Competition of Multi-Platform Ecosystems in the IoT

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Abstract

The Internet of Things (IoT) is a significant technology trend that may transform business and society. Consumer IoT devices, such as smartwatches and smart speakers, create significant value for consumers. This article proposes a novel analytical model that captures strategic behavior in the consumer IoT context. We introduce the concept of a *multi-platform ecosystem* orchestrated by a *multi-platform firm*. A multi-platform firm offers a *system of platforms*, such as a smartphone and a smart speaker. We analyze the competition of *multi-platform ecosystems,* and we show how firm choices affect consumers and market outcomes. Moreover, we identify distinct eras of competition that formalize the IoT evolution, which results from firms adding new device capabilities over time. We show that a vendor's smart platform device that is a networked complement for its smartphone may become a substitute, i.e. consumers will stop using the vendor's smartphone and they will use only the vendor's smart device (or the smart device of a competing vendor). We also characterize conditions under which it is profitable for a vendor to make its new platform device look more like its smartphone. Overall, we provide insights on *multi-platform firms* and how they differ from *platform firms.* We identify opportunities for future research on the economics and strategy of *multi-platform ecosystems*.

Keywords: Internet of Things (IoT), Platform, Ecosystem, Multi-platform Ecosystem, System of Platforms, Network Effects, Wearables, Multi-platform firm, Business model, Multi-platform business model, Cross-platform network effects, Digital Transformation, Competition, Analytical Model, Hotelling

1. Introduction

The Internet of Things (IoT) concept refers to everyday objects that feature processing power and software, sensor, and actuator capabilities, and interconnect with the rest of the Internet (Whitmore *et al*., 2015). IoT is one of the most significant contemporary technology and business trends, and it has the potential to transform business (Adamopoulos *et al.* 2020; Shim *et al.* 2019). IoT promises the integration of physical and digital worlds and the creation of new value. It could make supply chains more efficient and transform agriculture and several other industries. For consumers, smart IoT devices including smartwatches (e.g., Apple Watch) and smart home appliances (e.g., Amazon Echo) create new value for consumers.

Smart, connected products are transforming companies and competition (Porter & Heppelmann 2014, 2015). New IoT products and markets (Ng *et al.*, 2017; Nguyen *et al.*, 2017) and new IoT business models (Dijkman *et al.*, 2015; Metallo *et al.*, 2018) are expected to have a significant business and economic impact. However, there exists very little economic modeling research on IoT (Lu *et al.*, 2018). Our work fills this gap by proposing an analytical model of competition in the consumer IoT.

The first key observation that motivates our research is that a consumer IoT firm may offer two platform devices: A smartphone and another smart device, such as a smartwatch or smart speaker. Each device could be a platform that enables device users to interact with applications (apps) developed by outside app developers. A firm that offers multiple platform devices is a *multi-platform firm*. It offers a *system of platforms* and orchestrates a *multi-platform ecosystem*. The multi-platform ecosystem consists of all the users and app developers for all the platform devices offered by the firm.

Strategic behavior in the context of multi-platform ecosystems is a novel phenomenon not researched before. Our article formalizes the multi-platform ecosystem concept and proposes a novel analytical model of competition of multi-platform ecosystems. It considers two competing firms, each offering two platform devices, *i.e.,* a smartphone and another smart device. Devices of the same type are horizontally differentiated. The article characterizes strategic behavior in this setting and shows how firms' multi-platform design choices affect consumer choices and market outcomes.

The second key observation that drives our work is that the consumer IoT landscape is rapidly evolving as vendors add new device capabilities. For example Apple introduced Apple Watch in 2015, and it keeps releasing a new series yearly—the latest Series 5 was released in September 2019 (https://www.apple.com/watch/). In order to capture this IoT device evolution, our article identifies and formalizes four distinct eras for two different classes of devices. As a motivating example, let us consider smartwatches and smart speakers as two classes of devices in the consumer IoT spectrum. At present, many vendors have developed smart devices that depend on a compatible smartphone to function. Thus, the smart device (e.g., Apple Watch) functions as a hardware app that is a complement to its compatible smartphone platform (iOS) and adds value to that platform through cross-side network effects. However, as a smart device becomes independent enough and developers build applications for it directly, the next-generation smart device's network may transform from a *complement* to the original network into a *substitute* for it. Our article characterizes conditions for that transition (Proposition 4).

Overall, motivated by the consumer IoT context, this article addresses the research question of how the strategies of *multi-platform firms* differ from those of traditional platform firms. A *multi-platform firm* coordinates a *multi-platform ecosystem*. Whereas a traditional platform firm needs to consider the interaction between the platform sides (cross-side network effects) and competition from other platform firms, a *multi-platform firm* needs to consider the interaction between the sides of each platform it offers, the interaction between the platforms in their *system of platforms*, and competition from other platforms (which may themselves be part of multi-platform ecosystems).

We summarize the main questions we aim to answer: What is the effect of a firm transitioning from a *platform firm* to a *multi-platform firm*? How does competition of multi-platform firms differ from competition of platform firms? When does the new platform device becomes a *substitute* for the smartphone, such that users cease adopting the smartphone? What is effect of designing the new platform device to look more like the smartphone?

The rest of the article is structured as follows. Section 2 discusses the related literature. Section 3 presents the model. Section 4 provides analysis and results from the different eras of competition. Section 5 analyzes model extensions exploring *cross-platform network effects*. The last section discusses insights, managerial implications, and future research directions.

2. Related literature

The multisided platforms literature is the closest research stream to our work. A multisided platform provides an infrastructure that facilitates the interaction between two (or more) sides of platform participants. A platform firm needs to consider the cross-side network effects between the two sides and set a price structure and price level that maximizes the platform profit (Armstrong 2006; Rochet & Tirole, 2003; Rochet & Tirole 2006). The platform firm may charge both sides, let one side access the platform for free, or subsidize one side. The platform firm faces a coordination (chicken-and-egg) problem: agents from one side are unwilling to join the platform, unless agents from the other side are already in the platform. The firm must solve the coordination problem between the two sides in order to ensure platform survival and growth.

While the earlier literature on network effects (Katz & Shapiro, 1994; Economides, 1996) recognized that network effects play an important role in technology and digital markets, it was the platforms literature that recognized the importance of indirect network effects within platform business models and strategies. Technology giants, such as Apple, Google, Amazon, Alibaba, Tencent, Uber, AirBnB provide excellent examples of firms leveraging platform strategies to disrupt traditional industries and dominate new markets.

A large number of analytical modeling articles contribute to our understanding of the economics of platforms. Important issues concering platform firms include pricing (Parker & Van Alstyne, 2005; Hagiu, 2006; Yoo *et al.* 2007; Bakos & Katsamakas, 2008), openness (Boudreau, 2010; Economides & Katsamakas, 2006; Niculescu *et al.* 2018; Parker *et al.*, 2017; Parker & Van Alstyne, 2018; Katsamakas & Xin, 2019), seller competition on a platform (Belleflamme & Peitz, 2019a), and multihoming (Belleflamme & Peitz, 2019b). Eisenmann *et al.* (2011) propose an economic model of platform envelopment. Other work compares the platform business model to a reseller model (Hagiu & Wright, 2015). Most recent analytical models examine whether a platform should encourage new products and sellers (Hagiu & Wright, 2019), whether a product firm should become a platform by hosting rival firms (Hagiu *et al.*, 2020), and investments in platform integration (Tan *et al.* 2020). Lin *et al.* (2020) propose a dynamic model of platform competition and analyze the effects of decreasing hardware production costs over time.

Overall, previous analytical modeling literature examines multiple strategic considerations of platform firms and platform competition. Our article introduces the concept of a *multi-platform* firm that coordinates a *multi-platform ecosystem*. We define and formalize these concepts and we analyze competition of multi-platform firms in a rigorous analytical framework presented next.

3. Model

We consider a model in which two firms A and B compete in the consumer IoT by selling platform devices. Developers build apps for the platform devices and Consumers adopt platform devices to benefit from using the devices and their apps.

3.1 Firms A, B

At first each firm sells only a smartphone (Phone). Smartphones are platform devices. They connect app Developers with Consumers to create positive cross-side network effects. Developers benefit when more Consumers use the smartphone, and Consumers benefit when more Developers develop apps for the smartphone. We call this model setup Era W1/S1 and it is the baseline model (see Figure 1).

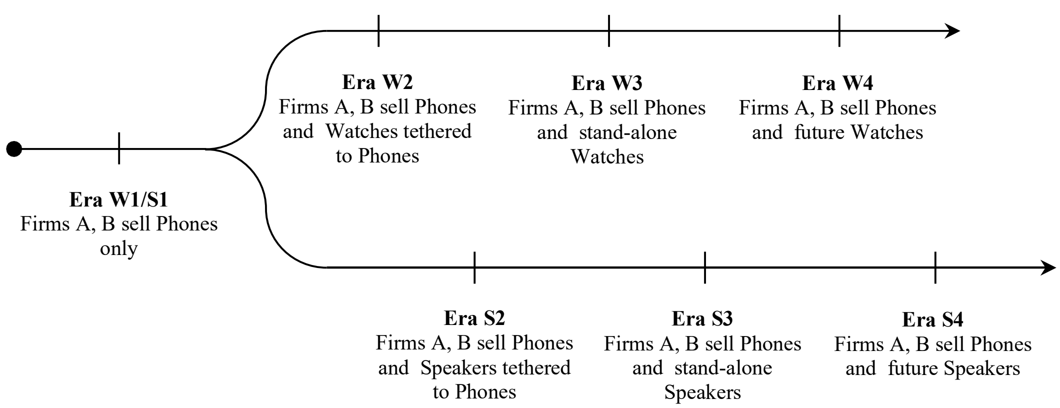

Figure 1: Consumer IoT platform eras as firms A, B introduce new platform devices over time. The two paths are distinct.

After Era W1/S1, firms A, B introduce new platform devices as they evolve their strategies in the consumer IoT landscape. We consider two types of new platform devices: smartwatches (Watches) and smart speakers (Speakers). These are formally defined in 3.4 below.

As firms introduce new platform devices over time, there are three different eras for each type of device. At first the new platform device is tethered to the Phone of the firm (Era W2 for the Watch, and Era S2 for the Speaker). This means that a consumer can use a Watch only is they have the matching Phone.

In the next era, firms offer a new platform device that can function as a stand-alone device (Era W3 for the Watch, and Era S3 for the Speaker). This permits consumers to mix and match between vendors if desired.

In the last era the firms introduce future Watches (Era W4) or future Speakers (Era S4). The fourth era adds additional phone-like functions to the new platform devices that lead to Consumers having positively correlated preferences between a given firm's devices.

The new platform devices (Watch in Eras W2-W4 or Speaker in Eras S2-S4) connect app Developers with Consumers to create positive cross-side network effects: Developers benefit when more Consumers use the new platform device, and Consumers benefit when more Developers develop apps for the platform device.

While in Era W1/S1 firms A and B are platform firms, after Era W1/S1, firm A is a *multi-platform firm* and firm B is a competing *multi-platform firm*. Each firm offers a *system of platforms*, and each firm orchestrates a *multi-platform ecosystem*. Our model considers how those *multi-platform ecosystems* compete under different eras. Figure 2 illustrates and Table 1 summarizes these concepts.

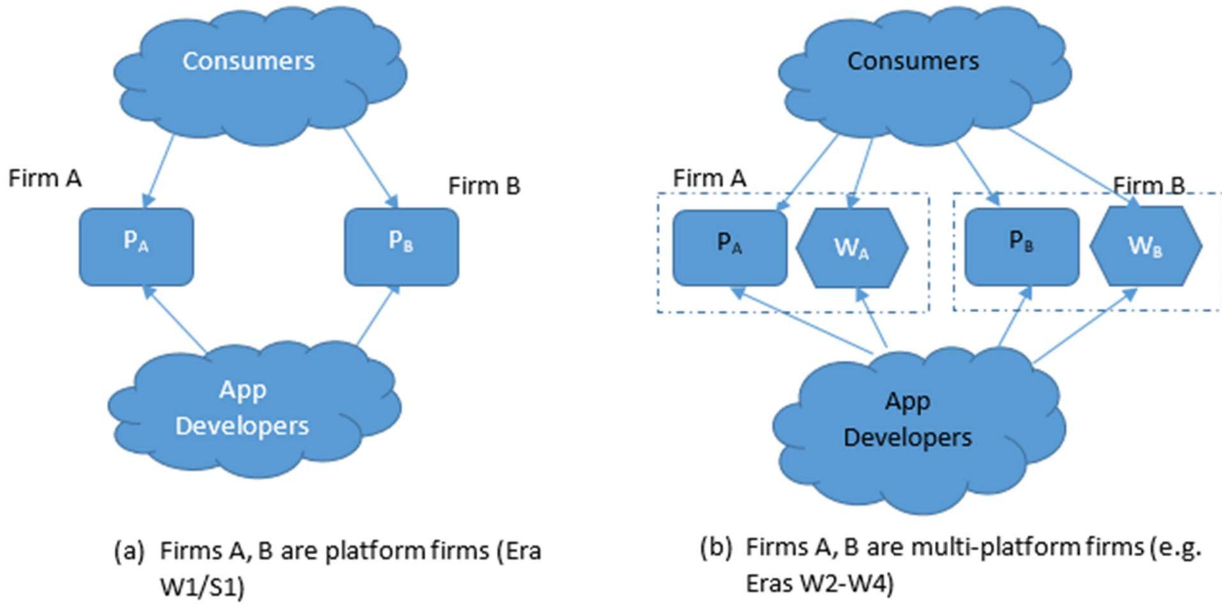

Figure 2: Illustration of our analytical framework contrasting competition of (a) platform firms, and (b) multi-platform firms.

Firms A, B maximize their profits from all platform devices they offer in a particular era. For each platform device that Firms A, B offer, they set a price for Consumers to purchase the device and an access price for Developers.

Table 1: Summary of concepts

	Era W1/S1	Eras W2-W4	Eras S2-S4
Firms	A, B	A, B	A, B
Platform devices	Phone A, Phone B	Phone A, Phone B Watch A, Watch B	Phone A, Phone B Speaker A, Speaker B
Type of firms	A, B are platform firms	A, B are *multi-platform firms*	A, B are *multi-platform firms*
Type of ecosystems	A, B orchestrate platform ecosystems	A, B orchestrate *multi-platform ecosystems*	A, B orchestrate *multi-platform ecosystems*
Type of competition	Platform competition	*Multi-platform competition*	*Multi-platform competition*

3.2 Consumers

We now focus on Consumer preferences for Phones and new platform devices. For expositional clarity let us discuss the case that the new platform device is a Watch[1]. Consumers have unit demand for at most one smartphone and at most one smartwatch. This means that they single-home separately for each type of device (e.g. a consumer that buys a Phone from firm A, will not buy a Phone from firm B, and a consumer that buys Watch from firm A will not buy a Watch from B).

Consumers are represented in a *Consumers' Hotelling square*: They have horizontal preferences for devices that we model as uniformly distributed locations in a Hotelling square (Figure 3a), with the x-axis related to smartwatches and y-axis related to smartphones. Distance from a device represents a misfit cost that might arise from the Consumer's tastes for specific features, form factors, and aesthetics. The example Consumer in Figure 3a has a distinct preference for smartwatch A over smartwatch B but prefers smartphone B only slightly over smartphone A. The location of each device is also illustrated in Figure 3a.

[1] We discuss Watches here for expositional clarity. The discussion about Speakers is similar, with a change in model parameters.

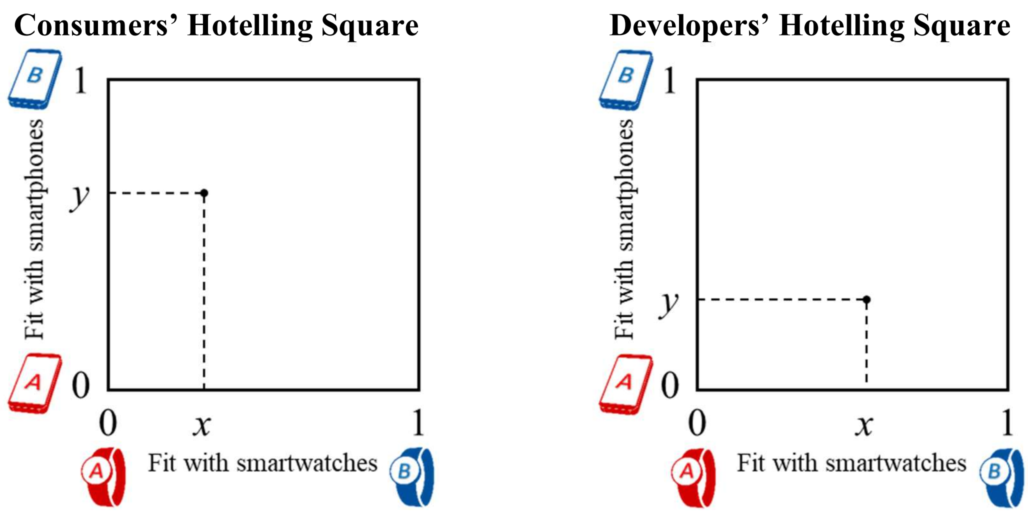

Figure 3: (a) Consumers' Hotelling square of preferences for using smartphones and smartwatches, and (b) Developers' Hotelling square of preferences for building apps for smartphones and smartwatches.

We index a system $\{i, j\}$ by the watch i and phone j purchased from firm A, firm B, or $\varnothing$ (no purchase) as illustrated in Figure 4. Then, the utility function of a Consumer located at (x, y) in the Consumers' Hotelling square using system $\{i, j\}$ is shown in equation (1). The utility is additively separable in utility from the watch u_{Wi},utility from the phone u_{Pj}, and prices P_{Wi} and P_{Pj}.

$$U_{i,j}(x, y) = u_{Wi}(x) + u_{Pj}(y) - P_{Wi} - P_{Pj} \tag{1}$$

The component utilities from the watch and phone derive from an intrinsic utility of the device itself as if it was the Consumer's ideal device (u_W and u_P), cross-side networks effects (N_W and N_P) scaled by the quantity of Developers associated with each device (q_{Wi} and q_{Pj}), and disutility (T_W and T_P) scaled by the difference between a Consumer's ideal device (x and y) and the actual device.

$$\begin{aligned} u_{WA}(x) &= u_W + N_W \cdot q_{WA} - x \cdot T_W & u_{PA}(y) &= u_P + N_P \cdot q_{PA} - y \cdot T_P \\ u_{WB}(x) &= u_W + N_W \cdot q_{WB} - (1-x) \cdot T_W & u_{PB}(y) &= u_P + N_P \cdot q_{PB} - (1-y) \cdot T_P \end{aligned}$$

The utility of the outside option (non-purchase) is normalized to zero. Our model's notation is summarized in Table 2.

Figure 4 shows examples of different adoption options for consumers. A consumer may adopt a Phone only as shown in 3(a), and that is feasible in all Eras (W1/S1, W2-W4, S2-S4). Figure 4(b) shows that a consumer may adopt a Phone and a new platform device from a single vendor, and that is feasible in all Eras except Era W1/S1. Recall that firms A, B sell Phone Figure 4(c) shows that a consumer may adopt devices from different vendors, and that is feasible in Eras W3-W4 and Eras S3-S4 only.

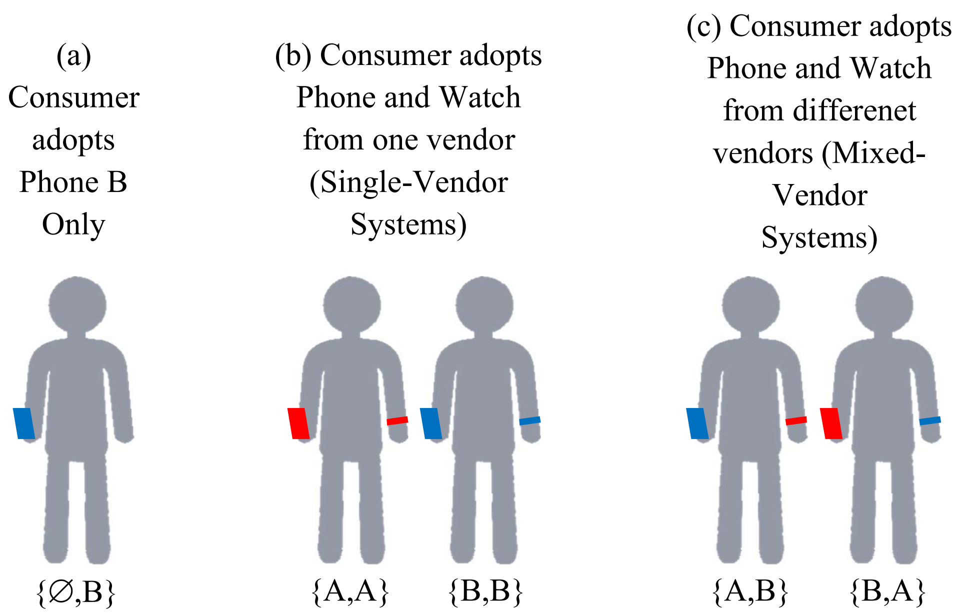

Figure 4: Illustrative cases of Consumer adoption patterns for smartphones and smartwatches. In each case, the red device is from firm A and the blue device is from firm B. Case (a) is feasible in all Eras; Case (b) is feasible in all watch Eras except W1/S1; Case (c) is feasible in watch Eras W3-W4 only.

3.3 App Developers

Developers develop apps to maximize their profit from apps. Developers are allowed to multi-home, so they develop apps for any combination of platform devices available in the market in a particular era. For example a developer may develop apps for Phone A, and Phone B, as well as Watch A and Watch B.

Developers are heterogeneous with respect to the cost of developing applications, and they are uniformly distributed across a *Developers' Hotelling square* (Figure 2), with the *x*-axis related to fit with specific smartwatches and *y*-axis related fit with specific smartphones. The distance along a dimension between the Developer and device creates a misfit cost that might arise from the availability of sensors, the device's form factor, the vendor's policies on content, and the platform's security posture. The example Developer depicted in Figure 2 has app ideas that have almost identical levels of misfit with each smartwatch, but can develop apps for smartphone A relatively easily.

The value function of a Developer located at (x, y) in Developers' Hotelling square is shown in equation (2). Value is additively separable in each device for which the Developer chooses to create apps, and each of these is in turn additively separable in economic value to the Developer (v) and prices paid to the platform (p).[2]

$$V_{i,j}(x,y)=\left(\sum_{i=\{A,B\}}\max\left[v_{Wi}(x)-p_{Wi},0\right]\right)+\left(\sum_{j=\{A,B\}}\max\left[v_{Pj}(y)-p_{Pj},0\right]\right) \quad (2)$$

The component value for each device derives from an intrinsic value of developing the app itself (*e.g.*, knowledge and digital assets less effort) on an ideal platform represented by v_W and v_P, cross-side network effects (marginal revenue from sales) represented by n_W and n_P, scaled by the quantity of Customer on that device represented by Q_{Wi} and Q_{Pj}, and disutility (t_W and t_P) scaled by the difference between a Developer's ideal device (x and y) and the actual device.

$$v_{WA}(x)=v_W+n_W\cdot Q_{WA}-x\cdot t_W \qquad v_{PA}(y)=v_P+n_P\cdot Q_{PA}-y\cdot t_P$$
$$v_{WB}(x)=v_W+n_W\cdot Q_{WB}-(1-x)\cdot t_W \quad v_{PB}(y)=v_P+n_P\cdot Q_{PB}-(1-y)\cdot t_P$$

[2] While the Developers pay fixed prices in our model, since there is no uncertainty, a fixed price is mathematically equivalent to a known commission. We will not analyze the case of Developers paying a commission as it does not add more insight for the purpose of this paper.

Our model employs the common convention that cross-side network effects are proportional to market share on the other side of the network. Market shares such as Q_{WA} are endogenously determined and range over [0, 1].

Table 2: Summary of Key Notation

$\{i, j\}$	Consumer adoption pattern (System) with watch/speaker from firm $i \in \{A,B,\varnothing\}$ and phone from firm $j \in \{A,B,\varnothing\}$ where $\varnothing$ stands for outside option
N_P, N_S, N_W	Cross-side network effects enjoyed by Consumers for phone, speaker, and watch
n_P, n_S, n_W	Cross-side network effects enjoyed by Developers for phone, speaker, and watch
P_{Pi}, P_{Si}, P_{Wi}	Prices paid by Consumers to acquire device i
p_{Pi}, p_{Si}, p_{Wi}	Prices paid by Developers to access device i
Q_{Pi}, Q_{Si}, Q_{Wi}	Quantity (market share) of Consumers for device i
q_{Pi}, q_{Si}, q_{Wi}	Quantity (market share) of Developers for device i
T_P, T_S, T_W	Transport/misfit cost for Consumers for phone, speaker, and watch
t_P, t_S, t_W	Transport/misfit cost for Developers for phone, speaker, and watch
$U_{i,j}$	Utility to Consumer for acquiring complement i and phone j
u_P, u_S, u_W	Intrinsic utility of acquiring a phone, speaker, and watch, respectively
u_{Pi}, u_{Si}, u_{Wi}	Partial utility for Consumer from device i
$V_{i,j}$	Value to Developer for accessing complement i and phone j
v_P, v_S, v_W	Intrinsic value of developing an app for phone, speaker, and watch
v_{Pi}, v_{Si}, v_{Wi}	Partial value for Developer from device i
x	Index of watch/speaker taste with range [0,1]
y	Index of phone taste with range [0,1]

3.4 Definitions of Watch and Speaker

We now explain the formal definition of a Watch and Speaker and justify the definitions. We also emphasize that Watches and Speakers should be seen as labels of classes of new platform devices that satisfy the formal definition.

Our definitions are based on the relationship of misfit costs of the smartphone and a new platform device. The tighter engineering constraints of the smartwatch form factor lead to drastic trade-offs among desired features, so it follows that misfit costs would be different in each dimension. For example, watch-sized cellular radios existed during era W2, but battery technology was not yet advanced enough to power a cellular radio for a reasonable length of time. Firms prioritized other features in era W2. Importantly, firms prioritized different features, leading to a wider feature space or equivalently a higher misfit cost.

Definition 1: A "Smartwatch" or "Watch" is a platform device for which tastes are stronger than smartphone tastes such that misfit costs have the relationship $T_W > T_P$ and $t_W \geq t_P$.■

Watches should be seen as classes of new platform devices that satisfy the misfit costs condition specified in Definition 1.

We also consider the market for the less-mobile complement (smart home appliance, a.k.a. smart speaker) to be separate from that of the more-mobile complement (smartwatch) because the two are not substitutes for one another. The difference is that as essentially immobile devices without serious size or power constraints and controlled primarily through voice commands, horizontal differentiation should be **weaker** than that of smartphones rather than stronger. The analysis would also apply to smart security systems, climate controllers, microwave ovens, *etc.*

Definition 2: A "Smart speaker" or "Speaker" is a platform device for which tastes are weaker than smartphone tastes such that $T_S < T_P$ and $t_S \leq t_P$.■

Again, Speakers should be seen as classes of new platform devices that satisfy the misfit costs condition specified in Definition 2.

4. Analysis and results

We present the results starting with the analysis of Era W1/S1 (Phones only), then the Eras with Watches as new platform device (W2-W4), and then the Eras with Speakers as new platform devices (S2-S4).

We treat each era as a separate game with the steps listed in Table 3 because none of the vendors, Consumers, or Developers can credibly commit to future actions. We analyze each era's game solving for the Nash equilibrium using backward induction.

Table 3: Game Steps within Each Era (W1/S1, W2-W4 and S2-S4)

1	Firms A, B noncooperatively set prices Consumer prices and Developer prices for the devices they offer in present Era.
2	Developers decide for which devices they will build and sell apps. Developers are nonstrategic, but have rational expectations of Consumer market shares given the schedule of prices.
4	Consumers decide which devices to purchase.
5	Consumer utility, Developer value, and vendor profit determined simultaneously

4.1 Era W1/S1: Firms A, B sell Smartphones only

Era W1/S1 is the baseline of our model. In that era, the only platform devices available are smartphones. Therefore the consumers can purchase a smartphone from firm A, a smartphone from firm B, or an outside option such as a feature phone.

We assume an interior solution for Developer market shares because this implies that some Developers sell on one platform but not the other, and this represents the real market for

Developers. Working backward to minimal conditions that would lead to an interior solution, we place a mild constraint on transport/taste costs, assuming that Developer misfit costs are at least

$t_P > (v_P/2 + n_P/4) > 0$ (A1).

With this mild constraint in hand, we derive a lemma that provides the foundation for some of our later results.

Lemma 1: The condition for full market coverage of smartphone Consumers in the presence of network effects is $T_P \le 2u_P + (N_P/t_P)\cdot(v_P + n_P/2)$, which is increasing in network effects or intrinsic utility for either side of the market. Firms charge Consumers T_P and Developers $v_P/2 + n_P/4$ when an interior solution obtains, serving a fraction $[v_P/2 + n_P/4]/t_P$ of Developers. Each firm's profit is $T_P/2$ from Consumers plus $\left[(v_P/2 + n_P/4)^2\right]/t_P$ from Developers.■

All proofs are in Appendix 1.

The intuition behind this result is that with symmetric firms, each competes away network effects on the Consumer side and charges a price equal to the transport cost T_P as shown analytically (Gabszewicz & Wauthy, 2004; Armstrong & Wright, 2007) and observed empirically (Rochet & Tirole, 2003, Table 1; Parker & Van Alstyne, 2005, Table 1). This results in the market outcome shown in Figure 5.[3] The free utility from cross-side network effects makes full coverage on the Consumer side likely. Firms attract Developers independent of their activity with the competing firm, so the prices offered to Developers are those of local monopolists.

[3] For the figures illustrating market outcomes, we choose model parameters that ensure that all purchase combinations of interest occur within the Hotelling square. These parameters are: $u_P = u_W = v_P = v_W = 1/10$; $t_P = t_W = 1/4$; $N_P = N_W = n_P = n_W = 1/2$. We recreate these figures in Appendix 2 over a broader range of parameter values to show that the patterns are robust to change in parameters.

In the rest of the analysis, we shall assume unless otherwise noted that the condition in Lemma 1 holds, so that Consumer misfit costs are $0 < T_P \leq 2u_P + (N_P/t_P)\cdot(v_P + n_P/2)$ (A2).

4.2 Era W2: Smartwatch works only with matching smartphone

This era begins when firms A and B introduce systems {A,A} and {B,B}, respectively. Firms will keep the existing phone prices – which guarantee a fully covered Consumer market for the older product – rather than bet on a risky new product being able to saturate the Consumer market with smartphone/smartwatch systems. Empirically, we observe that baseline smartphone prices have stayed fairly static (GSM Arena, 2018, second figure). Recall that from the Watch definition $T_W > T_P$ and $t_W \geq t_P$.

We will also extend the previous assumption (A1) to watch Developers, so that the Developer misfit costs are at least $t_W > (v_W/2 + n_W/4) > 0$ (A3).

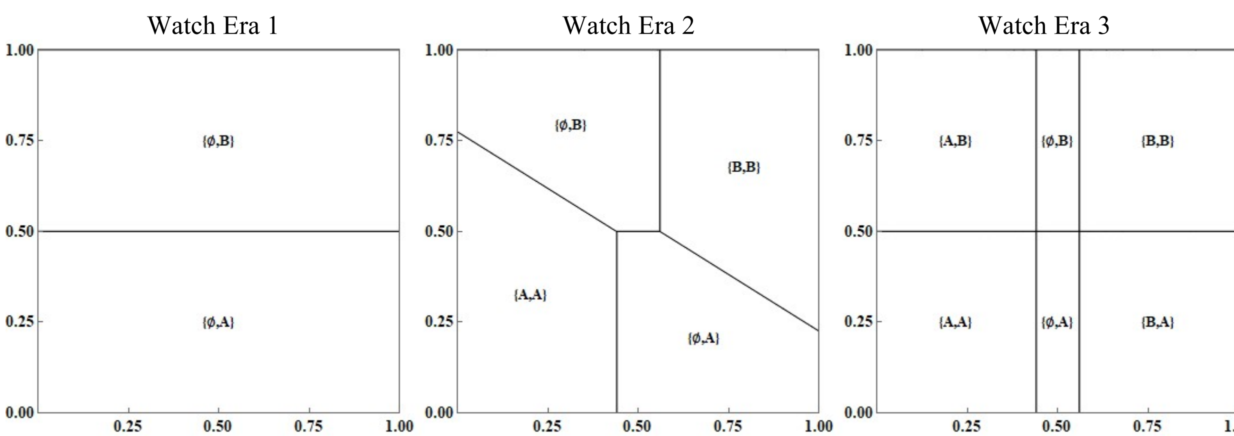

Figure 5. Consumer market shares across three eras with $T_W = 5/16$ and $T_P = 1/4$. The horizontal axis measures taste for watches while the vertical axis measures taste for phones. Developer market shares are much simpler because firms treat multi-homing developers as if the other firm does not exist.

The phone continues to be a stand-alone product, but the watch has Leontief complementarity with the phone. That is, a watch has zero utility without a matching phone. We derive the outcome of this market in Proposition 1.

Proposition 1: Firms charge Consumers T_W for smartwatches and Developers $v_W/2+n_W/4$ when an interior solution obtains, serving a fraction $\left[v_W/2+n_W/4\right]/t_W$ of Developers. Each firm's profit is $T_W/2$ from Consumers plus $\left[\left(v_W/2+n_W/4\right)^2\right]/t_W$ from Developers.■

If misfit costs are very low, all Consumers purchase the single-vendor systems. Otherwise, some Consumers keep their original "systems" of {∅,A} and {∅,B}. Although the market shares have changed shape, indicating platform switching, each firm still sells smartphones to 50% of the Consumers and sells smartwatches to some fraction of its Consumers. We illustrate the impact in the middle panel of Figure 5. Smartwatches are revenue-enhancing for both firms.

Corollary 1: A positive fraction of Era W2 Consumers purchase a phone but no watch if cross-side network effects are less than $N_W<\left(4t_W\cdot\left[2T_W-u_W\right]\right)/\left(n_W+2v_W\right)$.■

We introduce a definition to distinguish between two Era W2 market outcomes that will have a significant impact on Era W3's market outcomes.

Definition 3: Adoption of the smartwatch is "wide" if the indifference line between systems {A,A} and {∅,A} occurs at $x \geq 1/2$, and conversely the indifference line between systems {B,B} and {∅,B} occurs at $x \leq 1/2$. This requires $N_W \geq \left(4t_W\cdot\left[(3/2)T_W-u_W\right]\right)/\left(n_W+2v_W\right)$. Otherwise, the adoption of the smartwatch is "narrow" with $N_W<\left(4t_W\cdot\left[(3/2)T_W-u_W\right]\right)/\left(n_W+2v_W\right)$.■

The numerical example used in Figure 5 represents "narrow" adoption. Figure 6 shows Era W2 at three different levels of smartwatch adoption including both "narrow" and "wide."

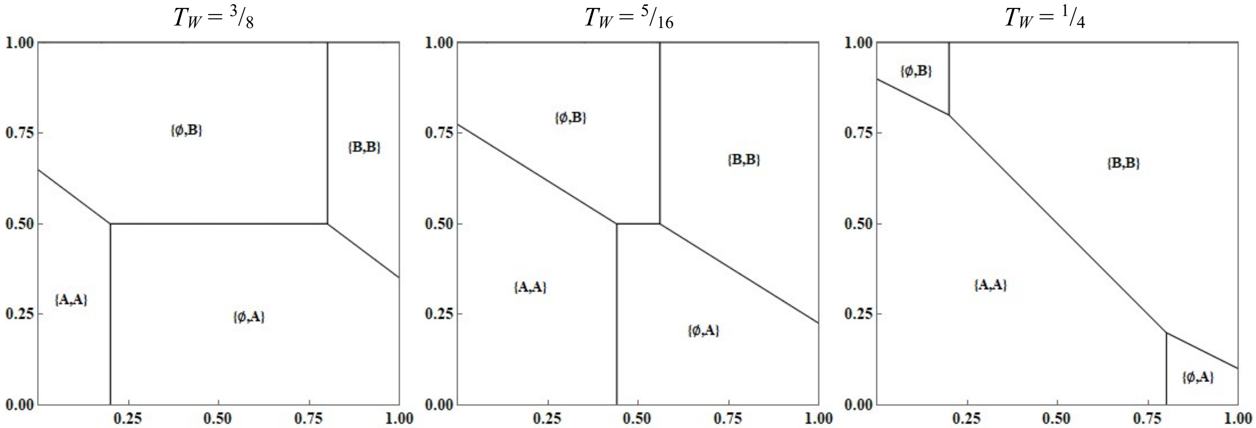

Figure 6. Consumer market shares in era W2 across three levels of T_W with $T_P = {}^1/_4$. The horizontal axis measures taste for watches while the vertical axis measures taste for phones. The first and second panels show "narrow" adoption according to Definition 3; the third panel shows "wide" adoption.

4.3 Era W3: Stand-alone smartwatches

This era adds systems {A,∅}, {A,B}, {B,∅} and {B,A}, for example enhancing the smartwatch with independent GPS and phone-call ability (*e.g.*, Apple Watch Series 3 but without requiring an iPhone for setup). Era W3 allows most of the holdouts in Era W2 to purchase a smartwatch that meets their tastes, further improving vendor revenues once the market reaches equilibrium. The right panel in Figure 5 shows the market outcome.

We now derive the conditions under which at least some consumers would prefer a mixed-vendor system.

Lemma 2: Mixed-vendor systems will have a positive market share if Consumer cross-side network effects are at least $N_W > \left(4t_W \cdot [T_W - u_W]\right) / \left(n_W + 2v_W\right)$.■

The intuition behind this result is that this range guarantees the indifference line between {B,A} and {∅,A} is located at $x < 1$.[4] Note that the maximum in Corollary 1 is deterministically higher than the minimum in Lemma 2, and both "narrow" and "wide" adoption of watches is possible in

[4] The other indifference line important for mixed-vendor systems is between bundles {A,A} and {B,A}. This line is always located at $x = {}^1/_2$ and therefore always located at $x < 1$.

this range. We will assume that both Corollary 1 and Lemma 2 hold, so that Consumer cross-side network effects are in the range

$$\left(4t_W \cdot \left[T_W - u_W\right]\right) / \left(n_W + 2v_W\right) < N_W < \left(4t_W \cdot \left[2T_W - u_W\right]\right) / \left(n_W + 2v_W\right) \quad \text{(A4).}$$

Under those conditions, we can state the following Proposition about the market outcome.

Proposition 2: In Era W3, each of the four systems captures an equal market share of Consumers. Under "wide" adoption of watches per Definition 3, each captures one-quarter with indifference lines at $x = {}^1/_2$ and $y = {}^1/_2$. Under "narrow" adoption of watches, there exists a group of Consumers centered on $x = {}^1/_2$ that purchase a phone but no watch. No Consumers purchase a watch but no phone.■

Under "narrow" adoption in Era W2, adding stand-alone smartwatches causes no Consumers to switch smartwatches, but some Consumers do purchase smartwatches who had not done so when they were only available in single-vendor systems. Some of the Consumers who purchased Era W2 systems switch back to their preferred smartphones, as shown in the right panel of Figure 5.

The outcome is similar under "wide" adoption in Era W2, except that Era W3 sees some Consumers switching to a preferred smartwatch. "Wide" adoption in Era W2 is sufficient to guarantee watches enjoy full Consumer market coverage in Era W3.

4.4 Era W4: Future smartwatches (Making the smartwatch look like the smartphone)

What is the effect of making the smartwatch more like the smartphone in terms of look and feel? In this era, firms A and B introduce a future watch with smartphone functionality that becomes its own device with a blending of the transport costs. The future smartwatch acquires some of the look and feel of the firm's smartphone offering. For a given fraction of phone-ness $0 \le \alpha < {}^1/_2$, the Consumer utility functions for these future watches are:

$$u_{WA}(x,y) = u_W + N_W \cdot q_{WA} - \left[\sqrt{1-\alpha^2} \cdot x \cdot T_W + \alpha \cdot y \cdot T_P\right]$$
$$u_{WB}(x,y) = u_W + N_W \cdot q_{WB} - \left[\sqrt{1-\alpha^2} \cdot (1-x) \cdot T_W + \alpha \cdot (1-y) \cdot T_P\right]$$

Setting $\alpha = 0$ recreates Era W3, but here we shall only consider the case of strictly positive α. Note that the ability to place phone calls is not in itself a differentiating feature in Era W4, as that feature became available in Era W3.

The presence of α slightly affects the feasible range of network effects. So we restate assumption (A4) taking into account nonzero α and this is assumption (A4A): Consumer network effects for smartwatches N_W are between the lower limit $\left(2t_W \cdot [\alpha \cdot T_P + 2T_W - 2u_W]\right) / (n_W + 2v_W)$ and the upper limit $\left(2t_W \cdot \left[\alpha \cdot T_P + 2 \cdot \left(1+\sqrt{1-\alpha^2}\right) \cdot T_W - 2u_W\right]\right) / (n_W + 2v_W)$.■

Definition 1 continues to hold in Era W4, except that now the indifference line is no longer vertical. One must measure x at the point where the indifference line crosses $y = {}^1/_2$. The threshold taking α into account is $N_W < \left(2t_W \cdot \left[\alpha \cdot T_P + \left(2+\sqrt{1-\alpha^2}\right) \cdot T_W - 2u_W\right]\right) / (n_W + 2v_W)$.

We summarize the impact of incorporating the phone's look-and-feel into the watch in Proposition 3.

Proposition 3: Under "wide" adoption of smartwatches per Definition 3, increasing misfit-relevant smartphone features in the smartwatch increases adoption of single-vendor systems at the expense of mixed-vendor systems with overall sales remaining constant. Under "narrow" adoption of smartwatches, increasing misfit-relevant smartphone features decreased sales of smartwatches.■

The intuition behind this result is that increasing α tilts all non-horizontal indifference lines counter-clockwise, with {A,A}~{∅,A} anchored at a point near[5] $y = 0$ and {B,B}~{∅,B} anchored at a point near $y = 1$. If smartwatch adoption is still "wide" measured at $y = {}^1/_2$ then {A,A}~{∅,A} is irrelevant and the {A,A}~{B,A} indifference line passes directly through the point $({}^1/_2, {}^1/_2)$. Rotating such an indifference line counter-clockwise will sweep previous {B,A} Consumers into {A,A} as well as {A,B} Consumers into {B,B}. Meanwhile {A,A}~{A,B} and {B,B}~{B,A} remain fixed at $y = {}^1/_2$ so that mixed-vendor systems receive no new adoption.

On the other hand, if smartwatch adoption is "narrow" when measured at $y = {}^1/_2$ then rotating the indifference lines widens the region where Consumers forego purchasing smartwatches, as shown in Figure 7.

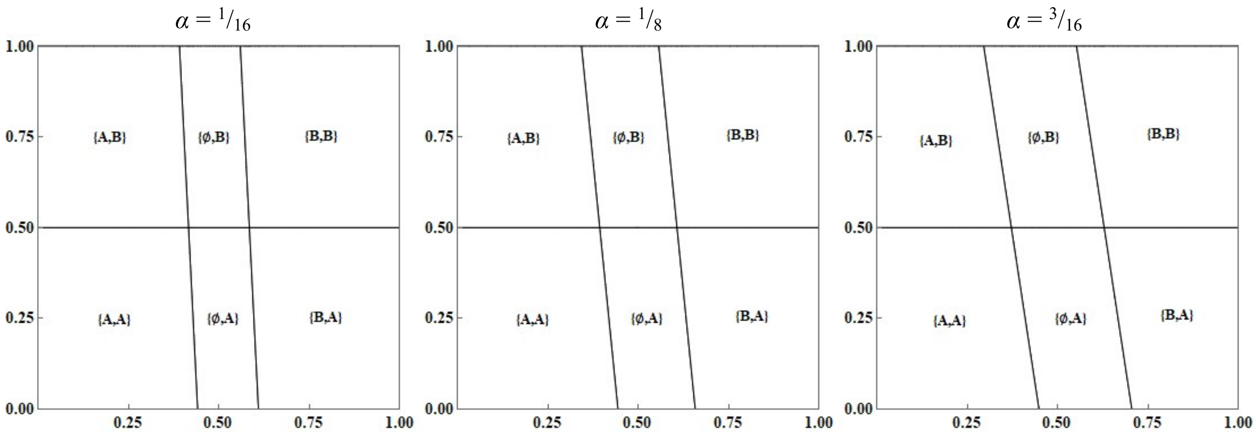

Figure 7. Consumer market shares with $T_W = {}^5/_{16}$ and $T_P = {}^1/_4$ when the future watch device becomes available over three values of α. The horizontal axis measures taste for pure watches while the vertical axis measures taste for phones.

Under "wide" adoption, increasing α homogenizes the market while under "narrow" adoption, increasing α makes the phone-like smartwatch unpalatable to more and more

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[5] The Era W3 and Era W4 {A,A}~{∅,A} indifference lines cross at the point $y = \left(\left[N_W \cdot (n_W + 2v_W) - 4t_W \cdot (T_W - u_W)\right] \cdot \left[1 - \sqrt{1-\alpha^2}\right]\right) \Big/ \left(4\alpha \cdot T_P \cdot t_W\right)$, which ranges from approximately 0.0172 to 0.0520 using the numeric examples in Figure 6.

Consumers. Note that α figures into the level of adoption at $y = {}^{1}/_{2}$, so it is possible for a previously “wide”-adopting market to tilt into a “narrow”-adopting one.

4.5 Eras S2 through S4: Smart speakers

We have alreasy analyzed Era W1/S1, which is the era before the new platform device is introduced by firms A, B. We now focus on Eras S2-S4, in which firms A, B introduce a Speaker as a new platform device. Era S2 follows the same path as era W2, except that assumption (A2) and Definition 2 combine to guarantee that adoption will always be “wide” as formalized in Corollary 2.

Corollary 2: A complementary product with lower misfit costs than the smartphone’s will always result in “wide” adoption in Eras S2 and S3, and adoption will remain “wide” in Era S4 under a broader set of market parameters than a complementary product with higher misfit costs.■

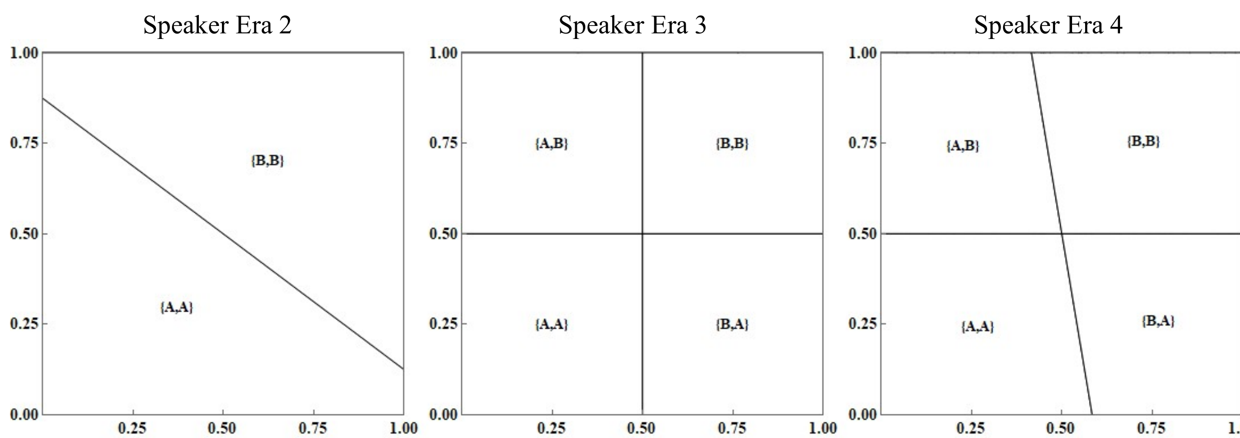

Figure 8. Consumer market shares with $T_S = {}^{3}/_{16}$ and $T_P = {}^{1}/_{4}$. The horizontal axis measures taste for speakers while the vertical axis measures taste for phones.

The intuition behind the Era S3 result is that since optimal prices can cover the Consumer market with smartphone-strength tastes, optimal prices will also cover the Consumer market for smart speakers with weaker tastes once the market reaches equilibrium. See Figure 8, which has the same parameter values as in Figure 5 except with $T_S = {}^3/_{16}$.

The result from Proposition 3 still holds, namely that adding taste-relevant smartphone features to the smart speaker will drive Consumers toward single-vendor systems unless α becomes so extreme that it tips adoption into the "narrow"-adoption range. As long as α is low enough for adoption to remain "wide," the Consumer market will remain fully covered. Should α be high enough to tip adoption into the "narrow" range, a threshold that depends on other model parameters, the firms will suffer lost sales as Consumer coverage for speakers falls below 100%.

4.6 New platform device becomes a substitute to the smartphone

We have already analyzed Eras W1-W4 in which the new platform device is a smartwatch and Eras S1-S4 in which the new platform device is a smart speaker, and we have clarified that smartwatch and smart speaker are labels for classes of new devices (recall Definitions 1 and 2). Now we want to examine under what conditions a new platform device that is initially a complement to the smartphone becomes a substitute to the smartphone, in which case some consumers use only the new platform device and cease adopting a smartphone. Proposition 4 shows that this is feasible in Eras W3-W4 and S3-S4 and defines the conditions.

Proposition 4 (smart speaker as substitute): A positive market share of Consumers who purchase the smart speaker and do not purchase the smartphone obtains: **(a)** In Era S3, if the misfit cost T_P is high enough that assumption (A2) is violated without losing all smartphone sales. **(b)** In Era S4, if the misfit cost T_P is high enough that assumption (A2) is violated without losing all smartphone sales **and** the smart speaker's phone-like quality is below the threshold

$$\alpha < (t_P/t_S)\cdot\left(\left[N_S(n_S+2v_S)-4t_S(T_S-u_S)\right]/\left[N_P(n_P+2v_P)-4t_P(T_P-u_P)\right]\right) \blacksquare$$

Note that a key condition for Proposition 4 is a high enough transport/misfit cost for phones. This could result either from exogenous technological constraints, or because *firms do focus on core customers' tastes* (Christensen, 2003) and invest to increase the transport/misfit cost (or more precisely, widen the feature space) for phones beyond the limit in assumption (A2).

Proposition 4 implies that the smart speaker's network evolves from a complement of the smartphone's network into a substitute for it. The intuition behind this result is that the increased misfit cost creates a group of Consumers with intermediate *y* indices would prefer an outside option to the smartphones offered. This outside option would be the modern version of a feature phone (including some social media features, but no app ecosystem). Figure 9 shows that depending on model parameters, some of these Consumers would maximize their utility with {A,∅} and {B,∅}, which never had positive market share in any other case analyzed earlier.

Note that violating assumption (A2) means that the smart speaker market could tip into "narrow" adoption, which would lead to a positive market share for {∅,∅} (a Consumer with a feature phone and no smart home appliance) which also never had positive market share since Era W1 reached equilibrium. In either case, Proposition 3 continues to hold, and adding phone-like features to the smart speaker reduces the adoption of mixed-vendor systems.

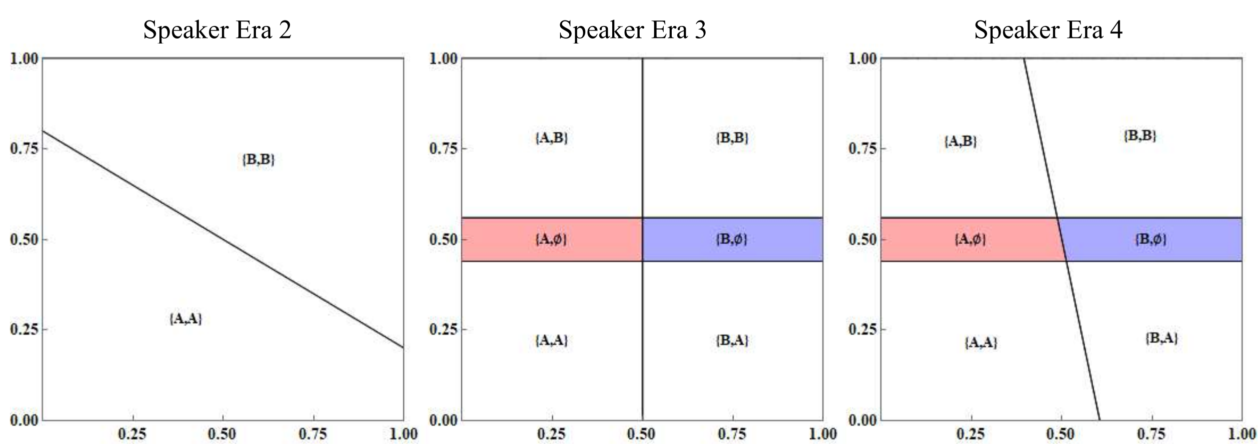

Figure 9. Consumer market shares with $T_S = {}^3/_{16}$ and $T_P = {}^5/_{16}$ (violating Assumption 2 as in Proposition 4). The horizontal axis measures taste speakers while the vertical axis measures taste for phones. Shaded areas represent sales of a speaker as a substitute for the phone.

As Proposition 4(b) shows, the market outcome with high-misfit smartphones is more complicated in Era S4 because α could potentially make the smart speaker so phone-like that Consumers who dislike the smartphone avoid the future speaker, too. Hence, there is a threshold α beyond which no Consumers purchase systems $\{A,\varnothing\}$ or $\{B,\varnothing\}$.

The same reasoning in Proposition 4 applies to smartwatches as well, although less likely to be a profit-maximizing strategy because by Definition 1 the smartwatch has a higher misfit cost than a smartphone and therefore at some point the firm would lose smartwatch sales, too.[6] We state this potential outcome formally in Corollary 3.

Corollary 3 (smartwatch as substitute): A positive market share of Consumers who purchase the smartwatch and do not purchase the smartphone obtains: **(a)** In Era W3, if the misfit cost T_P is high enough that assumption (A2) is violated, but T_W is such that some smartwatches are purchased. **(b)** In Era W4, if the misfit cost T_P is high enough that assumption (A2) is violated, but T_W is such that some smartwatches are purchased, **and** smartwatch's phone-like quality is below the threshold

$$\alpha < (t_P/t_W)\cdot\left(\left[N_W(n_W+2v_W)-4t_W(T_W-u_W)\right]\big/\left[N_P(n_P+2v_P)-4t_P(T_P-u_P)\right]\right). \blacksquare$$

5. Model extensions: cross-platform network effects

We extend the model to add synergy across platform devices from the same vendor. We explore *two* different utility specifications that achieve that.

The first specification incorporates *cross-platform network effects* ($\beta \geq 0$ measures the strength of cross-platform network effects):

[6] If T_P increases past T_W, the smartwatch would shift into the "speaker" class of devices.

$$U'_{i,j}(x,y) = u'_{Wi}(x) + u'_{Pj}(y) - P_{Wi} - P_{Pj}$$

$$u'_{WA}(x) = u_W + N_W \cdot (q_{WA} + \beta \cdot q_{PA}) - x \cdot T_W \qquad u'_{PA}(y) = u_P + N_P \cdot (q_{PA} + \beta \cdot q_{WA}) - y \cdot T_P$$
$$u'_{WB}(x) = u_W + N_W \cdot (q_{WB} + \beta \cdot q_{PB}) - (1-x) \cdot T_W \qquad u'_{PB}(y) = u_P + N_P \cdot (q_{PB} + \beta \cdot q_{WB}) - (1-y) \cdot T_P$$

The second specification incorporates superadditive utility for a single-vendor system ($\gamma \geq 0$ measures the superadditivity, and I is an indicator function):

$$U''_{i,j}(x,y) = \left[u_{Wi}(x) + u_{Pj}(y)\right] \cdot \left(1 + I_{i=j} \cdot \gamma\right) - P_{Wi} - P_{Pj}$$

While the new specifications complicate the mathematical formulas of the new results, the emergent adoption behavior is qualitatively similar to that discussed in the baseline model with some important differences. We illustrate and discuss these insights by recreating Figures 4 through 8 for both new specifications.

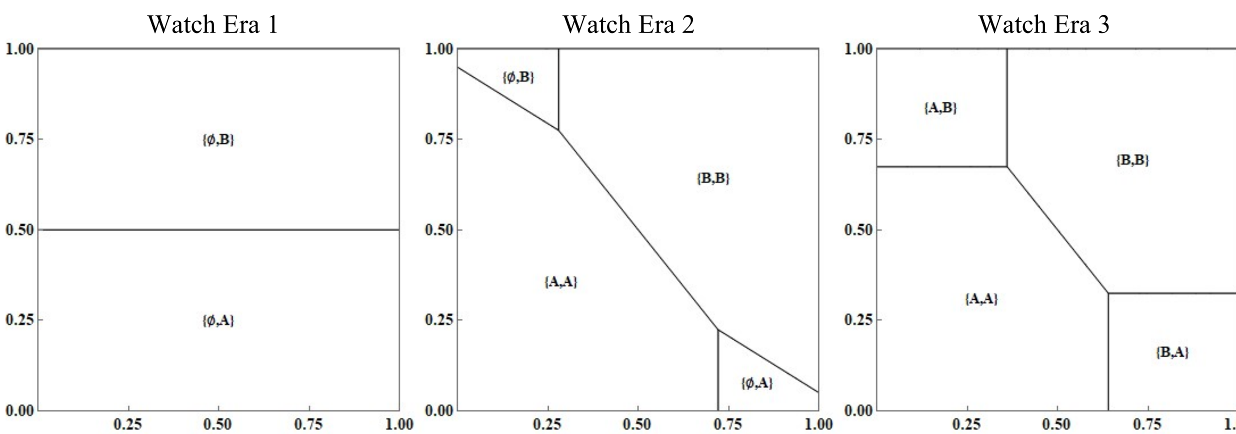

Figure 5′. Consumer market shares across three eras with $\beta = 1/8$, $T_W = 5/16$ and $T_P = 1/4$. The horizontal axis measures taste for watches while the vertical axis measures taste for phones. Developer market shares are much simpler because firms treat multi-homing developers as if the other firm does not exist.

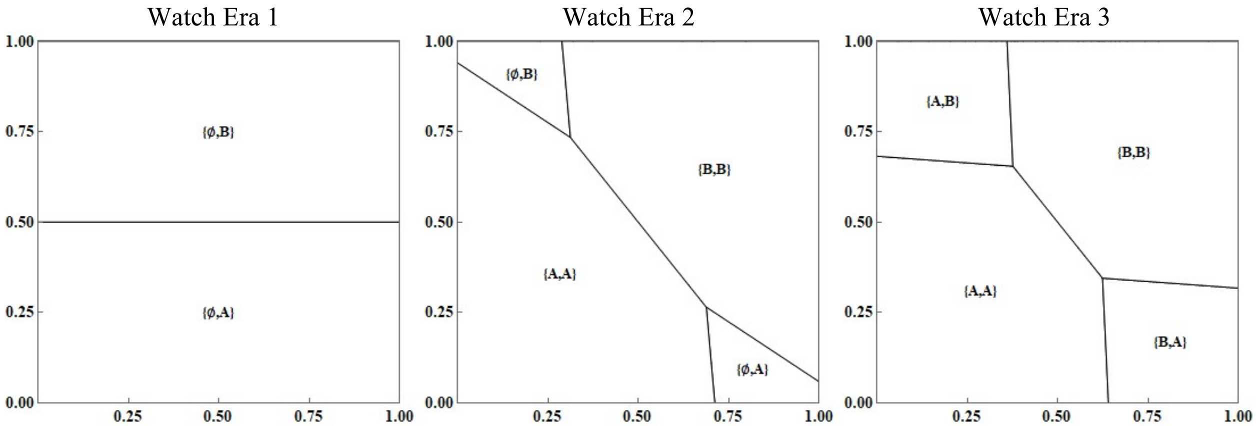

Figure 5″. Consumer market shares across three eras with $\gamma = {}^{1}/_{8}$, $T_W = {}^{5}/_{16}$ and $T_P = {}^{1}/_{4}$. The horizontal axis measures taste for watches while the vertical axis measures taste for phones. Developer market shares are much simpler because firms treat multi-homing developers as if the other firm does not exist.

The most obvious impact of explicitly modeling synergy is that using otherwise identical parameters, single-vendor systems reach higher market shares. The formulas for the indifference lines change as well to be far more cumbersome without any additional insight, so we do not include alternative versions of the analytical results.

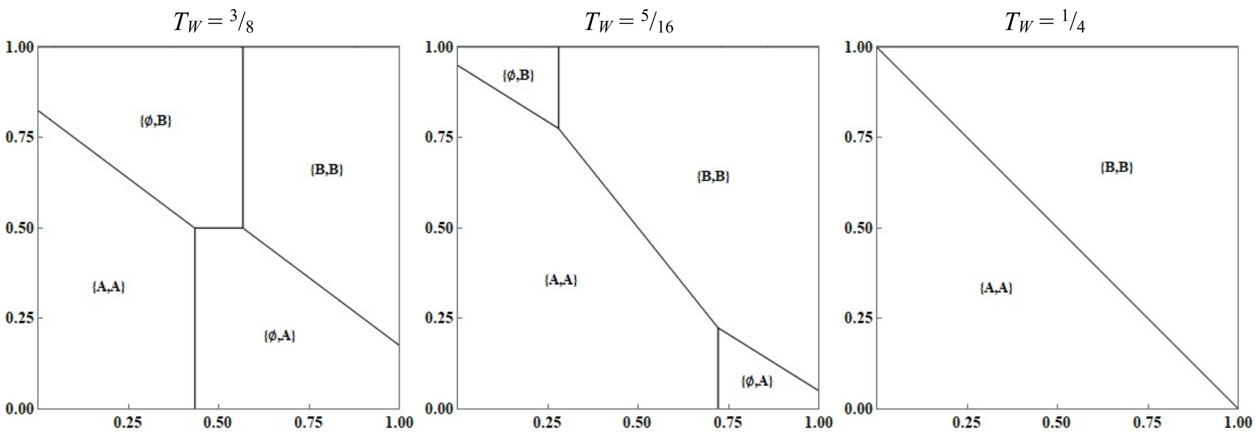

Figure 6′. Consumer market in shares in era W2 across three levels of T_W with $\beta = {}^{1}/_{8}$ and $T_P = {}^{1}/_{4}$. The horizontal axis measures taste for watches while the vertical axis measures taste for phones. The first panel shows "narrow" adoption according to Definition 3; the second and third panels show "wide" adoption.

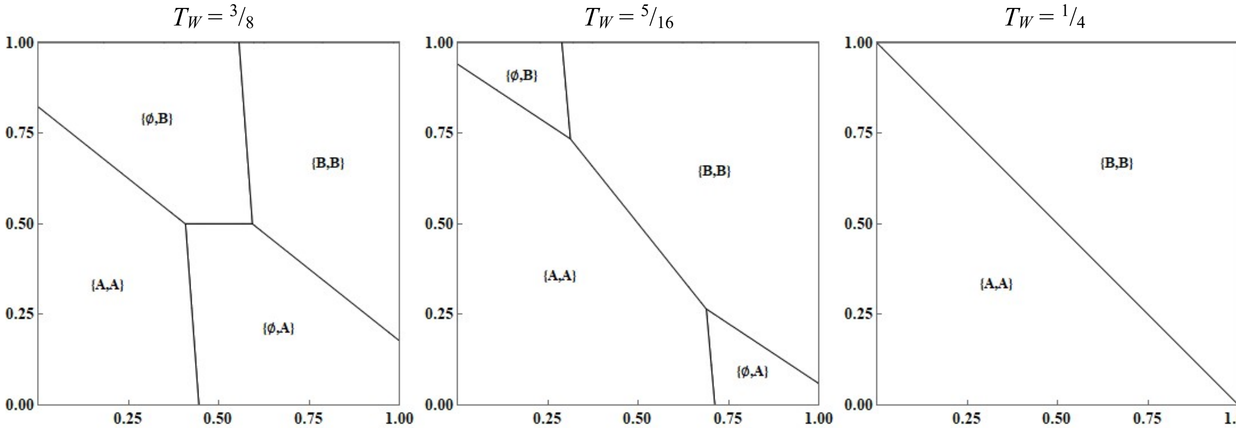

Figure 6″. Consumer market in shares in era W2 across three levels of T_W with S = $^1/_8$ and T_P = $^1/_4$. The horizontal axis measures taste for watches while the vertical axis measures taste for phones. The first panel shows "narrow" adoption according to Definition 3; the second and third panels show "wide" adoption.

The increase in adoption for single-vendor systems due to synergy severely reduces adoption of the phone-only systems {∅, A} and {∅, B}, but the directionality of α's effect from Figure 7 is still apparent in Figures 6′ and 6″.

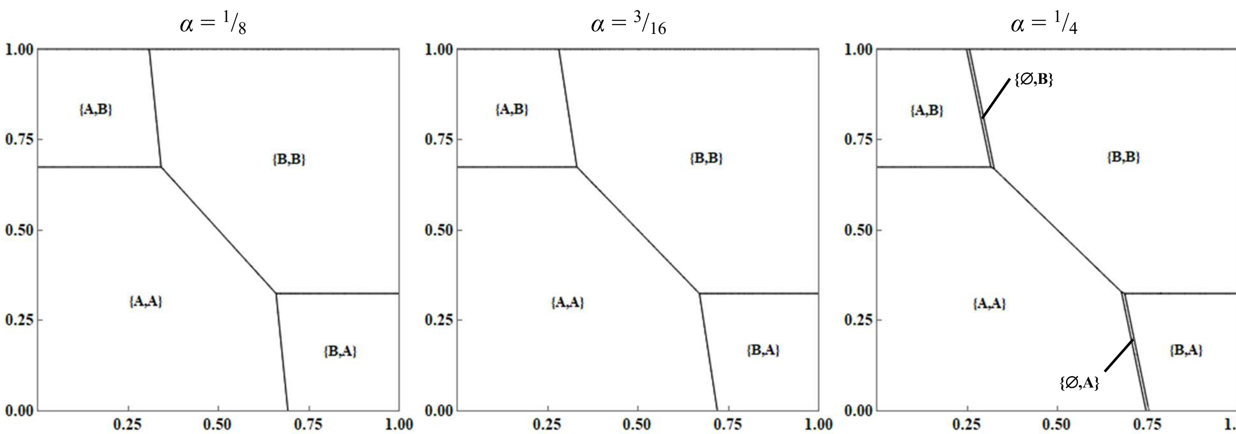

Figure 7′. Consumer market shares with β = $^1/_8$, T_W = $^5/_{16}$ and T_P = $^1/_4$ when the future watch device becomes available over three values of α.

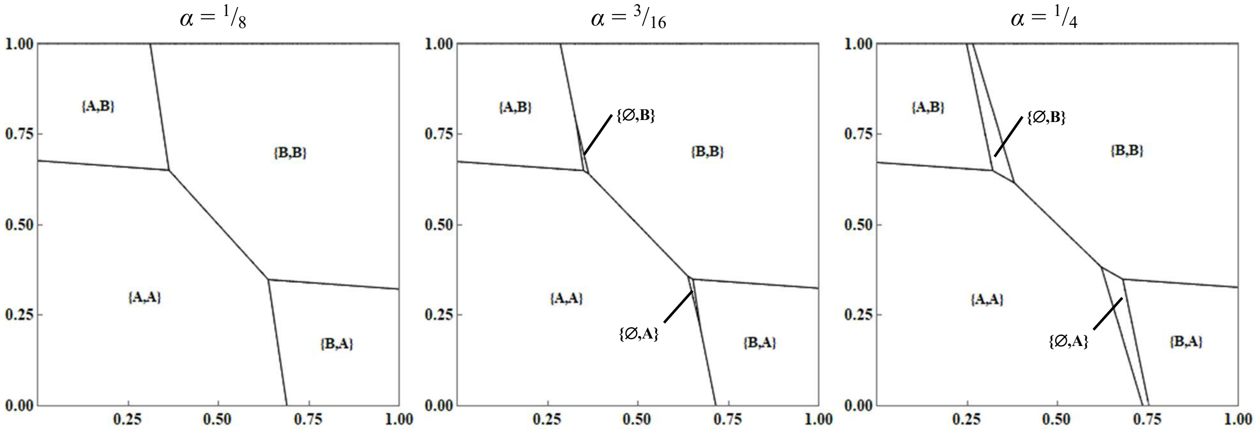

Figure 7″. Consumer market shares with $\gamma = {}^1/_8$, $T_W = {}^5/_{16}$ and $T_P = {}^1/_4$ when the future watch device becomes available over three values of α.

Figures 7′ and 7″ show a relationship to the base model's Figure 8 similar to that of Figures 4′ and 4″ to the base model's Figure 5. Corollary 2 continues to hold, ensuring "wide" adoption.

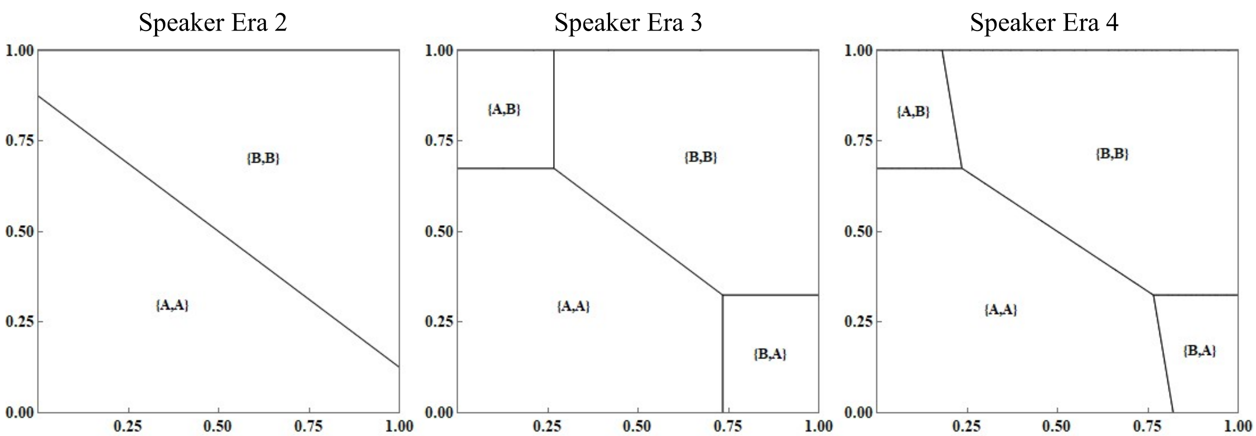

Figure 8′. Consumer market shares with $\alpha = {}^1/_8$, $\beta = {}^1/_8$, $T_S = {}^3/_{16}$ and $T_P = {}^1/_4$. The horizontal axis measures taste for speakers while the vertical axis measures taste for phones.

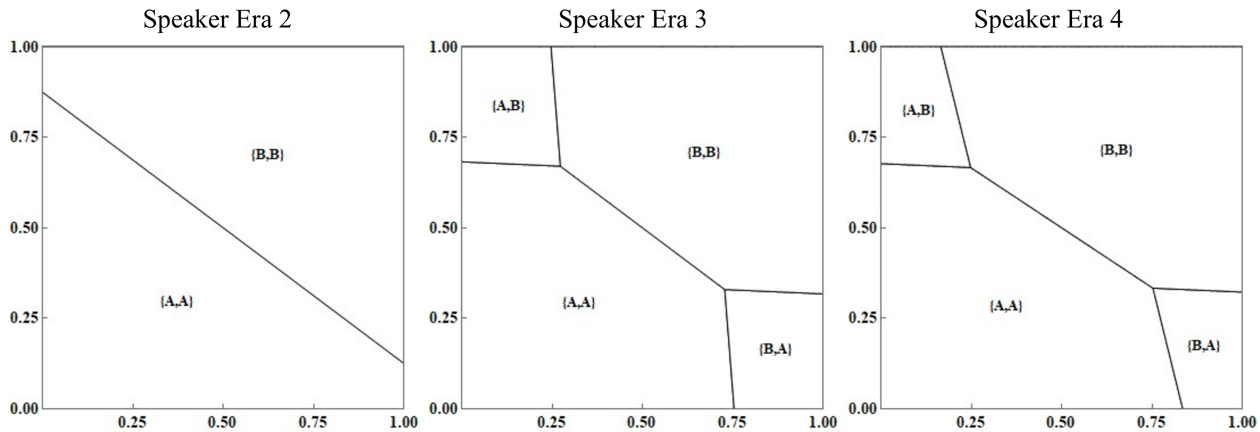

Figure 8″. Consumer market shares with $\alpha = {}^{1}/_{8}$, $\gamma = {}^{1}/_{8}$, $T_S = {}^{3}/_{16}$ and $T_P = {}^{1}/_{4}$. The horizontal axis measures taste for speakers while the vertical axis measures taste for phones.

The increased adoption of single-vendor systems in Figures 8′ and 8″ distorts the shapes of the market shares relative to Figure 9. An analytical proof would be lengthened by the many possibilities for systems adjacent to {A,∅}, but the intuition of Proposition 4 and Proposition 5 still holds. The smart speaker can evolve from a complement to a substitute even in the presence of cross-product network effects or synergy, although for a smaller share of the Consumer market relative to the baseline model.

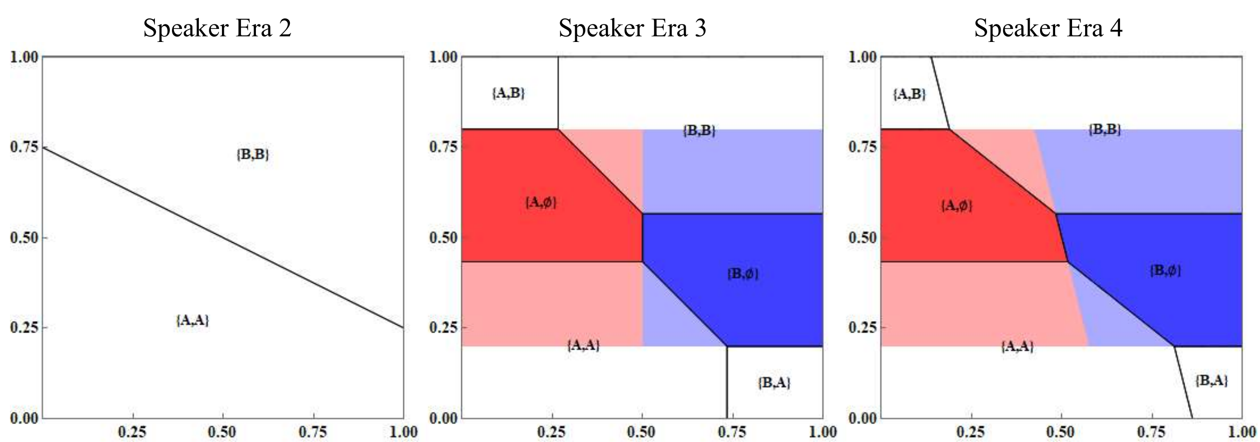

Figure 9′. Consumer market shares with $\alpha = {}^{1}/_{8}$, $\beta = {}^{1}/_{8}$, $T_S = {}^{3}/_{16}$ and $T_P = {}^{3}/_{8}$ (violating Assumption 2 as in Proposition 4). The horizontal axis measures taste for speakers while the vertical axis measures taste for phones. Lighter shaded areas represent sales of a speaker as a substitute for the phone without cross-product network effects. Darker shaded areas represent speaker substituting for a phone in the presence of cross-product network effects.

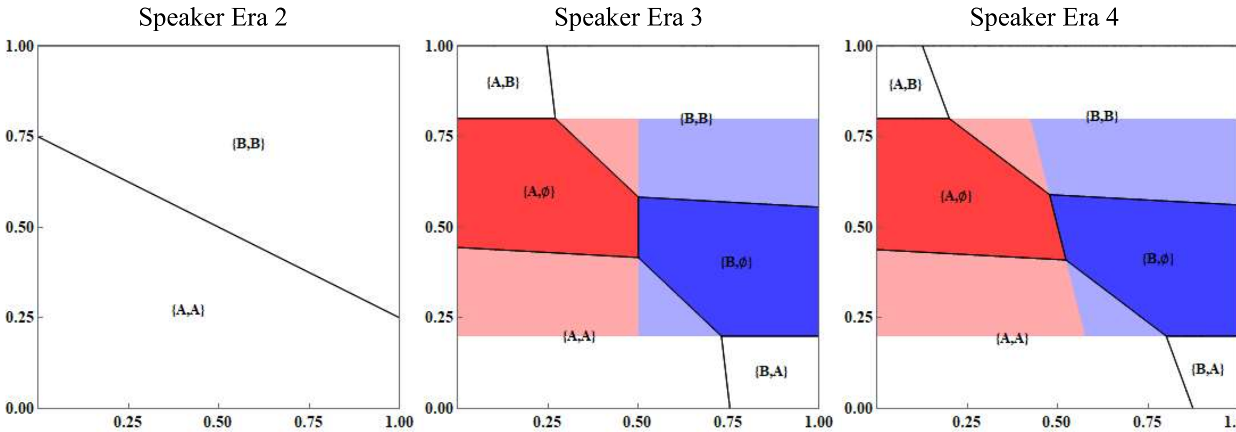

Figure 9″. Consumer market shares with $\alpha = {}^1/_8$, $\gamma = {}^1/_8$, $T_S = {}^3/_{16}$ and $T_P = {}^3/_8$ (violating Assumption 2 as in Proposition 4). The horizontal axis measures taste for speakers while the vertical axis measures taste for phones. Lighter shaded areas represent sales of a speaker as a substitute for the phone without synergy. Darker shaded areas represent speaker substituting for a phone in the presence of synergy.

In summary, introducing synergy across platform devices from the same vendor tends to increase the market share of single-vendor systems, and to shrink the area where the Consumers buy the speaker as a substitute for the phone. Moreover, the two new specifications explored tend to give very similar results to each other (*i.e.*, the two mechanisms are "close substitutes").

6. Discussion

This article proposed a novel analytical framework of competition between multi-platform firms inspired by the consumer IoT landscape. Our economic model of the Internet of Things (IoT) formalizes how the consumer IoT landscape evolves overt time, as firms introduce new IoT devices and devices acquire new capabilities. Our work sheds light on consumer IoT firm strategies and market outcomes. It clarifies the strategic impact of technology trends such as wearables (smartwatches) and AI-enabled connected devices (*e.g.*, smart speakers) on the incumbent mobile computing technology (smartphones) in one parsimonious analytical framework.

A key innovation of our research is the introduction of the concept of a *multi-platform* firm that offers a *system of platforms* and orchestrates a *multi-platform ecosystem*. These concepts are defined and formalized in a novel analytical framework.

Our framework allows for the analysis of a firm's transition from a platform firm to a multi-platform firm, as well as the analysis of competition of multi-platform firms. Our analytical framework features two firms A, B. They first compete as platform firms, each selling a smartphone (Era W1/S1). After that, firms introduce a new platform device (Watch or Speaker), so each firm becomes a *multi-platform firm* orchestrating a *multi-platform ecosystem*. The article characterizes firms' strategic behavior and market outcomes in this setting. We discuss insights and implications next.

6.1 Transition from a platform firm to a multiplatform firm

In the first era (Era W1/S1), firms A, B sell only smartphones, which is a platform device connecting Consumers and Developers of apps. They exhibit cross-side network effects from Developers to Consumers and from Consumers to Developers, but otherwise behave in a manner that is not affected from other networked markets. Complementary hardware such as cases and pedometers did exist, but these goods did not exhibit the kinds of cross-side network effects that would significantly affect the adoption of one smartphone over another.

The transition from a platform firm to a multi-platform affects adoption patterns of all devices, and firm profits. The precise effect depends on the class of the new platform device (Watch or Speaker), and the new platform design, which determines the Era.

6.2 Competition of multi-platform firms

In the second era, firms introduce a new platform device that might provide minimal functionality on its own, but only functions fully when paired with a smartphone from the same vendor. For example, an early generation Apple Watch was not capable of much without a constant connection to an iPhone.

Then the extent of adoption of the new platform device among consumers depends on the relative strength of network effects and tastes, with items that exhibit low misfit costs due to weak tastes (*i.e.*, smart home appliances) enjoying wide or even universal adoption, if the market remains in this era long enough to reach equilibrium. Items that exhibit high misfit costs due to strong tastes (*i.e.*, wearables) could end up with any level of adoption from niche to wide depending on the model parameters.

In the third era, the newer device achieves reasonable stand-alone functionality. An example of an Era 3 device is a smartwatch that does not require pairing with a smartphone. For the first time, a consumer who prefers devices from different vendors can expect each to work properly. Items that won wide adoption in the previous era have offerings spaced closely enough that every consumer has at least one combination of devices that yields positive utility at equilibrium prices.

We also formalized cross-platform network effects and explored two extensions in which two devices from the same firm enjoy positive synergy to utility. These extensions complicate the model's mathematical statements considerably, but the results are qualitatively similar to the results without synergy. The indifference lines shift to benefit single-vendor systems, because cross-platform network effects increase the value of single-vendor systems. However, the intuition behind "narrow" or "wide" adoption driving final market outcomes remains.

6.4 Designing a new platform device to be more phone-like

In the fourth era, we posit that vendors would import the look and feel of their incumbent platform to their new platform devices. Examples would include adding a home screen style interface to smart speakers (already observed in some models) or adding a large collection of gesture controls to smartwatch screens.

The impact of phone-like features depends on the extent of adoption of the device. For a class of devices with universal adoption (keeping in mind that consumers can mix-and-match smartphones with devices from any vendor), phone-like features tend to push marginal consumers toward single-vendor systems that may benefit firms. For devices with narrower adoption, introducing phone-like features decreases sales of the new device.

Firms should be cautious about increasing the correlation of misfit costs ("homogenizing the look and feel," represented by α in the model) between smartphones and devices that have stronger consumer tastes. We expect that wearables will follow a path toward high differentiation while smart home appliances will follow a path toward modest differentiation, but it is conceivable that either or both predictions may prove inaccurate. The key driver for market outcomes is whether differentiation precludes universal adoption once mixed-vendor systems become feasible.

6.5 The new platform device becomes a substitute for the smartphone

At this point, the new networked goods theoretically pose a substitution threat to the incumbent smartphone platforms. We show that the threat from wearables like smartwatches is probably hypothetical, but the threat from smart home appliances is plausible given the historical trends in industries where technical capability grows faster than consumers' collective ability to harness that capability (Christensen, 2003). The newer device becomes good enough for most consumers, and the incumbent device withers to perhaps just a remote peripheral of the smart home appliance.

A surprising implication of our analysis is that today's complement can evolve into tomorrow's substitute. This insight adds a more nuanced dynamic understanding to the conventional wisdom that any two products are either complements or substitutes. In particular, we identified cases in which an IoT device, such as a smart home appliance, is a networked complement initially, but as its capabilities evolve over time, it may become a networked substitute of the smartphone offered by the same vendor or competing vendors. Our examination of the relationship between wearables, mobile computing, and smart home devices shows that these relationships are not static: If smart appliances become common in homes, vehicles, places of business, *etc.* then the smartphone – today's essential must-have device – may find itself suddenly redundant.

6.7 Managerial implications

A *multi-platform firm* offers a *system of platforms* and orchestrates a *multi-platform ecosystem*. These concepts are an important conceptual contribution to the managerial understanding of platform strategies and ecosystems (Eisenmann *et al.*, 2006; Gawer & Cusumano, 2014; Parker *et al.*, 2016; Constaninides *et al.*, 2018; de Reuver *et al.*, 2018; Hein *et al.,* 2020).

Multi-platform firms are different than platform firms. A platform firm coordinates a platform ecosystem that consists of users, application developers and other providers of complementary products and services that affect the value of its platform. The firm seeks to enlarge the value of the platform ecosystem and it maximizes the platform profit. It needs to consider the interaction between the sides of the platform (cross-side network effects), and competition from other platform firms.

In contrast, a *multi-platform firm* offers two (or more) platforms and it coordinates a multi-platform ecosystem. The firm seeks to enlarge the value of the whole multi-platform ecosystem, while it maximizes its profit from all the platforms. The firm needs to consider the interaction between the sides of the platform (cross-side network effects), the interaction between its platform devices, and competition from other firms (platform firms, or multiplatform firms).

Managers of multi-platform firms must be aware of several important issues, starting with preferences of consumers and developers for each platform device, including the strength of cross-side network effects.

When a firm transitions from a platform firm to a multi-platform firm then consumer adoption patterns change and competition changes. It is important to know what is the class of the new platform device the firm offers: we identified two types of devices (Watch and Speaker) depending on the relative strength of consumer tastes.

We identified and characterized distinct eras that capture the evolution of smart IoT devices. In essence, this evolution embodies the digital transformation of IoT (enabled by increase in network speeds, increase in processing power, mobility and AI), which in turn leads to the digital transformation of business. Our analysis showed that Eras do matter, because strategic behavior and outcomes differ across eras. Therefore, it is important for managers to be aware under which era they compete. In Era W2 (or S2) the new platform device depends on the matching Phone to function. In Era W3 (or S3) the new platform device is stand-alone, which also opens the possibility that a consumer may not purchase the smartphone, or a consumer may mix-and-match devices across vendors. In Era W4 (or S4) the new platform device is further designed to be more phone-like.

For instance, the current generation of smartwatches drives sales primarily through complementarity with smartphones (Era W2), but not all consumers find this combination compelling. For example, someone may prefer the iPhone to an Android phone, yet simultaneously prefer an Android Wear watch to the Apple Watch. Tying smartwatches to smartphones in this way, therefore, generates some deadweight loss. Stand-alone smartwatches hold the promise of serving many of these consumers.

Technology vendors must keep the strength of consumer tastes in mind when moving look-and-feel features from one device to another. When consumer misfit costs (and therefore, platform adoption decisions) center on the smartphone, firms are no worse off for incorporating smartphone features to provide a consistent experience across devices. On the other hand, when misfit costs are higher for the complement (*e.g.*, wearable), then consumers may rebel against losing the complement's distinctiveness.

Moreover the firm must be prepared for thee possibility that a new platform device that complements its incumbent platform may evolve into a substitute for its incumbent platform. That is especially true when the firm falls into the trap of overinvesting in increasing the misfit/transportation cost for the incumbent platform device. Managing that transition will requiring maintaining control of all the platforms in their *system of platforms*, foreclosing the option of spinning off non-core businesses. Maximizing the value of the whole multi-platform ecosystem may be complicated by cross-platform network effects, as discussed in the extentions section.

6.8 Future research opportunities

We proposed a new analytical framework of competition of *multi-platform firms* motivated by the consumer IoT landscape. The article contributed to the economics of platforms, and the economics of consumer IoT, by applying platforms thinking to strategic issues in the consumer IoT space. Future research could extent the analytical framework in several directions.

We call for more research on the economics and strategic implications of *multi-platform firms* and *multi-platform ecosystems*, which is a novel concept introduced in this article. Our model examines the equilibrium outcome of each era, but future research can examine inter-temporal competition (Consumers strategically delaying a purchase), competition between multiple generations of the same device (such as selling W3 and W4 devices simultaneously), and more nuanced strategies for attracting developers (synergy as in Section 5 or some version of exclusive contracting).

There is is a need for more research on the economics consumer IoT, the context that motivated this article, as well as industrial IoT. IoT provides new research opportunities, as a complex and fast-changing landscape for vendors of digital platforms, for developers of complementary apps and services, and for consumers. We call for more research on the economics of IoT, and we hope that this will become a growing area of future research in information systems and related fields. Future work could consider challenges such as security and privacy (Ng, 2019), interaction of blockchain and IoT (Bakos & Halaburda, 2019) as well as other economic and strategic IoT effects.

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Appendix 1: Analytical proofs

Lemma 1: The condition for full market coverage of smartphone Consumers in the presence of network effects is $T_P < 2u_P + (N_P/t_P)\cdot(v_P + n_P/2)$, which is increasing in network effects or intrinsic utility for either side of the market. Firms charge Consumers T_P and Developers $v_P/2 + n_P/4$ when an interior solution obtains, serving a fraction $[v_P/2 + n_P/4]/t_P$ of Developers. Each firm's profit is $T_P/2$ from Consumers plus $\left[(v_P/2 + n_P/4)^2\right]/t_P$ from Developers.■

Proof of Lemma 1: Full market coverage of Consumers occurs if utility at the equilibrium price is positive at $y = {}^1/_2$. Determining utility requires first determining cross-side network effects, which requires knowing the fraction of Developers on the platform.

With costless multihoming, each firm prices as a monopolist for Developers. Substituting one-half for Consumer market share into the Developer utility function, we arrive at the market share assuming an interior solution.

$$y^* = \frac{v_P + \frac{n_P}{2} - p_{PA}}{t_P}$$

The firm then sets a profit-maximizing price.

$$\max_{p_{PA}} p_{PA} \cdot \frac{v_P + \frac{n_P}{2} - p_{PA}}{t_P}$$

The first-order condition provides the profit-maximizing price and market share.

$$\frac{\left(v_P + \frac{n_P}{2}\right) - 2p_{PA}^*}{t_P} = 0$$

$$p_{PA}^* = \frac{v_P}{2} + \frac{n_P}{4}$$

$$y^* = \frac{\frac{v_P}{2} + \frac{n_P}{4}}{t_P}$$

Substituting in the known market shares, the full market condition becomes

$$u_P + N_P \cdot \left(\frac{\frac{v_P}{2} + \frac{n_P}{4}}{t_P} \right) - (1/2) \cdot T_P > 0$$

$$T_P < 2u_P + \frac{N_P}{t_P} \cdot \left(v_P + \frac{n_P}{2} \right)$$

which is the condition to be proven.■

Proposition 1: Firms charge Consumers T_W for smartwatches and Developers $v_W/2 + n_W/4$ when an interior solution obtains, serving a fraction $[v_W/2 + n_W/4]/t_W$ of Developers. Each firm's profit is $T_W/2$ from Consumers plus $[(v_W/2 + n_W/4)^2]/t_W$ from Developers.■

Proof of Proposition 1: Given the optimal price to Consumers T_W and market share $^1/_2$, firm profit of $T_W/2$ from Consumers follows directly. The optimal price and market share for Developers are derived in Lemma 1. Total profit for firm i is

$$\Pi_i = P_{Pi} \cdot x^* + p_{Pi} \cdot y^*$$

$$= T_W \cdot \frac{1}{2} + \left(\frac{v_P}{2} + \frac{n_P}{4} \right) \cdot \frac{\frac{v_P}{2} + \frac{n_P}{4}}{t_P}$$

$$= \frac{T_W}{2} + \frac{\left(\frac{v_P}{2} + \frac{n_P}{4} \right)^2}{t_P}$$

from which the second term is collected from Developers.■

Corollary 1: A positive fraction of Era W2 Consumers purchase a phone but no watch if cross-side network effects are less than $N_W < \left(4t_W \cdot \left[2T_W - u_W\right]\right) / \left(n_W + 2v_W\right)$.■

Proof of Corollary 1: Without loss of generality, we consider system {∅,A}, which has simpler notation than {∅,B}. Consider the Consumer indifferent between systems {A,A} and {∅,A}:

$$\begin{aligned} U_{\varnothing,A}\left(x,y\right) &= U_{A,A}\left(x,y\right) \\ u_P + N_P \cdot q_{PA} - y \cdot T_P - T_P &= u_W + N_W \cdot q_{WA} - x \cdot T_W + u_P + N_P \cdot q_{PA} - y \cdot T_P - \left(T_P + T_W\right) \\ 0 &= u_W + N_W \cdot q_{WA} - x \cdot T_W - T_W \end{aligned}$$

and between systems {B,B} and {∅,A}:

$$\begin{aligned} U_{\varnothing,A}\left(x,y\right) &= U_{B,B}\left(x,y\right) \\ u_P + N_P \cdot q_{PA} - y \cdot T_P - T_P &= u_W + N_W \cdot q_{WB} - \left(1-x\right) \cdot T_W + u_P + N_P \cdot q_{PB} - \left(1-y\right) \cdot T_P - \left(T_P + T_W\right) \\ 0 &= u_W + N_W \cdot q_{WB} - \left(2-x\right) \cdot T_W - \left(1-2y\right) \cdot T_P \end{aligned}$$

Substituting in the known Developer market shares yields solutions for *x* and *y*:

$$x = \frac{u_W + N_W \cdot \left(\dfrac{\dfrac{v_W}{2} + \dfrac{n_W}{4}}{t_W} \right)}{T_W} - 1$$

$$y = \frac{1}{2} - \frac{u_W + N_W \cdot \left(\dfrac{\dfrac{v_W}{2} + \dfrac{n_W}{4}}{t_W} \right) - 2T_W}{2T_P} - \frac{T_W}{2T_P} \cdot x$$

A sufficient condition for system {∅,A} to have positive sales is $x < 1$ and $y > 0$. The *x* condition is straightforward:

$$\frac{u_W + N_W \cdot \left(\dfrac{\frac{v_W}{2} + \frac{n_W}{4}}{t_W} \right)}{T_W} - 1 < 1$$

$$N_W < \frac{4t_W \cdot \left(2T_W - u_W \right)}{n_W + 2v_W}$$

Substituting the definition of x into the definition of y yields a solution for y that is always positive with positive T_P and T_W, so it adds no additional constraint to the condition already derived.■

Lemma 2: Mixed-vendor systems will have a positive market share if Consumer cross-side network effects are at least $N_W > \left(4t_W \cdot [T_W - u_W]\right) / \left(n_W + 2v_W\right)$.■

Proof of Lemma 2: Without loss of generality, we consider system $\{B,A\}$. This system will have positive sales if the indifference line $\{B,A\}\sim\{B,B\}$ crosses the $\{A,A\}\sim\{B,A\}$ line (or the $\{\varnothing,A\}\sim\{B,A\}$ line under "narrow" adoption) at a point with $x < 1$ and $y > 0$.

First, under "wide" adoption, most terms in the $\{A,A\}\sim\{B,A\}$ line cancel out, leaving a deterministic solution at $x = {}^1/_2$. The N_W condition for "wide" adoption is tighter than the condition under consideration for this Lemma, so we shall not consider this case further.

Second, under "narrow" adoption the $\{\varnothing,A\}\sim\{B,A\}$ line is:

$$u_P + N_P \cdot q_{PA} - y \cdot T_P - T_P = u_P + N_P \cdot q_{PA} - y \cdot T_P + u_W + N_W \cdot q_{WB} - (1-x) \cdot T_W - (T_P + T_W)$$

$$0 = u_W + N_W \cdot \left(\left[\frac{v_W}{2} + \frac{n_W}{4} \right] \Big/ t_W \right) - (1-x) \cdot T_W - T_W$$

$$x = 2 - \frac{u_W + N_W \cdot \left(\left[\frac{v_W}{2} + \frac{n_W}{4} \right] \Big/ t_W \right)}{T_W}$$

which leads to the condition

$$2-\frac{u_W+N_W\cdot\left(\left[\frac{v_W}{2}+\frac{n_W}{4}\right]\Big/t_W\right)}{T_W}<1$$

$$N_W>\left[4t_W\cdot\left(T_W-u_W\right)\right]\big/\left(n_W+2v_W\right)$$

Third, most terms in the {B,B}~{B,A} line cancel out, leaving a deterministic solution at $y = {}^1/_2$.

Finally, since the y condition is always met and $N_W>\left[4t_W\cdot\left(T_W-u_W\right)\right]\big/\left(n_W+2v_W\right)$ guarantees the x condition is met, the Lemma is proved.■

Proposition 2: In Era W3, each of the four systems captures an equal market share of Consumers. Under "wide" adoption of watches per Definition 1, each captures one-quarter with indifference lines at $x = {}^1/_2$ and $y = {}^1/_2$. Under "narrow" adoption of watches, there exists a group of Consumers centered on $x = {}^1/_2$ that purchase a phone but no watch. No Consumers purchase a watch but no phone.■

Proof of Proposition 2: Under "wide" adoption, the indifference lines {A,A}~{B,A} and {B,B}~{A,B} always occur at $x = {}^1/_2$, while the indifference lines {A,A}~{A,B} and {B,B}~{B,A} always occur at $y = {}^1/_2$. Such an arrangement results in full coverage of the Consumer market with equal market share for each system.

Under "narrow" adoption, the indifference lines {A,A}~{A,B} and {B,B}~{B,A} still always occur at $y = {}^1/_2$. What remains to be proven is that the vertical, collinear lines {A,A}~{∅,A} and {A,B}~{∅,B} are the same distance from $x = 0$ that the vertical, collinear lines {B,B}~{∅,B} and {B,A}~{∅,A} are from $x = 1$.

The first indifference line lies where the marginal consumer receives zero utility from adding a watch to her system.

$$u_W + N_W \cdot \left(\left[\frac{v_W}{2} + \frac{n_W}{4} \right] \Big/ t_W \right) - x \cdot T_W - T_W = 0$$

$$x = \frac{u_W + N_W \cdot \left(\left[\frac{v_W}{2} + \frac{n_W}{4} \right] \Big/ t_W \right)}{T_W} - 1$$

Under the condition from Definition 1, we know that this $x < {}^1/_2$. We solve the second indifference line for "1 – x" to show that its width is identical.

$$u_W + N_W \cdot q_{WB} - (1 - x) \cdot T_W - T_W = 0$$

$$1 - x = \frac{u_W + N_W \cdot \left(\left[\frac{v_W}{2} + \frac{n_W}{4} \right] \Big/ t_W \right)}{T_W} - 1$$

The adoption regions for all four systems have the same height and same width, and therefore the same area.■

Proposition 3: Under "wide" adoption of smartwatches per Definition 1, increasing misfit-relevant smartphone features in the smartwatch increases the adoption of single-vendor systems at the expense of mixed-vendor systems with overall sales remaining constant. Under "narrow" adoption of smartwatches, increasing misfit-relevant smartphone features decreased sales of smartwatches.■

Proof of Proposition 3: There are three scenarios to consider when describing the impact of increasing α.

The first scenario is the most straightforward. If α increases enough to tip "wide" adoption into "narrow" adoption, sales of watches have decreased by definition, and the Proposition holds.

The second scenario is that the {∅,A} and {∅,B} regions exist due to "narrow" adoption. We must show that these regions widen as α increases. Although the slopes of indifference lines {A,A}~{∅,A} and {B,B}~{∅,B} change with α, the lines remain parallel so it is sufficient to measure the x distance between them at any given point (it would be multiplied by its constant height of one to find the area of phone-only systems). This distance is

$$\Delta x = \frac{2t_W \cdot \left[\alpha \cdot T_P + \left(2 + \sqrt{1-\alpha^2}\right) \cdot T_W - 2u_W \right] - N_W \cdot \left(n_W + 2v_W\right)}{2T_W \cdot t_W \cdot \sqrt{1-\alpha^2}}$$

The derivative of this distance with respect to α is not deterministically positive at every point (it turns negative as α nears $^1/_2$ if T_W is drastically higher than T_P), but the distance is always minimized by setting $\alpha = 0$.

$$\arg\min_{\alpha} \frac{2t_W \cdot \left[\alpha \cdot T_P + \left(2 + \sqrt{1-\alpha^2}\right) \cdot T_W - 2u_W \right] - N_W \cdot \left(n_W + 2v_W\right)}{2T_W \cdot t_W \cdot \sqrt{1-\alpha^2}} = 0$$

The third scenario is that "wide" adoption causes the single-vendor systems and mixed-vendor systems to divide the entire Consumer market. The colinear indifference lines {A,A}~{B,A} and {B,B}~{A,B} pass through the point ($^1/_2$, $^1/_2$), so we need only show that the line sweeps to the right at $y = 0$ (which implies that it sweeps to the left at $y = 1$). Substituting $y = 0$ into {A,A}~{B,A} yields:

$$x = \frac{u_W + N_W \cdot \left(\left[\frac{v_W}{2} + \frac{n_W}{4} \right] \Big/ t_W \right) - T_W}{\sqrt{1-\alpha^2} \cdot T_W}$$

Increasing α clearly decreases the denominator, which increases x at $y = 0$.

Having proven all three possible scenarios, the Proposition is proven.■

Corollary 2: A complementary product with lower misfit costs than the smartphone's will always result in "wide" adoption in Eras S2 and S3, and adoption will remain "wide" in Era S4 under a broader set of market parameters than a complementary product with higher misfit costs.■

Proof of Corollary 2: This result follows directly from Lemma 1, Definition 2, and Definition 3. If market shares meet in the middle for T_P, they must also meet in the middle for $T_S < T_P$. Note that decreasing the misfit cost lowers the N_W required for "wide" adoption.■

Proposition 4 (smart speaker as substitute): A positive market share of Consumers who purchase the smart speaker and do not purchase the smartphone obtains: **(a)** In Era S3, if the misfit cost T_P is high enough that assumption (A2) is violated without losing all smartphone sales. **(b)** In Era S4, if the misfit cost T_P is high enough that assumption (A2) is violated without losing all smartphone sales **and** the smart speaker's phone-like quality is below the threshold $\alpha < (t_P/t_S)\cdot([N_S(n_S+2v_S)-4t_S(T_S-u_S)]/[N_P(n_P+2v_P)-4t_P(T_P-u_P)])$ ■

Proof of Proposition 4: Violating Assumption 2 leads to "narrow" adoption of smartphones, opening a gap between {A,A} and {A,B} as well as between {B,B} and {B,A}. The indifference lines {A,A}~{A,∅} and {∅,A}~{∅,∅} occur at some $0 < y < 1/2$ while {B,B}~{B,∅} and {∅,B}~{∅,∅} occur at some $1/2 < y < 1$.

By Definition 2, the smart speaker has a lower misfit cost, and therefore the indifference line {A,∅}~{∅,∅} in Era S3 occurs at some $x > 0$, and happens to be further away from the $x = 0$ line than the {A,A}~{A,∅} line was from the $y = 0$ line. By similar reasoning, the indifference line {B,∅}~{∅,∅} occurs at some $x < 1$. If smart speaker misfit costs remain "wide," then the binding indifference line is {A,∅}~{B,∅}, which occurs at exactly $x = 1/2$.

The above conditions create regions with a nonzero area for systems {A,∅} and {B,∅}.

In Era S4, the colinear indifference lines {A,∅}~{∅,∅} and {A,A}~{∅,A} plus the colinear indifference lines {B,∅}~{∅,∅} and {B,B}~{∅,B} are all diagonal with the same (negative) slope that depends on α.

Without loss of generality, we will focus on system {A,∅}. For this system to have positive sales, line {A,∅}~{∅,∅} must cross $x = 0$ at some y higher than {∅,A}~{∅,∅}. This condition translates to

$$\frac{N_P\left(n_P+2v_P\right)+4t_P\left(T_P-u_P\right)}{4t_P T_P}<\left(\frac{1}{\alpha T_P}\left[\frac{N_S\left(n_S+2v_S\right)}{4t_W}-T_S\left(1+x\sqrt{1-\alpha^2}\right)+u_S\right]\right)\Bigg|_{x=0}$$

Since all the parameters are strictly positive and the radical term is eliminated by setting $x = 0$, the above unambiguously simplifies to a condition on α.

$$\alpha<\frac{t_P}{t_S}\cdot\frac{\left[N_S\left(n_S+2v_S\right)-4t_S\left(T_S-u_S\right)\right]}{\left[N_P\left(n_P+2v_P\right)-4t_P\left(T_P-u_P\right)\right]}$$

Since $t_S \le t_P$, the first ratio is at least unity (well higher than α's upper limit of $^1/_2$). The second ratio depends on exogenous variables that measure the relative strength of speaker network effects *vs.* speaker misfit costs compared to the relative strength of phone network effects *vs.* phone misfit costs. When the above inequality holds, system {A, ∅} has positive sales. By parallel reasoning, system {B, ∅} does as well, proving the Proposition.■

Corollary 3 (smartwatch as substitute): A positive market share of Consumers who purchase the smartwatch and do not purchase the smartphone obtains: **(a)** In Era W3, if the misfit cost T_P is high enough that assumption (A2) is violated, but T_W is such that some smartwatches are purchased. **(b)** In Era W4, if the misfit cost T_P is high enough that assumption (A2) is violated, but T_W is such that some smartwatches are purchased, **and** smartwatch's phone-like quality is below the threshold

$\alpha<\left(t_P/t_W\right)\cdot\left(\left[N_W\left(n_W+2v_W\right)-4t_W\left(T_W-u_W\right)\right]\big/\left[N_P\left(n_P+2v_P\right)-4t_P\left(T_P-u_P\right)\right]\right)$.■

Proof of Corollary 3: These results follow directly from Proposition 4 with a change in symbols. Since $t_W > t_P$, the condition in Era W4 will be met under a narrower set of exogenous parameters than in Era S4.■

Appendix 2: Visualization using a broader range of parameters

Parameters for the figures in the main text were chosen to guarantee that every product combination of interest had a positive market share. In this appendix, we show that the outcomes vary smoothly with the input parameters and that the results shown in the main paper were robust and not a special case.

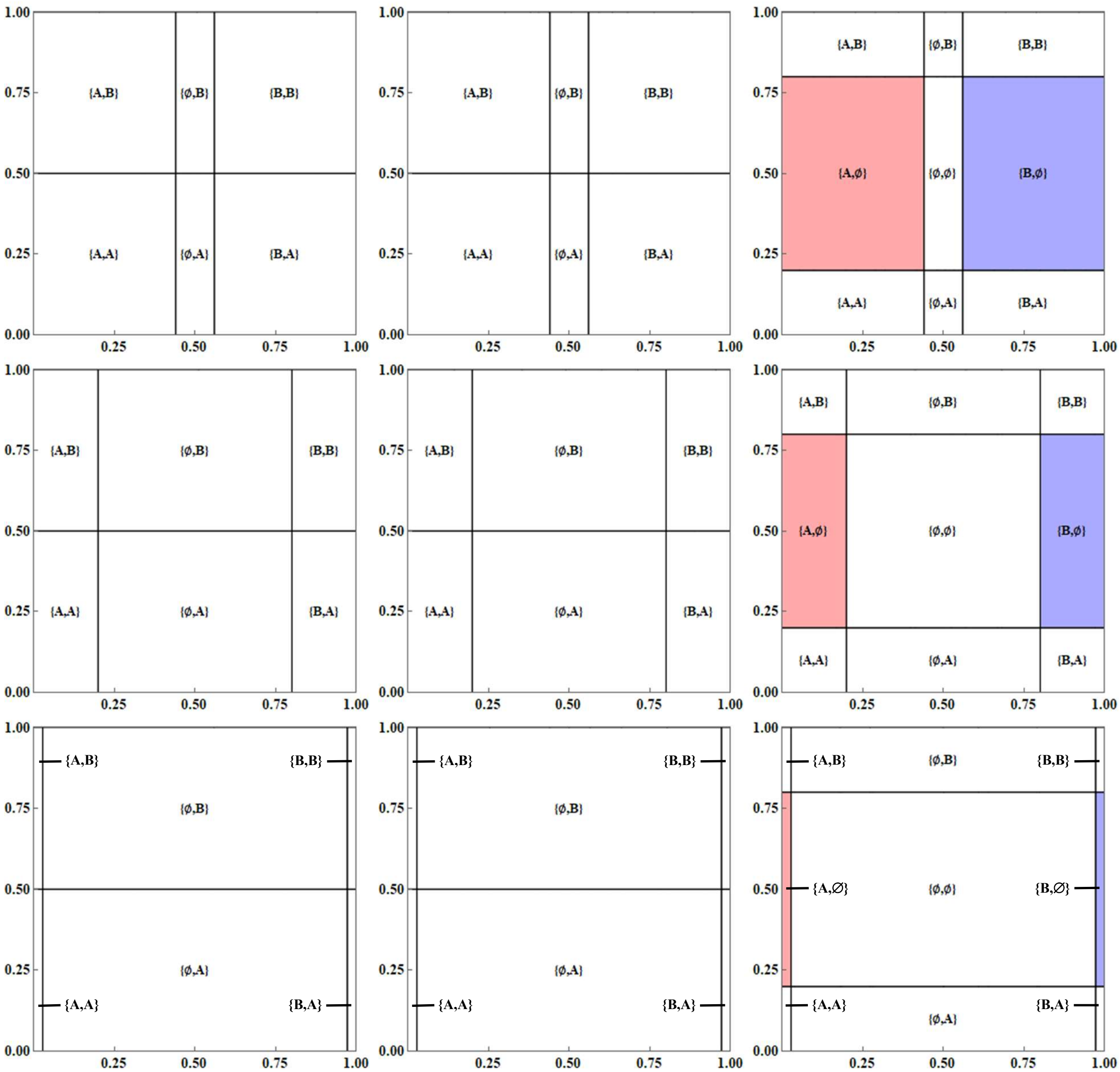

Figure 4*. Consumer market shares in era W3. The columns show T_P as $^1/_8$, $^1/_4$, and $^3/_8$, respectively. The rows show T_W as $^5/_{16}$, $^3/_8$, and $^7/_{16}$, respectively. Shaded areas represent sales of a speaker as a substitute for the phone.

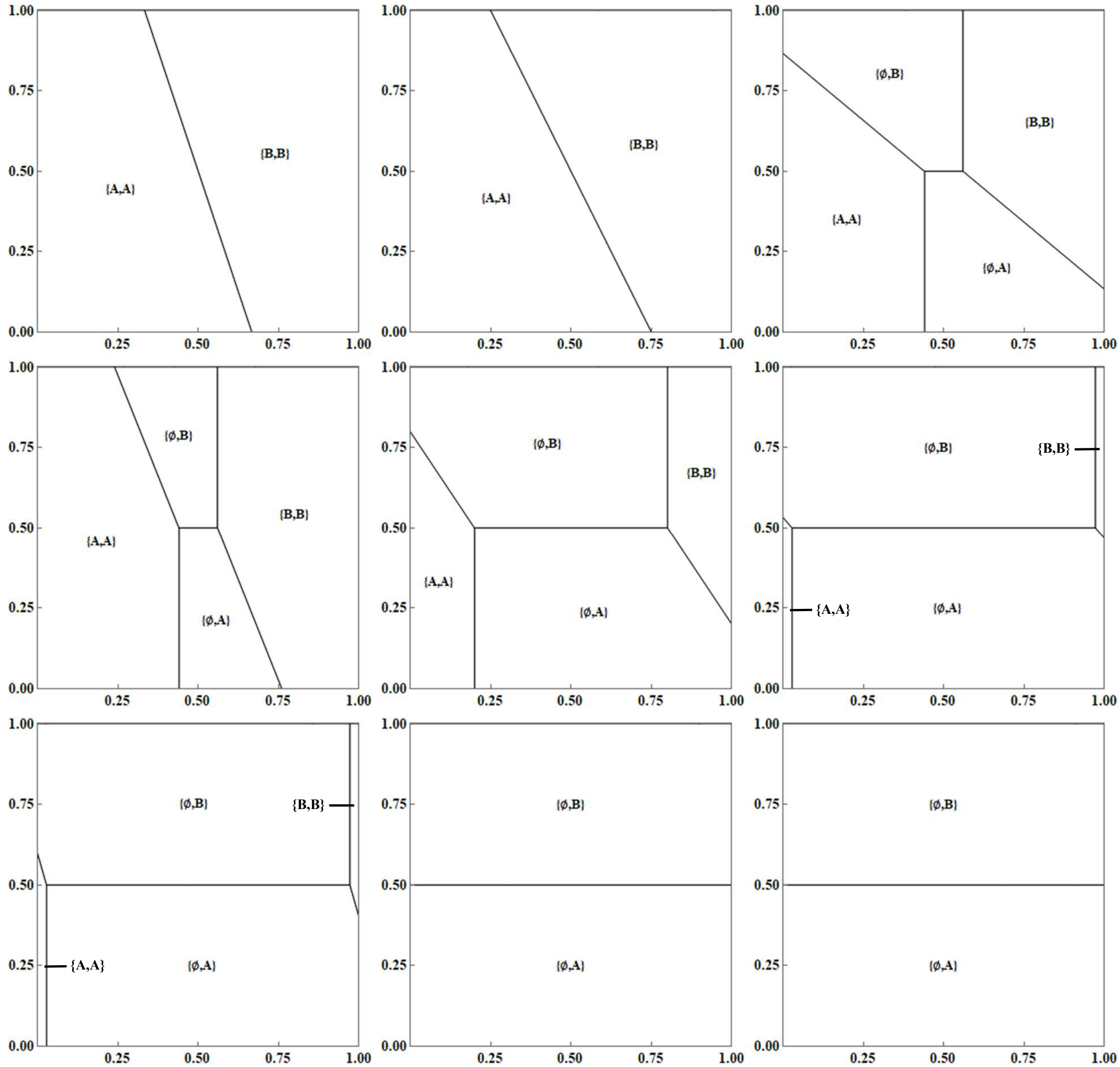

Figure 5*. Consumer market shares in era W2 across different levels of T_P and T_W. The columns show T_P at $^1/_{16}$, $^1/_8$, and $^3/_{16}$, respectively. The first row shows $T_W = T_P + {}^1/_8$; the second row, $T_W = T_P + {}^1/_4$; and the third row, $T_W = T_P + {}^3/_8$. The horizontal axis measures taste for watches while the vertical axis measures taste for phones. The first and second panels of the top row show “wide” adoption according to Definition 1; the remaining panels show “narrow” adoption.

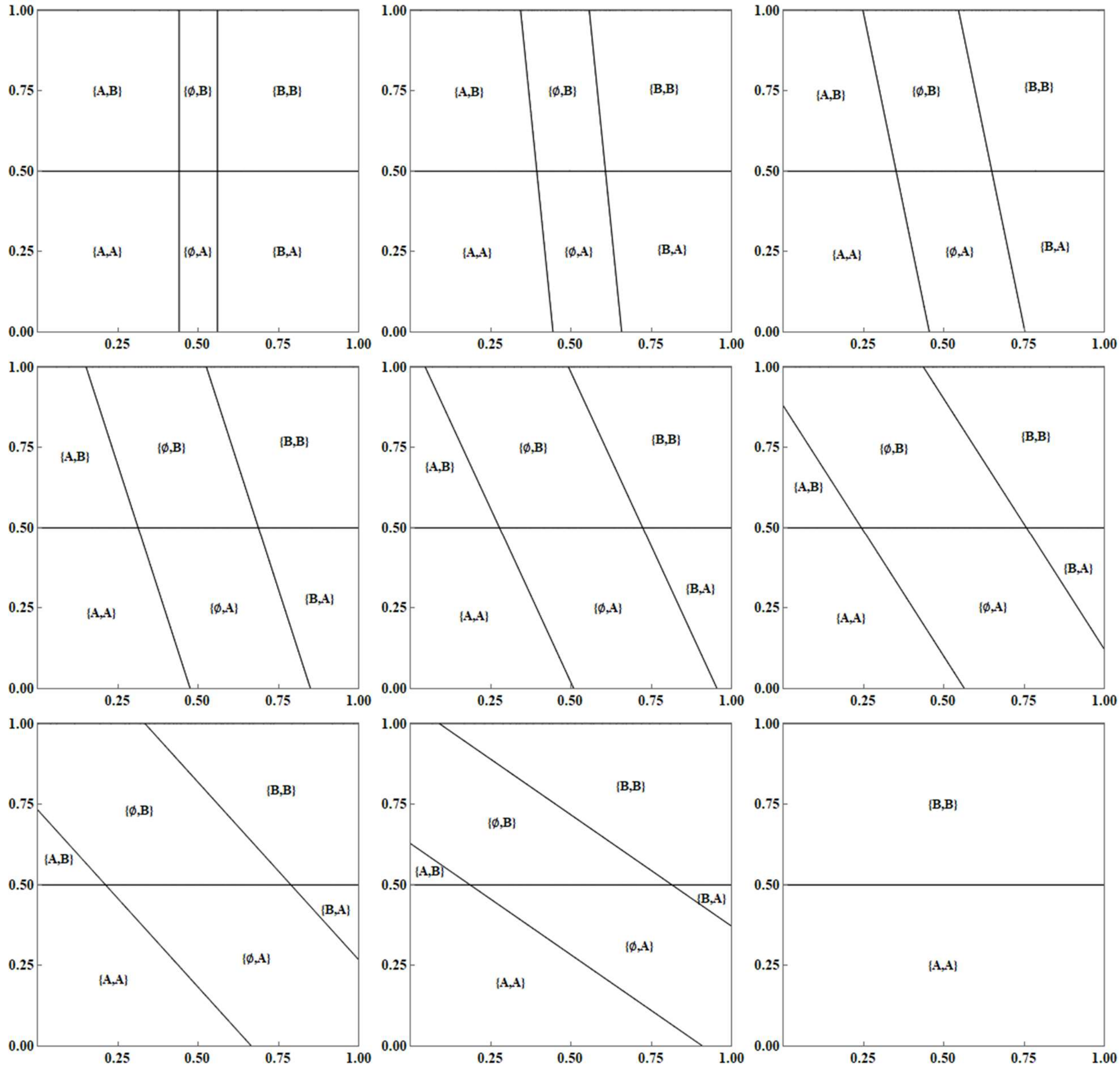

Figure 6*. Consumer market shares with $T_W = {}^5/_{16}$ and $T_P = {}^1/_4$ when the future watch device becomes available over nine values of α. Starting at zero in the top-left and advancing ${}^1/_8$ per panel until reaching the limiting case of $\alpha = 1$ in the bottom-right. The horizontal axis measures taste for pure watches while the vertical axis measures taste for phones.

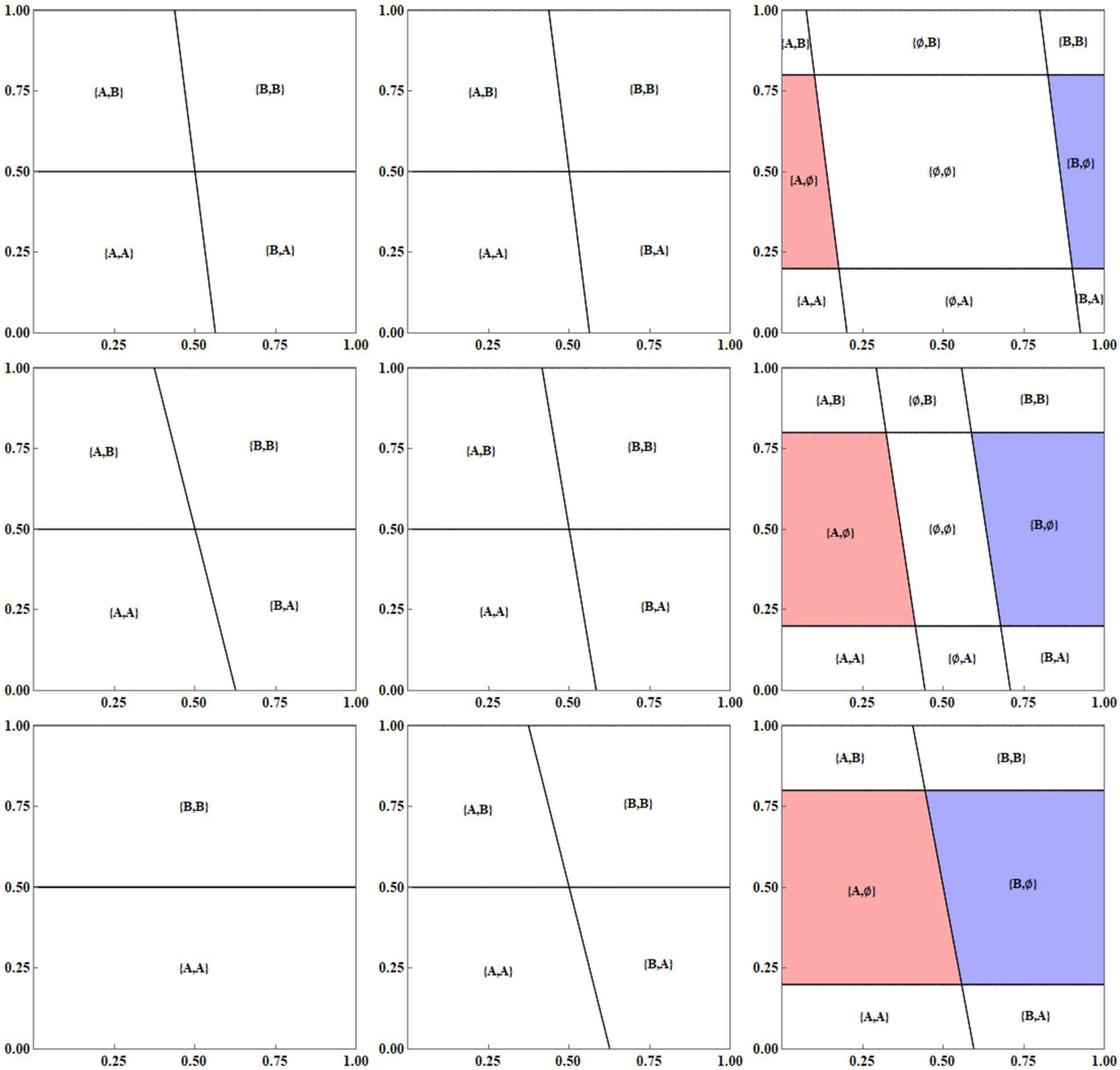

Figure 7*. Consumer market shares across different levels of T_P and T_S. The columns show T_P at $^1/_8$, $^1/_4$, and $^3/_8$, respectively. The first row shows $T_S = T_P$; the second row shows $T_S = T_P - {}^1/_{16}$; and the third row shows $T_S = T_P - {}^1/_8$. The horizontal axis measures taste for speakers while the vertical axis measures taste for phones. Shaded areas represent sales of a speaker as a substitute for the phone.

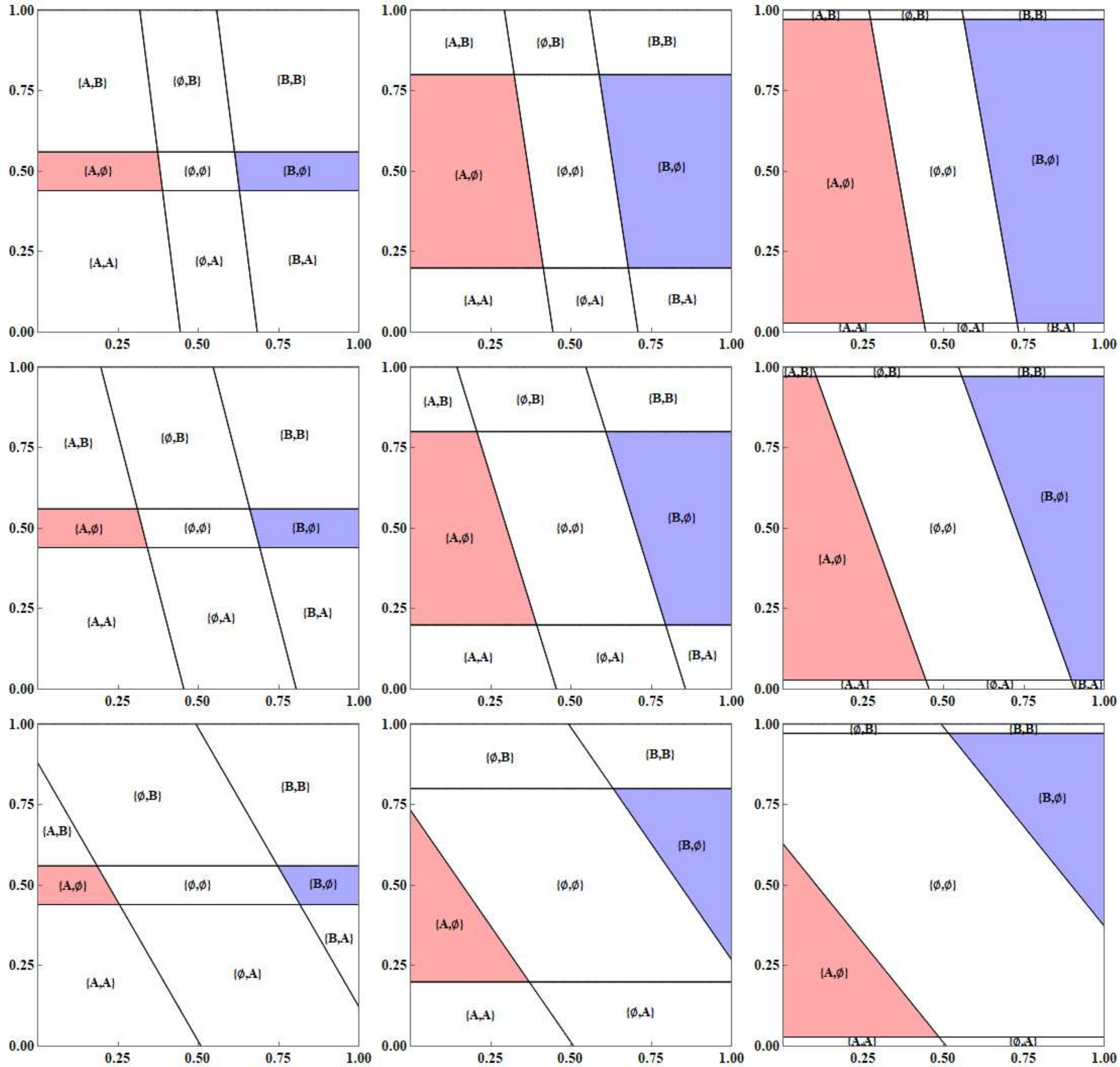

Figure 8*. Consumer market shares in era S4 with $T_S = {}^{3}/_{16}$ and high T_P that violates Assumption 2 as in Proposition 4. The columns show T_P at ${}^{5}/_{16}$, ${}^{3}/_{8}$, and ${}^{7}/_{16}$, respectively. The rows show α at ${}^{1}/_{8}$, ${}^{1}/_{4}$, and ${}^{1}/_{2}$, respectively. The horizontal axis measures taste speakers while the vertical axis measures taste for phones. Shaded areas represent sales of a speaker as a substitute for the phone.