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Centralized versus Decentralized Provision of Public Safety Networks

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Technology-based public safety networks are crucial for ensuring effective exchange of information among first responders, where the safety of the citizens is contingent upon timely and accurate information in emergency situations. This work provides a comprehensive framework for analyzing the key tradeoffs between centralized and decentralized provisions of public safety networks. We extend the classic fiscal federalism model to capture a critical unique property of public safety networks – potential interoperability issues. The interoperability of public safety networks is jointly determined by the local governments of districts under decentralized provision, whereas the interoprability is solely determined by the central government under centralized provision. We find that the equilibrium interoperability level increases in the degree of spillover from the value of public goods such as emergency response assets for both the centralized and the decentralized provision strategies. When adoption of centralized versus decentralized provision is considered as a collective decision by the local governments, we identify conditions when the districts deviate from the social optimum and thus a regulatory intervention is beneficial. We further show that the districts' incentive to adopt centralized provision critically depends on the sharing rule for the cost of integration effort. Compared to equal cost-sharing, spillover-based cost-sharing reduces the range of interoperability efficiency where the two districts have conflicting preferences for provision strategies. Finally, we propose an optimal cost sharing rule which leads to the social optimum.

Key words: Centralization, Decentralization, Interoperability, Public policy, Pubic Safety Networks.

1. Introduction

Modern consumer information and communication technologies and devices provide ubiquitous access to data, reliable coverage, resilient dependability, and dynamic capabilities. The same cannot be said about most of the United States' public safety communication systems, where the safety of its citizens is contingent on the ability of first responders to exchange timely and accurate information in emergency situations (Newman et al. 2010). New York City Police Commissioner Raymond Kelly bears witness to this statement, admitting that a teenager with a smartphone has more capabilities in the field than the average emergency responder does with a radio (Kelly 2011). Most current public safety systems provide responders with only voice communication services, but lack data driven services found on typical consumer networks, such as video capable devices to record condition of a patient or geo-location to guide a firefighter to a forest fire, and interoperability of systems to allow synchronized exchange of information between other responders like police and fire fighters. The addition of these types of information technology driven services would allow for many other beneficial tools and could make the difference between life and death for those in distress and first responders

Although why public safety agencies' information and communication systems have fallen so far behind consumer systems is unclear, the increasing variance between them is becoming more evident. Case in point, the lives of hundreds of first responders could have been saved during the 9/11 attack if first responder agencies had synchronized communication devices to broadcast the building evacuation call. Furthermore, the effects of Hurricane Katrina verified the need for a broader and more dependable public safety network where the absence of basic information and communication operability proved devastating (Victory 2006). Overwhelming occurrences like these demonstrate that the fragmented network approach previously adopted for public safety networks is inadequate. Moreover, compared to modern consumer information and communication technologies where provisions of the network is distributed evenly among users, the current provision of public safety networks are decentralized based on regional boundaries, leaving taxpayers with extremely costly and spectrally inefficient networks (Hallahan and Peha 2008). The cost is undoubtedly a result of policies regarding the networks being left to the decision of local and state agencies.

Accordingly, in March of 2010, the Federal Communications Commission (FCC) released the National Broadband Plan (NBP) which advocates for a nationwide interoperable wireless broadband network (Newman et al. 2010). The NBP suggests significant changes to current systems, claiming to bring about a centralized and highly dependable nationwide broadband network that is cost effective, yet will still meet the public safety's stringent network requirements. The NBP calls for responders to work on a centralized network, providing interoperability and simultaneously creating a means for a shared federal funding approach.

Unlike the decentralized approaches, the NBP suggests giving public safety access to a cohesive nationwide broadband network that leverages the commercial technology and infrastructure, ultimately lowering the taxpayers' expenses and providing a centralized system that serves both public safety and the general public (Newman et al. 2010). Policymakers must investigate the impact of decentralized and centralized provisions on the quality of services and how the cost of the provisions should be shared. Put simply, should there be a centralized system in which a single governing body makes the spending decisions about public safety networks that are financed by the general public, or a decentralized system in which local governments make the spending decisions that are financed by local citizens?

The centralized approach attempts to allocate the public safety network evenly throughout the United States to promote interoperability while financing the network with general public taxation. The obvious benefit is that there will be an interoperable network with a uniform quality of service; however, the concern is that it does not reflect specific local needs (e.g., different technology capabilities and public good preferences). Moreover, a fully interoperable network will be more expensive to build because the technical details and the interests of the different parties involved make the task complicated. This centralized approach is in contrast to the traditional approach where the allocation of public goods is determined by local governance and financed by local taxation, but leaving fragmented networks. The decentralized approach meets local public safety needs, but the drawback is that it neglects the effects of interoperability on public good spillovers to neighboring cities (e.g., Katrina and 9/11).

The city of Eau Claire in Wisconsin for example is participating the Comprehensive Community Infrastructure (CCI) portion of a recent Broadband Technology Opportunities Program (BTOP) grant to provide broadband services to the nearby city Chippewa Valley. Part of the project is a WiMax pilot to be used for public safety operations. The coverage area includes a majority of Eau Claire and Chippewa County and a portion of Dunn and Clark Counties. 20 different organizations from the multiple cities involved are utilizing 14 tower sites to provide the intended services. Significant integration effort were invested by all organizations, cities and counties involved aims to build a network that would allow any public safety official within the covered area to use standard communication device that operates on the same frequency as other emergency responders.

We build upon the Oates (1972) model, a classic model of fiscal federalism, to investigate the provision of public safety networks. We model two districts with heterogeneous preferences for public goods and the amount of integration effort invested in coordination to improve interoperability. In decentralized provision, each district chooses its own public good level and integration effort level. Consequently, individual districts' integration effort choices jointly determine the interoperability of public safety networks. In centralized provision, the central government chooses individual public good level for each district and a single integration effort level to maximize interoperability. With this model we address several research questions: what are the equilibrium integration effort level choices and public good levels in a centralized or a decentralized provision? What is the impact of spillovers and heterogeneous public good preferences on government agencies' choices? How do spillovers and integration effort heterogeneity jointly determine the interoperability of public safety networks? And most importantly, comparing the centralized and the decentralized provisions, which system is superior? On the one hand, if the public safety networks are provided through a decentralized system, then we find that equilibrium effort choices of the two districts are the same. A district's equilibrium public good level is mainly determined by its own public good preference rather than that of the other districts. The level of interoperability between the public safety networks of the two districts increases in the degree of spillover. On the other hand, if the public safety network is provided through a central government, then the equilibrium integration effort choice is jointly determined by the public good preferences from both districts and is affected by the degree of spillover. In contrast to common public opinion, we find that a decentralized system may provide higher social surplus than a centralized system when the efficiency of integration is high. More interestingly, we find that the district with higher public good preference has a higher incentive to select centralized system. Finally, in comparing public good levels and integration effort choices under centralized or decentralized provision with the social optimal outcome, centralized provision yields higher public good levels and interoperability than decentralized provision, however, in many cases, centralized provision over-provides on both public good levels and interoperability level for public safety network.

2. Literature Review

This paper is related to three literatures – communication networks, fiscal federalism, and technology compatibility and interoperability.

2.1. Communication Networks

Public safety agencies have produced a highly fragmented infrastructure consisting of many thousands of independent systems using a variety of technologies (Peha 2007). In terms of dependability, the most widely discussed issues are communications whenever multiple agencies or agencies in different geographical areas attempt to cooperate. The use of multiple, potentially incompatible, technologies leads to interoperability problems (Newman et al. 2010).

The public safety community has recognized public safety agencies' technology interoperability and the limited and fragmented radio spectrum as main concerns related to operations of public safety wireless communications. Previous studies mainly focus on the simulation and analysis of traffic in deployed communication networks to determine their operational status, their performance, and to identify and locate possible network congestion (Cackov et al. 2005; Cackov et al. 2004; Sharp et al. 2004; Song and Trajkovic 2005). Traffic modeling is the most commonly adopted approach for network provisioning, predicting utilization of network resources, and for planning network developments. These studies are used to improve network reliability, which is particularly important for networks used by public safety agencies. Detailed overviews regarding the technical aspects of public safety networks can be found in Peha (2006; 2007) and Newman et al. (2010).

Existing literature on communication networks in general, and public safety networks in particular, focus on technical issues. We contribute to the literature by taking the policy perspective and analyzing the provisions of public safety networks at the managerial level.

2.2. Fiscal Federalism

The traditional theory of fiscal federalism, first formulated in Oates (1972), lays out a normative framework for the assignment of functions to different levels of government. At the most general level, this theory contends that the central government should have the basic responsibility for macroeconomic stabilization and for resource redistribution in the form of assistance to regions of need. Specifically, the central government must provide certain "national" public goods (like national defense, flood control systems, etc.) that provide services to the entire population of the country.

Decentralized levels of government have their raison d'etre in the provision of public goods and services whose consumption is limited to their own jurisdictions. Fiscal federalism, under which provision of public goods is decentralized to subnational governments, allows public consumption levels to be tailored to suit the preferences of a heterogeneous population. This beneficial outcome is achieved via sorting of individuals into demand-homogeneous jurisdictions, each of which provides a different amount of the public good (Brueckner 2004; Brueckner 2006; Cerniglia and Longaretti 2012). The drawbacks of decentralized federalism, which have also been noted in the literature, include the sacrifice of scale economies due to smaller jurisdiction sizes (Alesina and Spolaore 1997; Oates 1972), losses from inter-jurisdictional tax competition when government revenue comes from taxation of a mobile tax base (Brueckner 2004), and failure to properly account for public-good spillovers across jurisdictions (Besley and Coate 2003; Oates 1972).

The modern case for decentralized government is well represented by Wolman (1990). Wolman groups his arguments concerning decentralization under two main headings: Efficiency Values and Governance values. Efficiency Values comprise the public choice justification for decentralization, where efficiency is understood as the maximization of social welfare. One argument highlighted by Wolman is that decentralization will complement, or even exacerbate, disparities among local governments with different economic means. In principle, however, this objection is easily addressed through grants administered centrally, designed to equalize localities' resources. A more serious objection according to Wolman is posed by the existence of externalities in the provision of local public goods, which reduce overall efficiency for society. This can also be resolved by reverting to higher levels of government, which internalize the externalities in its taxing and spending decisions.

We extend the classic Oates model of fiscal federalism to study the provision of public safety networks, and make three contributions to the literature of fiscal federalism: (i) In modeling heterogeneity, existing literature in fiscal federalism focuses on citizens' preferences for public goods. We contribute to the literature by introducing heterogeneous preferences for public goods by local governments and investigate the amount of technology integration effort invested by local governments to improve interoperability. (ii) We investigate the tradeoffs among heterogeneous preferences for public goods, heterogeneous preferences for integration effort, and spillovers. (iii) We identify the critical unique feature of public safety networks interoperability. Unlike common public goods, multiple incompatible technologies are available for public safety networks, which lead to potential interoperability issues. Consequently, interoperability has important moderating effect over the externality one district imposes on others. We model the interoperability feature as the result of integration effort choices by government agencies and explicitly study this moderating effect.

2.3. Technology Compatibility and Interoperability

Prior studies in systems competition and the economics of network externalities have explicitly considered compatibility. The standard framework of modeling compatibility was first explored by Katz and Shapiro (1985) and Farrel and Saloner (1985). A system of compatible components is treated as a single good characterized by positive consumption externalities. Such network externalities arise because the utility a consumer obtains from a system increases with the number of others using compatible products. With network externalities, the firms' incentives to produce compatible systems have been shown to depend on the firms' relative size and on how compatibility can be enforced. Cremer et al. (2000) model network externalities such that customers benefit from an increase in network size, and furthermore, the positive network effect is a function of the degree of compatibility (interoperability). They find that the firms may have incentives to degrade interconnection under a market sharing equilibrium. Mason (2000) models ISP-competition with both horizontal and vertical differentiated customers, and finds that interoperability results in reduced competitive pressure. The strategic effect of interoperability also has many similarities with the strategic effect of interconnect prices in telephony networks. The literature on two-way access pricing among telecommunication networks, initiated by Armstrong (1998) and Laffont et al. (1998a; 1998b; 2003) studies how access prices affect retail competition and interoperability through telecommunication networks' choice of retail tariffs. Whether their logic prevails over politics and corporate strategies in other industries requires further research and analysis such as the one we present.

Existing literature models technology compatibility as a discrete variable. Compatibility (interoperability) analysis is driven by the effect of network externalities due to asymmetric installed bases. Thus a general finding in the literature is that when networks are asymmetric, large networks might have an incentive to make the networks incompatible because complete compatibility means that large and small networks become equal. We contribute to the literature by modeling two districts with heterogeneous preferences for public goods and the amount of integration effort invested in coordination to improve interoperability, hence, the resulting interoperability is a continuous variable. Consequently, interoperability is driven by the tradeoff between catering to heterogeneous public good preferences among local governments and enjoying the benefit of spillovers.

3. Model

In this section, we first introduce the classic Oates model of fiscal federalism (Oates 1972). We then introduce technology integration efforts and the resulting interoperability to capture the unique properties of public safety networks.

3.1. The Oates Model

In the classic Oates model of fiscal federalism, the economy is divided into two distinct districts, indexed by $i = 1, 2$. In each district, the local government maximizes its own aggregate surplus. For the types of public goods of interest (e.g., roads, parks, etc.), the public good levels associated with the two districts are g_1 and g_2 respectively, with $g_i \in [0, \bar{g}]$, where $\bar{g}$ is the upper bound for the public good level, which is large enough to guarantee the feasibility of the interior solution. District i is also characterized by a public good preference parameter m_i. The district with a higher m_i values the public goods more. Let $p > 0$ denotes the cost parameter for producing the local public good and $\kappa \in [0, 0.5]$ denotes the degree of spillover. The aggregate surplus provided by public goods in district i is:

$$m_i \left[[1 - \kappa] \, g_i + \kappa g_{-i} \right] - p g_i^2 \tag{1}$$

The quadratic cost function captures the increasing marginal cost associated with producing the public good. When $\kappa = 0$, local governments only care about the public good in their own district; when $\kappa = 0.5$, they care equally about the public goods in both districts.

Without loss of generality, the Oates model and its extensions make the following assumption to differentiate the two districts.

Assumption 1. *The local government in District 1 prefer a higher public good level of public safety network than that in District 2, i.e.,* $m_1 \geq m_2$.

This assumption captures the two local governments' heterogeneous preferences for public good levels.

3.2. Modeling Interoperability

In order to analyze the provision of public safety networks, we introduce interoperability. Interoperability is an issue in both centralized and decentralized provision, and is made critical in the latter. Without effort the networks are not interoperable, and effort can be made to improve the interoperability among different networks with a cost. Integration effort levels are chosen by the central government in centralized provision and by local governments in decentralized provision to integrate different technologies to provide cross-district public safety services.

In centralized provision, the central government chooses its integration effort level $e \in [0, \bar{e}]$ to integrate the public safety network across districts. In decentralized provision, each local government chooses its integration effort level $e_i \in [0, \bar{e}]$, where $i = 1, 2$ and $\bar{e}$ is the maximum overall integration effort level, for its public safety network to integrate different technologies for different districts. In general, $\bar{e}$ is a large value. In this work, the specific condition $\bar{e} > \frac{\kappa[m_1^2 + m_2^2]^{\frac{1}{2}}}{2p^{\frac{1}{2}}\delta^{\frac{1}{2}}}$ ensures the existence of interior solution. Cross-district interoperability and hence the benefits derived from the public safety network service depends on the overall integration effort, i.e., $e_1 + e_2$. If the overall integration effort level is high, then both districts derive greater utility from the neighboring district in the presence of spillover.

To the extent that network integration does occur, it comes by linking together otherwise standalone networks, so that the output of one component serves as input to another. The coordination of different information technologies presents a challenge to local governments with dispersed public safety networks. In another word, decentralization may bring flexibility and fast response to changing local needs, as well as other benefits, but decentralization also makes systems integration difficult, presents a barrier to standardization, and acts as a disincentive toward achieving economies of scale (Zmud 1980, Desanctis and Jackson 1994, Krishnan et al. 2000, Harter et al. 2000, Schuff and Louis 2001, Gopa et al. 2003). Integration among unintegrated systems is usually coordinated through policies and protocols. The compatibility of network equipment will not be ensured unless highly centralized control of procurement is maintained. In the extreme cases, local governments may adopt the strategy of "maximum feasible incompatibility" (King 1983) in public safety network provision and make it difficult and costly for other networks to absorb them. Because integration is a more challenging task in decentralized provision, we use $\beta \in [0, 1]$ to represent the overall network interoperability efficiency of decentralized provision relative to the centralized provision, where for centralized provision β is normalized to 1 (i.e., $\beta = 1$).

Assumption 2. *Under decentralized provision, there is an efficiency loss in the integration effort for interoperability, i.e.,* $0 < \beta \leq 1$.

Let $\delta > 0$ denote the cost parameter for integration effort. In centralized provision $I(e) = \frac{e}{\bar{e}}$ represents interoperability. In decentralized provision, the cross-district interoperability I takes the form of $I(e_1, e_2) = \beta\left[\frac{e_1 + e_2}{\bar{e}}\right]$. Considering interoperability of public safety networks, district i derives the following aggregate surplus given levels of public goods and integration effort:

$$m_i\left[[1 - \kappa]\, g_i + \kappa I(e_1, e_2) g_{-i}\right] - p g_i^2 - \delta e_i^2 \tag{2}$$

Similar to the public goods, the quadratic cost function for integration effort captures the increasing marginal cost associated with effort to improve interoperability.

4. Decentralized Provision

In decentralized provision, local governments make their public good and integration effort decisions simultaneously to maximize the total surplus within their districts. The objective of the local government in District 1 is to maximize the aggregate value minus the cost of producing the public goods level g_{1d} (e.g., the cost of building g_{1d} cell towers) and the integration effort cost, where subscript id corresponds to District i under decentralized provision. The formulation in (3) presents the local government of District 1's decision problem.

$$\begin{aligned} &\max_{g_{1d},e_1} S_{1d}(g_{1d},e_1|g_{2d},e_2) = m_1\left[[1-\kappa]\,g_{1d} + \kappa\beta\left[\frac{e_1+e_2}{\bar{e}}\right]g_{2d}\right] - pg_{1d}^2 - \delta e_1^2 \\ &\text{Subject to: } 0 \le g_{1d} \le \bar{g},\ 0 \le e_1 \le \bar{e} - e_2 \end{aligned} \tag{3}$$

Given the public goods and integration effort choice of District 2 (g_{2d} and e_2), District 1 selects g_{1d} and e_1 by balancing the tradeoff between public goods preferences, that is, m_1 and the spillover effect captured by $\kappa\beta\left[\frac{e_1+e_2}{\bar{e}}\right]g_{2d}$. In decentralized provision, the spillover effect is partially determined by the interoperability between the two public safety networks. As both districts invest more effort in integration, the two public safety networks become more interoperable, hence the spillover effect is greater.

Similarly, the local government of District 2's decision problem is represented by the formulation in (4).

$$\begin{aligned} &\max_{g_{2d},e_2} S_{2d}(g_{2d},e_2|g_{1d},e_1) = m_2\left[[1-\kappa]\,g_{2d} + \kappa\beta\left[\frac{e_1+e_2}{\bar{e}}\right]g_{1d}\right] - pg_{2d}^2 - \delta e_2^2 \\ &\text{Subject to: } 0 \le g_{2d} \le \bar{g},\ 0 \le e_2 \le \bar{e} - e_1 \end{aligned} \tag{4}$$

Under decentralized provision, solving the above maximization problems yields the Nash equilibrium public good levels (g_{1d}^*, g_{2d}^*) and integration effort choices (e_1^*, e_2^*) for the two districts such that:

$$g_{1d}^* = \frac{m_1[1-\kappa]}{2p},\ g_{2d}^* = \frac{m_2[1-\kappa]}{2p},\ e_1^* = e_2^* = \frac{m_1 m_2\beta\kappa[1-\kappa]}{4\bar{e}\delta p}.$$

The resulting total surpluses for the two districts are:

$$S_{1d}^* = \frac{m_1^2[1-\kappa]^2\left[4\bar{e}p\delta + 3m_2^2\beta^2\kappa^2\right]}{16\bar{e}^2p^2\delta},\ S_{2d}^* = \frac{m_2^2[1-\kappa]^2\left[4\bar{e}p\delta + 3m_1^2\beta^2\kappa^2\right]}{16\bar{e}^2p^2\delta}.$$

Under Assumption 1, District 1 favors a higher public good level for the public safety network than District 2, i.e., $m_1 \ge m_2$. Intuitively, District 1 provides a higher public good level and enjoys a higher aggregate surplus than District 2 does in equilibrium, i.e., $g_{1d}^* \ge g_{2d}^*$ and $S_{1d}^* \ge S_{2d}^*$.

Proposition 1. **Decentralized Provision:** *Under decentralized provision, the equilibrium public good levels (g_{1d}^*, g_{2d}^*) and integration effort choices (e_1^*, e_2^*) for the two districts have the following properties:*

a. The equilibrium public good level of District 1, g_{1d}^*, is independent of the public good preference, m_2, of District 2, and vice versa.

b. The equilibrium integration effort levels of the two districts are the same, i.e., $e_1^* = e_2^*$, which increase in both the degree of spillover, κ, and the efficiency in integration effort, β.

c. The total integration effort level $e_1^* + e_2^*$ and hence the interoperability level $\beta\left[\frac{e_1^*+e_2^*}{\bar{e}}\right]$ increase in both the degree of spillover κ and the efficiency in integration effort β.

The proofs of all propositions and the detailed derivations of the equilibrium results are relegated to the appendices.

Proposition 1 shows that when deciding its public good level, each local government only takes into account the benefits received by itself, but not the benefits going to the other district. Hence, the equilibrium public good level of one district is independent of the public good preference of the other district.

Because $\frac{\partial S_{1d}}{\partial e_1} = \frac{\kappa\beta m_1 g_{2d}}{\bar{e}} - 2\delta e_1$, District 1's incentive to invest in integration effort, e_1, is determined by two factors: its own public good preference m_1 (a direct effect), and the public good level of the other district g_{2d} (an indirect effect). Similarly, District 2's incentive to invest in e_2 is determined by m_2 and g_{1d}. District 1 has a stronger incentive to invest in integration effort due to the direct effect ($m_1 \geq m_2$) while District 2 has a stronger incentive to invest in integration effort due to the indirect effect ($g_{1d} \geq g_{2d}$). In equilibrium, the overall combined effort incentive is the same for both districts leading to the same integration effort levels, i.e., $e_1^* = e_2^*$. The resulting effort levels selected by each district and the interoperability level depend on the public good preferences of both districts.

We also find that the equilibrium interoperability level increases in the degree of spillover. In other words, when one district derives more benefits from the public safety networks in the other district, then the equilibrium interoperability between local public safety networks is higher. This type of spillover effect for public safety networks is similar to other public goods. Unlike other public goods, however, the degree of integration between the two systems and the resulting interoperability moderate the overall benefits that spillover to the neighboring district. A stronger spillover effect (i.e., higher κ) provides a higher incentive for both districts to invest in the integration and interoperability of their public safety networks. As a result, it is not surprising to observe the positive impact of the degree of spillover on local governments' integration efforts and the resulting interoperability.

5. Centralized Provision

Following recent literature in fiscal federalism (Besley and Coate 2003; Stansel 2005), with centralized provision the central government chooses different public good levels of public safety networks,

g_{1c} and g_{2c}, for the two districts, where the subscript c indicates centralized provision. Furthermore, the central government chooses a single integration effort level e for interoperability.

In centralized provision, the central government simultaneously chooses g_{1c}, g_{2c}, and e to maximize the total surplus across both districts. Its decision problem is:

$$\max_{g_{1c},g_{2c},e} S_c(g_{1c},g_{2c},e) = m_1\left[[1-\kappa]\,g_{1c}+\kappa\left[\frac{e}{\bar{e}}\right]g_{2c}\right]+m_2\left[[1-\kappa]\,g_{2c}+\kappa\left[\frac{e}{\bar{e}}\right]g_{1c}\right]-p\left[g_{1c}^2+g_{2c}^2\right]-\delta e^2$$
$$\text{Subject to: } 0\le g_{1c},g_{2c}\le\bar{g},\ 0\le e\le\bar{e} \tag{5}$$

Under centralized provision, the optimal public good levels (g_{1c}^*, g_{2c}^*) for the two districts and integration effort level (e^*) are:

$$g_{1c}^*=\frac{m_1\bar{e}\,[1-\kappa]+e^*m_2\kappa}{2\bar{e}p},\ g_{2c}^*=\frac{m_2\bar{e}\,[1-\kappa]+e^*m_1\kappa}{2\bar{e}p}, e^*=\frac{2m_1m_2\bar{e}\kappa\,[1-\kappa]}{4\bar{e}^2p\delta-[m_1^2+m_2^2]\,\kappa^2}.$$

The resulting overall total surplus is:

$$S_c^*=\frac{[1-\kappa]^2\left[4\bar{e}^2p\delta\,[m_1^2+m_2^2]-[m_1^2-m_2^2]^2\,\kappa^2\right]}{4p\,[4\bar{e}^2p\delta-[m_1^2+m_2^2]\,\kappa^2]}.$$

Similar to decentralized provision, centralized provision results in a higher public good level for the district that values the public good more, i.e., $g_{1c}^*\ge g_{2c}^*$.

Proposition 2. **Centralized Provision:** *Under centralized provision, the optimal public good levels (g_{1c}^*, g_{2c}^*) for the two districts and integration effort level (e^*) have the following properties:*

a. The optimal public good level of District 1 g_{1c}^* increases in the public good preference level m_2 of District 2, and vice versa.

b. The integration effort level e^* and hence the interoperability level $I(e^*)=\frac{e^*}{\bar{e}}$ increase in the degree of spillover for all $\kappa\in[0,0.5]$.

In contrast to decentralized provision, the central government selects the public good levels by simultaneously considering the public good preferences of both districts. Thus, the optimal public good levels now depend on the public good preferences of both districts. Under centralized provision, a single integration effort level is chosen to maximize the interoperability while accommodating districts' heterogeneous preferences for public goods. Thus, the central government internalizes the externalities the two districts impose on each other through the choices of integration effort and public good levels.

6. Centralized versus Decentralized Provision under Different Cost-Sharing Strategies

It is well known that decentralized provision of public goods modeled as non-cooperative games often lead to inefficient under-provision (see, for example, Bergstrom, Blume and Varian (1986)) as individual district have incentives to free ride. To overcome the free-riding problem, economists have proposed several mechanisms that would set proper incentives for individual districts to make contributions toward efficient provisions of public goods (see among others, Clarke (1971), Groves (1973), Walker (1981), Varian (1994)).

In this section, we consider the decision of centralized versus decentralized provisions as a collective decision by the local governments. Local governments compare their surpluses under each system and select the one with higher surplus. If both districts prefer centralized provision, then centralized provision is adopted; otherwise, decentralized provision is adopted.

6.1. Equal Cost-Sharing under Centralized Provision

To begin our analysis, we focus on a simple cost-sharing rule which stipulates that each district equally shares the cost of integration effort to improve the interoperability of the public safety network. Thus, their corresponding surpluses are:

$$S_{1c}(g_{1c}, g_{2c}, e) = m_1 \left[[1-\kappa]\, g_{1c} + \kappa \left[\frac{e}{\bar{e}}\right] g_{2c} \right] - p g_{1c}^2 - \frac{\delta e^2}{2},$$

$$S_{2c}(g_{1c}, g_{2c}, e) = m_2 \left[[1-\kappa]\, g_{2c} + \kappa \left[\frac{e}{\bar{e}}\right] g_{1c} \right] - p g_{2c}^2 - \frac{\delta e^2}{2}.$$

On the one hand, the public good levels are separable between the two districts, each district therefore bears the cost of its allocated public good. On the other hand, the cost of integration effort, δe^2, is not separable between districts, and the central government allocates it equally across the two districts.

The resulting total surpluses for the two districts under centralized provision are:

$$S_{1c}^* = \frac{m_1^2 [1-\kappa]^2 \left[16\bar{e}^4 p^2 \delta^2 - 8\bar{e}^2 p \delta m_1^2 \kappa^2 + [m_1^4 + 6 m_1^2 m_2^2 - 7 m_2^4]\, \kappa^4\right]}{4p \left[4\bar{e}^2 p\delta - [m_1^2 + m_2^2]\, \kappa^2\right]^2},$$

$$S_{2c}^* = \frac{m_2^2 [1-\kappa]^2 \left[16\bar{e}^4 p^2 \delta^2 - 8\bar{e}^2 p \delta m_2^2 \kappa^2 - [7m_1^4 - 6 m_1^2 m_2^2 - m_2^4]\, \kappa^4\right]}{4p \left[4\bar{e}^2 p\delta - [m_1^2 + m_2^2]\, \kappa^2\right]^2}.$$

Similar to decentralized provision, centralized provision results in higher social surplus for the district that values the public good more, i.e., $S_{1c}^* \geq S_{2c}^*$.

Individual districts compare their surpluses under centralized provision (S_{1c}^* and S_{2c}^*) to those under decentralized provision (S_{1d}^* and S_{2d}^*) and select the system with higher surplus. The centralized provision is only chosen if both districts have higher surplus under centralized provision. Let β_i denotes the threshold value where the surplus from the decentralized provision is equivalent to the surplus from the centralized provision for District i. The corresponding thresholds for the two districts are:

$$\beta_1 = \frac{4\bar{e} p^{\frac{1}{2}} \delta^{\frac{1}{2}} \left[2\bar{e}^2 p\delta + [m_1^2 - 2m_2^2]\, \kappa^2\right]^{\frac{1}{2}}}{3^{\frac{1}{2}} \left[4\bar{e}^2 p\delta - [m_1^2 + m_2^2]\, \kappa^2\right]},$$

$$\beta_2 = \frac{4\bar{e}p^{\frac{1}{2}}\delta^{\frac{1}{2}}\left[2\bar{e}^2p\delta - \left[2m_1^2 - m_2^2\right]\kappa^2\right]^{\frac{1}{2}}}{3^{\frac{1}{2}}\left[4\bar{e}^2p\delta - \left[m_1^2 + m_2^2\right]\kappa^2\right]}.$$

Proposition 3 delineates conditions under which centralized or decentralized provision is adopted.

PROPOSITION 3. **Adoption of Centralized or Decentralized Provision with Equal Sharing of Intergration Cost:** *Analyzing the local governments' decisions for centralized provision and decentralized provision, we find:*

a. If $\beta \leq \beta_i$, then District i prefers centralized provision.

b. District 1 prefers centralized provision over a greater range of interoperability efficiency than District 2, i.e., $\beta_1 \geq \beta_2$.

c. If $\beta \leq \beta_2$, then both districts prefer centralized provision and thus centralized provision is adopted; If $\beta_2 < \beta \leq \beta_1$, then District 1 prefers centralized provision but District 2 prefers decentralized provision; If $\beta > \beta_1$, then both districts prefer decentralized provision. In both cases decentralized provision is adopted.

Figure 1 depicts the results in Proposition 3. As shown in Figure 1, the aggregate surpluses of individual districts under centralized provision do not depend on interoperability efficiency β (i.e., S_{1c} and S_{2c} are flat lines), whereas the aggregate surpluses of individual districts under decentralized provision increase in interoperability efficiency β (i.e., S_{1d} and S_{2d} are upward sloping). The aggregate surplus of District 1 is greater than that of District 2 ($S_{1d} > S_{2d}$) as District 1 has higher preference for public goods ($m_1 > m_2$). Each district compare its aggregate surplus under centralized versus decentralized provision to determine its preferred provision strategy. There exists a threshold for interoperability efficiency, β_i, where District i is indifferent between centralized and decentralized provision. Threshold β_i corresponds to the intersection of S_{ic} and S_{id}. Proposition 3 and Figure 1 reveal that individual districts prefer centralized provision when the interoperability efficiency is sufficiently low, i.e., β is low. Two thresholds (β_1 and β_2) are identified for the two districts, respectively. Comparing these two thresholds shows that District 1 has a higher incentive to select centralized provision because of its stronger preference for the public good level of public safety networks. However, because the adoption of centralized provision requires unanimous approval by both districts, District 1 may not achieve its preferred option. Specifically, when $\beta_2 < \beta \leq \beta_1$, the two districts have conflicting preferences for provision strategies.

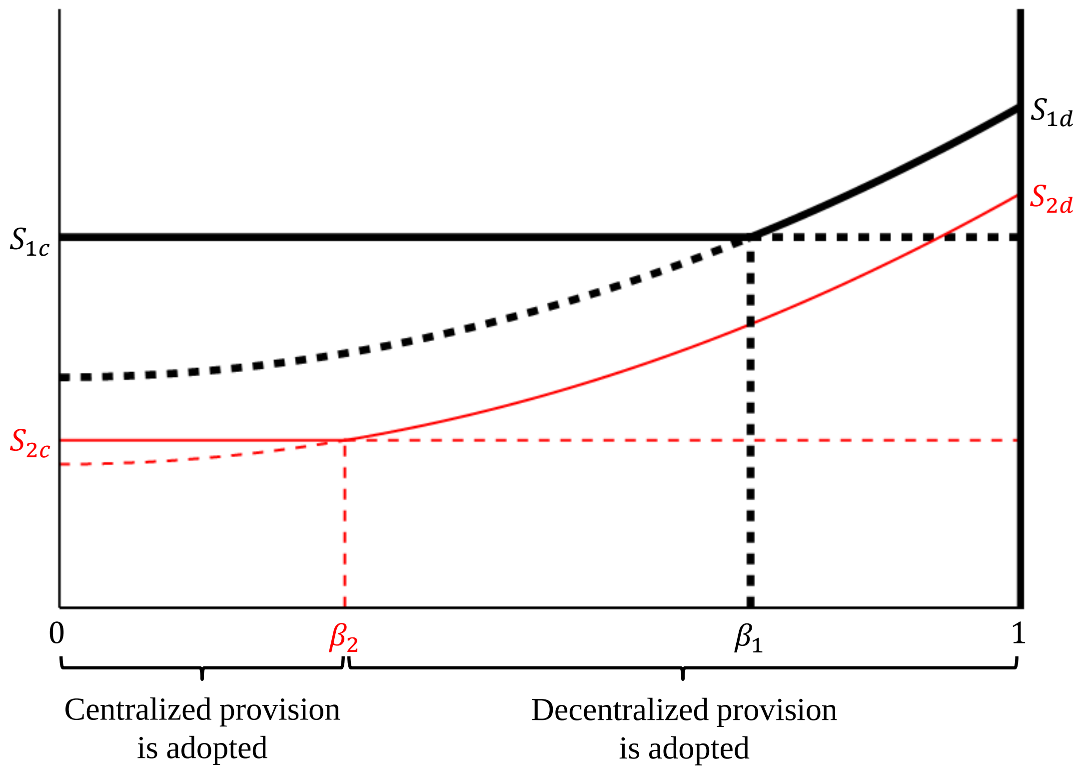


Figure 1 **Adoption Decisions of Centralized or Decentralized Provision under Equal Sharing of Integration Cost**

6.2. Spillover-based Cost-Sharing

It is quite obvious that under centralized provision, the local government with lower spillover benefits (i.e., District 2) is less likely to agree on sharing the integration cost equally with the district that enjoyes higher spillover benefits (i.e., District 1). Unless a social planner is involved and mandates the equal sharing rule, under such a rule individual districts may lack necessary incentives to collectively endorse the centralized provision. Conversely, a spillover-based cost-sharing rule derived from the externality benefits enjoyed by each district may provide proper incentives for both districts. Under the spillover-based cost-sharing, District i bears the integration cost that is proportional to the spillover benefits it enjoys due to the interoperability of the public safety network (i.e., $\frac{m_i\kappa\left[\frac{e}{\bar{e}}\right]g_{-ic}}{m_i\kappa\left[\frac{e}{\bar{e}}\right]g_{-ic}+m_{-i}\kappa\left[\frac{e}{\bar{e}}\right]g_{ic}} = \frac{m_i g_{-ic}}{m_i g_{-ic}+m_{-i}g_{ic}}$). Thus, the corresponding surpluses for both districts are:

$$\tilde{S}_{1c}(g_{1c}, g_{2c}, e) = m_1\left[[1-\kappa]\, g_{1c} + \kappa\left[\frac{e}{\bar{e}}\right] g_{2c}\right] - pg_{1c}^2 - \frac{m_1 g_{2c}}{m_1 g_{2c} + m_2 g_{1c}}\delta e^2,$$

$$\tilde{S}_{2c}(g_{1c}, g_{2c}, e) = m_2\left[[1-\kappa]\, g_{2c} + \kappa\left[\frac{e}{\bar{e}}\right] g_{1c}\right] - pg_{2c}^2 - \frac{m_2 g_{1c}}{m_1 g_{2c} + m_2 g_{1c}}\delta e^2.$$

Similar to the cost-sharing strategy for the public good levels, the individual district now bears the overall integration effort cost proportional to the spillover benefits it enjoys. Under this sharing rule, individual districts once again compare their surpluses under centralized provision to those under decentralized provision and select the system with higher surplus. Another pair of thresholds, $\tilde{\beta}_1$ and $\tilde{\beta}_2$, can be found such that the surplus from the decentralized provision is equivalent to the surplus from the centralized provision under the spillover-based cost-sharing strategy. The corresponding thresholds for the two districts are:

$$\tilde{\beta}_1 = \frac{8^{\frac{1}{2}}\bar{e}p^{\frac{1}{2}}\delta^{\frac{1}{2}}\left[4\bar{e}^2p\delta + [m_1^2 - 3m_2^2]\,\kappa^2\right]^{\frac{1}{2}}}{3^{\frac{1}{2}}\left[4\bar{e}^2p\delta - [m_1^2 + m_2^2]\,\kappa^2\right]},$$

$$\tilde{\beta}_2 = \frac{8^{\frac{1}{2}}\bar{e}p^{\frac{1}{2}}\delta^{\frac{1}{2}}\left[4\bar{e}^2p\delta - [3m_1^2 - m_2^2]\,\kappa^2\right]^{\frac{1}{2}}}{3^{\frac{1}{2}}\left[4\bar{e}^2p\delta - [m_1^2 + m_2^2]\,\kappa^2\right]}.$$

Proposition 4 compares the thresholds under spillover-based cost-sharing, $\tilde{\beta}_i$, with the thresholds under equal cost-sharing, β_i.

PROPOSITION 4. **Spillover-based versus Equal Sharing of Integration Effort Cost:** *Analyzing the local governments' decisions for centralized provision and decentralized provision under both spillover-based and equal sharing of the integration effort cost, we find:*

a. District 1 prefers the decentralized provision over a greater range of inteoperability efficiency under spillover-based cost-sharing than under equal cost-sharing, i.e., $\tilde{\beta}_1 < \beta_1$.

b. District 2 prefers the centralized provision over a greater range of interoperability efficiency under spillover-based cost-sharing than under equal cost-sharing, i.e., $\tilde{\beta}_2 > \beta_2$.

c. The two districts are more likely to prefer the same system for their public safety network provisions under spillover-based cost-sharing than under equal cost-sharing, i.e., $\tilde{\beta}_1 - \tilde{\beta}_2 < \beta_1 - \beta_2$.

Figure 2 depicts the results in Proposition 4. As shown in Figure 2, compared to the levels under equal cost-sharing, under spillover-based cost-sharing, the aggregate surplus of District 1 shifts down ($\tilde{S}_{1c} < S_{1c}$) while the aggregate surplus of District 2 shifts up ($\tilde{S}_{2c} > S_{2c}$). As a result, the thresholds under spillover-based cost-sharing ($\tilde{\beta}_1$ and $\tilde{\beta}_2$, corresponding to the intersections of $\tilde{S}_{ic}$ and $\tilde{S}_{id}$) are closer to each other than the thresholds under equal cost-sharing (β_1 and β_2, corresponding to the intersections of S_{ic} and S_{id} in Figure 1). In other words, Proposition 4 and Figure 2 demonstrate that compared to equal cost-sharing, spillover-based cost-sharing reduces the range of interoperability efficiency where the two districts have conflicting preferences for provision strategies.

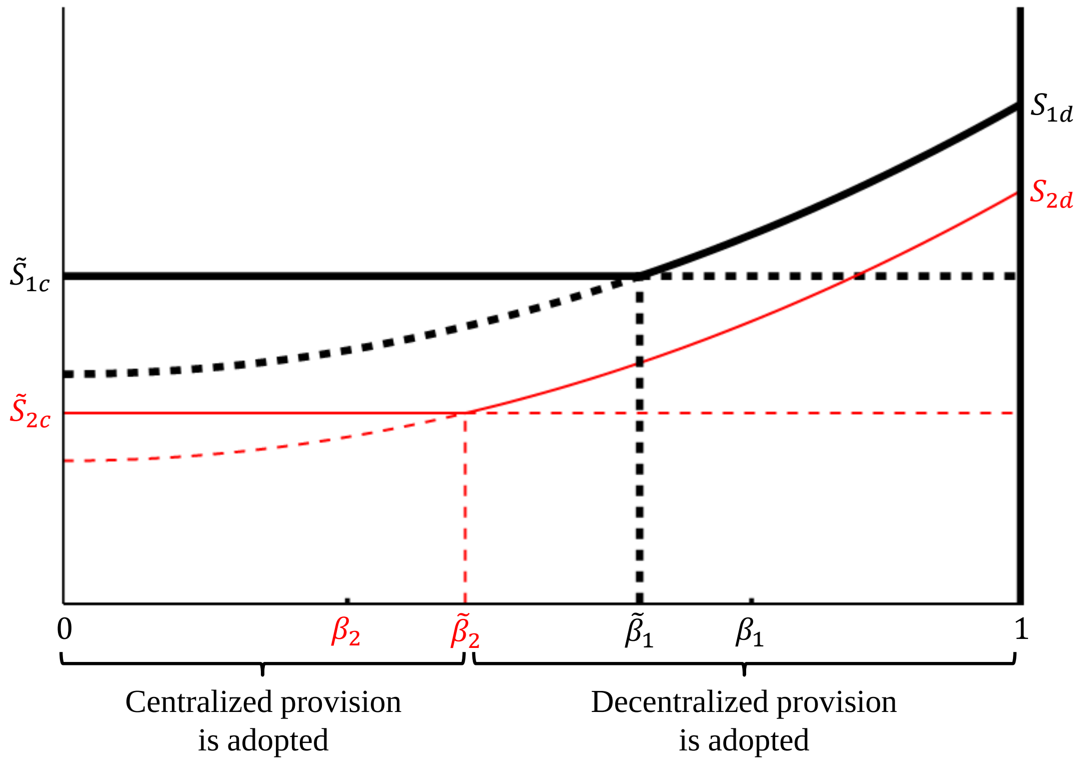


Figure 2 **Adoption Decisions of Centralized or Decentralized Provision under Spillover-based Sharing of Integration Cost**

7. Social Optimum

In this section, we study the socially optimal provision of public safety networks. In other words, the social planner decides upon centralized or decentralized provision to maximize overall social welfare. In contrast to centralized provision where without a social planner both districts needed to prefer centralized system in order to obtain centralized provision, a social planner may choose either centralized or decentralized provision when such a system provides greater overall social welfare. The overall social welfare is defined as the total surplus of both districts, i.e., $S_{1d} + S_{2d}$, under decentralized provision (specified in (3) and (4)) and S_c under centralized provision (specified in (5)). Let $\hat{\beta}$ denotes the threshold value where the social welfare is the same under either decentralized provision or centralized provision. By solving $S_{1d} + S_{2d} = S_c$, we find the corresponding threshold:

$$\hat{\beta} = \frac{8^{\frac{1}{2}} \bar{e} p^{\frac{1}{2}} \delta^{\frac{1}{2}}}{\left[12\bar{e}^2 p\delta - 3\left[m_1^2 + m_2^2\right]\kappa^2\right]^{\frac{1}{2}}}.$$

Proposition 5 outlines the socially optimal outcomes.

PROPOSITION 5. **Social Optimum:** *Comparing the overall social surplus under centralized and decentralized provision, we find that centralized provision is socially optimal if the interoperability efficiency is low, i.e., $\beta \leq \hat{\beta}$; otherwise, decentralized provision is socially optimal.*

Although the central government aims to maximize the total surplus, the local public good levels and the technology integration effort level under centralized provision are only surplus-maximizing when the interoperability efficiency of decentralized provision β is sufficiently small. In the presence of spillover effects, centralized provision seems strictly better than decentralized provision by providing higher total public goods and greater interoperability (see our results in Proposition 7). However, the centralized provision may not always be desirable from a social welfare perspective as local public goods and the corresponding integration effort are over-provided. Decentralized provision leads to a higher total surplus if local governments work closely with each other and provide higher interoperability efficiency (i.e., β is large) with chocies of better underlying technology for the public safety network. Taking into account the local needs and preferences, a decentralized system provides the exact amount of public goods needed and invests the right amount of integration effort in interoperability to achieve higher social welfare.

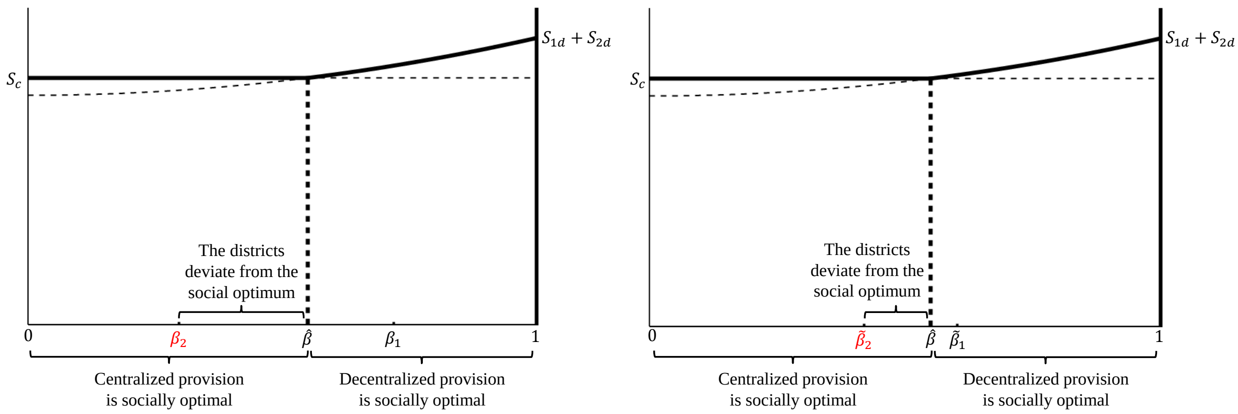
PROPOSITION 6. **Comparison of Decentralized, Centralized and Social Optimum Provision:** *Comparing centralized, decentralized and social optimal provision, we find that:*

a. District 1 prefers the centralized provision over a greater range of interoperability efficiency than the social planner while District 2 prefers the centralized provision over a smaller range of interoperability efficiency than the social planner, i.e., $\beta_1 \geq \hat{\beta} \geq \beta_2$.

b. The districts deviate from the social optimum if $\beta_2 < \beta \leq \hat{\beta}$, i.e., District 1 prefers centralized provision while District 2 prefers decentralized provision resulting in a decentralized system, which is welfare inferior to a centralized system.

Proposition 6 reveals the conditions under which a regulatory intervention (i.e., a social planner mandates the choice of public safety network provision) would be beneficial from the social welfare perspective. Threshold $\hat{\beta}$ is when the social planner is indifferent between centralized and decentralized provision as shown in Figure 3. In Figure 3a, thresholds β_i represent District i is indifferent between centralized and decentralized provision under equal sharing of integration cost. When $\beta < \beta_2$ (or $\beta > \hat{\beta}$), the collective decisions made by individual districts leading to centralized (or decentralized) provision is socially optimal. There is no need for a social planner to coordinate the districts' choices. In contrast, when $\beta_2 < \beta \leq \hat{\beta}$, although centralized provision yields higher social welfare than decentralized provision, District 2's benefit from centralized provision does not justify the cost, resulting in the adoption of the decentralized provision. In Figure 3b, thresholds $\tilde{\beta}_i$

represent District i is indifferent between centralized and decentralized provision under spillover-based sharing of integration cost. Compared to equal cost sharing (as shown in Figure 3a), Figure 3b shows that spillover-based cost sharing reduces the range of interoperability efficiency where the two districts' choices deviate from the social optimum.



(a) Equal cost-sharing (b) Spillover-based cost-sharing

Figure 3 Social Optimum and its Comparison to Equilibrium Results

7.1. Socially Optimal Cost-Sharing

As we discussed in Section 6, the cost-sharing mechanism plays a key role in determining the final outcome of the public safety network when decentralized versus centralized provision is modeled as a collective decision by the local governments. With the intervention of a social planner, next we relax the conditions of equal or the spillover-based cost-sharing of the integration effort cost under centralized provision and find the socially optimal cost-sharing approach. A social planner may allocate different proportions of the integration effort cost to different districts. Let $\phi \in [0,1]$ and $1-\phi$ be the proportions for District 1 and District 2, respectively. This flexible sharing rule for the integration cost of public safety networks grants the social planner an extra instrument to coordinate local governments' choices by providing necessary incentives for the districts to collectively select the socially optimal outcome. The resulting surpluses for both districts under centralized provision are:

$$S_{1c}(g_{1c}, g_{2c}, e) = m_1 \left[[1-\kappa]\, g_{1c} + \kappa \left[\frac{e}{\bar{e}}\right] g_{2c} \right] - p g_{1c}^2 - \phi \delta e^2,$$

$$S_{2c}(g_{1c}, g_{2c}, e) = m_2 \left[[1-\kappa]\, g_{2c} + \kappa \left[\frac{e}{\bar{e}}\right] g_{1c} \right] - p g_{2c}^2 - [1-\phi]\, \delta e^2.$$

Individual districts once again compare local social surplus under the new sharing rule and choose either the centralized or decentralized provision with the higher surplus. Similar to the equal or spillover based cost-sharing, there exist a pair of threshold values $\beta_1(\phi)$ and $\beta_2(\phi)$ such that the surplus from decentralized provision is equivalent to the surplus from centralized provision. Hence, District 1 and 2 prefer centralized provision if β is less than the corresponding threshold values:

$$\beta_1(\phi) = \frac{4\bar{e}p^{\frac{1}{2}}\delta^{\frac{1}{2}}\left[2\bar{e}^2p\delta\left[1-\phi\right] + \left[m_1^2 - 2m_2^2\right]\kappa^2\right]^{\frac{1}{2}}}{3^{\frac{1}{2}}\left[4\bar{e}^2p\delta - \left[m_1^2 + m_2^2\right]\kappa^2\right]},$$

$$\beta_2(\phi) = \frac{4\bar{e}p^{\frac{1}{2}}\delta^{\frac{1}{2}}\left[2\bar{e}^2p\delta\phi - \left[2m_1^2 - m_2^2\right]\kappa^2\right]^{\frac{1}{2}}}{3^{\frac{1}{2}}\left[4\bar{e}^2p\delta - \left[m_1^2 + m_2^2\right]\kappa^2\right]}.$$

The optimal cost-sharing proportion ϕ^* solves $\beta_1(\phi) = \beta_2(\phi) = \hat{\beta}$. In order to obtain the optimal cost-sharing proportion, the social planner must balance the benefit gap of local governments taking into account both centralized and decentralized provisions. The benefit gap for district i is defined as the absolute social surplus difference between centralized and decentralized provision for district i (i.e., $|S_{ic} - S_{id}|$). On the one hand, if the two districts obtain the same benefits by switching from decentralized to centralized provision, i.e., $|S_{1c} - S_{1d}| = |S_{2c} - S_{2d}|$, the social planner should allocate the overall integration cost equally between the two districts (i.e., $\phi^* = 0.5$). On the other hand, if District 1 obtains higher benefits comparing centralized to decentralized provision, i.e., $|S_{1c} - S_{1d}| > |S_{2c} - S_{2d}|$, then the social planner should allocate more integration effort cost to the district with higher benefits difference. By allocating a proportion ϕ^* of the integration effort cost to District 1, the social planner is aligning the incentives for the two districts to adopt the same system as $\beta_1(\phi^*) = \beta_2(\phi^*)$. Moreover, social welfare is maximized since the threshold values for both districts, i.e., $\beta_1(\phi^*)$ and $\beta_2(\phi^*)$, coincide with the socially optimal threshold $\hat{\beta}$. Proposition 7 shows the form of such ϕ^* and its properties.

PROPOSITION 7. **Optimal Sharing Rule for Integration Effort Cost:** *The social optimum can be achieved if the central government chooses the optimal cost-sharing proportion given by:*

$$\phi^* = \frac{1}{2} + \frac{3\left[m_1 - m_2\right]\left[m_1 + m_2\right]\kappa^2}{8\bar{e}^2p\delta}.$$

The optimal cost- sharing proportion has the following properties:

a. A greater proportion of the cost should be allocated to the district with higher public good preference (i.e., District 1), which increases in the difference between the public good preferences (i.e., $m_1 - m_2$*).*

b. A greater proportion should be allocated to District 1 if the degree of spillover is higher, i.e., $\frac{\partial \phi^*}{\partial \kappa} > 0$.

c. A greater proportion should be allocated to District 1 if the cost parameters are higher, i.e., $\frac{\partial \phi^*}{\partial p} < 0$ *and* $\frac{\partial \phi^*}{\partial \delta} < 0$.

As the social planner gradually increases the cost-sharing burden for the district with higher public good preference (i.e., ϕ increases from 0.5 to ϕ^*), the two threshold values $\beta_1(\phi)$ and $\beta_2(\phi)$ approach each other. By taking a greater proportion of the integration effort cost, District 1 transfers benefits to District 2 so that the two districts collectively choose the type of provision, centralized or decentralized that is socially optimal.

PROPOSITION 8. **Socially Optimal Centralized versus Decentralized Provision:** *Comparing the public good and the integration effort levels under both type of provisions we find that:*

a. Centralized provision yields higher public good levels for both districts than decentralized provision, i.e., $g_{ic}^* > g_{id}^*$.

b. Centralized provision yields higher interoperability than decentralized provision, i.e., $I_c = \frac{e^*}{\bar{e}} \geq I_d = \beta \left[\frac{e_1^*+e_2^*}{\bar{e}}\right]$.

c. Compared to the social optimum, if $\beta > \hat{\beta}$*, the centralized system over-provides on both public good levels and integration effort for public safety networks; If* $\beta \leq \hat{\beta}$*, the decentralized system under-provides on both public good levels and interoperability level for public safety networks.*

We find that the centralized provision always results in higher levels of public good and interoperability of public safety networks. However, from the social welfare perspective, when the interoperability efficiency of decentralized provision is greater than $\hat{\beta}$, the cost of providing a higher public good or interoperability level outweighs its corresponding benefit and, therefore, the centralized system over-provides. Similarly, the decentralized system under-provides when the interoperability efficiency of decentralized provision is lower than $\hat{\beta}$. These differences between centralized and decentralized provisions are driven by the tradeoff between the scope and the scale of public safety networks. On the one hand, when implementing public safety networks, centralized provision is more efficient than decentralized provision in integrating and coordinating the individual components, leading to a higher level of interoperability. As a result, centralized provision outperforms decentralized provision in terms of managing the scope of public safety networks. On the other hand, decentralized provision is more cost-efficient than centralized provision in the integration of public safety networks because the scale of the aggregate public safety networks under centralized provision is much larger than the scale of local public safety networks under decentralized provision. As a result, the decentralized provision outperforms the centralized provision in terms of managing the scale of public safety networks.

8. Conclusion

The debate over centralized versus decentralized provision of public safety network has been around for a long time. This work introduces one important dimension – interoperability– to the problem of providing public safety network. From the technology perspective, public safety networks are unique compared to other public goods. For most public goods such as highways, available technologies are standard and thus interoperability is not an issue. For public safety networks, however, multiple available technologies exist (e.g., radio frequencies allocated, wireless communication standards, communication devices, etc.) and thus local or central jurisdictions preferences for integrating these technologies to create an interoperable network are highly heterogeneous. This work captures the unique properties of public safety networks through the choices of integration effort and public good levels selected by local and central governments. The interoperability, public good levels, and the overall social surplus of the resulting systems are compared between centralized and decentralized provisions. We find that the equilibrium interoperability level increases in the degree of spillover from the value of public safety network for both centralized and decentralized provision strategies. We further show that the districts' incentive to adopt centralized provision critically depends on the sharing rule for the cost of integration effort. Compared to equal cost-sharing, spillover-based cost-sharing is more appropriate to set proper incentives for individual districts toward efficient provisions of public safety network. Finally, we propose an optimal cost-sharing rule, which leads to social optimum but requires a regulatory intervention such as a social planner mandates the proportion of the integration cost for individual district.

Our work also provides a comprehensive framework for analyzing the key tradeoffs between centralized and decentralized provision of public safety networks. Findings in this paper shed light upon provision policies regarding public safety networks. The majority of public opinion suggests maximizing interoperability through centralized provision. Our findings identify several potential drawbacks of this implementation strategy: (i) local needs are compromised; (ii) optimal cost-sharing that leads to social optimum cannot be achieved without a regulatory intervention under centralized provision; (iii) compared to the social optimum, the centralized system over-provides on both public good levels and integration effort for public safety networks when the integration efficiency of decentralized system is high. These drawbacks from centralized provision must be weighed against the benefits of improved interoperability in determining provision policies.

Appendix. Proof of Propositions

Proof of Proposition 1 – Decentralized Provision

In decentralized provision, local governments make their public good and integration effort decisions simultaneously to maximize the total surplus within their districts.

Proposition 1a: follows immediately from the equilibrium results of the optimal public good levels (g^*_{1d}, g^*_{2d}) by solving the two maximization problems in formulations (3) and (4) simultaneously.

Proposition 1b: To show that the integration effort levels of the two districts increase in the degree of spillover κ and the efficiency in integration effort β, we take the partial derivatives of the optimal integration effort level of each district with respect to both parameters:

$$\frac{\partial e_1^*}{\partial \kappa} = \frac{\partial e_2^*}{\partial \kappa} = \frac{m_1 m_2 \beta\,[1-2\kappa]}{4\bar{e}p\delta}$$
$$\frac{\partial e_1^*}{\partial \beta} = \frac{\partial e_2^*}{\partial \beta} = \frac{m_1 m_2 \kappa\,[1-\kappa]}{4\bar{e}p\delta}$$

Since $m_1 > 0$, $m_2 > 0$, $\bar{e} > 0$, $p > 0$, $\delta > 0$ and $\kappa \in [0, 0.5]$, we have $\frac{\partial e_1^*}{\partial \kappa} = \frac{\partial e_2^*}{\partial \kappa} > 0$ as well as $\frac{\partial e_1^*}{\partial \beta} = \frac{\partial e_2^*}{\partial \beta} > 0$.

Proposition 1c: follows from the proof of Proposition 1b. The total integration effort level $e_1^* + e_2^*$ and hence the interoperability level $\beta\left[\frac{e_1^*+e_2^*}{\bar{e}}\right]$ increase in both κ and β because the equilibrium integration effort levels of both districts (i.e., e_1^* and e_2^*) increase in the degree of κ and β.

Q.E.D.

Proof of Proposition 2 – Centralized Provision

In centralized provision, the central government chooses different public good levels g_{1c}, g_{2c} of public safety networks and a single integration effort level e for interoperability by solving the maximization problem as in formulation 5. In order to use the FOCs to obtain the optimal equilibrium results, we must check the second order conditions for g_1, g_2 and e with respect to the total social surplus function $S_c(g_{1c}, g_{2c}, e)$:

$$\frac{\partial^2 S_c(g_{1c}, g_{2c}, e)}{\partial {g_1}^2} = -2p$$
$$\frac{\partial^2 S_c(g_{1c}, g_{2c}, e)}{\partial {g_2}^2} = -2p$$
$$\frac{\partial^2 S_c(g_{1c}, g_{2c}, e)}{\partial e^2} = -2\delta$$

Since $p > 0$ and $\delta > 0$, we have $\frac{\partial^2 S_c(g_{1c}, g_{2c}, e)}{\partial {g_1}^2} < 0$, $\frac{\partial^2 S_c(g_{1c}, g_{2c}, e)}{\partial {g_2}^2} < 0$ and $\frac{\partial^2 S_c(g_{1c}, g_{2c}, e)}{\partial e^2} < 0$, indicating the total social surplus function in centralized provision is strictly concave with respect to all three decision variables. Hence, the FOCs yield the optimal results that maximize the total social surplus function.

Proposition 2a: To show that the optimal public good level of both districts (i.e., g^*_{1c} and g^*_{2c}) increase in the degree of the public good preference level of the other district, we take the partial derivatives of the optimal public good level of each district with respect to the public good preference level of the other district. Note that although the integration effort levels of e_1^* and e_2^* do not affect the equilibrium public good levels

g_{1d}^* and g_{2d}^* in the decentralized provision, the single integration effort level e^* does affect the equilibrium public good levels g_{1c}^* and g_{2c}^* in the centralized provision.

$$\frac{\partial g_{1c}^*}{\partial m_2} = \frac{2m_1m_2\left[1-\kappa\right]\kappa^2\left[4\bar{e}^2p\delta - {m_1}^2\kappa^2\right]}{p\left[4\bar{e}^2p\delta - \left[{m_1}^2+{m_2}^2\right]\kappa^2\right]^2}$$
$$\frac{\partial g_{2c}^*}{\partial m_1} = \frac{2m_1m_2\left[1-\kappa\right]\kappa^2\left[4\bar{e}^2p\delta - {m_2}^2\kappa^2\right]}{p\left[4\bar{e}^2p\delta - \left[{m_1}^2+{m_2}^2\right]\kappa^2\right]^2}$$

Since $m_1 > m_2 > 0$ and $4\bar{e}^2p\delta - {m_2}^2\kappa^2 > 4\bar{e}^2p\delta - {m_1}^2\kappa^2 > 4\bar{e}^2p\delta - \left[{m_1}^2+{m_2}^2\right]\kappa^2 > 0$, we have $\frac{\partial g_{1c}^*}{\partial m_2} > 0$ and $\frac{\partial g_{2c}^*}{\partial m_1} > 0$.

Proposition 2b: To show that the integration effort level e^* and hence the interoperability level $I(e^*) = \frac{e^*}{\bar{e}}$ increase in the degree of spillover, we take the partial derivative of the optimal integration effort level e^* with respect to κ:

$$\frac{\partial e^*}{\partial \kappa} = \frac{2\bar{e}m_1m_2\left[4\bar{e}^2p\delta\left[1-2\kappa\right] + \left[{m_1}^2+{m_2}^2\right]\kappa^2\right]}{p\left[4\bar{e}^2p\delta - \left[{m_1}^2+{m_2}^2\right]\kappa^2\right]^2}$$

Since $m_1 > 0$, $m_2 > 0$, $\bar{e} > 0$, $p > 0$, $\delta > 0$ and $\kappa \in [0, 0.5]$, we have $\frac{\partial e^*}{\partial \kappa} > 0$.

Q.E.D.

Proof of Proposition 3 – Adoption of Centralized or Decentralized Provision

Individual district compare their surpluses under centralized provision (S_{1c}^* and S_{2c}^*) to those under decentralized provision (S_{1d}^* and S_{2d}^*) and select the system with higher surplus.

Proposition 3a: Individual district prefers the centralized provision over decentralized provision if and only if the centralized provision brings higher social surplus to the local district than the decentralized provision, i.e., $S_{ic}^* > S_{id}^*$. Since β_i denotes the threshold value where the surplus from the decentralized provision is equivalent to the surplus from the centralized provision for District i, if $\beta < \beta_1$, then $S_{1c}^* > S_{1d}^*$ indicating District 1 prefers centralized provision. Similarly, if $\beta < \beta_2$, then $S_{2c}^* > S_{2d}^*$ indicating District 2 prefers centralized provision.

Proposition 3b: Define $W_i = {\beta_i}^2$

$$\left[\beta_1+\beta_2\right]\left[\beta_1-\beta_2\right] = {\beta_1}^2 - {\beta_2}^2 = W_1 - W_2 = \frac{16\bar{e}^2\left[{m_1}^2-{m_2}^2\right]p\delta\kappa^2}{\left[4\bar{e}^2p\delta - \left[{m_1}^2+{m_2}^2\right]\kappa^2\right]^2}$$

Since $m_1 \geq m_2$ by Assumption 1, we have $W_1 - W_2 = \frac{16\bar{e}^2\left[{m_1}^2-{m_2}^2\right]p\delta\kappa^2}{\left[4\bar{e}^2p\delta - \left[{m_1}^2+{m_2}^2\right]\kappa^2\right]^2} \geq 0$. Therefore $\left[\beta_1+\beta_2\right]\left[\beta_1-\beta_2\right] \geq 0$. Since $\beta_1 > 0$ and $\beta_2 > 0$, in order to have $\left[\beta_1+\beta_2\right]\left[\beta_1-\beta_2\right] \geq 0$, we must have $\beta_1 - \beta_2 \geq 0$, indicating $\beta_1 \geq \beta_2$.

Proposition 3c: follows immediately by the description and the definitions of β_i, as we consider the outcome of centralized or decentralized provisions as a collective decision by the local governments.

Q.E.D.

Proof of Proposition 4 – Spillover-based versus Equal Sharing of Integration Effort Cost

Define $W_i = {\beta_i}^2$ and $\tilde{W}_i = {\tilde{\beta}_i}^2$

Proposition 4a: Compare the threshold under spillover-based cost-sharing, $\tilde{\beta}_1$, with the threshold under equal cost-sharing, β_1.

$$\left[\tilde{\beta_1}-\beta_1\right]\left[\tilde{\beta_1}+\beta_1\right]=\tilde{\beta_1}^2-\beta_1^2=\tilde{W_1}-W_1=-\frac{8\bar{e}^2\left[m_1^2-m_2^2\right]p\delta\kappa^2}{3\left[4\bar{e}^2p\delta-\left[m_1^2+m_2^2\right]\kappa^2\right]^2}$$

Since $m_1>m_2$, we have $\tilde{W_1}-W_1=-\frac{8\bar{e}^2\left[m_1^2-m_2^2\right]p\delta\kappa^2}{3\left[4\bar{e}^2p\delta-\left[m_1^2+m_2^2\right]\kappa^2\right]^2}<0$. Since $\tilde{\beta_1}>0$ and $\beta_1>0$, in order to have $\left[\tilde{\beta_1}-\beta_1\right]\left[\tilde{\beta_1}+\beta_1\right]<0$, we must have $\tilde{\beta_1}-\beta_1<0$, indicating $\tilde{\beta_1}<\beta_1$.

Proposition 4b: Compare the threshold under spillover-based cost-sharing, $\tilde{\beta_2}$, with the threshold under equal cost-sharing, β_2.

$$\left[\tilde{\beta_2}-\beta_2\right]\left[\tilde{\beta_2}+\beta_2\right]=\tilde{\beta_2}^2-\beta_2^2=\tilde{W_2}-W_2=\frac{40\bar{e}^2\left[m_1^2-m_2^2\right]p\delta\kappa^2}{3\left[4\bar{e}^2p\delta-\left[m_1^2+m_2^2\right]\kappa^2\right]^2}$$

Since $m_1>m_2$, we have $\tilde{W_2}-W_2=\frac{40\bar{e}^2\left[m_1^2-m_2^2\right]p\delta\kappa^2}{3\left[4\bar{e}^2p\delta-\left[m_1^2+m_2^2\right]\kappa^2\right]^2}>0$. Since $\tilde{\beta_2}>0$ and $\beta_2>0$, in order to have $\left[\tilde{\beta_2}-\beta_2\right]\left[\tilde{\beta_2}+\beta_2\right]>0$, we must have $\tilde{\beta_2}-\beta_2>0$, indicating $\tilde{\beta_2}>\beta_2$.

Proposition 4c: Compare the threshold difference under spillover-based cost-sharing i.e., $\tilde{\beta_1}-\tilde{\beta_2}$, with the threshold difference under equal cost-sharing, i.e., $\beta_1-\beta_2$.

From Proposition 4a we have $\tilde{\beta_1}-\beta_1<0$

From Proposition 4b we have $\beta_2-\tilde{\beta_2}<0$

Adding the above inequalities together, we have $\tilde{\beta_1}-\beta_1+\beta_2-\tilde{\beta_2}=\left[\tilde{\beta_1}-\tilde{\beta_2}\right]-\left[\beta_1-\beta_2\right]<0$

Indicating $\tilde{\beta_1}-\tilde{\beta_2}<\beta_1-\beta_2$

Q.E.D.

Proof of Proposition 5 – Social Optimum

Based on the analyses in Section 4, we know that $S_{1d}^*=\frac{m_1^2[1-\kappa]^2\left[4\bar{e}p\delta+3m_2^2\beta^2\kappa^2\right]}{16\bar{e}^2p^2\delta}$ and $S_{2d}^*=\frac{m_2^2[1-\kappa]^2\left[4\bar{e}p\delta+3m_1^2\beta^2\kappa^2\right]}{16\bar{e}^2p^2\delta}$. Thus, $S_d^*=\frac{[1-\kappa]^2\left[2\bar{e}^2p\delta\left[m_1^2+m_2^2\right]+3m_1^2m_2^2\beta^2\kappa^2\right]}{8\bar{e}^2p^2\delta}$. Based on the analyses in Section 5, we know that $S_c^*=\frac{[1-\kappa]^2\left[4\bar{e}^2p\delta\left[m_1^2+m_2^2\right]-\left[m_1^2-m_2^2\right]^2\kappa^2\right]}{4p\left[4\bar{e}^2p\delta-\left[m_1^2+m_2^2\right]\kappa^2\right]}$. Therefore, $S_c^*\geq S_d^*$ if and only if $\beta<\hat{\beta}=\frac{8^{\frac{1}{2}}\bar{e}p^{\frac{1}{2}}\delta^{\frac{1}{2}}}{\left[12\bar{e}^2p\delta-3\left[m_1^2+m_2^2\right]\kappa^2\right]^{\frac{1}{2}}}$.

Q.E.D.

Proof of Proposition 6 – Comparison of Decentralized, Centralized and Social Optimum Provision

Based on the results in Proposition 3, District 1 prefers centralized provision if $\beta\leq\beta_1=\frac{4\bar{e}p^{\frac{1}{2}}\delta^{\frac{1}{2}}\left[2\bar{e}^2p\delta+\left[m_1^2-2m_2^2\right]\kappa^2\right]^{\frac{1}{2}}}{3^{\frac{1}{2}}\left[4\bar{e}^2p\delta-\left[m_1^2+m_2^2\right]\kappa^2\right]}$ and District 2 prefers centralized provision if $\beta\leq\beta_2=\frac{4\bar{e}p^{\frac{1}{2}}\delta^{\frac{1}{2}}\left[2\bar{e}^2p\delta-\left[2m_1^2-m_2^2\right]\kappa^2\right]^{\frac{1}{2}}}{3^{\frac{1}{2}}\left[4\bar{e}^2p\delta-\left[m_1^2+m_2^2\right]\kappa^2\right]}$. Based on the results in Proposition 5, the social planner prefers centralized provision if $\beta\leq\hat{\beta}=\frac{8^{\frac{1}{2}}\bar{e}p^{\frac{1}{2}}\delta^{\frac{1}{2}}}{\left[12\bar{e}^2p\delta-3\left[m_1^2+m_2^2\right]\kappa^2\right]^{\frac{1}{2}}}$. Since $\frac{\beta_1^2}{\hat{\beta}^2}\geq 1\geq\frac{\beta_2^2}{\hat{\beta}^2}$, we get $\beta_1\geq\hat{\beta}\geq\beta_2$.

Q.E.D.

Proof of Proposition 7 – Optimal Sharing Rule for Integration Effort Cost

District 1 would prefer the centralized provision if $\beta<\beta_1(\phi)=\frac{4\bar{e}p^{\frac{1}{2}}\delta^{\frac{1}{2}}\left[2\bar{e}^2p\delta[1-\phi]+\left[m_1^2-2m_2^2\right]\kappa^2\right]^{\frac{1}{2}}}{3^{\frac{1}{2}}\left[4\bar{e}^2p\delta-\left[m_1^2+m_2^2\right]\kappa^2\right]}$ and District 2 would prefer the centralized provision if $\beta<\beta_2(\phi)=\frac{4\bar{e}p^{\frac{1}{2}}\delta^{\frac{1}{2}}\left[2\bar{e}^2p\delta\phi-\left[2m_1^2-m_2^2\right]\kappa^2\right]^{\frac{1}{2}}}{3^{\frac{1}{2}}\left[4\bar{e}^2p\delta-\left[m_1^2+m_2^2\right]\kappa^2\right]}$. Solving $\beta_1(\phi)=\beta_2(\phi)=\hat{\beta}$ yields $\phi^*=\frac{1}{2}+\frac{3[m_1-m_2][m_1+m_2]\kappa^2}{8\bar{e}^2p\delta}$. Since $m_1>m_2$, we know that $\phi^*>\frac{1}{2}$. Furthermore, $\frac{\partial\phi^*}{\partial[m_1-m_2]}=\frac{3[m_1+m_2]\kappa^2}{8\bar{e}^2p\delta}>0$, $\frac{\partial\phi^*}{\partial\kappa}=\frac{6[m_1-m_2][m_1+m_2]\kappa}{8\bar{e}^2p\delta}>0$, $\frac{\partial\phi^*}{\partial p}=-\frac{3[m_1-m_2][m_1+m_2]\kappa^2}{8\bar{e}^2p^2\delta}<0$, and $\frac{\partial\phi^*}{\partial\delta}=-\frac{3[m_1-m_2][m_1+m_2]\kappa^2}{8\bar{e}^2p\delta^2}<0$.

Q.E.D.

Proof of Proposition 8 – Socially Optimal Centralized versus Decentralized Provision

Based on the analyses in Section 4, we know that $g_{1d}^* = \frac{m_1[1-\kappa]}{2p}$, $g_{2d}^* = \frac{m_2[1-\kappa]}{2p}$, $e_1^* = e_2^* = \frac{m_1 m_2 \beta\kappa[1-\kappa]}{4\bar{e}\delta p}$. Based on the analyses in Section 5, we know that $g_{1c}^* = \frac{m_1[1-\kappa]\left[4\bar{e}^2 p\delta - \left[m_1^2 - m_2^2\right]\kappa^2\right]}{2p\left[4\bar{e}^2 p\delta - \left[m_1^2 + m_2^2\right]\kappa^2\right]}$, $g_{2c}^* = \frac{m_2[1-\kappa]\left[4\bar{e}^2 p\delta + \left[m_1^2 - m_2^2\right]\kappa^2\right]}{2p\left[4\bar{e}^2 p\delta - \left[m_1^2 + m_2^2\right]\kappa^2\right]}$, $e^* = \frac{2\bar{e} m_1 m_2 \kappa[1-\kappa]}{4\bar{e}^2 p\delta - \left[m_1^2 + m_2^2\right]\kappa^2}$. Since $\frac{4\bar{e}^2 p\delta - \left[m_1^2 - m_2^2\right]\kappa^2}{4\bar{e}^2 p\delta - \left[m_1^2 + m_2^2\right]\kappa^2} > 1$, we know $g_{1c}^* > g_{1d}^*$. Since $\frac{4\bar{e}^2 p\delta + \left[m_1^2 - m_2^2\right]\kappa^2}{4\bar{e}^2 p\delta - \left[m_1^2 + m_2^2\right]\kappa^2} > 1$, we know $g_{2c}^* > g_{2d}^*$. Since $\frac{e^*}{\bar{e}} - \beta\left[\frac{e_1^* + e_2^*}{\bar{e}}\right] = \left[\frac{m_1 m_2 \kappa[1-\kappa]}{2}\right]\left[\frac{4}{4\bar{e}^2 p\delta - \left[m_1^2 + m_2^2\right]\kappa^2} - \frac{\beta^2}{\bar{e}^2 p\delta}\right] \geq 0,\ I_c = \frac{e^*}{\bar{e}} \geq I_d = \beta\left[\frac{e_1^* + e_2^*}{\bar{e}}\right]$. If $\beta > \bar{\beta}$, then the decentralized system is socially optimal and thus the centralized system over-provides on both public good levels and integration effort for public safety networks. If $\beta \leq \hat{\beta}$, then the centralized system is socially optimal and thus the decentralized system under-provides on both public good levels and interoperability level for public safety networks.

Q.E.D.

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