitting the order, the order is immediately abandoned or buffered for a specified period of time from the risk parameters.

Hedging Strategy:

[0174] FIG. **13**C provides an example of pipelined logic for carrying out a Hedging strategy **506**. The operations of FIG. **13**C can be implemented via parallelized logic resources on the chip **500** so that each operation can operate concurrently with the other operations. The pipeline of FIG. **13**C ingests and listens for new order fills from one or more Market Gateways **530**/**532**. The pipeline decides whether to create hedging orders in response to new order fills.

[0175] For example, when a new fill for an instrument is received from a Market Gateway **530/532**, the pipeline will determine the aggregate change in the position for the instrument at step **1350** (e.g., this can be performed by the Position Update Engine **1372** shown in FIG. **13**D). The new position information is updated in the position memory for the instrument (e.g., see Position Memory **1374** in FIG. **13**D). At step **1350**, the pipeline can also retrieve hedging parameters applicable to the instrument, which may include parameters such as the hedging instrument and the hedging ratio.

[0176] At step **1352**, the pipeline retrieves the current position in the hedging instrument and compares the current ratio of instrument position to hedging instrument position relative to the hedging ratio parameters. If the comparison at step **1352** results in a determination that the position ratio does not match the specified hedging ratio, then the pipeline at step **1352** generates a hedging order for the hedging instrument to achieve the specified ratio.

[0177] FIG. **13**D shows an example embodiment where a hedging circuit **1370** is combined with the aggressing circuit **1350** of FIG. **13**B to decide whether hedges should be created with respect to any of the aggressing orders generated by the aggressing circuit **1350**. In the example of FIG. **13**D, transmission of orders by the Order Scheduler **1358** can trigger the Hedging Order Generator component **1376** that makes a decision on whether to generate a hedging order as per step **1352**.

Canceling Strategy:

[0178] The example embodiment of FIG. **5** for the VTE also implements a Canceling strategy **508**. Distinct from the canceling logic included in the aforementioned market making circuits, the logic resources that implement the Canceling strategy **508** (which can take the form of a canceling circuit) monitor the markets for conditions that represent significant risk and, when detected, enter a lockdown state. If the lockdown state is entered, the system so notifies the user via the User Terminal, Visualization component **510** and performs a set of prescribed actions by the user via the Command and Control component **512**. In addition to the canceling operations described below, the trading system may also take actions such as sending messages to automated trading systems in other locations to enter a lockdown state. The prescribed actions also define when the lockdown state is exited

[0179] FIG. **15**A provides an example of pipelined logic for carrying out a canceling strategy. The operations of FIG. **15**A can be implemented via parallelized logic resources on the chip **500** so that each operation can operate concurrently with the other operations. The pipeline of FIG. **15**A ingests and listens for (1) new quotes on derivatives from the market and (2) new trade reports about derivatives or underlying instruments from the market. At step **1500**, the pipeline retrieves cancellation boundaries for the pricing of the subject derivative(s). These boundaries can be stored in a cancellation boundary memory and generated on the basis of parameters stored in a parameter memory as populated based on input from the system's command and control interface. The pipeline can also retrieve parameters applicable to the subject derivative (e.g., parameters that can be used to define a scope of cancellation if needed). At step **1502**, the pipeline determines whether lockdown conditions are met for the subject derivative based on criteria that include new market data and the retrieved cancellation boundaries. At step **1504**, the pipeline generates a cancellation order if the lockdown conditions are found to be met at step **1502**. The scope of this cancellation order can be defined based on the retrieved parameters. Furthermore, when operating based on new trade report data, the pipeline can also determine which derivatives are impacted by the new trade report data (step **1510**). The process flow of steps **1500**-**1504** can then investigate whether cancellation orders are needed with respect to any of the impacted derivatives.

[0180] The cancellation parameters can also include a time window component. For example, the parameters can define a time window such as a rolling time window. This rolling time window would then encompass the execution prices for the subject instrument that fall within the window (e.g., the last 1 second of execution prices). The cancellation parameters can also include a price delta threshold. The logic can then identify the highest and lowest execution price for the subject instrument in this time window. The canceling strategy can then evaluate whether a given quote or order for the subject instrument has entered a cancellation zone. For example, using the last execution price for the subject instrument and the bid/offer update, the logic can subtract each of the last execution price, the most recent bid price, and the most recent offer price from the stored highest and lowest execution prices from the time window. This yields six values (namely, the differences between the three prices and the highest execution price and the differences between the three prices and the lowest execution price). If the absolute value of any of these six values is greater than or equal to the defined price delta threshold, then the logic determines that the subject instrument has entered the cancellation zone (which triggers the cancellation actions of the canceling strategy).

[0181] In an example embodiment, the Canceling circuit does not exit the lockdown state until prescribed by the user via the Command and Control component **512**. Alternatively, the user may specify a timeout period whereby the Canceling circuit automatically exits the lockdown state following the prescribed timeout.

[0182] As a result of entering the lockdown state, the Canceling circuit cancels posted mass quotes, posted orders, and/or pending orders as prescribed by the canceling scope parameters provided by the user via the Command and Control component **512**. The user may specify the scope of cancellation for all quotes and orders for all instruments traded by the user, for all instruments traded by the given VTE instance, for a defined group of underlying instruments and their associated derivatives, for a given underlying instrument and its associated derivatives, or for the specific instrument that triggered the lockdown condition. The canceling scope parameters also define the behavior of the lockdown filter which prevents all mass quote and order messages from being transmitted to the trading venue for the instruments within the scope. Note that additional canceling messages may be transmitted to the trading venue, e.g. in the case that a cancellation message was rejected due to exceeding bandwidth limits.

[0183] Note that a given VTE instance will have a limit on the number of instruments that may be enabled for trading. For example, the size of available memories on the reconfigurable logic device or ASIC (or other suitable chip) is a determiner of the number of instruments that may be traded by a VTE instance. As a result of practical limits, multiple

instances of a VTE may be deployed to trade the desired number of instruments on a given trading venue. The user has the ability to define the canceling scope of the Canceling circuit within each VTE instance to match the set of instruments traded by each VTE instance. Alternatively, the user may define the canceling scope of one or more VTE instances to be all instruments traded by the user across all VTE instances. In this configuration, VTE instances notify peer VTE instances when a lockdown condition has been detected and all instances enter the lockdown state and perform the lockdown actions prescribed by the user.

[0184] FIG. **14** provides an example of canceling logic detecting a lockdown condition. In this example, the user defines cancel boundaries by specifying an offset relative to the current BBO prices for the subject instrument. Prices higher than the best offer plus the cancel offset or prices lower than the best bid minus the cancel offset fall within the canceling zone. If a trade occurs within the canceling zone, the reporting of this trade triggers a transition to the lockdown state, cancellation of posted mass quotes and pending orders according to the defined canceling scope, activation of the lockdown filter, and potential notification of peer VTE instances of the lockdown condition.

[0185] Note that additional conditions may be specified that trigger a transition to a lockdown state. For example, a posted best bid price higher than a posted best offer price represents a "crossed market". The existence of such a "crossed market" may be an unexpected error condition in a market, rather than an immediate arbitrage opportunity. A user may specify such a logical check as an additional canceling condition.

[0186] An embodiment of a Canceling circuit **1550** is shown in FIG. **15**B. Canceling parameters are passed from the user via the Command and Control component **512** to the Parameter Update Engine **652** and stored in the Parameters Memory **660**. The current BBO prices for enabled instruments are stored in the BBO Quote Memory **1552** and continuously updated via market data messages from one more Feed Handler components **520**/**522**. Lockdown Engine **1556** can process the trade report data and cancellation boundary data using the techniques discussed above to determine if a canceling trigger should be generated to indicate a lockdown condition. When a lockdown condition is detected, e.g. a trade report that contains a price within a specified canceling zone, the Lockdown Engine **1556** triggers mass quote and order cancellation messages per the user-defined scope to the Message Scheduler **1558** and notifies the user and peer VTE instances via the Command and Control component **512**.

[0187] The Message Scheduler **1558** transmits the cancel messages to the Market Gateway component **530**/**532** at the maximum rate allowed by the venue. If any cancel messages are rejected by the venue as reported by the Market Gateway component **530**/**532**, then the Message Scheduler **1558** resends the messages until it receives confirmation that all quotes and orders have been successfully cancelled.

[0188] In an example embodiment, the VTE logs all messages that it transmits to Market Gateways **530**/**532**, Command and Control component **512**. It also logs all messages received from Market Gateways **530**/**532**.

[0189] In an example embodiment, the VTE provides monitoring metrics for operational staff to ensure proper operation. Monitoring metrics include the number of enabled instruments, the state of connectivity to market gateways, the count of rejected messages by a market gateway, the count of pending cancelation messages, an indicator of lockdown state, the rate of mass quote updates transmitted to trading venues, the number of rejected mass quote updates, etc. Monitoring interfaces that can be used include the Simple Network Monitoring Protocol (SNMP) and JavaScript Object Notation (JSON) formatted metrics delivered in response to Hypertext Transfer Protocol (HTTP) requests.

[0190] Furthermore, in an example embodiment where multiple strategies such as at least two of market making, aggressing, hedging, and canceling are deployed on the chip **500** together, a scheduler circuit can be shared by the different strategies (e.g., aggregating **666**, **1358**, and/or **1558**) to prioritize transmission of various messages generated by the automated trading engine. For example, cancelation orders can be prioritized over mass quotes. As another example, aggressing orders can be prioritized over mass quotes. As yet another example, mass quote cancellations can be prioritized over new mass quotes or mass quote updates. Prioritization parameters in this regard can be defined via configuration parameters specified by a user. Parallelized logic resources can evaluate queued mass quotes, aggressing orders, etc. to determine which should be given priority for transmission.

[0191] While the invention has been described above in relation to its example embodiments, various modifications may be made thereto that still fall within the invention's scope. Such modifications to the invention will be recognizable upon review of the teachings herein.

What is claimed is:

1. An apparatus for market making at low latency, the apparatus comprising:

a processor having parallelized computational resources that implement a plurality of market making strategies, wherein the marketing making strategies include at least two members of the group consisting of (1) basic market making, (2) joining market making, and (3) bettering market making;

wherein the processor is configured to receive (1) streaming underlying market data, the underlying market data pertaining to a plurality of financial instruments underlying a plurality of derivatives, (2) streaming derivatives market data, the derivatives market data comprising pricing pertaining to the derivatives, (3) a plurality of pricing parameters pertaining to the derivatives, and (4) a plurality of configuration parameters for operational control of the market making strategies; and

wherein the parallelized computational resources are configured to generate a plurality of quotes for one or more of the derivatives in accordance with the market making strategies based on a plurality of conditions applied to the streaming underlying market data, the streaming derivatives market data, the pricing parameters, and the configuration parameters, wherein the generated quotes are for transmission to one or more derivatives trading venues.

2. The apparatus of claim **1** wherein the parallelized computational resources comprise a plurality of logic resources that operate in parallel with each other to implement the market making strategies, wherein the logic resources implement different portions of the market making strategies.

3. The apparatus of claim **2** wherein the market making strategies include a combination of the basic and the joining market making strategies.

4. The apparatus of claim **2** wherein the market making strategies include a combination of the basic and the bettering market making strategies.

5. The apparatus of claim **2** wherein the market making strategies include a combination of the joining and bettering market making strategies.

6. The apparatus of claim **2** wherein the market making strategies include a combination of the basic, joining, and bettering market making strategies.

7. The apparatus of claim **2** wherein the market making strategies are capable of applying different pricing strategies to different sides of the generated quotes.

8. The apparatus of claim **7** wherein the logic resources are further configured to adjust the best bid price or the best offer price for a generated quote of a subject derivative to be a defined number of tick size increments outside a subject exclusion boundary if a market making strategy would have otherwise blocked generation of the quote for having pricing that falls within the subject exclusion boundary.

9. The apparatus of claim **1** wherein the processor is further configured to control which of the market making strategies are used to generate quotes based on a plurality of criteria.

10. The apparatus of claim **9** wherein the criteria include derivative-specific criteria.

11. The apparatus of claim **9** wherein the criteria include trading venue-specific criteria.

12. The apparatus of claim **2** wherein the streaming underlying market data includes a plurality of new events for the financial instruments underlying the derivatives, wherein the logic resources are configured to compute theoretical fair prices for derivatives impacted by the new events at a rate that supports a tick to trade latency less than 1 microsecond, and wherein the generated quotes are based on the computed theoretical fair prices.

13. The apparatus of claim **12** wherein the logic resources include a plurality of parallel logic instances that compute the theoretical fair prices for derivatives impacted by the new events in parallel.

14. The apparatus of claim **12** wherein each parallel logic instance computes a theoretical fair price for a subject derivative impacted by a new event based on (1) first data within the streaming underlying market data that pertains to the financial instrument underlying the subject derivative, (2) second data within the streaming pricing parameters that pertains to the subject derivative, and (3) third data within the received configuration parameters that pertain to the subject derivative.

15. The apparatus of claim **12** wherein the market making strategies include joining market making and/or bettering market making, and wherein the computed theoretical fair prices define exclusion boundaries that govern conditions for decisions to generate joining and/or bettering quotes.

16. The apparatus of claim **15** wherein the market making strategies include bettering market making, wherein the configuration parameters include parameters that define a number of tick size increments by which the generated bettering quotes will better an existing quote, and wherein the logic resources include logic that defines conditions for the bettering market making strategy to adjust pricing for the generated quotes by the defined number of tick size increments.

17. The apparatus of claim **12** wherein the market making strategies include basic market making, and wherein the computed theoretical fair prices define best bid and offer (BBO) pricing for a plurality of the generated quotes in combination with defined offsets for the generated quotes to establish minimum spreads for the generated quotes.

18. The apparatus of claim **2** wherein the market making strategies include joining market making, wherein the logic resources are configured to generate a quote for a subject derivative that matches pricing for an existing market quote for the subject derivative if the pricing for the existing market quote does not fall within an exclusion boundary for the subject derivative as defined by the logic resources, and wherein the logic resources are further configured to define the exclusion boundary for the subject derivative based on a generation of theoretical fair prices for the subject derivative.

19. The apparatus of claim **2** wherein the market making strategies include joining market making, wherein the logic resources are configured to cancel an existing quote for a quoted derivative if updated current pricing for the quoted derivative as reflected in the streaming derivatives market data falls within an exclusion boundary for the subject derivative as defined by the logic resources, and wherein the logic resources are further configured to define the exclusion boundary for the quoted derivative based on a generation of theoretical fair prices for the quoted derivative.

20. The apparatus of claim **2** wherein the market making strategies include bettering market making, wherein the logic resources are configured to generate a quote for a subject derivative that betters pricing for an existing market quote for the subject derivative by a defined number of tick size increments if the bettered pricing for the existing market quote does not fall within an exclusion boundary for the subject derivative as defined by the logic resources, and wherein the logic resources are further configured to define the exclusion boundary for the subject derivative based on a generation of theoretical fair prices for the subject derivative.

21. The apparatus of claim **2** wherein the market making strategies include bettering market making, wherein the logic resources are configured to cancel an existing quote for a quoted derivative if updated current pricing for the quoted derivative as reflected in the streaming derivatives market data falls within an exclusion boundary for the subject derivative as defined by the logic resources, and wherein the logic resources are further configured to define the exclusion boundary for the quoted derivative based on a generation of theoretical fair prices for the quoted derivative.

22. The apparatus of claim **2** further comprising a quoting boundary memory that is configured to store data defining exclusion boundaries for a plurality of derivatives.

23. The apparatus of claim **22** wherein the market making strategies include joining market making, wherein the logic resources are further configured to generate a quote for a subject derivative with pricing that matches a new market quote for the subject derivative from the streaming derivatives market data if the new market quote has pricing that falls outside the exclusion boundary in the quoting boundary memory for the subject derivative.

24. The apparatus of claim **22** wherein the market making strategies include bettering market making, wherein the logic resources are further configured to generate a quote for a subject derivative with pricing that betters a new market quote for the subject derivative from the streaming derivatives market data by a defined number of tick size increments if the bettered new market quote has pricing that falls outside the exclusion boundary in the quoting boundary memory for the subject derivative.

25. The apparatus of claim **1** wherein the processor comprises a field programmable gate array (FPGA), and wherein the parallelized computational resources are implemented as a hardware logic engine on the FPGA.

26. The apparatus of claim **1** wherein the processor comprises an application-specific integrated circuit (ASIC), and wherein the parallelized computational resources are implemented as a hardware logic engine on the ASIC.

27. The apparatus of claim **1** wherein the processor comprises a graphics processing unit (GPU), and wherein the parallelized computational resources are implemented on the GPU.

28. The apparatus of claim **1** wherein the parallelized computational resources are further configured to analyze a plurality of the generated quotes in parallel to prioritize the quotes for scheduled transmission to a trading venue.

29. The apparatus of claim **1** wherein the generated quotes include single-sided quotes and/or double-sided quotes.

30. A method for market making at low latency, the method comprising:

receiving streaming underlying market data, the underlying market data pertaining to a plurality of financial instruments underlying a plurality of derivatives;

receiving streaming derivatives market data, the derivatives market data comprising pricing pertaining to the derivatives;

receiving a plurality of pricing parameters pertaining to the derivatives;

receiving a plurality of configuration parameters for operational control of a market making engine deployed in parallelized computational resources; and

the parallelized computational resources implementing a plurality of market making strategies to generate a plurality of quotes for one or more of the derivatives based on a plurality of conditions applied to the streaming underlying market data, the streaming derivatives market data, the pricing parameters, and the configuration parameters, wherein the generated quotes are for transmission to one or more derivatives trading venues, and wherein the market making strategies include at least two members of the group consisting of (1) basic market making, (2) joining market making, and (3) bettering market making.

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