CESifo WORKING PAPERS

9014
2021

April 2021

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Impressum:

CESifo Working Papers
ISSN 2364-1428 (electronic version)
Publisher and distributor: Munich Society for the Promotion of Economic Research - CESifo GmbH
The international platform of Ludwigs-Maximilians University's Center for Economic Studies and the ifo Institute
Poschingerstr. 5, 81679 Munich, Germany
Telephone +49 (0)89 2180-2740, Telefax +49 (0)89 2180-17845, email office@cesifo.de
Editor: Clemens Fuest
https://www.cesifo.org/en/wp

CESifo *Working Paper No. 9014*

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Abstract

Millions of citizens and firms lack access to high speed internet, even though governments pledged to spend huge sums of money to subsidize internet networks. In this paper we review some systematic flaws of present subsidy policies and outline a promising alternative. We propose that governments should treat the broadband infrastructure as a public responsibility and set up intelligently designed public-private partnerships that fund and temporarily operate the broadband in exchange for collecting service fees and, if necessary, subsidies. Simple “least-present value of revenue” auctions should be used to award all concessions, not only those that require subsidies, and concessions should flexibly revert to public ownership depending on realized revenues. This procurement method is easy to use, immune to strategic manipulations and renegotiations, and has already proven successful in procuring toll-roads and bridges.

JEL-Codes: D440, D470, D860, H200, H540, L960.

Keywords: public-private partnerships, auctions, universal service auctions, high-speed broadband provision, public finance.

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April 10, 2021

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1 Introduction

A comprehensive network of high-speed broadband internet connections is an essential part of a nation's infrastructure, comparable to the network of roads, railways, and airports, and letting private firms use public space to construct a network of broadband internet cables and operate internet services is similar to letting private firms construct and operate toll-roads and bridges. Inspired by this similarity, we propose a promising alternative approach to fund and operate a universally accessible broadband infrastructure that is closely aligned with innovative methods developed to procure other infrastructure such as toll-roads and bridges.

In this alternative approach the government treats the broadband infrastructure as a public responsibility. It sets up public-private partnerships (PPPs) that fund and temporarily operate the broadband in exchange for being allowed to charge service fees and, if necessary, collect subsidies. The terms of concessions is flexible and auctions are used to allocate the concession. Unlike in the standard universal service auction approach, auctions are employed to allocate *all* projects, not only those in "white areas" that need to be subsidized, the network is flexibly reverted to public ownership, depending upon the realized profile of demand and costs, and the auctions are surprisingly simple and immune to strategic manipulations such as "low-balling" followed by threats of bankruptcy and strategic renegotiations.

Before we outline the proposed alternative approach, we first review the standard universal service auction approach that has been used in the U.S.. Countries like Germany have not made full use of structured auction and the promised high-speed broadband provision has progressed at a slow pace.

2 The standard universal service auction approach

The common approach to procure a broadband infrastructure is to let firms freely install and operate cables in areas where this is likely to be profitable and offer subsidies for provision in “white areas”, where private provision is otherwise not forthcoming.[1] Auctions come into play, if at all, only for projects that need to be subsidized, and their only purpose is to determine the firm that promises to roll out service for the lowest possible subsidy. This approach has a long tradition in universal service auctions that have been used to subsidize the supply of services in remote areas, ranging from access to telephony, postal services, railways, and electricity.[2]

In recent years, the FCC organized several such auctions to procure a broadband infrastructure in areas where no supply was forthcoming without public subsidies. Millions of Americans have no access to modern internet service; the estimates range between 14.5 and 157 million people (Ovide, 2021).

In this section, we briefly review the main features of the most recent such universal-service auction, known as “Rural Digital Opportunity Fund Phase I Auction” (in brief “Auction 904”) that went online on October 29, 2020 (for the complete details see FCC, 2020a).

That auction specifies a large set of biddable areas where no broadband service is available yet, based on census blocks. All biddable areas compete in one auction. Prior to the auction potential bidders are screened and shortlisted; only shortlisted bidders can participate in the auction.

Bidders must choose the quality of their broadband service from a given menu of bandwidth-latency combinations, with four levels of bandwidth and two levels of latency. Latency is a measure of the time it takes to send information from one point to the next and the speed of the internet connection is determined by the combination of latency and bandwidth. Preferably, one wants to have low latency and a high level of bandwidth. Each bandwidth-latency combination is given a tier/latency weight, w, displayed in Table 1 whee a lower weight w indicates higher quality. Shortlisted bidders may be restricted to bid only on particular performance tier-latency levels, depending upon their technical capability.

Performance Tiers – Latencies							
Minimum		Baseline		Above Baseline		Gigabit	
High Latency	Low Latency	High Latency	Low Latency	High Latency	Low Latency	High Latency	Low Latency
$w = 90$	$w = 50$	$w = 75$	$w = 35$	$w = 60$	$w = 20$	$w = 40$	$w = 0$

Table 1: Tier/Latency Weights (w)

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[1] In the EU state aid to companies is forbidden unless it contributes to economic development and passes the so-called “balancing test”. Another exception are small subsidies that qualify as “de minimis” which do not even require approval by the EU competition authority. Both exceptions have been invoked to justify public subsidies for building broadband infrastructure in white areas.

[2] For an analysis of universal service auctions and an assessment of which designs are susceptible to collusion, see Laffont and Tirole (2000, Ch. 6).

The auction is a hybrid between an open descending bid auction and a descending clock auction. There, bids are evaluated by a scoring rule and the subsidies paid to the winners of the auction are set by a rule that resemble a second-price (Vickrey) auction, subject to reserve price requirements that are specific for each area.

A bid for a particular area has two dimensions: a *financial bid*, b, that states the requested annual subsidy as a percentage of the area's reserve price, R, and a promised *tier-latency combination*, w . Bids are evaluated by the scoring rule, S, that maps two-dimensional bids into a one-dimensional score, which is called the bid's "implied support":

$$S(b,w) := \min\left\{R, \frac{b-w}{100}R\right\}. \tag{1}$$

In each round of the auction, the auction "clock" specifies the permitted range of bids, as a percentage of the reserve price R, and that clock ticks down until one reaches the "clearing round", where an estimate of the total subsidies exhausts the available budget. After the clearing round the auction may continue if there is a chance to fund some more projects and come closer to exhaust the budget.

As long as the budget has not cleared, all bids at the clock percentage carry forward to the next round at the same percentage. These carried forward bids may be considered after the clearing round.

Bidders can bid on particular areas or submit package bids, which may be assigned in whole or in part. A package bid specifies a financial bid, b, a tier-latency weight, w, a list of areas, and a "minimum scale condition" that indicates, as a percentage, the bidder's lowest acceptable partial assignment. However, bidders cannot both bid on a particular area and submit a package bid that include that same area. All areas included in a package bid must specify the same financial bid b and the same tier-latency weight, w, and must be located in the same State. Once a bid has been submitted for a particular area with a tier-latency weight, w, that weight cannot be changed during the auction. Bidders are also subject to an "activity rule"[3] and a restriction on switching from one set of areas to another.

If a bid for a particular area is assigned, the bidder is obliged to provide service in the specified location at the specified performance-latency tier in exchange for a subsidy that is equal or greater to the bid's implied support, $S(b,w)$.

The mechanics of the auction and its allocation and transfer rules is best explained with an example that is analyzed in detail in Appendix A. There we also summarize some critical issues of the auction design.

3 Alternative policy approach

We now outline the alternative policy approach that makes use of intelligently designed Public-Private Partnerships (PPPs) to procure universal access to high-speed broadband internet.

PPPs are increasingly used to fund and operate toll-roads, toll-bridges, and airports. Initially these partnerships were motivated by governments' shortage of funds, which is why they were particularly popular in countries with weak tax systems. Another reason is that investments by PPPs are generally not included as part of the public deficit. Therefore, PPPs have allowed governments

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[3] A bidder's "activity" is defined as the sum of his implied supports, $S(b,w)$ for all bids submitted during a given round. The activity rule requires that a bidder's activity cannot be higher than his activity during the preceding round.

to bypass fiscal restrictions like the ones imposed on members of the eurozone by the Maastricht Treaty. Unfortunately, many of the early PPPs were not well designed and plagued by costly renegotiations combined with strategic low-balling and threats of bankruptcy. However, one has learned from this experience. In the meantime PPPs have developed into efficient and relatively easy to implement procurement mechanisms that are successfully applied to various infrastructure projects in various countries (see the detailed surveys by Engel, Fischer, and Galetovic, 1997b; Engel, Fischer, and Galetovic, 2020).

Major lessons from this experience are that PPPs should minimize firms' exposure to income risk, that the infrastructure facility should flexibly revert to public ownership depending upon the profile of realized demand and costs, and that, if the concession terminates and reverts to public ownership, service fees should be maximized in order to reduce welfare distorting taxes. At that point the government should either manage the facility itself or, preferably, auction a new concession.[4]

3.1 Major concerns

At the outset we summarize some major concerns that must be addressed by a successful PPP, regardless of whether one deals with funding highways or a broadband infrastructure:

Income risk and winners' curse problems If one awards the concession to the firm that requests the lowest subsidy or the shortest term or lowest service fee, the PPP is subject to high income risk due to unpredictable demand or cost and may fall prey to the "winner's curse". In return, bids will include a premium as compensation for risk. This makes the procurement unduly expensive. This problem is particularly severe if the contract contains a "claw-back" rule that allows the public authority to siphon off high profits and thus makes firms bear the downside risk while curtailing their benefiting from the upside risk.

The winners' curse problem is particularly severe in the presence of common value components, which are present if demand is uncertain or costs are correlated.[5]

Strategic low-balling, threats, and renegotiations In the face of income uncertainty, firms may engage in renegotiations if demand happens to be low or if cost overruns occur. They then ask for change orders and may threaten bankruptcy if their demands are not met.

In the expectation of renegotiations experienced bidders may submit artificially low bids ("low-balling"), anticipating that they will be able to improve the terms of the contract. Cost overruns or shortages of demand are then notoriously induced almost with certainty. Firms may even choose a financial structure that is lopsided towards debt in order to make the threat of bankruptcy credible (see Menezes and Ryan, 2014).

Distortion free government revenue Taxes have major side-effects that cause considerable welfare distortions. For example, income taxes adversely affect the labor-leisure choice, destroy gains from the division of labor,[6] contribute to black market transactions, and more. Therefore, the government should replace taxes with fees for services or the use of public resources, whenever possible. This principle has guided the leasing of radio spectrum to telecom operators through spec-

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[4] Under public provision, governments tend to be subject to political pressure that makes them set notoriously low service fees.

[5] Moreover, standard auctions do not perform well for common value problems (see Bulow and Klemperer, 2002; Bergemann, Brooks, and Morris, 2020).

[6] In Germany, the proliferation of do-it-yourself stores is a visible sign of how income taxes distort the division of labor.

trum auctions, and it should equally guide the allocation of public space for deploying broadband internet cables.

Therefore, auctions should not only be used to minimize subsidies for procuring broadband internet services in “white areas”. Auctions should also be used to efficiently procure these services in profitable, high population density areas to generate distortion free government revenue after the facility is reverted to public ownership.

Obstruction of future technical change Granting firms the permanent right to operate the deployed broadband cables may obstruct the introduction of future technical change. A case in point is the German Telecom that is on record for having aggressively defended the use of its old copper cables against the full scale roll-out of optical fiber-based cables. This indicates that a good PPP mechanism should also determine how much compensation a provider can rightfully claim, if any, whenever the public authority wants to introduce new technology.

Quality issues PPPs may give rise to a moral hazard problem if the concessionary can adjust quality after winning the concession.[7] However, in the case of broadband provision quality is easily monitored simply by checking bandwidth and latency. Therefore, it should be easy to enforce the promised quality.

3.2 Welfare optimal public-private partnerships

We now review the main properties of welfare optimal PPPs and the auction designs that implement them. The exposition follows closely the seminal work of Engel, Fischer, and Galetovic (1997a), Engel, Fischer, and Galetovic (2001), and Engel, Fischer, and Galetovic (2013) who pioneered the analysis of welfare optimal PPP’s and propagated their use for funding and operating toll-roads.

The analysis requires that one first characterizes the ideal, welfare maximizing contract and then show how it can be implemented with minimal information requirements by a strategically simple auction. Of course, procuring toll roads and broadband internet provision raises some particular issues which are addressed in Subsection 4.

Assumptions

As a starting point suppose a public authority plans to employ a PPP to build an operate a well specified high speed broadband internet project, with a given tier-latency combination, in a particular location. That project requires an upfront investment, $I > 0$, and delivers a long-term flow of service. The demand for the network service is subject to demand uncertainty, characterized by a commonly known probability distribution, F, of the potential present value of service fees, V, that the network can deliver over its lifetime. V can be interpreted as the customers’ discounted willingness to pay for using the network which sets an upper limit for the present value of service fees.[8] F is differentiable and has a finite support, $[\underline{v}, \bar{v}]$, $\bar{v} > \underline{v} \geq 0$.

For simplicity, maintenance cost and depreciation are ignored. Alternatively, one may interpret v as the present value of maximum service fees, net after deducting the present value of maintenance costs.[9]

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[7] These issues are the focus of Hoppe and Schmitz (2021) and Iossa and Martimort (2008).

[8] As a rule, we denote a random variable by a capital letter and its realization by a lower-case letter, such as V and v.

[9] This should take care of an issue raised by Nombela and De Rus (2004).

The authority can award the project to one among several firms. All firms are identical and have the same strictly concave v. Neumann-Morgenstern utility function, U, defined on firms' profit, and require the same investment, I. The government is less risk averse than firms, and for simplicity it is assumed to be risk neutral.

Later we take into account that firms may differ and their necessary investments, I, are their private information. Later, in Section 3.6 we also take into account that firms may offer different tier-latency combinations from a given menu (as in the "Auction 904" reviewed in the previous section).

The contract awarded to a PPP (referred to as "concessionary") specifies the state-dependent present value of service fees, $R(v)$, the present value of subsidies, $S(v)$, and the termination rule that specifies when the facility shall be reverted to public ownership.

Assessing the welfare properties of a contract, one must take into account that taxes are subject to a dead-weight loss of taxation, reflected in the mark-up factor $\delta := 1+\lambda > 1$, and the handling of subsidies by the government is subject to an additional dead-weight loss, reflected in the mark-up factor $1+\xi > 1$, leading to the compounded mark-up factor $\delta_d := \delta(1+\xi)$. The latter is relevant because collecting service fees is less expensive than transferring funds through a government bureaucracy that tends to be overstaffed and subject to the risk corruption.

An immediate implication is that subsidies should only be prescribed after one has exhausted potential service fees. In other words, service fees dominate subsidies. By the same token, the government should charge maximal service fees, $v - R(v)$, either directly or indirectly by auctioning a new concession, and let service fees (or the auction revenue) replace welfare distorting taxes, in the event if the concession is terminated and the facility is reverted to public ownership. Of course, $R(v) \in [0, v]$ as the present value of service fees cannot exceed consumers' maximum willingness to pay, v.

Suppose the public authority has selected one firm as concessionary.

Denote consumer and producer surplus by $C(v), \Pi(v)$. The welfare optimal contract, $(R(v), S(v))$ between that firm and the public authority is defined as the maximizer of the expected social surplus subject to the firm's participation and feasibility constraints:

$$\max_{\{R(v),S(v)\}} E\left[C(V) + \alpha\Pi(V)\right], \quad \text{s.t.} \quad E\left[U(\Pi(V))\right] \geq U(0), \quad R(v) \in [0,v], \quad S(v) \geq 0. \tag{2}$$

There, $\alpha \in [0,1]$, represents the weight assigned to producer surplus and $U(0)$ the firm's outside option value.

Consumer surplus takes into account that subsidies may be subject to a double dead-weight loss, represented by the compounded social cost markup $\delta_d = \delta(1+\xi)$, and that the government should charge maximum service fees (or allow the new concessionary to charge maximum fees), $v - R(v)$, in the event when the contract is terminated, which replaces taxes and thus reduces the dead-weight loss of taxation by $\lambda(v - R(v))$. Therefore,

$$C(v) := v - R(v) - \delta_d S(v) + \lambda(v - R(v)) \tag{3}$$

$$\Pi(v) := R(v) + S(v) - I. \tag{4}$$

Substituting (3) and (4) problem (2) is equivalent to the following variational problem:

$$\min_{\{R(v),S(v)\}} (\delta - \alpha) E\left[R(V)\right] + (\delta_d - \alpha) E\left[S(V)\right] \tag{5}$$

$$\text{s.t.} \quad E\left[U(R(V) + S(V) - I)\right] \geq U(0), \quad R(v) \in [0,v], \quad S(v) \geq 0, \tag{6}$$

where the constants αI and $(1+\lambda)E[V]$ have been omitted from the objective function because they do not affect the solution.

3.3 Implementation with a "least-present-value-of revenue" (LPVR) auction

In several cases one can employ a simple "least-present-value-of revenue" (LPVR) auction and yet implement the welfare optimal contract.

That auction proceeds as follows: 1) Potential firms submit a bid, b, that states their requested present value of revenue; 2) the concession is awarded to the lowest bidder; 3) the winner receives a present value of revenue equal to b through collection of service fees or subsidies (or, alternatively, in a Vickrey specification, equal to the second lowest bid); 4) if $b < v$, the concession will terminate and the facility is reverted to public ownership as soon as the present value of service fees has accumulated to b; otherwise, the concession never terminates.

Prior to the auction the public authority has to mandate the interest rate used in computing present values, after consulting with firms.

3.4 Three special cases

There are three special cases in which the welfare optimal contract and its implementation are particularly simple.

Case 1: No double dead-weight loss ($\delta_d = \delta > 1$). In that case the welfare optimization problem is greatly simplified, because both the objective function (5) and the participation constraint (6) depend only on total transfers, $T(v) := R(v) + S(v)$. Therefore, the welfare optimal contract minimizes $E[T(V)]$ subject to $E[T(V) - I] \geq U(0)$.

Because the firm is risk averse and the government risk neutral, the optimal transfer is state independent: $T(v) = T$, and the firm's participation constraint reduces to $T \geq I$. It cannot be optimal to satisfy that constraint with inequality, because then one could reduce T and use the freed up funds to reduce welfare distorting taxes.[10] It follows that $T = I$ and, because only total transfers matter for welfare, any combination of $R(v) \in [0, v]$ and $S(v) \geq 0$ that adds up to I is optimal. In particular, it is optimal to fund the project exclusively with subsidies or with a combination of service fees and subsidies or, if $v \geq I$, with service fees only.

Case 2: Demand is high with probability one ($\underline{v} \geq I$). In that case the project can be self-financed from service fees and because service fees dominate subsidies, it is optimal to set $S(v) = 0$ for all v. Because the firm is risk averse and the government is risk neutral, it is optimal to make $R(v)$ state independent: $R(v) = R$. Firms' participation constraint requires $R \geq I$. Again, it cannot be optimal to satisfy that constraint with inequality. Therefore, the optimal contract prescribes $R = I$, and the contract terminates as soon as the present value of service fees has accumulated to I. After termination, the government collects service fees equal to $v - I$ that can be used to reduce welfare distorting taxes. The termination date is endogenous and is inversely related to v.

Case 3: Demand is low with probability one ($\bar{v} > I$). In that case the project cannot be self-financed from service fees and subsidies need to be paid. Again, it is optimal to make the firm's present value of income state independent and satisfy the participation constraint with

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[10] Every dollar paid to the firm increases welfare by $\alpha \in [0,1)]$ dollars, yet increases the social cost by $1+\delta$ dollars. Because $1+\delta \geq 1 > \alpha$, it cannot be optimal to pay the firm more than strictly necessary.

equality, which is achieved by prescribing $R(v)+S(v)=I$. Because subsidies are subject to a double dead-weight loss, subsidies must be minimized by setting $R(v)=v$; therefore $S(v)=I-v$. The contract never terminates (the government could not earn income after terminating the contract).

IMPLEMENTATION In all three cases the welfare optimal contract can be implemented by a LPVR auction. If firms are identical and have the same I, in equilibrium at least two firms must bid $b=I$ (while others bid I or more). If firms have different I's which is their private information, each firm makes a bid equal to its I, provided one uses the Vickrey specification of the LPVR. In that case, the winning bidder will earn a positive rent with probability one, provided the I's are independently drawn from a continuous probability distribution.

Of course, the auction rules must also specify how the transfer is broken down into service fees or subsidies. However, this detail does not affect bidding.

It is noteworthy that the designer of the LPVR auction needs to know neither I nor F nor U (except that U exhibits risk aversion). The public authority can be quite ignorant and yet implement the welfare optimal contract.

Altogether, the concessionary does not request a risk premium because he faces no income risk and there is no winner's curse issue.

3.5 Generalization

Now assume that it is not known with certainty whether demand is either high or low, i.e., $\underline{v}<I<\bar{v}$. Then, one cannot predict whether the project is either self-financing or needs subsidies.

In that case full insurance is no longer welfare optimal. Instead, the optimal contract is a two-thresholds contract that guarantees a minimum revenue equal to $m<I$, prescribes a cap on revenue equal to $M>I$, and, in intermediate states, $v\in(m,M)$, prescribes $S(v)=0$ and $R(v)=v$. The proof of these properties is summarized in Appendix B.

Using this two-thresholds property of the welfare optimal contract, and setting $\Delta := {}^{\delta_d-\alpha}/_{\delta-\alpha}$, the welfare optimization problem (5)-(6) simplifies drastically to:[11]

$$\min_{\{m,M\}} W(m,M), \quad W(m,M) := \left(M(1-F(M)) + \int_{\underline{v}}^{M} v dF(v) \right) + \Delta \int_{\underline{v}}^{m} (m-v) dF(v) \tag{7}$$

$$\text{s.t.} \quad F(m)U(m-I) + \int_{m}^{M} U(v-I)dF(v) + (1-F(M))U(M-I) = U(0). \tag{8}$$

There the participation constraint is written as an equality because it must be binding.

Equating the first-order conditions for m and M, one finds:[12]

$$U'(m-I) = \frac{\delta_d-\alpha}{\delta-\alpha} U'(M-I). \tag{9}$$

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[11] Unlike in (5)-(6), here one chooses *variables*, m and M, rather than *functions*, $R(v)$ and $S(v)$.

[12] Incidentally, this condition is already obtained from the proof of the two-threshold property in the Appendix.

It follows immediately, that the optimal threshold levels solve the participation constraint (8) together with condition (9), and the welfare optimal contract prescribes:[13]

$$(R(v),S(v)) = \begin{cases} (v, m-v) & \text{if } v < m \\ (v,0) & \text{if } v \in [m,M) \\ (M,0) & \text{if } v \geq M. \end{cases} \tag{10}$$

Therefore, the concessionary is exposed to income risk and suffers a loss (in present value) equal to $\min\{I-v, I-m\}$ if $v < I$ and earns a positive profit (in present value) equal to $\min\{v-I, M-I\}$ if $v > I$.

IMPLEMENTATION The welfare optimal contract can again be implemented by an auction that is however a bit more complicated than the simple LPVR auction.

In that auction, firms are asked to make a two-dimensional bid, (m,M), that states their requested minimum income guarantee, m, and their offered cap on service fees, M. Bids are evaluated by the scoring rule $W(m,M)$ that coincides with the welfare maximizer's objective function stated in (7). The concession is awarded to the lowest scoring bidder, and the winner is subjected to the minimum income and service fee cap of his bid (or, alternatively, in a Vickrey specification, to the second-lowest scoring bid).

If all firms have the same I, in equilibrium at least two bidders bid the same (m,M) as in the optimal contract, while others may submit the same or a higher scoring bid.

The equilibrium implements the welfare optimal contract simply because the scoring rule induces bidders to maximize welfare, and therefore perfectly aligns incentives, while competition eliminates expected profits and restrains bids in the same way as the participation constraint (8) restraints the welfare optimal contract.

If firms have different I's which is their private information, one should use a Vickrey specification and subject the winner of the auction to the second lowest scoring bid. In that case, in equilibrium all firms submit bids that coincide with the optimal contract for their respective I and the winner earns a surplus with probability one.

Again, it is noteworthy that the designer of the auction neither needs to know I nor U. However, knowledge of F, δ, and δ_d is crucial. Therefore, the information requirements are stronger than in a LPVR auction.

We mention that knowing whether the project is either high of low demand with probability one is advantageous because the two-threshold contract is more "expensive" as the winner needs to be paid a risk premium as compensation for risk and a winner's curse may occur.

Of course, one could also apply a simple LPVR auction even if one does not know for sure that demand is either high or low, at some loss in welfare. In Section 3.1 we emphasized that subjecting the concessionaire to income risk may give rise to costly renegotiations and the potential to renegotiate may adversely affect bidding. Moreover, the auction design of the two-threshold scoring auction has stronger information requirements. Therefore, it may be altogether preferable to stick to the LPVR auction even though, under ideal conditions, it could be improved.

Finally we mention that a LPVR auction also determines how much compensation a provider can rightfully claim if the public authority wants to terminate the concession prematurely in order

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[13] Of course, all of this applies only if the optimal threshold levels are "within range", i.e., if $m > \underline{v}$ and $M < \bar{v}$, so that $F(m) > 0$ and $1 - F(M) > 0$. This is assured if $U'(\underline{v} - I) > \Delta U'(\bar{v} - I)$.

to introduce new technology. One only needs to compute the difference between the promised present value of revenue and the present value of already collected user fees and subsidies. This difference, no more and no less, is the compensation that the provider is entitled to receive if the public authority wants to terminate the concession before it was originally scheduled to terminate.

3.6 Flexible choice of quality (tier-latency levels)

Broadband connections can be provided at different quality levels, measured by their performance tier/latency levels (TL). The choice of quality should depend on demand relative to cost. In high population density areas it is efficient to choose a higher quality level than in "white areas" where population density is low. The PPP should flexibly choose the optimal quality level for each location.

This can be achieved by amending the LPVR auction as follows: 1) The public agency states a *menu of quality levels*: $\{TL_1, \dots, TL_r\}$, like the one stated in Table 1, and a *scoring rule*, S, that maps bids, b, and an estimate of consumers' willingness to pay as a function of quality, $\tilde{v}_{TL}$, into a score: $S(b, \tilde{v}_{TL})$;[14] 2) The agency asks firms to submit a collection of bids, one for each performance tier/latency combination. 3) Finally, the agency assesses the lowest bids for each quality level, denoted by $\{b_{TL_1}, \dots, b_{TL_r}\}$, with the scoring rule and awards the concession to the bidder that achieves the highest score.

For example, the scoring rule that scores the lowest bid for quality TL_k, could be as follows:

$$S(b_{TL_k}, \tilde{v}_{TL_k}) = \tilde{v}_{TL_k} - b_{TL_k}, \quad \text{with } \tilde{v}_{TL_k} := E[V_{TL}]. \tag{11}$$

Because equilibrium bids are equal to the required investments, the lowest bid for quality level TL_k is equal to the lowest investment, denoted by I_{TL_k}. Therefore, if the scoring rule (11) is applied, the amended LPVR auction implements the efficient quality level that maximizes $\tilde{v}_{TL_k} - I_{TL_k}$.

4 Discussion

Providing universal access to broadband internet services requires a multitude of PPPs in locations across the country. This is unlike setting up a single PPP for the construction and operation of a particular toll-bridge or highway and thus raises some particular design issues.

One major issue is to assure sufficient competition among potential concessionaires. Auctions can only perform well if they attract sufficient bidder participation. Obviously, two bidders is the absolute minimum number for running an auction, but small numbers greater than two may not be enough to prevent collusion. In rural areas where elaborate underground cables have to be installed that reach only a small number of customers, it may be difficult to attract bidders.

Another major issue is that the push for a speedy roll-out may easily become self-defeating. The installation of broadband cables requires the construction of underground trenches, which utilizes specialized equipment and staff that are in limited supply. If one tries to procure more jobs than can be done with the capacity available during a given time window, all that happens is that prices of the specialized inputs skyrocket. In that case, the auction may select the least cost provider and minimize subsidies at given investment costs, I, but the overall outcome may be grossly inefficient because it unnecessarily drives up that very cost.

With these two issues in mind it is advisable to proceed as follows.

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[14] Of course, S must be decreasing in b, and increasing in $\tilde{v}_{TL}$.

Draw a representative sample of areas where broadband cable shall be constructed within a given time window. That sample should include both urban and rural areas. The construction should be feasible with the given capacity of specialized equipment and staff. Reduce the number of projects in that sample a bit to assure competition and put it up for a simultaneous auction.

In that auction a collection of PPPs is auctioned. If one uses a sealed-bid format, each bidder should be allowed to make multiple mutually exclusive bids. After sealed bids have been submitted, the public authority selects the collection of winners that minimizes the sum total of guaranteed present values of revenue, if an LPVR auction is employed. If a two-threshold sealed-bid auction is employed one should, ideally, select winners in such a way that the sum total of the expected values of present values of present values of revenue is minimized although that is considerably more complicated and exhibits sensitivity to the assumed probability distribution. In either case, the auction is similar to package auctions (which have been increasingly used in recent spectrum auctions), where bidders are allowed to make a collection of mutually exclusive bids and the public authority optimizes the selection of winners. That format serves the purpose to prevent coordination failures which would occur if bidders happen to concentrate bidding for particular PPPs while ignoring others.

Alternatively, one can use an open, descending bid format where bidders are restricted to bid on a limited number of projects and let bidders coordinate during the course of the auction. Such an open format is more user friendly and takes care of the coordination problem just as well.

An open format is also advised on the ground that bidders can acquire information about other bidders values by observing at which prices other bidders quit the auction, which is valuable because uncertainty about the demand in a given area introduce a common value component and costs may be correlated (see Milgrom and Weber, 1982). However, this learning effect can already be achieved by a sequence of two sealed-bid auctions, where only the two bidders who submitted the lowest bids for a given area during the first round are allowed to bid (not less than their first-round bid) in the second round, after all other first-round bids are revealed to them (see Perry, Wolfstetter, and Zamir, 2000). The latter format has the advantage that it leaves no room for potentially harmful gaming such jump bidding.

Altogether this suggests to use a hybrid open-sealed bid format where bidders are allowed to coordinate during a number of rounds of open descending-bidding, followed by a final sealed-bid auction among those bidders who have not already quit bidding.

Of course, one could also use a sequential in lieu of a simultaneous auction format and auction PPP's one after another. However, simultaneous auctions have the benefit that all projects compete with each other and leaves less room for gaming.

This is just a first sketch of how one should proceed. More thought and fine tuning is required, accounting for specific details of the allocation problem. It is also advisable to conduct experimental tests of alternative design specifications in the lab, as it is done customarily before one finalizes the design of spectrum auctions.

Finally, we stress again that all projects, strong and weak, in urban and rural areas, should be auctioned. High demand projects promise to generate government revenue that can be used to reduce welfare distorting taxes, while low demand projects must be subsidized to assure universal service.

A Appendix: More on the standard universal service auction approach

Here we explain the mechanics of the most recent standard universal service auction, called "auction 904", using an example from FCC (2020b, p. 18 ff.). We also discuss some critical issues of that auction design.

A.1 Mechanics of "auction 904"

The following example assumes five areas, $\{1,2,3,4,5\}$, with reserve prices $(R_1,R_2,R_3,R_4,R_5) = (2000,2000,1000,2000,1000)$, three bidders, $\{A,B,C\}$, whose bids are summarized in Table 2, and a budget of 6,800. There, a set such as $\{2,3,4\}$ indicates a package bid for areas 2, 3, and 4, and a singleton, such as $\{4\}$, indicates a bid for area 4, each at the indicated clock percentage and tier-latency weight w. All bidders have set a 50% minimal scale requirement, i.e., the smallest acceptable partial assignment of a package bid is 50%.

Round (Clock %)	Bids of A (with w=0)	Bids of B (with w=0)	Bids of C (with w=20)
1 (110%)	{1,2,3,4} at 110%	{3} at 110%	{1} and {2,3,4} at 110%
2 (100%)	{1,2,3,4} at 100%	{3} at 100%	{2,3,4,5} at 100%
3 (90%)	{1,2,3} at 90%, {4} at 98%	{3} at 90%	{2,3,4,5} at 90%

Table 2: Bids of bidders $\{A,B,C\}$ in rounds 1-3

The *opening clock percentage* is set at 100% plus the highest w of any submitted bid, say equal to 120%, assuming that the highest w for which bidders have been qualified to bid on is equal to 20. The clock ticks down in each round by 10%, from 120% to 110%, to 100%, to 90%, etc..

Bidding starts in *Round 1*. There the clock is set a 110% and bidders can submit financial bids $b \in [110\%, 120\%]$. Bids are processed by computing their implied supports, $S(b,w)$. These are equal to R for example if $b = 110\%$ and $w = 0$ but lower than R if $b = 110\%$ and $w = 20\%$.

Bids for each area are processed by computing the "aggregate cost", which is defined as follows: consider the bids *at the round's clock percentage* (ignoring bids at higher percentages) and compute the corresponding implied supports, applying the formula $S(110\%, w)$, as it is done in Table 3(a). Then compute the maximum implied supports for each area, displayed in the last column of the table, and add up these maximum supports over all areas. This sum is the "aggregate cost" in round 1 at clock percentage 110%.

Note: only the bids *at the round's clock percentage* count for the aggregate cost.

If the aggregate cost exceeds the available budget, the auction goes into a next round; otherwise, the current round is the *clearing round*.[15] In the example, the aggregate cost is equal to \$7.000 which is greater than the available budget of \$6.800. Therefore, the auction proceeds to round 2.

In *Round 2* the clock is set at 100%. Again, bids are processed and one can easily confirm that the aggregate cost is equal to \$7.800, and thus again higher than the budget (even higher than in round 1!). Therefore, the auction proceeds to round 3.

In *Round 3* the clock is set at 90%. Again, the bids are processed by computing the aggregate cost, which is summarized in Table 3(b). Note, the bid of A for area 4 does not count because

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[15] Therefore, if all bids exceed the round's clock percentage, the current round is trivially the clearing round.

	Implied Supports at 110%			
Area	for A	for B	for C	Max
1	R_1	-	$0.9R_1$	2000
2	R_2	-	$0.9R_2$	2000
3	R_3	R_3	$0.9R_3$	1000
4	R_4	-	$0.9R_4$	2000
5	-	-	-	0
Aggregate cost in round 1				7000

(a) Round 1: Clock percentage 110%

	Implied Supports at 90%			
Area	for A	for B	for C	Max
1	$0.9R_1$	-	-	1800
2	$0.9R_2$	-	$0.7R_2$	1800
3	$0.9R_3$	$0.9R_3$	$0.7R_3$	900
4	-	-	$0.7R_4$	1400
5	-	-	$0.7R_5$	700
Aggregate cost in round 3				6600

(b) Round 3: Clock percentage 90%

Table 3: Computing the aggregate cost in rounds 1 and 3

the *b* exceeds the clock percentage. The aggregate cost is \$6.600, which is less than the budget. Therefore, round 3 is the clearing round.

From there on, winners are assigned and subsidies are determined.

Assignment of bids submitted in the clearing round In a first step, one determines which of the bids submitted in the clearing round will be assigned. For this purpose bids are processed in ascending order of the financial bids, *b*, and bids with the same *b* are processed in ascending order of their tier-latency weights, *w*. Ties are broken at random. If two or more financial bids for a particular area *at the clock percentage* and exhibit the same *w*, that area will not yet be assigned. In that case, the bids have indicated that the bidders involved may compete more for that area; hence, the assignment awaits a further round of bidding.

Given the prescribed order of bid processing, one first considers the bids *at the clock percentage* and $w = 0$. The bids of *A* and *B* for area 3 tie. Therefore, area 3 is not yet made available for assignment. Areas 1 and 2 are assigned to bidder *A* (note, the package bid of *A* without area 3 meets his 50% minimal scale requirement).

Next in order, consider the bids at the clock percentage with the higher weight, $w = 20$. This leads us to the bids of bidder *C*. Because areas 1 and 2 are already assigned and area 3 is not yet available for assignment, bidder *C* is assigned the areas 4 and 5 (which also meets *C*'s 50% minimal scale requirement).

Finally, one considers bids above the clock percentage, i.e., at $b > 90\%$. There is one such bid by bidder *A* for area 4 at $b = 98\%$. However, that area has already been assigned to bidder *C*. Therefore, all areas are assigned, except the area 3 that has been set aside for further competition.

Clearing price point and subsidy determination In a second step one determines the "clearing price point" which, together with the second-price rule, is used to determine the subsidies to be paid. That price point is defined as the highest price point $p \in [90\%, 100\%]$ (i.e., in between the clock percentage in the clearing round and the preceding round) at which the aggregate cost is smaller or equal to the budget.

The *aggregate cost at p* is computed in Table 4 by taking the sum over the subsidies determined in its third column. In this computation of subsidies one applies the "second-price rule" to all areas for which a competing offer below *p* was submitted, which is the case for areas 2 and 3, and, if $p \geq 98\%$, also for area 4. In turn, the clearing price point is applied to areas for which either no

Area	Status	Subsidy	Comments: Implied supports
1	assigned to A	$\frac{p}{100}R_1$	at p (no competing bid)
2	assigned to A	$0.9R_2$	at competing bid
3	not assigned	$0.9R_3$	at competing bid
4	assigned to C	$\frac{Min\{p,98\}-20}{100}R_4$	at $\min\{p, \text{competing bid}\}$
5	assigned to C	$\frac{p-20}{100}R_5$	at p (no competing bid)

Table 4: Subsidies and aggregate cost at p

competing offer was submitted, as in the case of area 5, of if a competing offer was submitted that however exceeds the clearing price point p (which may apply to area 4).

Adding up the stated implied supports at p, one can easily confirm that the clearing price point is $p = 94\%$, and the assigned areas are subsidized by the implied supports listed in the third column of Table 4, after substituting $p = 94\%$.[16]

Assignment of area 3 Because the assignment of area 3 was set aside for further competition, the auction proceeds with another round of bidding for area 3.

In that *Round 4* the clock percentage is 80%. All bids for area 3 are carried forward to that round, yet can be lowered to $b \in [80\%, 90\%)$ (while maintaining the previous weight w). Bids are now processed in ascending order of their tier-latency weight, and then in ascending order of their price point, and the subsidy is determined by the second-price rule (note, this order differs from that in the clearing round). Specifically, if bidders A and B submit no new bids, area 3 is assigned to either A or B, determined by the flip of a fair coin, and the winner gets a subsidy equal to $0.9R_3 = \$1.800$,[17] whereas, if bidder B submits a new financial bid, $b_B \in [80\%, 90\%)$, that is lower than that of A, area 3 is assigned to B with a subsidy equal to $b_A R_3$.

Extensions In the above example, all areas could be assigned. If this is not the case, in the round after the clearing round one also takes into account all carried forward bids for non-assigned areas from the previous round as well as package bids from the clearing round that could not be assigned without violating the minimal scale requirement (if they exist). This way one may assign additional areas without violating the budget constraint. This can make a difference if many bidders have quit bidding in the clearing round and the auction would end up with a large budget surplus if one did not recycle the carried forward bids.

A.2 Some critical issues of this auction design

The auction rules are carefully designed, albeit a bit cumbersome.[18] We close with a discussion of some potentially critical issues.

Carried forward bids: A bidder who bids the clock percentage is almost certainly willing to bid lower. The carried forward bids are all at the clock percentage of the round preceding the clearing round. Therefore, those who did not bid lower during the clearing round were most likely speculating on being reconsidered after the clearing round, which they would not have done, if one

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[16] Suppose $p < 98\%$ and use this hypothesis to compute p, and the hypothesis confirms.

[17] Bidder C cannot change the outcome, because he is bound to set $w = 20$, while A and B have $w = 0$ which gives them priority.

[18] In private communication I was told that the auction was designed “in house” at the FCC.

did not recycle those carried forward bids. This suggests that the carrying forward of bids may induce strategic gaming.

Strategic demand reduction and tacit collusion: Bidders may engage in strategic demand reduction and sustain tacit collusion. Specifically, if bidders can predict the equilibrium outcome of the allocation of funds to regions, they may engage in strategic demand reduction and bid only on those regions that are part of the equilibrium allocation already early on and bid at the clock percentage. If everyone plays in this fashion, the auction reaches the clearing round and ends already at high subsidy levels. This is part of an equilibrium because if some bidder deviates, and the auction does not end, bidders can simply continue to bid and achieve what they would achieve without strategic demand reduction.[19] While this is likely to work if there are only few bidders who know each other's characteristics, it may not happen if there are many bidders and many areas.

Open vs. sealed-bid auction Due to demand uncertainty, the auction has a strong common value component which makes bidders susceptible to the winners' curse. This is why the auction is set up as an open (hybrid) clock auction, where bidders can acquire information about other bidder's assessment of demand during the auction. The flip side is the increased risk of tacit collusion. However, the desired learning effect can be achieved equally well by a two-round auction where only the two lowest bidders bid in the second round, after the auctioneer has revealed all losing bids to them (see Perry, Wolfstetter, and Zamir, 2000). This way one has the full benefit of learning without the increased risk of tacit collusion.

Capacity restrictions: The FCC auctions all so called white areas in the country in one simultaneous auction. However, the deployment of broadband cables in underground trenches utilizes highly specialized equipment and staff that are in limited supply. In a given time window one can only deploy cables in a limited number of areas. The attempt to serve a large number of areas may thus become self-defeating, because it only raises the price of specialized inputs. In that case, the auction may minimize subsidies, but the overall outcome may be grossly inefficient because it unduly drives up the cost of deployment and thus subsidies.

Market structure: The auction allocates areas to at most one bidder. This rules out competition within the market. It may thus not achieve an efficient market structure.[20] This is, however, not a problem if the areas are unambiguously too small to justify multiple suppliers.

Are all areas equally valuable? The auction assumes that all areas are equally worthy to be served so that only the amount of the required subsidy matters. Given the commitment to universal service, this may be reasonable if all areas can be served within a given time framework. However, the auction will lead to rationing and the social benefits of serving different areas are likely to be very different. This suggests that the auction does not implement a fully efficient allocation of subsidies. Taking into account different social benefits gives rise to a more complex *knapsack problem*.[21]

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[19] Grimm, Riedel, and Wolfstetter (2003b) and Riedel and Wolfstetter (2006) showed that dynamic multi-unit clock auctions with complete information have a unique sequential equilibrium where bidders engage in strategic demand reduction. They illustrate this result with the GSM spectrum auction in Germany.

[20] The literature on universal service auctions had targeted both competition *for* the market and competition *in* the market, and one has designed auctions that achieve also an efficient market structure. See Milgrom (1996) and Laffont and Tirole (2000, Ch. 6) and, using different assumptions, the optimal mechanism design to implement an efficient market structure by Dana and Spier (1994) and Grimm, Riedel, and Wolfstetter (2003a).

[21] Giebe, Grebe, and Wolfstetter (2006) analyze the use of auctions for allocating R&D subsidies, taking into account preferences over projects that bid for public support.

B Appendix: Proof of the “two-threshold property”

Here we prove the “two-threshold property” of the welfare optimal contract stated in Section 3.5.

Consider the Euler-Lagrange conditions of (5)-(6) for states v in which the project will be terminated and for states in which subsidies are paid, one finds (in this order):

$$U'(R(v)-I)=\frac{\delta-\alpha}{\mu}, \qquad U'(v+S(v)-I)=\frac{\delta_d-\alpha}{\mu}, \tag{B.1}$$

where $\mu > 0$ is the Lagrange multiplier of the participation constraint (6), which must again be binding. Hence, in each of these two cases the firm’s revenue must be state independent. Denote the revenue in states when the project will be terminated by M and in states where subsidies are paid by m. Then, by (B.1) on has $U'(m-I)=\frac{\delta_d-\alpha}{\delta-\alpha}U'(M-I)$. Because $\delta_d > \delta > \alpha$, we conclude: $U'(m-I) > U'(M-I)$, and, because U is strictly concave, $M > m$. Combined with the binding participation constraint this implies $m < I < M$.

By exclusion, in intermediate states subsidies cannot occur and the revenue cap cannot bind; therefore, in intermediate states, $m < v < M$, where neither the revenue cap nor the minimum income guarantee bind, one must have $S(v)=0$ and $R(v)=v$.

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