June 12, 2019

WHITE PAPER
FUEL for 5G: Flexible Use and Efficient Licensing

Table of Contents

Executive Summary 2

Introduction 3

Objectives for a C-Band Auction 3

License Definitions 5

FUEL Auction Design 6

- Two-Round Structure 6
- "Bid Groups" and the FUEL Bidding Language 7
- Reserve Bids 11
- Winner and Payment Determination 11
- Assignment Stage 12

The FUEL Design Satisfies the Objectives for a C-Band Auction 13

- Quick 13
- Efficient 13
- Simple for All Participants 15

Alternative Auction Designs Are Not Suitable 16

- Multi-Round Combinatorial Auctions (CCA) 16
- Multi-Round Non-Combinatorial Auctions (SMR or Clock) 17
- Incentive Auctions 17

Conclusion 18

Appendix 19

- Example: Competition Among Large and Small Packages 19

Executive Summary

The urgent need to make part of the C-Band spectrum quickly available to use with 5G technologies is widely recognized but it is challenging to accomplish that in a way that is fast, fair, efficient, and simple for participants and also avoids disrupting current users. Auctionomics has developed its FUEL (Flexible Use and Efficient Licensing) for 5G proposal to promote just such an outcome.

One key element of the FUEL proposal is that licenses would be sold in 20 MHz blocks on a PEA basis. These areas are small enough to allow bidders with many different business plans to participate and large enough to keep the number of licenses small enough for an effective auction.

Another key element of the proposal is for the CBA – a consortium of satellite providers – to repurpose spectrum in a novel, sealed-bid package auction. Sealed bid auctions are much faster and simpler than the multi-stage auctions most often used for spectrum sales in the US and around the world. They require less time and, less bidder training, and due to their reduced data entry, reduce the risk of bidding errors. When suitably designed, package auctions improve efficiency by avoiding the "exposure problem" associated with the FCC's traditional auction designs in which bids for each PEA are separate. Viable business plans depend on winning a suitable package of licenses, with sufficient bandwidth in each area and sufficient geographic coverage, but bidders in a traditional auction are exposed to the risk of winning an unsuitable package. Well-designed package auctions also avoid the inefficient license assignments that can result from implicit collusion by bidders. These advantages of package auctions have contributed to the popularity of the combinatorial clock auction design (CCA) in many countries around the world.

The CCA design, however, does not scale well to applications as large as the C-Band sale in the US and has the additional disadvantage of imposing large complexity costs on bidders. The FUEL auction design is constructed to be simple, efficient and quick. As a sealed-bid second-price auction using a novel concept of "bid groups," its simplicity makes bid entry easy, reduces strategizing, eliminates real-time decision making and extensive data entry, and makes the auction quick, and its second-price rule promotes efficiency. No traditional design enjoys all of these benefits.

Introduction

Auctionomics has been retained by the C-Band Alliance (CBA) to present an auction design for the repurposing of a portion of C-Band spectrum. The CBA is a consortium of satellite companies providing fixed satellite service to customers in the continental United States. Auctionomics and its Co-founder Paul Milgrom specialize in spectrum auction design, and Auctionomics' team members have worked with the Federal Communications Commission (FCC) and its expert staff for more than 20 years.

In this document, we first set out the objectives and requirements for a successful private market-based C-Band auction design. We then describe our *Flexible Use and Efficient Licensing ("FUEL") for 5G* auction design and explain how our design satisfies those objectives. We conclude by discussing the shortcomings of alternative auction designs.

Objectives for a C-Band Auction

All parties recognize the need to make mid-band spectrum quickly available for flexible use for wireless broadband connectivity. This spectrum is critical to secure U.S. leadership in 5G and other advanced services. Repurposing a significant amount of C-Band spectrum is a vital part of that plan. The CBA plan is designed to allow for the rapid reallocation of mid-band spectrum using a private, market-based process based on the FCC's extremely successful secondary market policies.

The CBA's member companies share the C-Band spectrum to provide service to the continental United States ("CONUS");"); all use the same 500 MHz from different orbital locations. As explained below, this fundamental attribute of the C-Band means that this reallocation problem requires a different solution than the incentive approach adopted for clearing the exclusive licenses in the 600 MHz band. In addition, clearing the C-Band is a complex process involving the installation of tens of thousands of filters at earth stations, as well as the launches of new satellites. Consequently, a successful clearing plan must manage the transition process, assure in the public interest continuity of service for existing satellite users, and provide incentives for the incumbent spectrum users to relinquish valuable spectrum rights.

A successful private C-Band auction design should repurpose spectrum for 5G use as soon as possible, meaning that the auction process itself must be **quick**. Traditional auctions take years of procedural deliberations followed by many months of software coding and bidder training, months more of bidding planning to evaluate strategies and contingencies, all followed by a long auction process that by itself can take many months. After all that, spectrum clearing in a band with incumbent users through a reverse and forward auction takes significant time – even without the complication of nonexclusive spectrum rights. By contrast, if the FUEL market-based approach is approved by the Commission, it can be implemented quickly. The FUEL design satisfies the requirements of all stakeholders, makes participation straightforward for all bidders, minimizes software, training and strategic planning delays, and can be run and implemented very quickly: the first C-Band spectrum would be available for use 18 months after the Commission's final order approving the plan.

The C-Band reallocation must also be **efficient and fair**. By virtue of its package bidding language, the FUEL design eliminates the exposure problem – that is, it precludes the possibility that a bidder might win too little spectrum in an area for a viable network, or too few areas for a viable business plan. This makes broad participation safe for many bidders, and allows direct, fair competition among all bidders: big and small, national and rural. By using a second-price rule, the FUEL design also discourages strategizing that, in other designs, is costly and time-consuming and promotes inefficient outcomes, in which winners may not be those with the highest and best use for the spectrum. The FUEL second-price design encourages the *right bidders* to express the *right values* for the *right combinations* of licenses. The FUEL sealed-bid format treats all bidders equally, which is critical for reallocating C-Band spectrum fairly and it accommodates and protects the C-Band's important incumbent users while still ensuring that reallocation will get spectrum to 5G providers quickly.

Finally, to encourage maximum participation and minimize bidding errors, especially by smaller bidders, the design must be **simple** for all participants. The FUEL combinatorial auction design has been created to offer bidding that is intuitive and tractable. Its two-round bidding process is dramatically simpler, faster, less expensive, and less error-prone than traditional processes, which require at least ten times more bidding entries from each successful bidder. The flexible FUEL *bid groups* allow bidders to easily express many specific package bids for different combinations of PEA-based licenses. In this way, the auction allows bidders seeking only enough spectrum to serve a targeted geographic area can compete on even terms with bidders seeking much more bandwidth or geographic coverage. The

FUEL design can accommodate rural, tribal, and small-business incentives in the usual way, and unlike other combinatorial auctions, which cannot be scaled easily to the U.S. context, the FUEL design makes winner and price determination easily computable.

Below we expand upon each of these points, highlighting how the proposed FUEL auction design – and the FUEL design alone – is *quick*, *efficient* and *simple for all participants*. First, we introduce the band plan, the licenses for sale and the FUEL design itself.

License Definitions

The CBA has proposed to conduct the C-Band spectrum market-based process based on 20 MHz blocks using the Partial Economic Areas (PEA) geographic definition.[1] The CBA plans to make all 180 MHz (9 blocks) of the spectrum available within 36 months of the FCC's final order. In addition, 60 MHz (3 blocks) of those spectrum rights in 46 of the largest 50 PEAs[2] could be available earlier, as soon as 18 months after the FCC's final order. Accordingly, the 60 MHz "early cleared tranche" of spectrum available in those "top 46" urban PEAs is distinguished in the auction process.

Using the PEA geographic definition allows C-Band auction participants to bid for the licenses they need, in *any* geographic combinations. Offering licenses for PEAs permits even a small regional bidder with limited objectives to participate and acquire spectrum – for example, as little as 20 MHz in a single PEA. On the other hand, bidders with appetites for larger Economic Area (EA)-wide or national packages are also accommodated: because the FUEL auction design allows package bidding (explained in detail below), larger bidders can ensure that they will win sufficient coverage and not a just subset of their desired spectrum. Offering both early- and later-cleared spectrum further allows bidders to express customized deployment timing preferences that best suits their needs.

---

[1] See Letter from Bill Tolpegin, CBA Chief Executive Officer, filed May 21, 2019 ("May Tolpegin Letter").

[2]Excluding the Baltimore-Washington, Atlanta, Denver and Honolulu PEAs (numbers 5, 11, 20 and 42). See May Tolpegin Letter.

In a phrase, the license definition is "by PEA in 20MHz blocks, sold at one time but for early and later flexible use."

FUEL Auction Design

To satisfy the objectives and to allow Flexible Use while promoting Efficient Licensing, we offer our customized *FUEL for 5G auction design*.

The FUEL C-Band auction consists of two *stages*: an allocation stage and an assignment stage. The *allocation stage* determines the number of early and later spectrum blocks allocated to each winning bidder. The blocks that the bidders acquire in this stage are "generic blocks," because they do not specify the particular frequencies to which rights are acquired. Once the allocation of generic blocks is fixed, an *assignment stage* determines which particular frequencies are awarded to each winning bidder. The majority of this document describes and discusses the allocation stage.

Two-Round Structure

The allocation stage of the FUEL auction consists of two sealed-bid *rounds*: an initial "Coordination" round and a subsequent "Main Bidding" round.

In the optional **Coordination round**, each bidder may submit two *package bids* at prices that are prescribed in the auction rules based on the prices paid for similar spectrum in auctions around the world. A bidder may submit one package bid entirely for later spectrum (a *later* bid), and another for early spectrum in the 46 PEAs where early spectrum is available and later spectrum in the other PEAs (an *early/mixed* bid). A Coordination round bid that is smaller (in total MHz-Pop) than some pre-defined size limit will be treated as a set of EA-based package bids, each of which could win independently of the other EA-based packages in the same bid, while a bid at or above this size limit may, at the bidder's option, be treated as an all-or-nothing package bid.[3] No bidder is required to submit any bid in the Coordination round.

---

[3] This limit will be defined precisely prior to bidding, but we anticipate that a reasonable approach would be to set it at the MHz-pop equivalent of two national licenses. The FCC used a similar metric (for a different purpose) in the Broadcast Incentive Auction proceeding. See Incentive Auction Bidding Procedure Public Notice, FCC 15-78, released August 11, 2015 at para.12.

The Coordination round bids of each bidder are revealed to all participants, without identifying bidders by name. There are significant reasons for a bidder to voluntarily participate in the Coordination round. Some bidders, especially smaller ones, may wish to use the Coordination round to advertise their preferred packages (but not their final bid prices) to enable and encourage other bidders to bid for packages that fits well with those. Well-fitting sets of packages have a better chance of becoming winning in the auction. The Coordination round serves the same important package discovery role as the much longer and more complicated clock rounds in the widely used Combinatorial Clock Auction design.[4]

In the **Main Bidding round**, bidders may submit two different kinds of *bid groups* using the FUEL bidding language. Each bid group can be used to express many package bids simply and compactly. A bid group identifies a single *base package* and a *base price*, with optional adjustments (*increments* or *decrements*) that, for each PEA, add licenses to or subtract licenses from the base package, with corresponding adjustments to the base price. A "later bid group" includes only later spectrum for both the base package and any increments or decrements while for an "early/mixed bid group," the base package includes early spectrum in each PEA up to the amount of early spectrum available in that PEA and later spectrum for any quantity in excess of that amount, and any increments refer to later spectrum.. These two kinds of bid groups and the flexible FUEL bidding language are explained in greater detail below.

The packages chosen in the Main Bidding round can include the packages submitted in the Coordination round but need not do so. Bids in both the Coordination round and the Main Bidding round are firm commitments as discussed below, *all* submitted bids are used to determine the winners and prices of the allocation stage.

"Bid Groups" and the FUEL Bidding Language

The C-Band auction will contain 406 PEAs[5] with and nine blocks in each, so there are 10^{406} packages that a bidder could possibly bid on, which is vastly more than any bidder can realistically evaluate and consider individually. The FUEL bidding language makes it easy and intuitive for participants to submit large groups of

[4] The clock rounds of the CCA design, however, require repeated real-time decision-making subject to complex constraints several times a day for weeks or months. Their extra data entry requirements create more opportunities for error than the simpler Coordination round of the FUEL design.

[5] See May Tolpegin Letter.

package bids for many different license combinations and has the additional benefit of keeping the computations manageable for the auctioneer. This allows the auction to proceed on an accelerated basis and make mid-band spectrum available for 5G quickly.

As noted above, each bidder in the Main Bidding round submit its bids using "bid groups." For each bid group, the bidder specifies a "base package," which may consist of any number of licenses in each PEA (up to 9) and an associated "base price" for that package. The base package and base price describe a single package bid. The FUEL language also allows a bidder to express additional package bids in the bid group by identifying "increments" (increases in the number of licenses) and "decrements" (reductions in the number of licenses) for its base package in each PEA, and additions to or subtractions from its base price in case those licenses are added to or subtracted from its base package.

There are two kinds of bid groups: ones for later spectrum only ("*later bid groups*") and ones in which some or all of the spectrum bid is early spectrum (called "*early/mixed bid groups*").

For each package bid in an *early/mixed* bid group, any quantity of spectrum up to the quantity in the base package (and within the overall amount of early spectrum available in that PEA) must be supplied with *early* spectrum, but any additional licenses acquired as increments can be satisfied with *later* spectrum.[6] The following table shows an example of an *early/mixed* bid group in the case of a base package with three PEAs. For simplicity of presentation, the example supposes that there are only four licenses available in each PEA. The two PEAs with asterisks (A and C) denote ones in which early spectrum licenses are available.

[6] That is, if early spectrum is offered in a PEA and the base package includes no more than three 20 MHz licenses in that PEA, then those licenses are understood to be all early spectrum licenses. If the base package includes four or more 20 MHz licenses in the PEA, then those are understood to consist of three early licenses with the remainder as later licenses.

	Number of Licenses				
PEA	**0**	**1**	**2**	**3**	**4**
A*			Base	$10	$15
B			Base	$20	
C*	$–15		Base	$5	
Base price:	**$200**	**EARLY/MIXED BID GROUP**			

In this example, the bidder has specified an *early/mixed* bid group. The chosen base package consists of 2 early licenses in PEAs A and C and 2 later licenses in PEA B, and a base price of $200. If this package is winning, then the bidder wins two early licenses in PEAs A and C and two later licenses in PEA B. Looking at the increments and decrements, we see that the table specifies that the bidder would pay an extra $20 for an additional later license in PEA B (an "increment"), an extra $10 or $15 for one or two additional later licenses in PEA A, and an extra $5 for an additional later license in PEA C. In addition, the bidder would reduce its offer by $15 for giving up both early licenses in PEA C (a "decrement"). These increments and decrements can be combined additively – for example, this bid group implies a package bid of $205 = $200+$20–$15 for the package consisting of 2 A licenses, 3 B licenses, and 0 C licenses. In this way, the six numbers in the table specify prices for eighteen ($18 = 3 \times 2 \times 3$) different combinations of licenses.[7]

A similar table can be used to express bids for later licenses only, as shown below.

	Number of Licenses				
PEA	**0**	**1**	**2**	**3**	**4**
A			Base	$10	$15
B			Base	$20	
C	$–15		Base	$5	
Base price:	**$200**	**LATER BID GROUP**			

[7] A hypothetical bidder that bid for a package covering the 406 PEAs with one increment and one decrement in each PEA would be bidding for 3^{406} combinations, vastly more bids than would be possible in any other spectrum auction.

The FUEL language has some built-in redundancy, allowing the any *later* bid group to be expressed in different ways. For example, the bid group described below includes exactly the same package bids as those described by the table above.[8]

	Number of Licenses				
PEA	**0**	**1**	**2**	**3**	**4**
A			–$15	–$5	Base
B			–$20	Base	
C	$–20		–$5	Base	
Base price:	**$240**	**LATER BID GROUP**			

To ensure computational feasibility, while maintaining sufficiently flexible to accommodate bidder preferences, each bid group will be classified as either "small" or "large" depending on the size (in MHz-pop) of its base package.[9] A small bid group will be restricted to include only licenses for PEAs within a single Economic Area (EA), while large bid groups will not be subject to this restriction. Bidders will also be limited in the total numbers of small (EA-based) and large (unconstrained) bid groups that they can submit.[10]

Package bids submitted in the Coordination round will similarly be classified as small or large using the same MHz-pop threshold and will be similarly restricted: small package bids can combine PEAs only within a single EA, while large package bids can include licenses from any number of EAs. For the purposes of winner determination, a bidder may ultimately win *one* large package bid or any number of small package bids but may not win both large and small package bids at once.

[8] This applies only to *later* bid groups. If these same two tables were labelled to apply to *early/mixed* bid groups with early spectrum available in all three areas, then the second group would include bids only packages of early spectrum while the first would include bids for various packages that mix early and later spectrum.

[9] These size categories will be defined precisely prior to bidding, but we anticipate that a reasonable approach would be that bid groups with base packages equaling or exceeding the MHz-pop equivalent of two national licenses would be classified as large. The FCC used a similar metric (for a different purpose) in the Broadcast Incentive Auction proceeding. See Incentive Auction Bidding Procedure Public Notice, FCC 15-78, released August 11, 2015 at para.12.

[10] These limits, to be precisely defined and publicly disclosed before bidding, will be determined in part by simulations to assess computational feasibility.

Furthermore, a bidder cannot win more than one small package bid in any given EA. This last restriction is a defining characteristic of package bidding that enables its great advantages: it frees the bidder from needing to make guesses about which combination of bids might wind up winning in any economic area.

If public policy objectives require it, the FUEL bidding language is also sufficiently flexible to allow further restrictions to be placed upon allowable bids.[11]

Reserve Bids

The FUEL auction will use reserve prices to determine the minimum value at which a bid can be winning. The FUEL auction will use a second-price rule (described below); thus, in certain circumstances, the reserve prices may also affect the price that a winner pays. In a combinatorial auction, where various combinations of bidding packages must be considered, reserve prices are best implemented as bids placed on behalf of the seller. If a seller's reserve bid is winning, then the second-bid price is below the reserve and the corresponding licenses are unsold in the auction.

For the C-Band auction, an "aggregate" reserve bid could be set based on international $/MHz-pop benchmarks (adjusted to the U.S. market). As the FCC has done before, individual PEA reserve prices in this auction would be determined by distributing the aggregate reserve price across PEAs in the same proportion as prices in historical FCC auctions; the full supporting data and distribution methods will be disclosed in advance of the auction. These reserve bids will be low enough to ensure sale in areas where spectrum has valuable near-term uses but high enough to determine fair minimum prices for licenses that might attract little competition.

Winner and Payment Determination

After bids from both the Coordination and Main Bidding rounds are received, the auction system will determine the winners of generic blocks in the allocation stage as well as the amount of spectrum, if any, that goes unsold. The auction system will compute results using the bids made by auction participants and the reserve bids, in the manner described below. The computations will be fully transparent: precise

[11] For example, it is possible to reserve spectrum for smaller participants without losing any of the FUEL auction's desirable properties.

mathematical descriptions will be made available to all bidders as part of the customary pre-auction bidder training and education.

As in many auctions around the world, including the assignment round of the FCC's recent Broadcast Incentive Auction, winner determination and the price that each winner pays (payment determination) are separate calculations. The winning bids are those that maximize the total bid price, subject to several constraints: [1] each bidder can have only one winning package bid covering any EA; [2] the total number of early spectrum licenses allocated in any PEA does not exceed the available number for that PEA; and [3] the total number of licenses, for early and later flexible use, allocated in any PEA does not exceed the available amount. If any reserve bids are winning, then the corresponding generic licenses in the auction will remain unsold. The winner determination will consider the reserve bids as well as all bids submitted in *both* the Coordination and Main Bidding rounds, such that a bidder can win either a large bid from either round or any combination of small EA-based bids from the two rounds, but no more than one small bid per EA.

Once the winners are determined, prices that bidders pay for generic licenses would be set using a "Vickrey-nearest core-selecting" rule, which is also used by the combinatorial clock auction (CCA) format, to promote efficient allocations of licenses. Under this "second-price" rule, the price that a bidder pays is determined primarily by the value that other bidders have offered to pay to acquire that spectrum in addition to what they have already won. In this calculation, in practice, the price that a winning bidder pays for what it has won usually does not depend on the prices that bidder has offered. The "Vickrey-nearest core-selecting" rule is currently the most common pricing rule worldwide for package auctions of radio spectrum. As in the winner determination, the payment determination will equally consider bids submitted in both the Coordination and Main Bidding rounds.[12]

Assignment Stage

The allocation stage, described above, will determine which bidders win how many blocks of early-cleared and/or later-cleared spectrum in each PEA. The subsequent *assignment stage* will give bidders the opportunity to place additional bids to be

---

[12] This is analogous to the rule in the CCA that each bidder's bids from the final sealed-bid round are considered together with its bids from the clock rounds in determining the winners and prices. It encourages bidders to make only serious bids in the Coordination round, because those bids might wind up as winning.

awarded preferred frequencies within the band. Following best practice in spectrum auctions, bidders that win multiple early blocks or multiple later blocks in the allocation stage are guaranteed to have their corresponding frequencies adjacent within a given PEA; there may also be some limited guarantee of adjacency across PEAs.

The FUEL Design Satisfies the Objectives for a C-Band Auction

Quick

The FUEL auction's computational and practical simplicity will permit 180 MHz of C-Band spectrum to be repurposed for 5G mobile use as quickly as possible. The FUEL design is intended to encourage fair, efficient competition among a heterogenous group of likely participants; it is aligned with the interests of all stakeholders, encouraging a fast comment and approval process. The FUEL auction is straightforward for participants, reducing the time needed for bidder training.

The coordination stage and main bidding stage itself would take place over 2–4 weeks, or less. The simplicity, emphasized below, will all bidder software training to be completed within 120 days from the FCC's authorization of the final auction design, and the limited strategic analyses to be completed soon after. The auction itself could start 30 days after. Early spectrum would be available for 5G deployment within 18 months from a final FCC Order.

Efficient and Fair

The FUEL design also encourages an **efficient** and **fair** outcome – a reallocation in which the *right participants* submit the *right values* for the *right combinations*.

As described above, the FUEL auction design allows *effective participation by many categories of spectrum buyers* and provides direct competition among bidders with very different uses, for large or small geographic areas and large of small bandwidth requirements. The use of FUEL bid groups with PEAs creates a flexible, open and efficient process in which users of all kinds of bidders can participate and compete. It is critical for the reallocation process that all interested bidders are afforded a **fair** opportunity equally to compete for C-Band licenses, both to ensure that the bidders with the highest values obtain their desired spectrum and to encourage a smooth and accelerated regulatory process.

In addition to encouraging wide participation, the FUEL auction offers bidders guidance to help them submit the package bids that are most likely to be winning. The simple FUEL bidding language enables bidders to submit a large number of valuable variations of their base package, increasing the chances that competing bidders can find matching combinations that make the bids winning. The two-round allocation stage provides bidders with an opportunity to present their target packages to other bidders, allowing those bidders to bid for combinations that fit well, so that both bidders can be winning.[13]

The FUEL auction's second-price rule encourages bidders to submit their true, highest prices for desired packages. This in turn ensures that the auction selects a winning set of bidders that *values the spectrum the most*.

The FUEL auction design encourages an efficient auction, with wide participation and expansive and competitive bidding. Robust competition and minimization of strategic bidding will help to generate an outcome that ensures that the revenue raised is sufficient to motivate participation by incumbent C-Band users.

To promote efficient outcomes, the auction must provide effective competition between regional bidders seeking to serve smaller geographic areas and national bidders seeking to serve wider areas. The FUEL design encourages competition among such bidders, in particular by allowing small bidders to compete against the increments and decrements of large bidders (rather than against their base packages). To illustrate how the FUEL system promotes competition among such bidders, we offer a simplified numerical example in the appendix to this document.

[13] Information discovery and truthful bidding inducement is particularly useful for smaller or rural bidders, especially when combined with the flexible bidding language. As an example, a bidder who wishes to buy only four licenses in rural Illinois may wish to make this known, so that others can bid to combine with the rural bid or use decrements for those areas. In a sealed-bid auction without information discovery, this rural bidder might fail to win because larger opponents would not know to decrement their national bids in rural Illinois; in a multi-round auction with a less flexible bidding language, a national bidder might be unable or unwilling to express such that decrement, due either to the difficulty of expressing many subset bids or to outright restrictions upon the number of package bids allowed.

Simple for All Participants

Our proposed sealed-bid design has been created with the primary goal of ensuring **simple participation for all bidders**. The FUEL design is simpler, both mechanically and strategically, than either the ascending clock auction or the combinatorial auctions used for spectrum sales around the world.

The FUEL bidding language has been designed to reflect and accommodate the way that spectrum bidders value spectrum licenses. In our experience, major bidders in recent spectrum auctions typically have "base" or "target" packages. They could form their groups of bids around the base package that they value most highly, ensuring that they will only win a combination of licenses that is sufficient for their business needs. Using increments and decrements, bidders can make simple, consistent adjustments to their base packages to accommodate competitive risks and realities.

The FUEL bid groups make it easy and intuitive for bidders to compactly express a *very large* set of distinct package bids. For example, a bidder that wants to incrementally enlarge or reduce its base package by adding or subtracting one license in each of 10 PEAs uses only 21 numbers to express $3^{10} = 59{,}049$ package bids. The FUEL language achieves this efficiency and simplicity of expression by placing realistic restrictions on the kind of package bids that bidders can submit.

Furthermore, the *package* bidding offered in the FUEL auction design avoids the "exposure problem," which can occur if – as in other auction designs – a bidder is at risk of winning a set of licenses that is not consistent with any valuable business plan. Conversations with potential participants suggest that the exposure problem could be significant for the C-Band. For example, some bidders may have a high minimum scale for the amounts of bandwidth in each area. Avoiding the exposure problem assures bidders that they will not wind up with an undesired package of blocks and second-pricing allows those bidders to safely bid their true values for desired packages. In combination, this greatly simplifies the problem of bidding effectively.

Finally, the customized FUEL bidding language tames the combinatorial complexity and allows easy computations of winners and prices, despite the very large numbers of packages that receive bids. General combinatorial auctions with large numbers of unstructured combinations of packages and prices can defeat the optimization capabilities of even the most modern computers and algorithms, but the FUEL design is immune to that problem. Unlike general combinatorial auctions, the FUEL design has the property that, for any given set of winning bidders, the problem of determining the optimal set of winning bids decomposes into 406 small problems (one for each PEA), which makes fast computation an easy task for a computer.

Alternative Auction Designs Are Not Suitable

The FUEL design shares features with auctions that have been used successfully for spectrum sales worldwide, but also possesses substantial advantages over those auction designs. Compared to previous combinatorial designs, the FUEL design is fast, simple to implement, and easy to solve.

In addition to the specific problems described below, multi-round auctions share the common disadvantage that they are extremely time-consuming, and in the case of an auction covering 406 PEAs would require substantial strategic preparation, and multiple weeks – if not months – for the bidding itself, often with close supervision by senior executives of the bidders. The much larger numbers of bids that must be made in such auctions make them correspondingly more susceptible to bidder error, which also makes participation more costly.

Multi-Round Combinatorial Auctions (CCA)

The Combinatorial Clock Auction (CCA) is a combinatorial auction design that has been used for spectrum sales worldwide. It has been regarded by many as the best format efficient sales of high-value radio spectrum. Although the CCA has many desirable properties, including avoiding the exposure risk and promoting efficiency through the use of a second-price rule, the CCA design is also exceedingly complex for bidders, involves challenging and sometimes intractable computations, and often vulnerable to inefficiencies arising from strategic bidding in its clock stage. The FUEL auction design uses the same winner and price determination rule as the CCA and also allows combinatorial bidding but is dramatically simpler for bidders and can be run to completion in much less time.

If C-Band spectrum is best sold in PEA regions and the advantages of package bidding are recognized, then the FUEL language is essential, because a “standard” design would add an unmanageable degree of complexity. Assuming that a bidder can bid for 0-9 blocks in each CONUS PEA, there are 10^{406} distinguishable combinations. With early spectrum available in 46 PEAs to be distinguished as a product from later spectrum, the number of combinations is much larger than that.

In other combinatorial spectrum allocations around the world – even those with far fewer areas, blocks and bidders – auctioneers have restricted the number of package bids that bidders may could submit, in order to reduce the computational complexity of the auction and make it feasible to solve for the winners and prices. Such restrictions come at a cost to simplicity and efficiency, making bidders guess which bids are most likely to be winning and all but ensuring that some relevant bids will be omitted. The FUEL bid groups limit the computational complexity of the auction, allowing the auction to consider vastly more package bids than traditional combinatorial auctions while still ensuring that winners and prices can be feasibly computed. It is even possible, by including prices for all the possible increments and decrements (3654 numbers), to express bids for every one of the 10^{406} possible packages.

Multi-Round Non-Combinatorial Auctions (SMR or Clock)

The Simultaneous Multiple Round (SMR) auction and related clock designs have also been used frequently for spectrum sales, including some FCC auctions. These auctions sell licenses individually, making bidders substantially vulnerable to the exposure risk. The exposure risk can deter bidders from participating and sometimes limits the aggressiveness of those who do participate. Package bidding, as used in the FUEL design, avoids the exposure risk that comes when bids can only be expressed for individual licenses.

Furthermore, in SMR and other clock auctions bidders can affect their *own* prices with their bidding behavior. Bidders find that they can often reduce the prices they pay for the spectrum they win by a strategy called "demand reduction," in which the bidder bids to win an inefficiently small package of spectrum and avoids bidding for more than this limited quantity. In spectrum auctions around the world, demand reduction has been well-documented and associated with market splitting and collusive behavior, depressing competition and promoting inefficient allocations.

Incentive Auctions

The FCC has also used an "incentive auction" to reallocate existing spectrum holdings of TV broadcasters in the 600 MHz band. However, the successful implementation of that design relied on the ability of TV broadcasters to free blocks of spectrum for new, flexible uses through independent, voluntary decisions. Substantial incentives were provided to these broadcasters through payments in the broadcast incentive auction. The C-Band is different, because the same frequencies are used by multiple parties, none of which can unilaterally make any frequencies available for flexible use. All the users need to cease certain operations for any of the spectrum to be cleared. For that reason, the incentive auction framework cannot be applied to the case of the C-Band.

Conclusion

The FUEL auction design satisfies multiple public interest goals in that it: allows fair opportunities for both the largest national bidders and the smallest regional bidders to acquire spectrum; is simple enough to enable and encourage participation by all bidders, large and small; promotes efficient allocations; can ensure that incumbent C-Band users will be suitably accommodated; and can be run quickly and reliably. For these reasons, it is the best auction design to enable the repurposing and efficient licensing of C-Band for terrestrial 5G use.

Appendix

Example: Competition Among Large and Small Packages

This example illustrates how the FUEL design enables and encourages effective competition between small and large bidders. Suppose that there are three areas with licenses for sale, labelled A, B and C, and four 20 MHz licenses available in each area. In this example all available spectrum is later-cleared spectrum. Areas A and B are large top-50 urban areas, with reserve prices of $100 per license, while area C is a small rural area, with a reserve price of $10 per license.

Licenses Offered for Sale			
Area Name	**Type**	**Reserve Price**	**Number of Licenses**
A	Urban	$100	4
B	Urban	$100	4
C	Rural	$10	4

There are just two bidders in this example. **National bidder X** would like to acquire 80 MHz of spectrum in all three areas, but cares most about winning licenses in areas A and B. If bidder X can win 80 MHz in the urban areas, it is willing to pay up to twice the reserve price for every license it acquires. **Regional bidder Y** would like to acquire only one license in area C. Its overall budget is much smaller than that of bidder X, but it is willing to pay five times the reserve ($50) for its desired spectrum. In this situation, it is efficient for bidder Y to acquire one license in area C and bidder X to acquire the remaining licenses.

<u>Efficient Allocation</u>

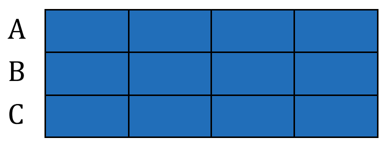
In an auction that limits the number of package bids or makes identifying the correct combinations difficult, bidder X might fail to submit bids that include fewer than 4 blocks in area C, leading to an inefficient allocation, and one that could be expensive for bidder X.

In the same situation but using the FUEL auction design, it is optimal for bidder Y to bid $50 for one license in area C, and for bidder X to specify a bid group that includes a base package for all the available licenses in areas A, B and C at a price of $1680 and a decrement for one C license at a price of $20.[14]

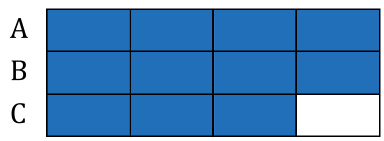
Bidder X: Optimal Bid Group

	Number of Licenses				
PEA	**0**	**1**	**2**	**3**	**4**
A					Base
B					Base
C				$–20	Base
Base price:	**$1680**	**LATER**			

Bidder X: Package Bids expressed by Optimal Bid Group



Price: **$1680**



Price: $1680 – $20 = **$1660**

With the optimal bid groups from each bidder, the allocation of the last C license is determined by comparing bidder Y's bid of $50 with bidder X's decrement of $20. Since bidder Y's bid is higher, it would win that C license and, by the second-pricing rule, it would pay a price of $20. Bidder X would win a package consisting of the remaining 11 licenses (all the A and B licenses and three C licenses). By the second-pricing rule, it would pay a price equal to the reserve for the 11 licenses, which is $830. At this outcome, bidder Y's profit would be $30 (=50–20) and bidder X's profit would be $830 (=1660–830).

In order to have won the last C license, bidder X would have to have bid a decrement higher than $50, or no decrement at all.[15] In that case, bidder X would win all twelve licenses. By the second-pricing rule, it would pay a price equal to $880 for its winning package. Thus, to add the last C license to its package, bidder X must pay an extra $50 (=880–830). In the FUEL design, bidder X's bid for the single license competes directly with bidder Y's decrement for the last C license, as if that were the only license being offered. As in any second-price auction, the (extra) price paid by the winner is set by the loser's bid.

[14] The same bid group can be submitted in another way: bidder X can specify a base package consisting of four A and B licenses and three C licenses, with a base price of $1660 plus an increment of one C license at $20.

[15] Bidding no decrement has the same effect as bidding an extremely high decrement.