Thailand Independent Market Operator

A non-government organization to conduct an efficient and transparent wholesale market in mobile communications

Forward Market Design LLC (formally Cramton Associates LLC)

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Summary of proposal - competition policy

This note addresses the essential question of competition policy (Cave et al. 2019). The fundamental question is how the auction design best supports competition in the auction and the downstream mobile communications market. After carefully considering approaches, we find that imposing obligations on winners to sell at least 15 percent of capacity in an open access wholesale market conducted by a new entity, the Thailand Independent Market Operator (TIMO), is the best approach (Cramton 2024).

TIMO's mission is to encourage competition and innovation in mobile communications through efficient and transparent trade of wholesale capacity. TIMO enables wholesale competition among MNOs, MVNOs, and wholesale customers. This fosters competition and innovation in the retail market. It ensures available capacity is put to its best use, maximizing total welfare. The market promotes efficient investment in network enhancements, maximizing long-run welfare through transparent and efficient communications pricing.

The spectrum rights are attached to the obligation to sell in the TIMO market. Spectrum rights come with conditions similar to those in prior auctions, with one addition: an obligation to sell 15 percent of communications capacity in the open access market conducted by TIMO. Stringent buildout and coverage requirements are not included.

We describe the market in (Cramton et al. 2024a). Here, we present further details.

MVNOs as a source of competition

Mobile virtual network operators (MVNOs) have strengthened competition in wholesale and retail communications in many countries. The approach has yet to blossom in Thailand because of the challenges of negotiating profitable MNO-MVNO contracts for capacity. The solution to this challenge is for NBTC to facilitate an efficient wholesale market by creating TIMO.

One example of the success of the MVNO competition is the cable operators' communications arm. These companies can leverage infrastructure and customer relationships to provide mobile communications as an MVNO or MNO. The cable operators typically have limited coverage, cherry-picking the regions to build infrastructure and relying on contracts with MNOs to provide deeper coverage. The cable operators usually negotiate with the dominant incumbent mobile network operators and secure good deals and reasonable pricing for communications nationwide, such as in the United States. Then, they cherry-pick where to build infrastructure and provide a service as an MNO. Cherry-picking is an effective strategy for cable companies entering the mobile market. It is also perfect for negotiating an MVNO contract with a mobile network operator (MNO).

We have seen this happen in many countries in North America and Europe. Having MVNOs is a good thing, as it is a source of competition. It occurs effectively in the US because the regional licenses offered in the US enable the cherry-picking strategy. The US has split the country into hundreds of regions if not thousands. Comcast or Charter (the cable guys) can strategically identify spots for buildout. This is likely, not possible in Thailand when there are nationwide licenses because the operators would buy a nationwide license and then only build out some small spots. Yet, the company must pay a hefty price for the nationwide permit.

NBTC could have a set-aside for a new entrant, which is likely inefficient. A set aside would enable the new entrants to buy the nationwide license at a lower price, but it would be wasteful. The entry should come in the MVNO form instead of a redundant new network.

Satellite optical mesh networks are a source of competition

Another source of entry and competition is from satellite networks, such as Starlink. Amazon is also building an optical mesh network in space that can compete in providing communication services. There are lots of new entrants coming forward in different ways. We do not want the auction to discourage this entry in any way.

Competition is essential for innovation and investment

It is important to be realistic that building a third robust network throughout Thailand is economically questionable. If somebody wants to do this, it is excellent. We are not discouraging any new entrant, but NBTC will not want to do a considerable set aside for an economically unrealistic possibility. That is our view.

Competition is essential to foster innovation. However, it is unlikely that a new entrant will be willing to come as an MNO. But we want competition on the margin and as many margins as possible. We want to bring in the satellite competition. We want to bring in competition from fixed broadband, expanding, improving Wi-Fi capability, etc. All these things are practical for the consumer in disciplining the mobile network operators' pricing.

NBTC wants to promote investment and innovation. The license conditions need to support Thailand's competitive and innovative future. Since it is unlikely that there will be a third redundant network in Thailand, competition is better addressed by introducing an efficient wholesale market conducted by an independent market operator. We will describe how that works below.

With this independent market operator, we can compete among service providers, the MVNOs, and compete to provide innovative plans and services for the retail customer. We will also get lots of innovation from the MVNOs. To the extent that the MVNOs want to build a commendable network, we are not excluding them from building a network in our proposal. In our proposal, we want access to spectrum through secondary spectrum markets. We will describe how that would work below. We are proposing to invigorate wholesale competition for communication services, which will also be a vehicle for allowing more flexible sharing of spectrum through vibrant trade.

Competition requires an effective competition policy that supports wholesale competition.

The cornerstone of the competition policy is the obligation to provide access and connect, not create bottlenecks. We recommend that the spectrum winners in the auction sell 15 percent of their wholesale capacity at all times and locations. Another target could be 20 percent, but let us say 15 percent now. The spectrum auction winners must sell 15 percent of their capacity in an open access wholesale market conducted by the Thailand Independent Market Operator (TIMO).

What is TIMO? TIMO is an independent market operator with a straightforward mission, which we will describe below. TIMO conducts the wholesale market under open access terms, identifying competitive market prices for communications by time and location. This idea has come from something our grouping has been working on for many years. In addition to communications, we have worked for decades in electricity markets. Many parts of the world have restructured electricity markets by introducing an independent market operator, often called in the United States, an independent system operator. The ISO aims to enable wholesale competition through an open access marketplace. The ISO conducts this market with the oversight of the regulator. It is something we have been involved with for 25 years. For five and a half years, Peter Cramton was an independent director of the board of ERCOT, which is the ISO operating in Texas, one of the more advanced systems.

In February 2021, Texas had an extreme winter storm. The lights went out for 25 percent of Texans for multiple days, even though Texas has one of the most developed electricity markets in the world. Cramton has advised many system operators in the United States, Europe, and other countries. Having an ISO is an approach that works exceptionally well in electricity. And it is an approach that can work in communications. That is what we are going to discuss further below.

TIMO's mission is straightforward: to encourage competition and innovation in mobile communications through efficient and transparent trade of wholesale capacity. That is a great, straightforward mission. It also enables wholesale competition among the MNOs, the MVNOs, and wholesale customers. Thailand has large wholesale customers who can participate directly in the market without an MVNO or MNO. They can buy what they want from a competitive marketplace, and this will foster competition and encourage innovation in the retail market.

The market ensures available capacity is put to its best use, maximizing total welfare. It also promotes sufficient investment in network enhancement, maximizing long-term welfare.

What is needed as a competition measure is an obligation attached to the licenses to sell a fraction, say 15 percent, of communication capacity in this open access market. This 15 percent is defined by the regulatory rules by time and location, so the MNO can't cherry-pick and sell in places where they want to, but not in others, and abuse the MVNOs and make their life miserable. Our understanding is that is what has happened in Thailand. It has happened in many other countries as well. But we do not want that.

We can measure the communications at the cell sector level. Measurement implies the ability to define and enforce market rules. It is a much better alternative than imposing stringent buildout and coverage requirements that are better addressed through universal service plans.

TIMO administers an efficient wholesale market

The independent market operator is well thought out. Our paper recently appeared in *Telecommunication Policy (Cramton et al. 2024a)*. It is freely available under open access.

This paper, a presentation, an interactive demo, and a sample code are available to give NBTC and others a better sense of the platform. Our team has been working hard for many months, building a platform that can implement TIMO. We are happy to share our open-source code and help customize it for TIMO.

Right now, we are doing extensive testing with electricity data, including a 12-year backcast of the electricity market in Texas, which is a much more complicated situation than communications.

Electricity has many more network constraints because of Kirchhoff's law, how electricity flows, etc. That work will be completed in the next few months. As soon as we finish it, we will publish it (Cramton et al. 2024b).

Good governance promotes continuous improvement.

Governance is important. What experience does NBTC have with doing something like this? Well, fortunately, NBTC has a talented staff that is highly educated and motivated and can take on the oversight for TIMO. We are not suggesting that NBTC be TIMO. They can understand what TIMO is and then conduct a procurement or a regulatory approach to create TIMO. TIMO would operate as a non-governmental organization, similar to independent system operators in the United States and Europe.

Now, for electricity, the most critical task is keeping the lights on. That is physics. It is tough to keep the lights on. That is job number one. The second is economics. Economics is optimization with physics, understanding incentives, and addressing market failures. When you combine physics and economics, you get the least cost-reliable electricity. It is the same thing in communications. Of course, like everything, there is this third animal: politics. And politics is where bad things can happen. The problems we have with electricity are when politics come into play. The idea is to do the physics and economics so well that politicians want to stay out. It is the same thing in communications. Politics are at play; sometimes, they interfere with least-cost reliable communications.

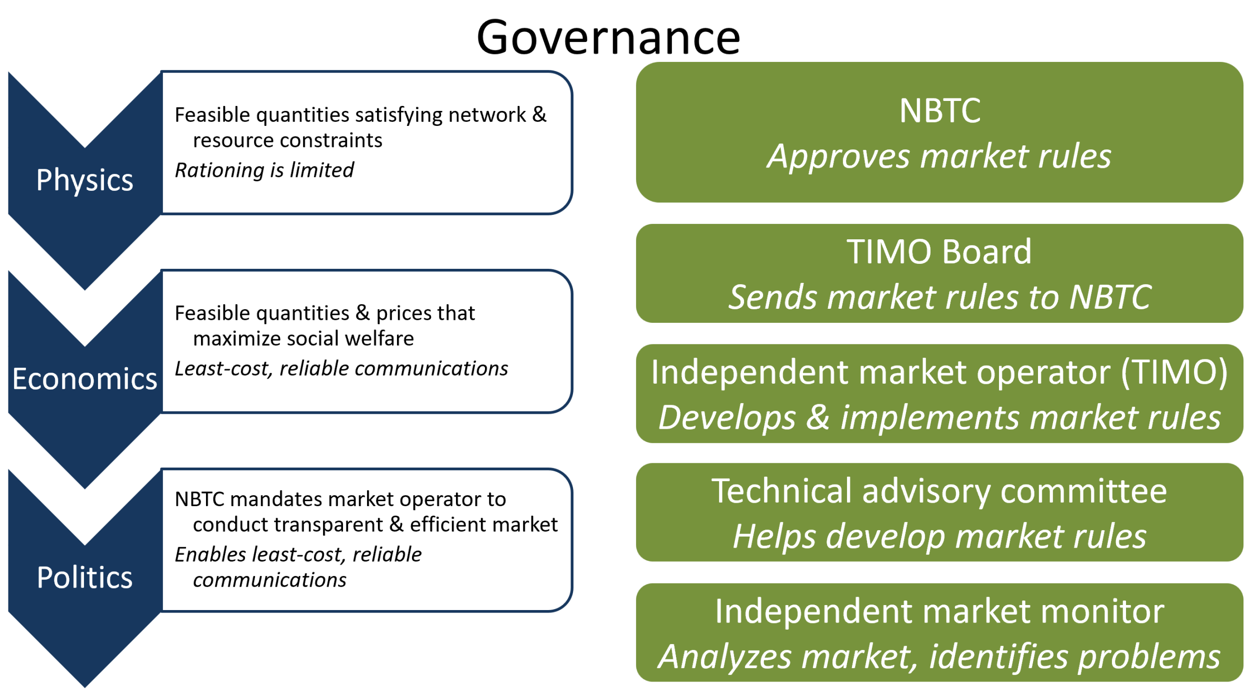

Figure 1: Governance structure of TIMO (right) and the fields of influence (left)

We do not want that to happen, so we put politics at the bottom of the list in Figure 1. Regarding the market, NBTC approves the market rules and initiates the construction of TIMO. TIMO has a board that sends the market rules to NBTC for final approval. TIMO, the independent market operator, develops and implements the market rules. TIMO has a technical advisory committee that helps them develop the regulations. That is the stakeholder process, and the stakeholders come together, providing their input with the expertise of TIMO to create market rules that make sense.

In the US, we also have an independent market monitor who watches the market, has access to all the information, and can make recommendations. The market monitor identifies problems, suggests improvements, and so on. Importantly, the market monitor is not a judge. The regulator is the judge. The regulator can impose fines, identify rules violations, and so on, but not the independent market monitor. The market monitor identifies problems and proposes solutions.

This proposed structure has proven effective. It is a governance structure that works well.

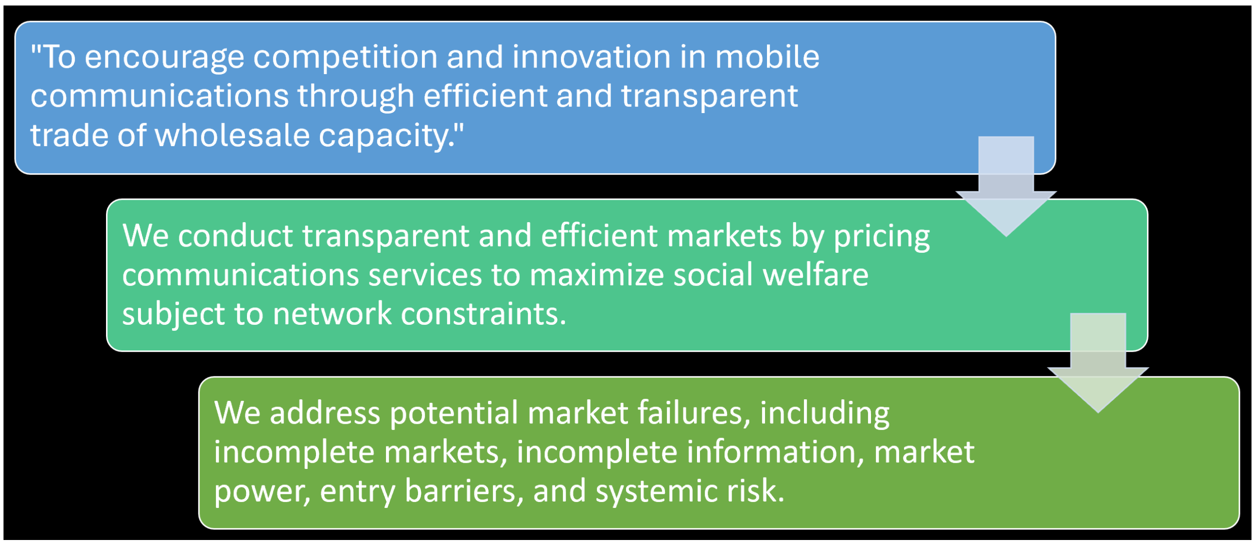

Figure 2: TIMO's mission statement with further translation into economic terms

TIMO's mission is shown in Figure 2. The mission is to encourage competition, innovation, and mobile communications through efficient and transparent trade of wholesale capacity. That is a great, straightforward mission. We can further translate that into economic terms. TIMO conducts transparent and efficient markets by pricing communication services to maximize as-bid social welfare subject to network constraints. That is a mathematical statement of what the network can do. And that is why it can be so effective. It is precisely what we do with electricity. The market rules for the independent system operator are a mathematical expression of how the market is run.

It is highly transparent and efficient, and there is a tendency for continuous improvement as new ideas are developed. We use new algorithms that can optimize better than the old ones for this marketplace. Finally, TIMO addresses potential market failures, including incomplete markets, incomplete information, market power, entry barriers, and systemic risk.

All these are wonderful things. TIMO is an organization people want to be part of. TIMO maximizes welfare for the people of Thailand. TIMO staff like their job because they know they are doing something good. They have this clear mission. Working for an organization with a clear public service mission is rewarding. TIMO is creating value for society. All the system operators in the United States work reasonably well, and some are better than others. They are all highly efficient in their operation. If we can do it in the United States, there is no reason we cannot do it in Thailand.

The TIMO board promotes good governance, supporting TIMO's mission

We provide a structure for the TIMO board, shown in Figure 3. Three independent directors are nominated by the TIMO board and approved by NBTC. The independent directors are not affiliated with any stakeholder. They are not the regulator. They are not on the buy side or the sell side.

Three independent directors	Nominated by TIMO Board Approved by NBTC
Four affiliated directors	Appointed by stakeholder group Two affiliated with supply (one from each dominant incumbent MNO) Two affiliated with demand (MVNO, wholesale customer, consumer organization)
Two non-voting directors	NBTC Chair TIMO CEO

Figure 3: Board structure to support the mission statement

The board consists of three independent directors. Then, four affiliated directors are appointed by a stakeholder group: two on the supply side and two on the demand side. This yields a balance. Including the affiliates is nice because the board gets direct input from the stakeholders onto the board, but it is a balanced representation. Then, there are two non-voting directors, the TIMO CEO and the NBTC Chair. This structure is the one we used at ERCOT, and it worked well. Independent directors can steer things towards efficiency.

If some market rule were proposed that improved efficiency, one side, either the sell or the buy side, would favor it, and all the independent directors would favor it. And so it would carry a majority. The others are non-voting: the NBTC chair and TIMO.

We have experienced and practiced this structure for many years in essential economic sectors, such as electricity. We have also been involved with it on the communication side in emerging applications, such as the one described in the paper on telecommunications policy: the low Earth orbit satellite constellations using optical mesh networks, which is coming. It is not up and running yet, but it will come.

TIMO's structure fosters continuous improvement

TIMO's public interest task is grounded in continuous improvement, as shown in Figure 4. That is what we have seen in electricity: constant improvement in the restructured markets in the United States. Europe is farther behind the US for reasons we do not discuss here, but they are also making gradual improvements. The improvements in the US are gradual, too.

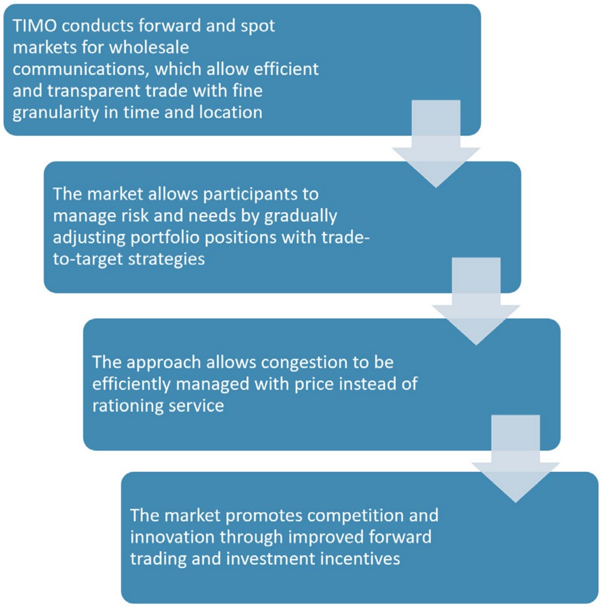

Figure 4: TIMO's public interest task is grounded in continuous improvement

The market also creates a virtuous cycle, illustrated in Figure 5. TIMO conducts a forward and spot market for wholesale communications, which allows efficient and transparent trade and refined granularity in time and location. The market allows the participants to manage their risks and needs by gradually adjusting portfolio positions, using trade-to-target strategies. In this standard trading technique, participants have a product portfolio and an ideal point (the target). Then, the question is, how do you move in product space from your current position to your perfect point? That is called a trade-to-target strategy. That is easy to implement in the trading structure we will present now. The approach allows congestion to be efficiently managed and priced instead of rationing service. What we do in communications today is when there is congestion, we ration it. You see a spinning wheel, a call is dropped, whatever.

Figure 5: The virtuous cycle of forward trade to efficient operation, investment, and innovation

Your quad HD goes down to regular HD or standard video. Rationing is the norm in communications. We do not use price to manage congestion, and that is inefficient. Price is a better instrument for managing concession. People get to buy what they want. When you go to the grocery store and want some bananas, we do not say, "Sorry, we do not have any bananas." You have to wait in line. And if you are not in the line early enough, you do not get any bananas. But no, you can get bananas in Thailand and the United States at the grocery store. And if there are not enough bananas around because of some issue with the supply chain, the price goes up.

We use price to ration. It is much better than dropping calls. It is the future, and it is doable today. All you need is to measure use. Then, you can conduct a spot and forward market for the communication asset. That is what we are proposing. We will outline the particulars of how this can be accomplished.

The proposal promotes competition and innovation through improved forward trading and investment incentives. Forward trading gives you price information so you can make investment decisions. Any investment is made by estimating the cash flows that will come in the future.

How can you calculate the cash flows in the future? The best way is to buy a quantity with a future-forward contract. A forward market enables you to establish the forward prices. Now, even if you do not want to buy today, knowing there is this competitive forward market where people are putting real money on the line to trade the forward products, that price information is invaluable in understanding where investment is needed. You are going to invest more in places where the price is higher. And this price information is compelling but is absent in communications markets today. The carriers only understand the congestion. They hold that information to themselves. They manage congestion themselves, but they do not manage it with price.

That is a sign of a monopoly and not a sign of competition. Even a monopolist would want to manage congestion with a price. They could do better, just like the airlines. An airline might be the only one with a nonstop route from Bangkok to Los Angeles. Then, this airline is a monopolist on that route. How are they going to price seats? They will have dynamic pricing that does revenue management. They will price the seats all based on demand. If there is a significant demand for this nonstop flight, the monopolist will charge high prices. If business customers are not price-sensitive, the airline will charge high prices for them. If economy customers are price-sensitive and have indirect routes to LA, the airline will charge economy passengers low prices. That is revenue management. That creates the most value. The monopolist does not make money by selling the plane at non-market prices and then rationing the rest of the people, saying, no, sorry, we do not have any seats.

TIMO creates a virtuous cycle to foster efficient behavior and promote competition

The forward market creates a virtuous cycle where we have vibrant, forward trade, creating these forward prices that are foundational for the efficient operation of the network resources. These forward prices provide input for future network resources, whether those resources are coming from the existing MNOs or an entrant wanting to take advantage of an opportunity, a particular time and location that they see from the price information. These prices foster innovation, and they encourage resiliency in the market. These are all good things, as shown in Figure 6.

How can we have such a market? We already have electricity in real-time and the day ahead. What we do not have is further forward. We have forward electricity markets. Still, the forward markets are relatively liquid as we move close to day-ahead. They are good a month ahead, but as we move more than a month ahead, then there is inadequate liquidity. Then, they are also not granular enough. Because of the way forward trade takes place in current markets around the world, they use an inferior trading technology that hampers liquidity and is expensive. In particular, they encourage all the liquidity to shift to a minimal number of products, and you get incomplete markets.

Trading technology is critical. We will describe a trading technology that avoids all these problems. It is implemented and widely used in day-ahead and real-time electricity markets.

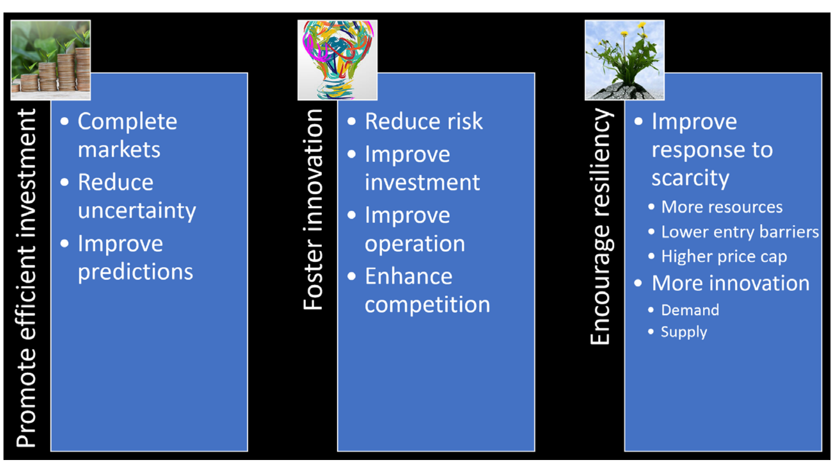

Figure 6: Key benefits of transparent forward prices updated hourly with ample liquidity

Key market features

We propose extending it to the communications market, as described in our paper (Cramton et al. 2024a). What it does is it promotes efficient investment by completing markets, reducing uncertainty, improving predictions, fostering innovation by reducing risk, improving investment, improving operation and enhancing competition, and encouraging resiliency by improving response to scarcity, no more drop calls, more response lower entry barriers and more innovation on both the demand side and the supply side. The key features shown in Figure 7 are fine granularity and time and location since communication is a time and location product. It is delivered from point A to point B or broadcast from Point A out one way or the other. And it is time-specific. This means that there needs to be lots of products so that participants can have the flexibility to manage risk and position—the portfolio of products they have at all times and locations in Thailand. There is lots of time. There are lots of places.

Figure 7: Key features of the TIMO market

Another feature is gradual coordinated trade. This gradual coordinated trade reduces risk and market power. It is how participants naturally want to trade, enabling robust clearing prices with ample liquidity. The market participants offer are wholesale participants; this is a wholesale market, not a retail market for consumers, but a wholesale market. They provide persistent portfolio flow orders, which we will describe quickly. It is easy to participate in these effective trade strategic strategies. There are lots of applications. It is used as a merger remedy in mobile communications. It has been proposed to be used for satellite constellations for global communications. It can be used for efficient and transparent forward and real-time trade of spectrum inputs. You can have vibrant spectrum sharing in the future. And it is enabled by the flexibility of our technologies. The fact that our phones and our cell towers are so powerful with software-defined radios.

Data from Mexico City illustrates congestion by cell tower and hour

To get a sense of congestion in mobile broadband, let us look at data from Mexico City at the cell tower level in 2017. Figure 8 shows the cell sites in Mexico City, which is not too different from Bangkok. It is a much higher altitude, a different country, but otherwise, it is a major urban center.

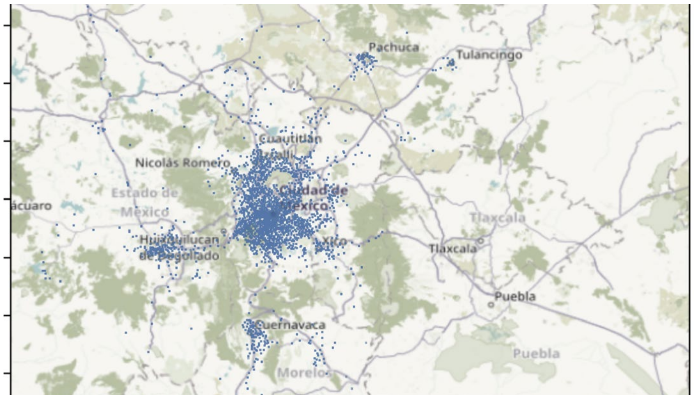

Figure 8: An example of an urban center's (Mexico City) cell towers

Figure 9 shows the utilization of each cell site by hour. Utilization is often low, although there are many hours when utilization is 100 percent for some towers. However, the point is that the average utilization is relatively low, even during the day in an urban center. Despite the low average utilization of around 20 percent, there are many periods when the cell sectors are congested. Congestion varies by tower and time of day.

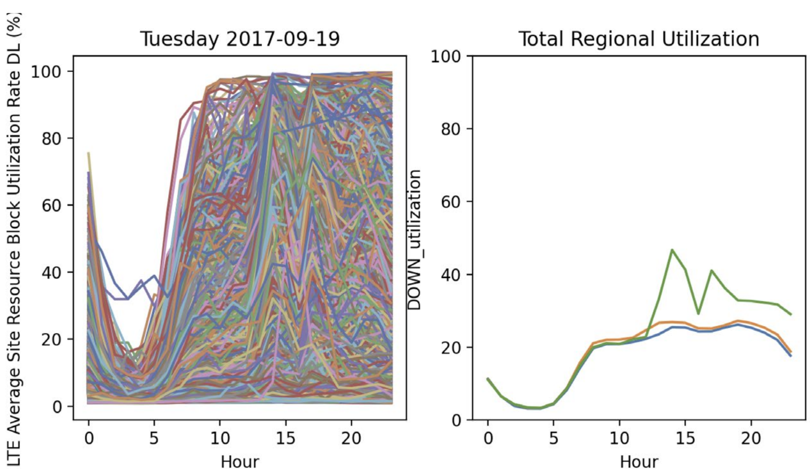

Figure 9: Average cell tower utilization by time of day and aggregate utilization (Mexico City)

Congestion is real. It is specific to time and location. This is true in Bangkok, where the different cell towers have different utilizations based on the time of day. It is worthwhile to manage congestion with price at the wholesale level.

Structure of the real-time market

We can manage congestion with a real-time and forward market. The real-time market defines a communication commodity. A natural definition of real-time products is into three product groups as shown in Figure 10—fast (low latency), where speed latency is optimized over reliability; a premium service that is never rationed; and a regular service that is rationed occasionally but primarily price is doing the rationing.

We cannot exclude the possibility of rationing because the consumers get to consume whatever they want. Even when buyers form their best estimates of what they wish to do, the forecast might be wrong, in which case some rationing might be necessary. We want minimal rationing based on priorities (Chao et al. 1986). The premium service gets served first, and then the regular. It is a physical market, so we must respect physical constraints in real time. That happens for all commodities. The financial products become physical in real-time.

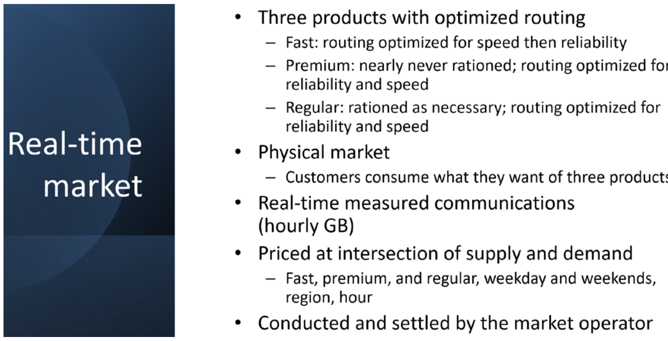

Figure 10: Description of the real-time market for mobile communications

Here, physical communication is the actual communication measured in gigabits or gigabytes. How do we price in the real-time market? It is based on the intersection of supply and demand. The market operator conducts and settles the transaction. The forward market is voluntary. People can participate however they want except for the duopolist MNOs who are obligated to sell 15 percent of real-time capacity in every hour and at every location. The MNOs do have complete flexibility about when they make the sale. They naturally sell gradually over an extended period to best manage their risk and needs. Forward trade allows this.

Structure of the forward market

Effectively, the forward market enables participants to manage risk and positions to get what they want at the best possible terms with minimal risk. We have described several products and how they could work. This is a good starting point.

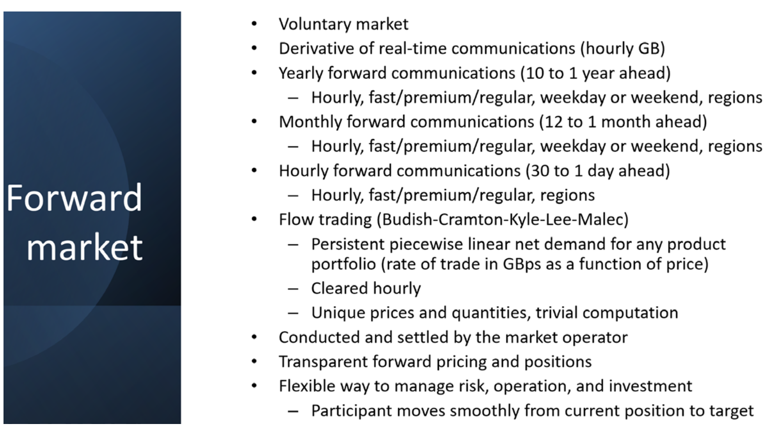

Figure 11: Description of the forward market for mobile communications

The way these markets evolve starts with one level of time and location granularity. And then, as they mature, they become finer and finer. Eventually, you can get down to the cell sector. The particular angle of a specific cell tower is where congestion occurs, so this is where pricing is best utilized to balance supply and demand. It is all done in mathematics. Participants express a preference in this market for downward-sloping net demands, as shown in Figure 12. Here, there are strictly downward-sloping demands for a portfolio of products, which is a compelling and flexible way to express a rich preference. Any monotone preference in product space can be expressed. It could include thousands or even millions of products. The computation is easy enough to handle any level of granularity in time and place.

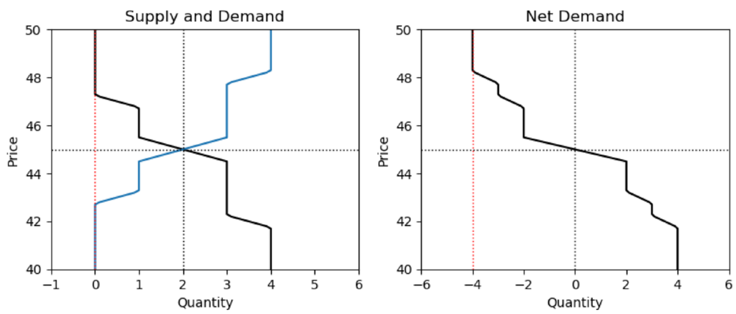

Figure 12: An example of an individual piecewise linear supply, demand, and net demand

Solving the optimization problem for unique quantities and prices that maximize social welfare is easy. It is a simple problem. In optimization, there are two types of problems: challenging and easy. Complex problems are nonconvex. Easy problems are convex. This problem is convex because the bidders must submit downward-sloping demand curves. That makes the problem locally quadratic, the best convex function to work with. We can optimize it quickly.

Efficient trading

We envision five years of annual forwards (by hour, weekday-weekend), 12 months of monthly forwards (by hour and weekday-weekend), and 30 days of hourly forwards for each region and product type (premium, regular, and fast). This implies (3 product types) × (24 hours/day) × [(2 day types) × (5 years + 12 months) + 30] = 4,608 products per region. With five hundred regions, this is 2.3 million products.

We can summarize the key features of the bidding language in two theorems from Budish et al. (2025) and an immediate corollary. The mathematics below borrows freely from Budish et al. (2025).

Let $V_i(x_i)$ denote the dollar utility of order i from a trade rate of $x_i = D_i(p_i)$ in portfolio units per hour, where flow portfolio demand $D_i(p_i)$ is given by equation (1):

$$D_i(p_i | \boldsymbol{w_i}, q_i, p_i^L, p_i^H) \coloneqq q_i trunc\left(\frac{p_i^H - p_i}{p_i^H - p_i^L}\right) \; where \; trunc(z) \coloneqq \begin{cases} 1 \; for \; z \geq 1 \\ z \; for \; 0 \leq z < 1. \\ 0 \; for \; z \leq 0 \end{cases} \tag{1}$$

To find $V_i(x_i)$, we first define the marginal utility function $M_i(x_i)$ as the inverse demand curve, $p_i = M_i(x_i)$. The inverse demand curve maps order i's trade rate $x_i \in [0, q_i]$ into prices $p_i \in [p_i^L, p_i^H]$.[1] Rearranging equation (1), we have:

$$M_i(x_i) := p_i^H - \frac{p_i^H - p_i^L}{q_i} x_i \qquad \text{for } x_i \in [0, q_i]. \tag{2}$$

The value of $M_i(x_i)$ measures marginal as-bid flow value in dollars per portfolio unit. Utility $V_i(x_i)$, as a function of the trade rate x_i, is defined as the integral of the marginal utility function over the interval $[0, x_i]$:

$$V_i(x_i) := \int_0^{x_i} M_i\,(u)\; \mathrm{d}u. \tag{3}$$

Since the marginal value is linear in x_i, the total value is quadratic and strictly concave in x_i:

$$V_i(x_i) = p_i^H x_i - \frac{p_i^H - p_i^L}{2q_i} {x_i}^2. \tag{4}$$

We assume $V_i(x_i)$ as defined for all $x_i \in \mathbb{R}$, with order specifications imposing the constraint $x_i \in [0, q_i]$.

Our problem of finding market-clearing prices is formulated as two optimization problems: a primal problem of finding quantities that maximize as-bid dollar value and a dual problem of finding prices that minimize the cost of non-clearing prices. The first-order conditions for the optimality of these two problems imply market-clearing prices and quantities.

The market operator, acting analogously to a social planner, chooses a vector of trade rates for all orders $\boldsymbol{x} = (x_1, \dots, x_I)$ to maximize aggregate value, defined as the sum of pseudo-utility functions across orders,

$$V(\boldsymbol{x}) := \sum_{i=1}^{I} V_i(x_i) \qquad \text{for } \boldsymbol{x} \in \mathbb{R}^I, \tag{5}$$

subject to market-clearing constraints and trade-rate constraints:

$$\max_{\boldsymbol{x}} \; V(\boldsymbol{x}) \qquad \text{subject to} \begin{cases} \sum_{i=0}^{I} x_i\, \boldsymbol{w}_i = \boldsymbol{0} & \text{(market-clearing constraints)} \\ x_i \in [0, q_i] \text{ for all } i & \text{(trade-rate constraints).} \end{cases} \tag{6}$$

The objective function $V(\boldsymbol{x})$ is concave because it is a sum of concave functions.

[1] For trade rates in the interval $(0, q_i)$, the fact that the order chooses an interior trade rate tells us that the order's as-bid marginal utility is equal to the corresponding price in the interval (p_i^L, p_i^H). The same logic extends to the boundary points 0 and q_i, corresponding respectively to prices p_i^H and p_i^L, by assuming as-bid utility is continuous.

Indeed, this is a quadratic program since the objective function is quadratic and the constraints are linear. To make this quadratic structure apparent using matrix and vector notation, let $\boldsymbol{W}$ denote the $N \times I$ matrix whose ith column is $\boldsymbol{w}_i$. Let $\boldsymbol{p}^H$ denote the column vector whose ith element is p_i^H. Let $\boldsymbol{D}$ denote the $I \times I$ positive definite diagonal matrix whose ith diagonal element is $(p_i^H - p_i^L)/q_i$. Then, the problem in equation (6) may be written compactly as

$$\max_{\boldsymbol{x}} \left[\boldsymbol{x}^T\boldsymbol{p}^H - \frac{1}{2}\,\boldsymbol{x}^T\boldsymbol{D}\boldsymbol{x}\right] \qquad \text{subject to} \qquad \boldsymbol{W}\,\boldsymbol{x} = \boldsymbol{0} \qquad \text{and} \qquad \boldsymbol{0} \le \boldsymbol{x} \le \boldsymbol{q}. \tag{7}$$

We first show that quantities that maximize aggregate utility exist. Then, we show that market-clearing prices exist by examining the dual problem of the utility maximization problem. We then show a unique mapping of orders into prices and quantities. The uniqueness of prices and quantities is essential for transparency. These are standard results of convex optimization (Bertsekas 2009), derived from strict convexity and continuity. Our presentation follows Budish et al. (2025).

Theorem 1 Existence and Uniqueness of Optimal Quantities. A unique vector of trade rates $\boldsymbol{x}$ exists, which solves the maximization problem in equation (7).

To prove that market-clearing prices exist, we exploit the duality between the problems of finding optimal prices and quantities. For this, we define a Lagrangian function of the vector of trade rates $\boldsymbol{x}$ with three constraints: (1) the market clears ($W\boldsymbol{x} = \boldsymbol{0}$); (2) the trade rates are greater than or equal to zero ($\boldsymbol{x} \ge \boldsymbol{0}$); (3) the trade rates are less than or equal to their maxima ($\boldsymbol{x} \le \boldsymbol{q}$). In vector notation, the Lagrangian is defined by

$$L(\boldsymbol{x}, \pi, \lambda, \mu) := \boldsymbol{x}^T\boldsymbol{p}^H - \frac{1}{2}\,\boldsymbol{x}^T\boldsymbol{D}\boldsymbol{x} - \pi^T\boldsymbol{W}\,\boldsymbol{x} + \mu^T\boldsymbol{x} + \lambda^T(\boldsymbol{q} - \boldsymbol{x}). \tag{8}$$

Since the multipliers associated with the market-clearing equality constraints have the economic interpretation of market prices for assets, we use the notation $\pi = (\pi_1, \dots, \pi_N)^\top$ for these multipliers. Two vectors of multipliers, $\mu = (u_1, \dots, \mu_I)^\top$ and $\lambda = (\lambda_1, \dots, \lambda_I)^\top$, are associated with inequality constraints on trade rates.

The dual problem associated with the primal problem of maximizing aggregate utility in equation (7) is then defined by

$$\hat{G}(\pi, \lambda, \mu) := \max_{\boldsymbol{x}}\; L(\boldsymbol{x}, \pi, \lambda, \mu) \qquad \text{for} \qquad \pi \in \mathbb{R}^N, \qquad \mu \ge \boldsymbol{0}, \qquad \lambda \ge \boldsymbol{0}. \tag{9}$$

The dual problem is a minimization problem with infimum g defined by

$$g := \inf_{\pi,\lambda,\mu} \hat{G}\,(\pi, \lambda, \mu) \qquad \text{subject to} \qquad \pi \in \mathbb{R}^N, \qquad \mu \ge \boldsymbol{0}, \qquad \lambda \ge \boldsymbol{0}. \tag{10}$$

The dual problem in equation (10) is formulated as an infimum rather than a minimum because we have not yet shown that a solution (π, λ, μ) exists that attains the infimum.

Theorem 2 Existence of market-clearing. There exists at least one optimal solution (π, λ, μ) to the dual problem in equation (10). The solutions $\boldsymbol{x}$ and (π, λ, μ) are a primal-dual pair which satisfies the strict duality relationship

$$g = V(\boldsymbol{x}). \tag{11}$$

Theorem 2 does not guarantee that market-clearing prices are unique. The set of market-clearing prices is convex and may be unbounded. A trivial example occurs when all orders are buy orders for individual assets, and there are no sell orders. Then, any sufficiently high price clears the market with zero trade. There may also be cases where the market-clearing price is not unique even when trade occurs. A trivial example occurs when there is one buy order and one sell order for the same asset (or portfolio) with the same maximum rate, and the buyer's lower limit price exceeds the absolute value of the seller's lower limit price. In this case, there is an interval of prices where both orders are fully executable. However, a natural tie-breaking rule makes the prices unique.

Closest-to-prior-prices rule. If more than one price vector supports the optimal quantity vector, select the price vector closest to the prior price vector.

Corollary 1 Uniqueness of quantities and prices. Prices and quantities are unique with the closest-to-prior-prices rule.

Proof. The set of prices that support the unique optimal quantities is convex. The closest point in a convex set to a point is unique. *End proof.*

The closest-to-prior-prices tie-breaking rule is especially appropriate in our frequent batch auction setting, in which prices evolve slowly from the gradual trade of persistent orders.

These unique prices and quantities can be found quickly. Flow trading involves the solution of the following optimization program:

$$\min_{x} \quad \frac{1}{2}x^\top Dx - p^\top x \quad \text{s.t.} \quad a \le x \le b \quad \text{and} \quad Wx = 0,$$

where D is a non-negative, diagonal matrix. To exploit the near-separability of the problem, we employ the alternating direction method of multipliers (ADMM) (Boyd et al. 2011). This technique solves an optimization problem of the form

$$\min_{x,z} \quad f(x) + g(z) \quad \text{s.t.} \quad Ax + Bz = c.$$

We define an indicator function $C(b) = 0$ if b is true and ∞ otherwise, i.e., $C(a \le x \le b)$ and $C(Wx = 0)$ will be used to enforce our problem constraints. We choose

$$f(x) = \frac{1}{2}x^\top Dx - p^\top x + C(a \le x \le b),$$

$$g(z) = C((1^\top \otimes I)z = 0),$$

and

$$A = \sum_i (e_i e_i^\top) \otimes (We_i), \qquad B = -I, \qquad c = 0,$$

where $\otimes$ denotes the Kronecker product. This splits the minimization across two sets of variables: x, which correspond to rates of execution of each order, and $z = (z_1, z_2, \ldots)$, which are the trade rates each fulfilled order imposes across the space of products, i.e. $(We_i)x_i = z_i$ for each order i.

ADMM proceeds by formulating the augmented Lagrangian, then repeatedly minimizing it via a Gauss-Seidel pass on the primal variables (x, z), followed by a dual ascent on y. When substituted into the ADMM framework, the splitting scheme yields a compelling algorithm. First, it is straightforward to show that the dual variable $y = 1 \otimes \pi$, where π are the shadow prices. Second, the two subproblems needing to be solved as part of the Gauss-Seidel pass are trivial.

The first subproblem, necessary for the x-update, takes the form.

$$\min_{x} \quad \frac{1}{2}x^{\top}(D + \rho I)x - r^{\top}x \quad \text{s.t.} \quad a \leq x \leq b,$$

for some r that varies per iteration. Being fully separable, we can write the solution explicitly:

$$x_i = \max\left(a_i, \min\left(b_i, r_i/(D_{ii} + \rho)\right)\right).$$

The second subproblem, necessary for the z-update, takes the form

$$\min_{\{z_k\}} \quad \sum_k \frac{1}{2} z_k^{\top} z_k - c_k^{\top} z_k \quad \text{s.t.} \quad \sum_k z_k = 0,$$

where the $\{c_k\}$ vary per iteration. This can be solved analytically using elementary calculus and evaluated by simply averaging the $\{c_k\}$.

Both subproblems efficiently scale to arbitrarily large problem sizes and are easily parallelized on a CPU or GPU. Research is ongoing to fine-tune the implementation's penalty and over-relaxation parameters.

We have built a prototype platform to implement forward markets in many domains, such as energy, communications, and transportation. The core infrastructure is a forward market system and a low-level flow trading system that performs optimization.

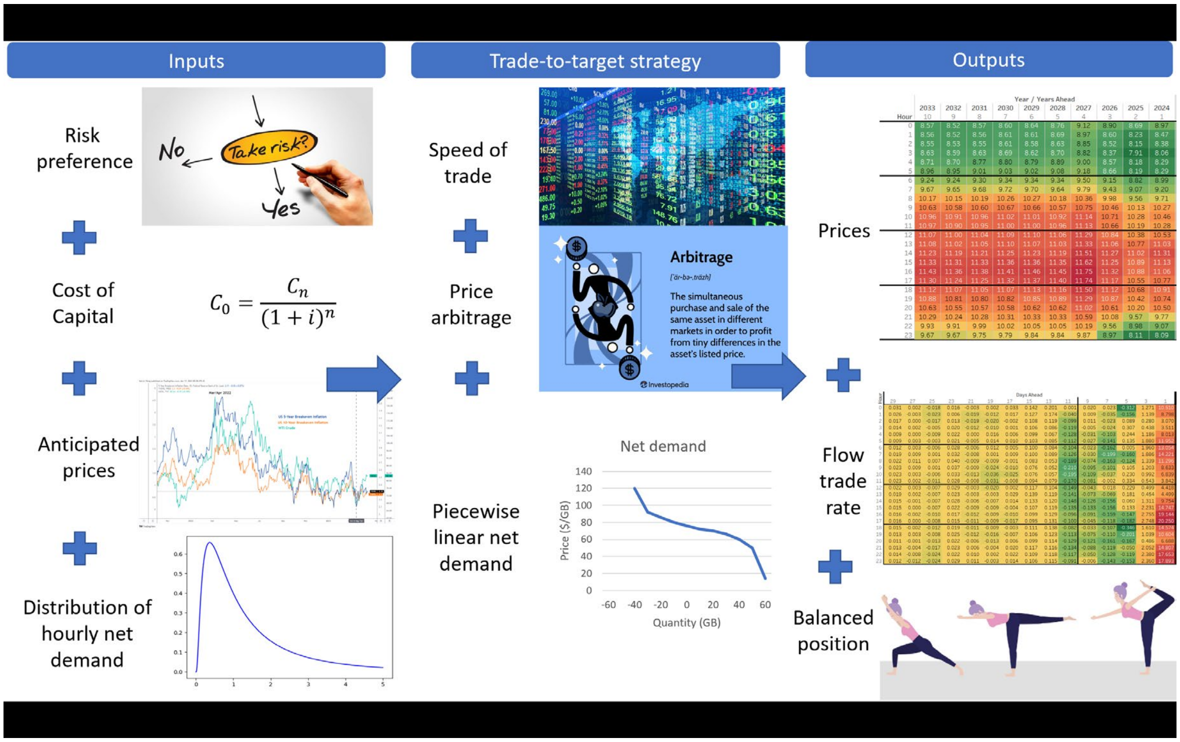

Figure 13: TIMO market participants' preferences are translated to trade-to-target strategies

Participation is straightforward with a trade-to-target strategy (Figure 13). Each bidder has preferences—the inputs in the left panel. The bidder translates these preferences with a participant tool into an effective trade-to-target strategy, a piecewise linear net demand curve for a portfolio of products, shown in the middle pane. The inputs are your risk preference, cost of capital, anticipated prices, and hourly demand distribution. Then, you turn that into the speed of trade and price arbitrage. That generates your piecewise linear net demand curves for various portfolios you want to bid on. On the right panel, the market platform optimizes, translating the bids into prices and flow trading quantities. Eventually, the net demands are consistent with needs, so the participant is in a balanced position in real-time. In such a state, the participant has ideal incentives—the best response is to bid true cost or value. In this way, the market achieves efficient outcomes. When your needs are distinct from what you own, you want to exercise market power. When the two are equal, you are in a balanced position; you have no incentive to exercise market power.

The uniqueness of prices and quantities stems from the strict convexity of the optimization problem. The lack of incentive to exercise market power comes from being in a balanced position. These are fundamental results in economics. Our optimization algorithms use interior point methods and alternating direction methods of multipliers (Boyd et al. 2011). The interior point methods are fast but are more complicated to warm start than the alternating direction method of multipliers.

Anticipating the needs of market operators in electricity and communications, we built a commercial-grade platform to conduct the market. It is done and available as open-source code.

Market architecture

We are applying the approach in many sectors of our economy. Communication is one of the critical applications. There is a forward market and trading systems (Figure 14). We are performing extensive problem tests to confirm computational feasibility.

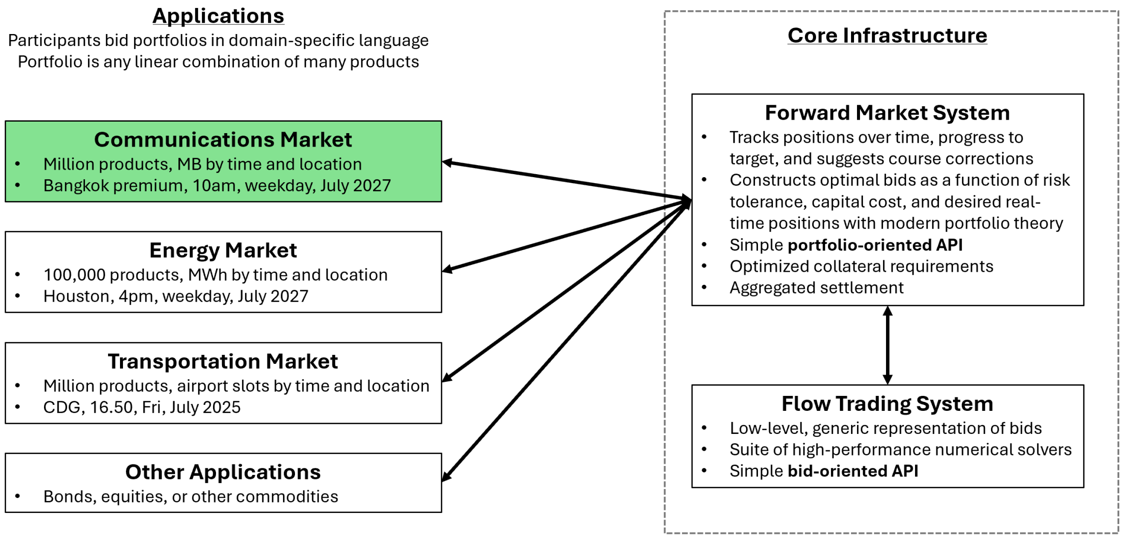

Figure 14: Architecture of the TIMO market applies to any time-and-location commodities

There is a database, and then the optimization engine solves the problem of finding the prices and quantities for every hour to maximize social welfare (Figure 15). It is powerful and revolutionary. For example, this system could trade all the world's financial securities on a single server. By contrast, what we use in today's financial markets conducted by the New York Stock Exchange, CME, ICE, and others all use the continuous limit order book trading technology, which has many problems.

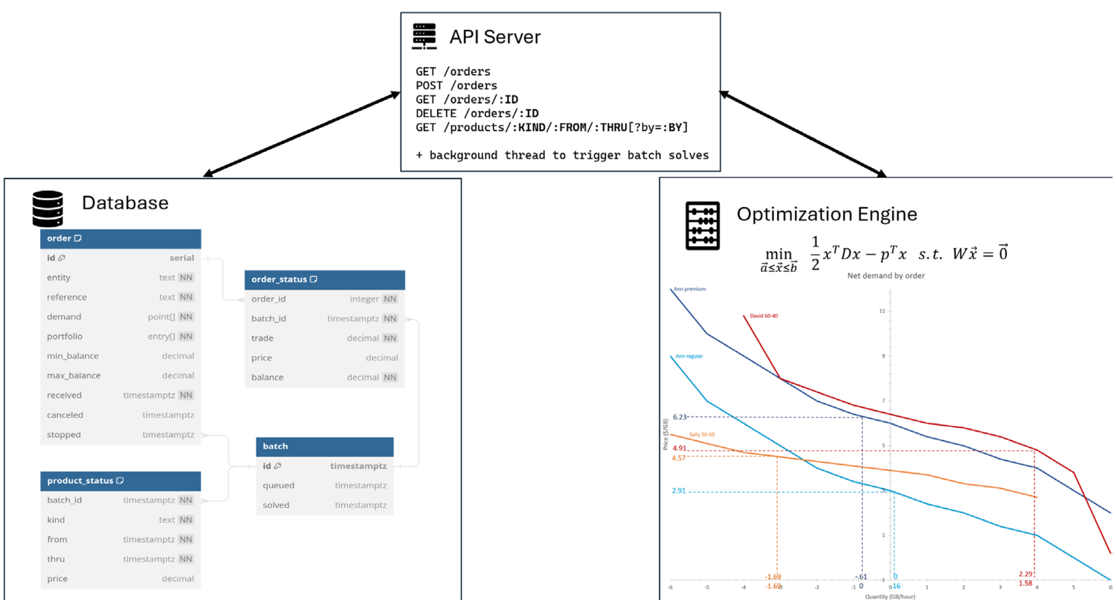

Figure 15: TIMO market translates strategies into unique optimal prices and quantities

A key problem with traditional exchanges is the arms race for speed. The fastest guy gets a prize, so there is a speed race (Budish et al. 2015). This creates demand for speed tools such as co-location and low-latency data feeds, which the exchanges sell to high-frequency traders. Exchanges make most of their money selling these speed tools, which is why they have little incentive to adopt more efficient market rules.

With the flow trading approach, we can have much richer bid expression and more power (Budish et al. 2025). You might wonder, if this is so great, why don't they do it? The answer is that they make a lot of money doing it inefficiently. And they are not about to change. Indeed, the regulations enforce the status quo in the lit markets. When we go to the regulator and say, "Look, if you use flow trading, the economy saves $10 billion a year." The high-frequency trades and the exchanges say, "Hey, that is my $10 billion. Do not you touch that." And guess what? The high-frequency traders and the exchanges win that argument every time. That is regulatory capture. It is alive and well in the United States. It is alive and well around the world. Still, it can be overcome. We do it with electricity. It works well.

To understand how this would work in Thailand, we have simulated Bangkok's premium price for weekdays, dollars per gigabit. Of course, as we said, we can have much finer granularity down to the cell sector. We can do this with any level of granularity. And it does not make any difference if thousands or millions of products exist. It is all the same. It is just a matrix in the computer. Spreadsheets do not care whether there are a million rows or ten, nor do humans because humans have algorithms for looking at all these prices and optimizing their strategies to maximize value. Again, we are talking about a wholesale market, not a retail market. We would not expect retail consumers to do this.

They do not have to do anything. These competitive wholesale providers are motivated to create value for them. Why do they want to create value for consumers? Because then they can sell to the consumer. That is nice. These are just different frequencies. The remarkable thing is that when we do these, this is a world where we do these auctions every hour for all these products. People can buy and sell gradually. They can adjust their positions gradually. That is powerful and effective. That is what people want to do. Even huge participants like Vanguard and BlackRock do this. For example, how does Vanguard conduct a $30 million trade? They split it up into millions of orders and execute those millions of orders over multiple days. This is among the most prominent participants. They still break everything into little pieces to minimize trading costs.

Figures 16-18 show the price matrices for forward products at three time granularities: yearly, monthly, and daily. In each cell, the price is shown numerically and in color as a heat map.

Hour	2033 (10)	2032 (9)	2031 (8)	2030 (7)	2029 (6)	2028 (5)	2027 (4)	2026 (3)	2025 (2)	2024 (1)
	Year / Years Ahead									
0	8.57	8.52	8.57	8.60	8.64	8.76	9.12	8.90	8.69	8.97
1	8.56	8.52	8.56	8.61	8.61	8.69	8.97	8.60	8.23	8.47
2	8.55	8.53	8.55	8.61	8.58	8.63	8.85	8.52	8.15	8.38
3	8.63	8.59	8.63	8.69	8.62	8.70	8.82	8.37	7.91	8.06
4	8.71	8.70	8.77	8.80	8.79	8.89	9.00	8.57	8.18	8.29
5	8.96	8.95	9.01	9.03	9.02	9.08	9.18	8.66	8.19	8.29
6	9.24	9.24	9.30	9.34	9.34	9.34	9.50	9.15	8.82	8.99
7	9.67	9.65	9.68	9.72	9.70	9.64	9.79	9.43	9.07	9.20
8	10.17	10.15	10.19	10.26	10.27	10.18	10.36	9.98	9.56	9.71
9	10.63	10.58	10.60	10.67	10.66	10.57	10.75	10.46	10.13	10.27
10	10.96	10.91	10.96	11.02	11.01	10.92	11.14	10.71	10.28	10.46
11	10.97	10.90	10.95	11.00	11.00	10.96	11.13	10.66	10.19	10.28
12	11.07	11.00	11.04	11.09	11.10	11.06	11.29	10.84	10.38	10.53
13	11.08	11.02	11.05	11.10	11.07	11.03	11.33	11.06	10.77	11.03
14	11.23	11.19	11.21	11.25	11.23	11.19	11.51	11.27	11.02	11.31
15	11.33	11.31	11.33	11.36	11.36	11.35	11.62	11.25	10.89	11.13
16	11.43	11.36	11.38	11.41	11.46	11.45	11.75	11.32	10.88	11.06
17	11.30	11.24	11.25	11.32	11.37	11.40	11.74	11.17	10.55	10.77
18	11.12	11.07	11.05	11.07	11.13	11.16	11.50	11.12	10.68	10.91
19	10.88	10.81	10.80	10.82	10.85	10.89	11.29	10.87	10.42	10.74
20	10.63	10.55	10.57	10.58	10.62	10.62	11.02	10.61	10.20	10.50
21	10.29	10.24	10.28	10.31	10.33	10.33	10.59	10.08	9.57	9.77
22	9.93	9.91	9.99	10.02	10.05	10.05	10.19	9.56	8.98	9.07
23	9.67	9.67	9.75	9.79	9.84	9.84	9.87	8.97	8.11	8.09

Price $/GB: 7.91 – 11.75

Figure 16: Example forward prices from simulation (yearly forwards by hour)

Hour	Dec (12)	Nov (11)	Oct (10)	Sep (9)	Aug (8)	Jul (7)	Jun (6)	May (5)	Apr (4)	Mar (3)	Feb (2)	Jan (1)
	Month / Months Ahead											
0	8.53	8.49	8.51	8.45	8.36	8.15	8.20	8.06	7.63	7.99	8.41	7.90
1	8.51	8.47	8.51	8.44	8.40	8.22	8.32	8.14	7.74	8.30	8.93	8.40
2	8.56	8.49	8.56	8.50	8.42	8.29	8.40	8.24	7.82	8.35	8.90	8.37
3	8.69	8.60	8.64	8.57	8.47	8.37	8.49	8.34	7.95	8.38	8.76	8.24
4	8.92	8.82	8.87	8.81	8.69	8.63	8.73	8.62	8.24	8.62	8.90	8.43
5	9.12	9.04	9.09	9.05	8.93	8.84	8.90	8.80	8.48	9.06	9.57	9.21
6	9.36	9.30	9.38	9.35	9.25	9.15	9.15	9.09	8.84	9.65	10.42	10.16
7	9.73	9.70	9.74	9.68	9.58	9.47	9.46	9.32	9.09	9.93	10.75	10.48
8	10.21	10.21	10.25	10.20	10.10	9.95	9.92	9.78	9.57	10.41	11.24	11.01
9	10.60	10.60	10.67	10.65	10.57	10.45	10.44	10.28	10.04	10.97	11.83	11.59
10	10.91	10.92	10.97	10.97	10.87	10.78	10.76	10.80	10.51	11.63	12.63	12.34
11	10.93	10.94	10.97	10.99	10.90	10.86	10.84	10.86	10.58	11.44	12.14	11.88
12	11.07	11.07	11.10	11.09	10.98	10.92	10.86	10.97	10.72	11.57	12.29	12.07
13	11.11	11.08	11.12	11.08	10.98	10.91	10.85	10.89	10.78	11.58	12.30	12.20
14	11.27	11.23	11.32	11.26	11.16	11.04	10.98	10.99	10.82	11.71	12.56	12.40
15	11.39	11.35	11.43	11.40	11.29	11.16	11.05	10.98	10.85	11.75	12.64	12.60
16	11.43	11.41	11.45	11.47	11.33	11.21	11.07	10.94	10.66	11.48	12.25	12.13
17	11.29	11.29	11.32	11.34	11.19	11.08	10.99	10.86	10.53	11.51	12.42	12.21
18	11.09	11.08	11.10	11.08	10.94	10.86	10.81	10.67	10.33	11.43	12.43	12.12
19	10.89	10.89	10.93	10.89	10.79	10.70	10.65	10.59	10.23	11.23	12.18	11.84
20	10.64	10.61	10.68	10.65	10.55	10.43	10.34	10.26	10.03	10.91	11.75	11.58
21	10.27	10.26	10.34	10.34	10.24	10.14	10.05	10.07	9.88	10.65	11.38	11.28
22	9.88	9.89	9.96	9.97	9.85	9.71	9.62	9.63	9.45	10.20	10.92	10.81
23	9.60	9.62	9.71	9.73	9.60	9.47	9.43	9.47	9.29	10.16	10.96	10.80

Price $/GB: 7.63 – 12.64

Figure 17: Example forward prices from simulation (monthly forwards by hour)

Days Ahead

Price $/GB: 2.26 – 11.53

Hour	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1
0	8.55	8.57	8.58	3.17	8.55	8.59	3.24	8.68	8.64	8.68	2.49	8.76	8.06	2.39	7.64
1	8.54	8.55	8.56	3.12	8.52	8.56	3.20	8.62	8.59	8.64	2.37	8.74	8.20	2.26	7.87
2	8.56	8.58	8.58	3.08	8.51	8.56	3.16	8.61	8.57	8.60	2.43	8.77	8.43	2.40	8.24
3	8.62	8.65	8.66	3.08	8.57	8.58	3.09	8.62	8.59	8.61	2.54	8.78	8.34	2.66	8.09
4	8.74	8.78	8.82	3.26	8.73	8.72	3.18	8.77	8.70	8.72	2.62	8.79	8.30	2.65	8.02
5	8.94	8.98	9.04	3.51	8.96	8.92	3.41	8.99	8.92	8.99	2.62	9.04	8.53	2.46	8.24
6	9.26	9.27	9.32	3.76	9.26	9.19	3.75	9.27	9.19	9.30	3.06	9.36	8.78	2.84	8.34
7	9.67	9.67	9.70	4.23	9.66	9.59	4.30	9.70	9.60	9.69	3.61	9.77	9.36	3.26	9.07
8	10.16	10.16	10.17	4.72	10.15	10.11	4.78	10.19	10.06	10.11	4.03	10.12	9.64	3.64	9.30
9	10.59	10.58	10.60	5.18	10.60	10.59	5.24	10.68	10.52	10.56	4.42	10.48	9.92	3.90	9.57
10	10.88	10.89	10.92	5.44	10.92	10.92	5.49	11.01	10.88	10.89	4.70	10.72	10.16	4.22	9.83
11	10.91	10.96	10.99	5.46	10.95	10.95	5.54	11.04	10.97	10.97	4.78	10.81	10.23	4.26	9.95
12	11.02	11.08	11.11	5.58	11.05	11.01	5.65	11.07	11.04	11.02	4.96	10.89	10.57	4.43	10.56
13	11.06	11.12	11.14	5.57	11.03	11.00	5.63	11.06	11.05	10.96	5.01	10.81	10.56	4.61	10.58
14	11.24	11.27	11.26	5.70	11.20	11.16	5.76	11.21	11.18	11.16	5.39	11.14	10.83	5.19	10.72
15	11.38	11.36	11.31	5.76	11.27	11.26	5.86	11.31	11.26	11.25	5.67	11.32	10.86	5.72	10.53
16	11.41	11.38	11.33	5.79	11.34	11.32	5.86	11.38	11.33	11.40	5.64	11.53	11.01	5.69	10.65
17	11.25	11.27	11.23	5.66	11.21	11.18	5.70	11.26	11.22	11.32	5.56	11.38	10.81	5.60	10.40
18	11.04	11.09	11.08	5.49	11.07	11.01	5.48	11.07	11.00	11.14	5.06	11.20	10.47	4.94	9.91
19	10.83	10.89	10.92	5.39	10.88	10.78	5.40	10.84	10.77	10.85	4.66	10.88	10.08	4.31	9.53
20	10.58	10.62	10.64	5.18	10.59	10.50	5.20	10.57	10.50	10.58	4.36	10.60	10.01	4.00	9.68
21	10.28	10.29	10.28	4.81	10.25	10.16	4.86	10.27	10.20	10.28	4.26	10.24	9.72	3.98	9.49
22	9.94	9.91	9.87	4.35	9.84	9.79	4.38	9.93	9.87	9.90	4.15	9.81	9.35	3.94	9.04
23	9.67	9.64	9.59	4.05	9.58	9.55	4.06	9.68	9.64	9.63	4.10	9.60	8.99	4.06	8.47

Figure 18: Example forward prices from simulation (daily forwards by hour)

Importantly, participants have thousands of auctions in which to adjust positions. They rationally take advantage of this flexibility to maximize their interests. Gradual purchase lets participants protect against adverse price impacts from its bids. Traders want to trade gradually to minimize trading costs. This technology enables them to do that effectively.

In Figure 19, we see that the quantities of a large participant purchase gradually over time. The matrix shows the flow trade rates. They are tiny, and that is a good thing. Then, as you get closer to real-time, the quantities go up.

Days Ahead

Flow trade rate (G..: -0.346 – 20.250

Hour	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1
0	0.031	0.002	-0.018	0.016	-0.003	0.002	0.033	0.142	0.201	0.001	0.020	0.023	-0.312	1.271	10.510
1	0.026	-0.003	-0.023	0.006	-0.019	-0.012	0.017	0.127	0.174	-0.040	0.009	-0.035	-0.156	1.139	8.798
2	0.017	0.000	-0.017	0.013	-0.019	-0.020	-0.002	0.108	0.119	-0.099	0.011	-0.023	0.089	0.280	3.070
3	0.014	0.002	-0.005	0.020	-0.012	-0.010	0.001	0.106	0.086	-0.119	-0.005	-0.024	0.307	0.438	3.511
4	0.009	0.000	-0.009	0.022	0.000	0.016	0.006	0.099	0.067	-0.128	-0.031	-0.103	0.244	1.186	8.013
5	0.009	0.003	-0.003	0.021	-0.005	0.014	0.010	0.103	0.085	-0.112	-0.027	-0.141	0.135	1.880	11.952
6	0.012	0.003	-0.006	0.028	-0.006	0.012	0.005	0.100	0.084	-0.104	-0.023	-0.162	0.005	1.960	13.054
7	0.019	0.009	0.001	0.032	-0.008	0.001	0.009	0.100	0.089	-0.126	-0.030	-0.199	-0.160	1.886	14.221
8	0.022	0.011	0.007	0.040	-0.009	-0.009	-0.001	0.083	0.053	-0.189	-0.074	-0.163	-0.124	1.339	11.296
9	0.023	0.009	0.001	0.037	-0.009	-0.024	-0.010	0.076	0.052	-0.210	-0.095	-0.101	0.105	1.203	8.633
10	0.023	0.003	-0.006	0.033	-0.013	-0.036	-0.025	0.076	0.057	-0.195	-0.109	-0.037	0.230	0.992	6.839
11	0.023	0.002	-0.011	0.028	-0.008	-0.031	-0.008	0.094	0.079	-0.170	-0.081	-0.002	0.334	0.543	3.842
12	0.022	0.003	-0.007	0.029	-0.003	-0.020	0.002	0.117	0.104	-0.149	-0.043	0.018	0.229	0.499	4.418
13	0.019	0.002	-0.007	0.023	-0.003	-0.003	0.029	0.139	0.119	-0.141	-0.073	-0.069	0.181	0.454	4.499
14	0.015	-0.001	-0.007	0.028	-0.006	-0.007	0.014	0.133	0.120	-0.148	-0.126	-0.156	0.060	1.311	9.754
15	0.015	0.000	-0.007	0.022	-0.009	-0.009	-0.004	0.107	0.119	-0.135	-0.133	-0.156	0.133	2.231	14.747
16	0.016	-0.002	-0.010	0.017	-0.012	-0.009	-0.010	0.099	0.129	-0.096	-0.091	-0.159	-0.147	2.755	19.144
17	0.016	0.000	-0.008	0.015	-0.011	-0.009	-0.017	0.095	0.131	-0.100	-0.045	-0.118	-0.182	2.748	20.250
18	0.015	-0.002	-0.012	0.019	-0.011	-0.009	-0.003	0.111	0.138	-0.082	-0.033	-0.107	-0.346	1.610	14.574
19	0.013	0.003	-0.008	0.025	-0.012	-0.016	-0.007	0.106	0.123	-0.113	-0.075	-0.110	-0.201	1.039	10.604
20	0.011	-0.001	-0.013	0.022	-0.006	-0.013	0.006	0.099	0.114	-0.129	-0.121	-0.161	-0.167	0.486	6.688
21	0.013	-0.004	-0.017	0.023	0.006	-0.004	0.020	0.117	0.116	-0.134	-0.088	-0.119	-0.050	2.052	14.807
22	0.014	-0.008	-0.024	0.022	0.010	0.002	0.022	0.109	0.118	-0.117	-0.050	-0.128	-0.119	2.380	17.653
23	0.012	-0.012	-0.024	0.029	0.011	-0.003	0.014	0.106	0.115	-0.091	-0.006	-0.143	-0.153	2.360	17.893

Figure 19: Example quantities traded for large MVNO from simulation (daily by hour)

The market design is well-tested over multiple decades of use in electricity markets.

In this 12-year backcast, we are performing highly detailed simulations at the hourly level in the enormous Texas market. We will report our results in the coming months.

For communications, we have conducted smaller-scale simulations. The output for one of our simulations is shown in Figures 20-23. The figures illustrate how the price information evolves throughout the week.

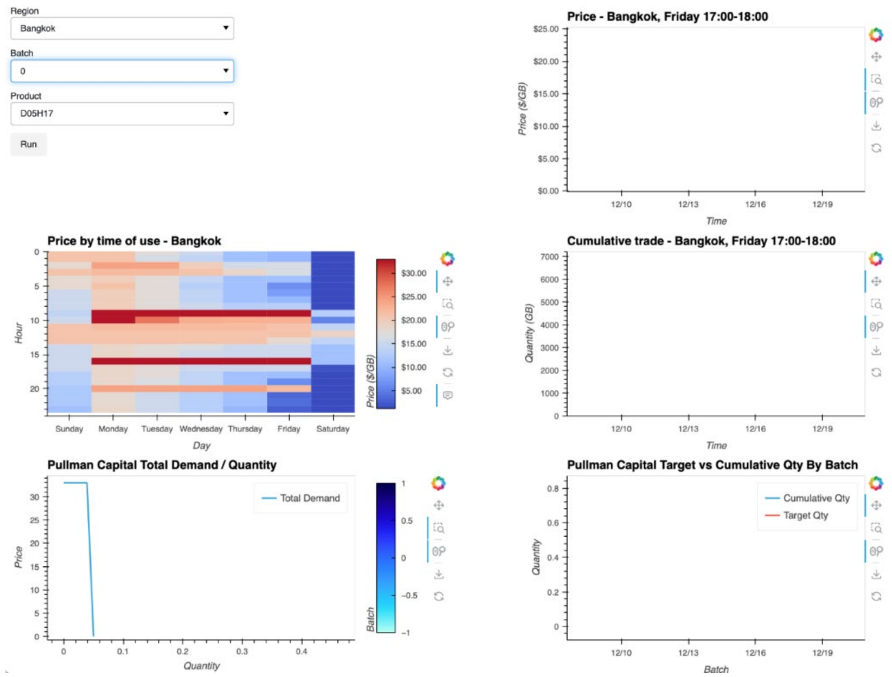

Figure 20: Seven-day market simulation of an urban center (start of week, Sunday)

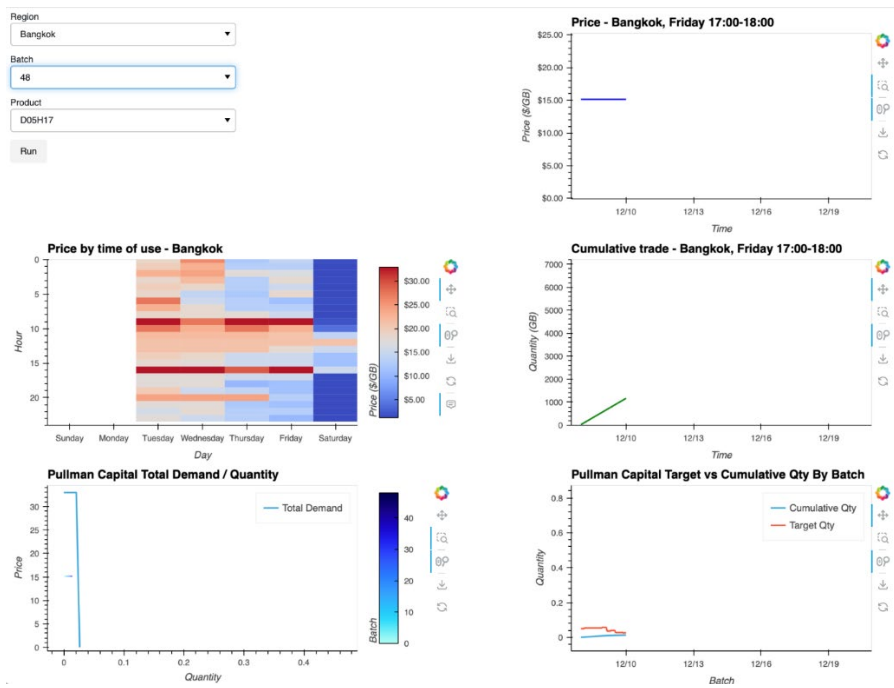

Figure 21: Seven-day market simulation of an urban center (from Tuesday)

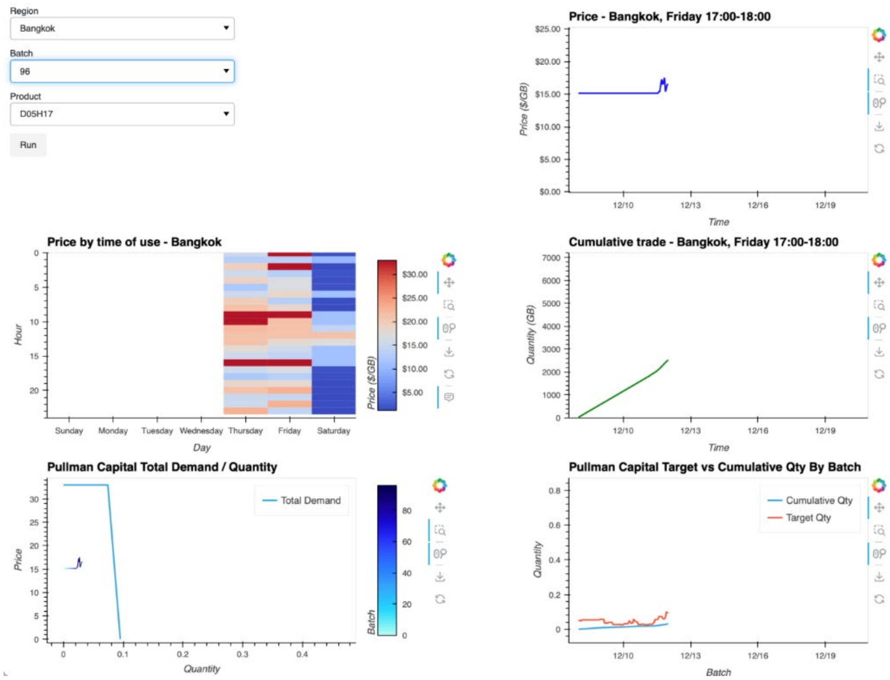

Figure 22: Seven-day market simulation of an urban center (from Thursday)

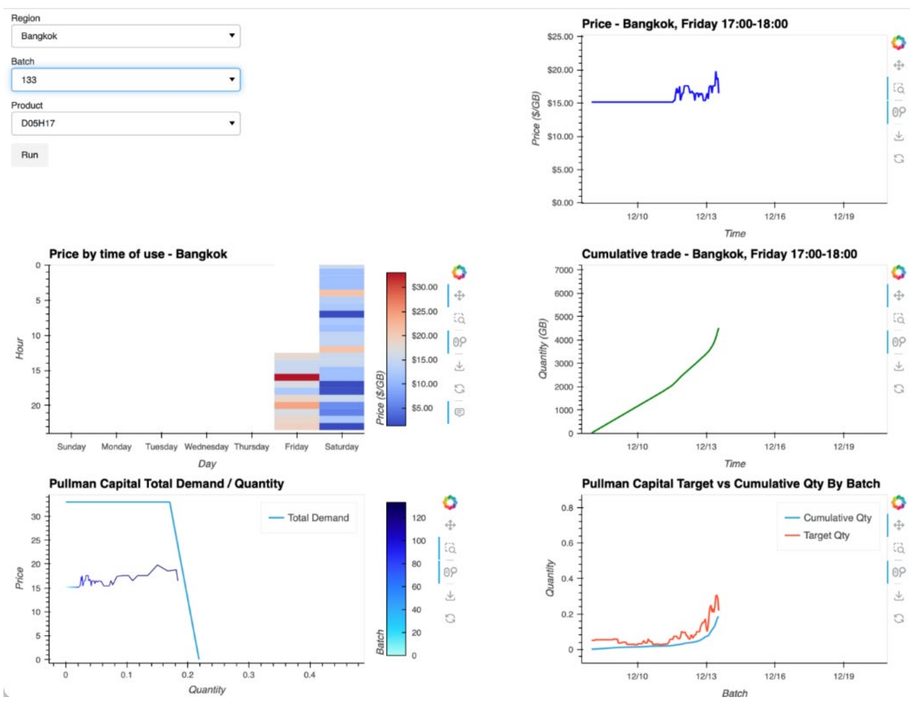

Figure 23: Seven-day market simulation of an urban center (from Friday)

TIMO can be introduced in two years

How long will it take for TIMO to be in operation? This is a question of regulation. The core systems are already built and can be customized for the Thailand market in six months. The regulatory process will take longer. Based on our experience in other countries, we estimate two years.

What experience do NBTC and the Thai mobile market have running something like TIMO? It is essential to recognize that NBTC provides oversight and does not conduct the market.

TIMO is comprised of experts who know how to run it. Thailand has a lot of local talent who understand how TIMO works and how it can be done.

The collaboration between MNOs and TIMOs is essential. The interface between TIMO, the MNOs, and the MVNOs is also necessary. That interface is critical and needs to be facilitated with NBTC oversight.

NBTC must not let the MNOs foreclose competition. This is readily accomplished with the obligation to sell capacity without a reserve price. Doing so aligns the MNOs' interests with social welfare. The MNOs want to see competitive prices in the wholesale market. This is the fundamental insight of Adam Smith expressed in the welfare theorems of economics.

Despite this alignment, it is essential to have market rules that further support economic efficiency. These rules include the possibility of fines or punishments for violating them. This is done in other markets, such as the wholesale electricity markets in the United States. It works well.

To date, MVNO competition has been stifled in Thailand. This can be reversed with good market design. TIMO is the key. In developing TIMO, we must recognize that it is not a theoretical construct. The approach is well-studied and tested. We have learned much from our experiences in other countries and sectors. This way, NBTC can avoid past mistakes and adopt a practical approach.

Feasibility of TIMO

Mobile Virtual Network Operators (MVNOs) and Mobile Virtual Network Aggregators (MVNAs) have faced challenges in Thailand. It is frustrating to see their potential hindered by an inadequate regulatory structure.

Something needs to change to promote competition in mobile communications. The approach described here provides a path forward. It is the best solution for Thailand.

Enforcement is an issue in the current regulatory framework, and this problem is not unique to Thailand. For instance, coverage and buildout obligations are not effectively enforced, though they are frequently included in license conditions. The administrative definition of these obligations is complex, and enforcement is often impractical.

The current policy is not the best solution. We need to align incentives to promote competition and foster innovation. Regulatory mandates have proven ineffective, as regulation often lags behind technological advances.

The TIMO structure we propose is effective and has the potential to significantly improve the landscape of mobile communications in Thailand. We can foster innovation and competition by aligning incentives with social welfare and encouraging continuous improvement through transparent markets with effective governance. With its strong theoretical basis and decades of successful application, this approach offers a promising future for the industry.

By contrast, better enforcement of existing policies has proven ineffective in many countries. The FCC has struggled to make license conditions effective in the US, such as buildout and coverage obligations. Enforcement has failed, even after repeated attempts to improve the rules.

Approaches that rely on market incentives have worked. Fixing the regulatory framework would better align incentives.

Our team includes a key member with more than twenty years of experience in Thailand, in addition to his international experience. Our extensive global experience gives us an understanding of mistakes to avoid and successes to exploit. Our judgments are informed, and our independence is established.

In Thailand today, the carriers have mainly ignored the MVNO capacity requirements established to promote competition, and regulatory enforcement has been weak. I accept your legitimate concern.

The problem with this approach is that it is easy for carriers to evade regulation by failing to sign contracts that promote competition. This is not surprising. An asymmetric duopoly is perhaps the most collusive market structure (Ausubel and Deneckere 1987). Mandating a company to take action against its interests is not a successful path.

In the merger remedy, NBTC redoubled its efforts to address the merged entity's reluctance to sign contracts and encourage successful MVNO entry.

Effective regulation of True and AIS would not negatively impact spectrum or retail pricing. When done well, effective regulation increases the value of the carrier's networks. MNOs and MVNOs benefit from the larger pie created by a competitive and innovative communications market. Ultimately, competition benefits everyone, especially Thai consumers. Still, every duopolist will resist competition. The gains from competition bring risks, as AT&T and Verizon are experiencing with the success of T-Mobile US.

A context-specific strategy is needed—one that prioritizes practical solutions. That is what we present here. It will not be easy, and it will not be instantaneous. However, it is valid and successful in other sectors and countries. It is also innovative. That is how progress is made.

The merger of True Corporation and Total Access Communications (Dtac) in Thailand was a significant event that transformed the telecom market into a duopoly dominated by True and AIS. As part of this merger, NBTC mandated that at least 20% of the combined network capacity be available to MVNOs to mitigate potential anti-competitive effects. However, concerns have been raised about implementing these measures and the overall health of the MVNO ecosystem in Thailand.

NBTC's conditions were established to foster competition and prevent monopolistic practices in the telecom market. The regulator emphasized that MVNO access should be guaranteed without discrimination and within specific timelines. NBTC established detailed conditions to ensure nondiscriminatory access for MVNOs following the merger. Key provisions include:

- *Guaranteed Access to Network Capacity*. The merged entity must allocate at least 20% of its total network capacity to MVNOs that are not affiliated with the company, ensuring fair access upon request.
- *Non-Discriminatory Practices*. The merged entity is prohibited from refusing service to MVNOs based on claims of insufficient network capacity. Access must be provided under equal terms and quality standards outlined by NBTC regulations.

- *Timely Service Activation*. MVNOs requesting access must be able to start using the network within 60 days of their request, ensuring prompt service availability.
- *Quality Standards*. The quality of service provided to MVNOs must align with the standards set by the NBTC, guaranteeing that MVNO customers receive services comparable to those offered directly by True.

These measures are part of broader regulatory remedies intended to mitigate potential anti-competitive effects of the merger, alongside commitments to maintain service quality, reduce prices, and expand 5G coverage. However, implementation has been scrutinized, with concerns raised about the actual execution of these conditions and transparency in reporting progress.

There are specific conditions on the pricing terms between True and MVNOs that request network capacity. NBTC imposed these conditions to ensure fair and competitive access for MVNOs. The key pricing-related measures include:

- *Wholesale Pricing Cap*. MVNOs' wholesale compensation rate must not exceed the average service fee offered per unit of each service (e.g., voice, data, SMS). This wholesale price must be at least 30% lower than the retail price for bundled packages or individual services. This ensures MVNOs can offer competitive pricing to their customers.
- *No Minimum Purchase Requirements*. The merged entity cannot impose minimum limits on MVNOs' purchase of services (e.g., voice, data, SMS). Charges must be based on actual usage, allowing MVNOs flexibility in managing their costs and offerings.
- *Transparency and Cost Verification*. The merged entity must submit cost information and necessary data to an inspection agency. This measure ensures pricing transparency and prevents anti-competitive practices such as margin squeezes.

Despite these pricing conditions, MVNO entry still faces challenges due to high wholesale costs and limited access to network capacity.

TIMO is the solution. It aligns the incentives of the regulator, MVNOs, and carriers toward maximizing social welfare. This is a successful—well-tested—path to competition in Thailand communications.

TIMO's mission is "To encourage competition and innovation in mobile communications through efficient and transparent trade of wholesale capacity." Like the Independent System Operators (ISOs) from the US electricity sector, the mission is operationalized by translating the mission into economic and mathematical terms:

- "We address potential market failures, including incomplete markets, incomplete information, market power, entry barriers, and systemic risk."
- "We conduct transparent and efficient markets by pricing communications to maximize social welfare subject to network and resource constraints."

Wholesale electricity has many similarities with wholesale communications; both are network industries with substantial shocks to supply and demand by time and location, requiring that efficient open-access pricing is defined by time and location. Market participants must manage needs and risks through forward trade. The key difference is that communication is more straightforward. The consequence of rationing when demand is more significant than supply is less costly. Supply and demand must be balanced every second, or the lights will go out on electricity.

Thousands of network and resource constraints must be satisfied, or essential equipment will be destroyed. Communications is much more tolerant of supply and demand imbalances. This is why today's communications markets work despite poor congestion management. Communications have more flexibility in real-time, so we see effective congestion management in electricity but not in communications.

TIMO introduces efficient congestion management through pricing—an approach used in highly evolved designed markets such as electricity and finance. Adam Smith's *The Wealth of Nations* presented the core idea and has been the centerpiece of economics ever since. From a regulatory perspective, the essential element is measured use. Carriers do this today. Every communication is measured by time and location. With measurement, it is possible to price use by time and location. Open access prices the resource—consumption of the communications commodity—with efficient pricing derived mathematically from the dual optimization of as-bid total welfare. This may sound complex, but it is easy since this step rests on the most basic and powerful ideas from optimization theory—convex optimization and duality theory.

As with any significant regulatory innovation, TIMO will take time to establish. It can be designed and implemented in Thailand in two years. The bottleneck is the regulatory stakeholder process. My team built a state-of-the-art trading platform that is open source and freely available in early 2025. Does this delay harm a timely auction in mid-2025? No. As long as NBTC establishes initial progress and intent before the auction starts, bidders can properly include regulatory and market uncertainties in their bids. This is how auctions work. Bidders inevitably face regulatory and market uncertainties. The bidders' bids translate their bids into market prices for the scarce spectrum input needed to provide communications services.

Conclusion

This note summarizes the core elements of TIMO.

Especially after the recent merger, NBTC must inject some competition into the mobile communications market. Competition is inadequate, given the duopoly structure. They could compete on price and try to undercut each other, but they both make more money if they keep prices high. They are motivated to play nice with each other but not with their customers. Coordinated pricing is inevitable absent entry. TIMO provides a means for entry by enabling competitive access to the communications commodity.

More competition means better prices, innovative services, and a more dynamic market overall. If TIMO works, Thai consumers will see lower phone bills, faster internet, and more choices.

TIMO will ultimately benefit everyone, even the dominant carriers. A competitive and innovative market expands the value of network resources, and everyone shares in this welfare improvement.

Price signals would encourage MVNOs to be more strategic about how and when they use capacity. It would also incentivize the big players to invest in expanding their networks, knowing they could sell that extra capacity at a premium during peak times. TIMO is more like a free market than a regulated one. Transparency lets stakeholders identify problems and address them. The result is a more vibrant and consumer-friendly mobile market in Thailand.

TIMO harnesses a robust trading platform where MVNOs can bid on network capacity. We have already built a state-of-the-art platform that could be adapted for Thailand. We have built the tools to make this happen. The platform uses algorithms to determine the most efficient allocation of capacity, considering real-time demand, network constraints, the bids submitted by the MVNOs, and others.

TIMO builds on the success of similar instruments in other countries and sectors. Similar market-based approaches have worked well in electricity, another critical commodity.

Mobile data is no longer a luxury. It is essential for many people. The market design principles that have worked in the electricity market can be adapted to address the specific challenges of the telecom market.

We estimate a two-year timeline for designing and implementing TIMO in Thailand. That is fast for something this big. The real bottleneck is the regulatory-stakeholder process, getting everyone on board and hammering out the details. However, the technical aspects of building the platform and designing the market mechanisms are achievable within that time frame. Technology is not the problem. The problem is political.

NBTC needs to create a system where everyone benefits: consumers, smaller players, and even the big incumbents. Thinking outside the box and being willing to challenge the status quo is essential.

We have presented a solid starting point for competition policy. It is based on promoting competitive MVNO entry.

Dynamic pricing is the most efficient and responsive approach.

TIMO includes safeguards to prevent market abuse. Still, it is ambitious. Detailed simulations make us confident that it can be created in two years. We have devoted considerable assets to developing a state-of-the-art trading platform that could be adapted for Thailand. The real bottleneck is the regulatory-stakeholder process—getting everyone on board and hammering out the details. Technology is not the problem.

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