Quality-Adjusted Prices of Japanese Mobile Phone Handsets and Carriers' Strategies*

Naoki Watanabe[†], Ryo Nakajima[‡], and Takanori Ida[§]

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Abstract

In order to discuss oligopolists' strategic determination of quality-adjusted prices (QAPs), we conducted a hedonic regression analysis using adjacent periods and estimated the QAPs of mobile phone handsets sold in Japan between 2002 and mid-2007 for each carrier. We observed (i) a decreasing trend in QAP for each carrier, (ii) a more rapid decrease in the QAPs of the two smaller carriers' handsets relative to that of the largest carrier, and (iii) a turnover cycle of the QAPs between the two smaller carriers. If both small carriers decrease their QAPs at roughly the same time, neither will significantly increase their subscriber share, which can generate a turnover cycle of QAPs.

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†corresponding author. Graduate School of Systems and Information Engineering, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573, Japan. Phone&Fax: +81-29-853-5166. E-mail: naoki50@sk.tsukuba.ac.jp.

‡Faculty of Economics, Yokohama National University, 79-3 Tokiwadai, Hodogaya, Yokohama 240-8501, Japan. E-mail: rn231@ynu.ac.jp.

§Graduate School of Economics, Kyoto University, Yoshida-honmachi, Sakyo, Kyoto 606-8501, Japan. E-mail: ida@econ.kyoto-u.ac.jp.

1 Introduction

In this study, we conduct a hedonic regression analysis and investigate the quarterly changes in the quality-adjusted prices (QAPs) of mobile phone handsets sold in Japan between 2002 and mid-2007 for each call service operator (carrier). The QAP is a price index measuring a subscriber's welfare by taking into consideration product characteristics (functions and quality).[1] By lowering QAPs relative to those of its rivals' products, a carrier can gain more subscribers because its subscribers' welfare improves on average. We discuss the QAP changes of each carrier in order to model oligopolists' strategic determination of QAPs within an industry.

Mobile phone markets are characterized by fierce competition and significant technological innovation in recent years, which makes these markets appropriate for the application of hedonic regression to measure QAPs. Such analysis is, however, still rare. Dewenter et al. (2006) estimated carriers' brand name premiums for mobile phone handsets in the German market, but their sampling period was between 1998 and 2003; thus, their analysis could not include mobile phones making use of technological advances allowing high-speed large-volume transmission (so called third-generation mobile phones). Therefore, we examine the Japanese market, where such high-performance mobile phones have been widely available since 2003.

There were three major mobile phone carriers in Japan during our sampling period, between 2002 and mid-2007. The biggest one had a market share of more than 50% of subscribers during this period, and the other two smaller carriers fiercely competed over the remaining market share. Our main findings are (i) a decreasing trend in QAP for each carrier, (ii) a more rapid decrease in the QAPs of the two smaller carriers' handsets relative to that of the largest carrier, and (iii) a "turnover cycle" of the QAPs between the two smaller carriers.

A large decrease in QAPs by a carrier that is roughly simultaneous with similar decreases of its rival will not much affect its relative subscriber share, and thus large asynchronous decreases in QAPs are possible for the two carriers that are fiercely

[1] We need a remark here to consider the QAP as a measure of subscriber's welfare. There are subscribers who have their willingness to pay for securing a product characteristic that exceed the marginal cost of production, in either a perfectly competitive market or an imperfectly competitive market. (In the perfectly competitive market, the hedonic coefficient that corresponds to a new characteristic equals to the marginal cost, while in an imperfectly competitive market, it may differ from the marginal cost. We will discuss this point in Subsect. 4.2.) More importantly, different subscribers have thei r different willingness to pay for it. Suppose that a product characteristic is optional in year t, but that it becomes standardized on all products in year $t+1$. It is then possible that the QAP itself does not increase, while some subscribers without their sufficient willingness to pay for the standardized characteristic are worse off. In fact, such a "mandatory standardization" of a new product characteristic frequently happens in mobile communication industries.

competing against each other. As a result, a turnover cycle of the QAPs can be generated. This aspect in particular is suggestive for modeling oligopolists' strategic determination of QAPs within an industry.

The rest of the paper is organized as follows: Sect. 2 briefly reviews the Japanese mobile phone industry and Sect. 3 describes the data that are used for our analysis. Sect. 4 specifies our hedonic regression model, discussing the recent literature on the estimation method. Sect. 5 presents the estimated QAPs of each carrier's handsets and discusses carriers' strategic determination of QAPs. This section also presents results from augmented Granger-causality tests. Sect. 6 offers final remarks on the related literature.

2 The Japanese Mobile Communication Industry

There were three major carriers between 2002 and 2007 in Japan: NTT DoCoMo (NTT), au by KDDI (KDDI), and Vodafone/SoftBank (SoftBank).[2] During this period, NTT had a subscriber market share of more than 50%, while the market shares of KDDI and So ftBank were roughly 25% and 15% percent, respectively. These carriers purchase mobile phone handsets from manufacturers, such as Sharp and Toshiba, and sell the handsets under their own brand names to their customers via their retail networks.[3]

The mobile phone handsets are "SIM-locked", so that they can only be used on the carriers' specific mobile communication network. The carriers can thus control the configurations, designs, and contents of handsets that are produced by the manufacturers for the carriers. As a result, each carrier provides exclusive services to its subscribers that are independent of the handsets made for the other carriers. Thus, we can say that each carrier has its "own" handsets, although manufacturers provide carriers with the handsets. In what follows, we employ this usage when referring to handsets, e.g., NTT (mobile phone) handsets.

[2] The structure of the "big three" has remained throughout the 2000s in Japan, but it has also experienced minor configuration changes due to mergers and acquisitions among carriers and brand-name changes in this period. In October 2000, KDDI was established. In October 2005, KDDI acquired TU-KA group companies and integrated the TU-KA subscribers into the "au" brand. In October 2003, the predecessor company of Vodafone, J-PHONE, changed its brand name to Vodafone. In March 2006, SoftBank began enabling Vodafone customers to change their subscription to the SoftBank service. A fourth carrier, EMOBILE, started its call service in March 2008 (data communication services in March 2007), but its market share remains very small.

[3] There were 22 manufacturers that provided handsets to carriers in the 2000s. Between 2002 and mid-2007, the market shares of the major mobile phone handset manufacturers were as follows: Sharp 13.90%, Toshiba 12.55%, Sanyo 11.91%, NEC 11.75%, Panasonic 10.30%, FUJITSU 8.67%, MITSUBISHI 7.85%, Sony Ericsson 7.55%, and Kyocera 4.28%.

As in many other countries, price subsidies have been employed in Japan since the ownership of mobile phone handsets was introduced in 1994.[4] The subsidy was as high as 90% of the handset price, so it was common that old models released just a few seasons before were sold for only one yen at retail, or sometimes even for free.

Of course, there was no free lunch. These carriers eventually recouped the cost of the price subsidies through service charges, principally from call charges. Therefore, handset sale and subscription to a service are "bundled".[5] Under the price subsidy system, mobile phone users in Japan paid relatively high communication service fees to carriers in exchange for the deep discount of handsets: in 2006, the average monthly service fees were about 6,700 yen for NTT, 6,610 yen for KDDI, and 5,510 yen for SoftBank (USD 1 = JPY 118), and the (weighted) average of such payments was the second highest among OECD countries.

The price subsidy system along with the bundling of handset sales and service subscriptions has been controversial. Opponents argue that it creates a price distortion because the true cost of a handset is hidden from consumers. Furthermore, it causes consumers to "lock in" to a particular mobile phone network by imposing on them a minimum subscription period, undermining competition in the mobile communication industry.[6] On the other hand, proponents defend the price subsidy system because it facilitates the diffusion of new handsets with more advanced technologies by lowering consumers' upgrade costs.[7]

[4] In Japan, retailers sold handsets to customers at a huge discount while receiving a rebate from the carrier for each new purchase. Therefore, price subsidies are often called "rebates" or "sales incentives" by retailers.

[5] Under the price subsidy system, customers could purchase handsets at discounted prices in return for committing themselves to use a service for a minimum subscription period, for example 12 months. See the report at `http://www.soumu.go.jp/menu_news/s-news/2008/090626_1.html`.

[6] The price subsidy system was criticized also for not providing subscribers clear information on the real charges for new services. In particular, long-term subscribers of the same handset model felt that they were treated unfairly compared to those who quickly upgraded to new models because of an unreasonable internal cross-subsidization.

[7] According to Ida (2 009), the rebate system facilitated replacement of existing models with the latest higher performing models each time a carrier launched a new or improved service, such as Internet connectivity (NTT initiated in February 1999), e-mail with photos (J-Phone, currently SoftBank, launched in November 2000), 3G (third-generation high-speed large-volume transmission) services (NTT began a trial service in May and commercial services in October 2001), Truetone (KDDI started in December 2002), packet transmission (KDDI launched in November 2003), and Truetone-Full (KDDI started in November 2004). These services were followed by such functions as music and movie downloading, Global Positioning System (GPS) navigation, mobile wallet (FeliCa, SuiCa, etc.), decorating e-mails with static and animated images (Decomail), and digital television broadcasting service for mobile phones (wan-segu). All these functions, listed in Table 2 in Sect. 3, are currently major characterist ics of mobile phones in Japan. The demand for various mobile phone services in Japan was reviewed by Iimi (2005) and Ida and Kuroda (2009).

Responding to surging criticism of the price subsidy system, the Ministry of Internal Affairs and Communications (MIC), the regulatory authority of communication services in Japan, issued new guidelines in June 2007 that recommended that mobile phone carriers lessen their heavy dependency on handset subsidies by the year 2010. The carriers responded to the guidelines immediately, and started establishing new pricing rules: They first reduced base call charges by half in September 2007, and, by 2008, consumers' cost of purchasing a handset rose substantially. For example, the average price of a handset for new service subscribers increased by about 20,000 yen over 12 months between 2007 and 2008. According to a March 2008 report issued by the MIC, at the beginning of September 2007, after all carriers had started reforming their fee structures, call charges in Tokyo were lowered by an average of 30% compared to those of the previous year.

3 Data

Mobile phone handsets are our base unit of observation. We collected the prices and characteristics of the mobile phone handsets of NTT, KDDI, and SoftBank that were sold in Japan from the first quarter of 2002 to the second quarter of 2007.[8] The sampling period roughly corresponds to the period from the introduction of 3G (third-generation high-speed large-volume tran smission) services through to the time that such services had become widespread in the Japanese mobile communication industry.[9] We do not use the period after the third quarter of 2007 because the price subsidy system was in the process of being abolished, starting September 2007, as mentioned in Sect. 2, and handset pricing has drastically changed since then.

In order to compute the quality-adjusted prices of handsets, we need to clarify

[8] Personal digital assistants (PDAs) with phonetic functions, so called "smart phones", are excluded from the sample pool of mobile phone handsets. They are widely recognized as products with information terminal functions rather than mobile phones. Also, during the sampling period covered by the present study, the smart phone market was still small in Japan, and so sufficient data were not available. In fact, NTT did not start selling BlackBerry smart phones for personal use until August 2008 (September 2006 for business use), to compete against the introduction of the iPhone by SoftBank in July 2008.

[9] The 3G technology, formally International Mobile Telecommunications-2000 (IMT-2000), is a family of standards for mobile telecommunications defined by the International Telecommunication Union. The principal advantages of the 3G technology is that it supports high-speed data transmission services and a greater range of advanced terminal capabilities, and so users can do everything from sending and receiving video images to settling financial transactions using the same terminal or handset. The 3G standards in Japan are W-CDMA and cdma2000. The former is used by NTT and SoftBank, and the latter is used by KDDI. NTT initiated 3G service in Japan as a trial service in May 2001 and as a commercial service in October 2001, as noted in footnote 6.

what the “true” price of a mobile phone handset is. As described in Sect. 2, each mobile phone handset is heavily subsidized, so that the retail price is substantially lower than the wholesale price at which the carrier purchases the handset from the manufacturer. Therefore, we define the unsubsidized prices of mobile phone handsets as the values computed by aggregating the retail price and the handset subsidy paid to the retailers by the mobile phone carriers.

First, we started with retail price information available from the Price Survey on the Mobile Phone Watch website that is maintained by the Impress Corporation, which collects the retail price information for all mobile phone handsets sold at major retail stores in Tokyo and Osaka.[10] Although all consumers receive a subsidy when purchasing handsets, the amount of the subsidy depends on the type of subscription. Generally, new subscribers have the least discount, while existing subscribers who exchange their handsets after only short periods obtain the deepest discounts. In the analysis that follows, for simplicity, we use the handset price for a new subscriber as its retail price.

Second, we obtained price subsidy information from the financial reports that are issued quarterly by each carrier, where the average subsidy amount in yen per new mobile phone handset is available. Table 1 shows a summary of the annual average of the price subsidy per new handset for each carrier. The values for 2007 indicate the average over two quarters.

Table 1: The Average Subsidiy Amount per New Handset (in yen)

Year	NTT DoCoMo	au by KDDI	Vodafone/SoftBank
2001	30,000	42,000	40,000
2002	30,000	40,000	37,000
2003	31,000	36,000	32,500
2004	34,000	38,000	38,300
2005	36,000	37,000	45,000
2006	37,000	37,000	35,000
2007*	33,500	37,500	34,200

NOTE: * The values in 2007 indicate the average in two quarters.

Finally, we obtained the unsubsidized price of a handset of a carrier for each quarter by matching the retail price for that quarter with the average carrier subsidy for the quarter. We convert the unsubsidized price to a monthly payment by assuming that the replacement cycle of the mobile phone handset is 24 months. In the analysis that follows, we use the monthly payment for a handset as the base unit of price, and call it the price of the handset.

Figs. 1 and 2 show the average handset price from the first quarter of 2002

[10] http://k-tai.impress.co.jp

through to mid-2007, for the aggregated carriers and the disaggregated carriers, respectively. All the handset prices are deflated by the quarterly-adjusted consumer price index for all items (base period is the first quarter of 2000). It is apparent that the handset price, on average, has fluctuated greatly during the study period. Although all carriers lowered their average prices from 2002 to the second half of 2003, thereafter there was no common trend in relative highs and lows.

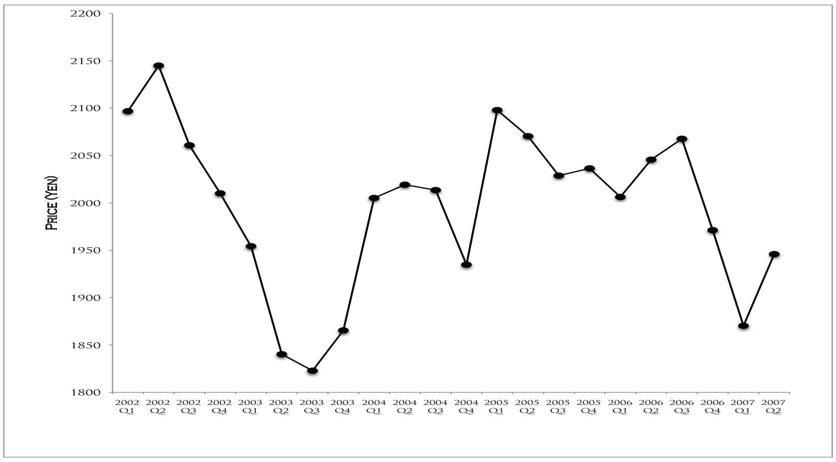

Figure 1: Average Handset Price for All Carriers

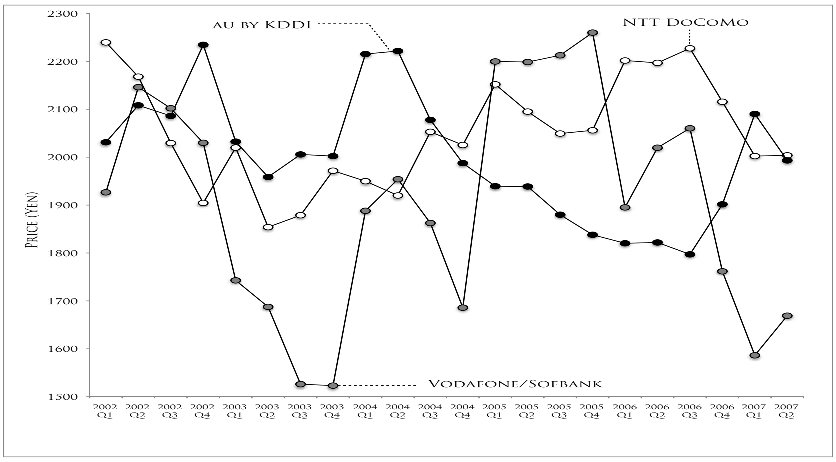

Figure 2: Average Handset Price by Each Carrier

Data on mobile phone characteristics were collected from Showcase on the Mobile Phone Watch website, White Paper on Mobile Phones 2008, and the Mobyrent Database operated by CELLANT Corporation. In order to measure the impact of advances in mobile communication technology on handset prices, we included as extensive a set of handset characteristics as possible given the information available to us.

The summary statistics of major variables are presented in Table 2. The non-binary characteristics, such as communication speed, camera resolution, screen resolution, and battery duration, are presented in the first part of Table 2. They mainly concern the performance or the quality of a mobile phone handset. We also consider the length of time after a handset is released as the "age" of the handset, and control for it in our estimation. All other characteristics in Table 2 are binary.[11] Manufacturer dummy variables are included as the last item in the table.

Table 2: Name and Definition of Handset Characteristics

Variable name	Description	Mean	Std. Dev.	Min	Max
Log Speed	Transmission speed of a handset measured by kbps (in logarithm)	4.9503	1.7255	2.2618	8.1887
Log Camera	Resolution of equipped camera measured by megapixel (in logarithm)	4.5192	0.9614	1.9459	6.2146
Log Screen	Screen resolution measured by megapixel (in logarithm)	5.0208	0.1939	4.0943	5.6699
Log Duration	Battery duration indicated by talk time in minutes (in logarithm)	5.8376	0.3860	4.0073	6.5511
Ringtone	The number of polyphonic ringtones.	60.1965	30.3301	16.0000	128.0000
Age	Elapsed periods in quarter periods after the first release	1.1601	1.1727	0.0000	7.0000
Truetone	Equal 1 if a handset has Truetone (Chaku-uta).	0.6202	0.4853	0.0000	1.0000
Truetone Full	Equal 1 if a handset has Truetone Tull.	0.2093	0.4068	0.0000	1.0000
G3	Equal 1 if a handset is the third generation.	0.6566	0.4749	0.0000	1.0000
Java	Equal 1 if a handset has Java application compatibility.	0.8220	0.3825	0.0000	1.0000
Flash	Equal 1 if a handset has Adobe Flash application compatibility.	0.5063	0.5000	0.0000	1.0000
QR	Equal 1 if a handset has Quick Response code compatibility.	0.5903	0.4918	0.0000	1.0000
FeliCa	Equal 1 if a handset is equipped with non-contact IC chip.	0.1832	0.3869	0.0000	1.0000
Mobile SuiCa	Equal 1 if a handset has electronic wallet.	0.1340	0.3406	0.0000	1.0000
Full Browser	Equal 1 if a handset has full browser compatibility.	0.1311	0.3375	0.0000	1.0000
GPS	Equal 1 if a handset is equipped with GPS.	0.2826	0.4503	0.0000	1.0000
Decomail	Equal 1 if a handset has static and animated images compatibility.	0.2178	0.4127	0.0000	1.0000
Movie	Equal 1 if a handset has movie compatibility.	0.6299	0.4828	0.0000	1.0000
Music	Equal 1 if a handset has music compatibility.	0.3063	0.4610	0.0000	1.0000
Radio	Equal 1 if a handset has FM radio compatibility.	0.1409	0.3480	0.0000	1.0000
TV	Equal 1 if a handset has TV viewer.	0.3697	0.4827	0.0000	1.0000
Location	Equal 1 if store location is in Tokyo; 0 if in Osaka	0.5000	0.5000	0.0000	1.0000
Manufacturer dummy variables defined for 22 manufacturers*					

NOTE:*Manufacturer dummy variables are defined for Casio, Denso, Fujitsu, Hitachi, JRC, Kenwood, Kokusai, Kyocera, LG, Mitsubishi, Motorola, NEC, Nokia, Pantech, Panasonic, Pioneer, Samsung, Sanyo, Sharp, Sony, Sony Ericsson, and Toshiba.

It should be noted that not all of the characteristics presented in Table 2 were

[11]QR code is a two-dimensional bar code (matrix code) invented by the Japanese company Denso-Wave. Handsets equipped with FeliCa incorporate a non-contact IC chip developed by Sony Corp., and Mobile Suica is an electronic wallet service for public transport facilities for handsets equipped with FeliCa. Decomail is a service that enables the use of more advanced e-mail features, including static and animated images, by supporting the compact HTML (cHTML) standard. Decomail has rapidly become popular in Japan. In July 2008, SoftBank began selling the Apple iPhone 3G, but the sales have not increased as quickly as expected. A major reason is that the iPhone lacks many popular functions such as Decomail, Mobile SuiCa, and digital television broadcasting service (wan-segu).

observed through the entire sampling period. Due to the rapid growth of mobile communication technology in Japan in recent years, many new features have been introduced to mobile phone handsets. For example, Truetone (Chaku-uta), which is a service that transforms the ringtone of a handset into a piece of music, was first introduced in new models released by KDDI in the fourth quarter of 2002. Truetone-Full is an extended version that covers almost the full length of a song. This service has been rapidly spreading to almost all handsets, but it was not available on any handset before its release.[12] The introduction of new technology produces the so called "new characteristic" proble m of price index computation, which will be discussed in detail in the next section (Sect. 4.2).

By using a dummy variable for third generation, we can observe the transition from second- to third-generation mobile phones. Third-generation mobile phones accounted for 10% of all handsets at the beginning of 2002, but their share increased to nearly 95% by the second quarter of 2007. The share increased drastically in 2007 with the dissemination of digital television broadcasting service (wan-segu).

4 Estimation Method

4.1 Hedonic Regression Analysis

Two hedonic approaches have been widely employed to measure the quality-adjusted price index: the *hedonic imputation indexes approach* and the *time dummy hedonic indexes approach*. (See Tripplett 2004 for details.) Both approaches are based on hedonic price regressions. Let the price of handset i at period t be p_{it}. The hedonic price regression takes the following form as a function of the characteristics:

$$\log(p_{it}) = \alpha_t + \sum_{j=1}^{J} \beta_{jt} x_{ijt} + \varepsilon_{ijt}, \tag{1}$$

where x_{ijt} represents the j-th handset characteristic of handset i in period t. This variable is log-transformed when it is a non-binary characteristic.[13]

The hedonic imputation indexes approach is based on the interpretation that the coefficients of the hedonic regression represent the implicit prices of the characteristics. One can use the following price imputation measures, which are the *Paasche-type* price index and the *Laspeyres-type* price index. As shown in Berndt and Rappaport (2001), the Paasche-type price index for period t relative to period $t-1$ is computed by

[12] The share of handsets supporting Truetone was 28% in 2003Q4, 58% in 2004Q4, 86% in 2004Q4, 91% in 2005Q4, and 95% in 2007Q4, respectively, where Qi indicates the i-th quarter of the year.

[13] See, e.g., Berndt et al. (1995) and Berndt and Rappaport (2001).

$$p_{t,t-1}^{PAS} = \frac{p_t(\hat{\beta}_{jt}, \bar{x}_{jt})}{p_{t-1}(\hat{\beta}_{jt-1}, \bar{x}_{jt})} \tag{2}$$

where $p_t(\hat{\beta}_{jt}, \bar{x}_{jt})$ and $p_{t-1}(\hat{\beta}_{jt-1}, \bar{x}_{jt})$ represent the year-t and year-$(t-1)$ characteristic prices at the year-t average characteristic $\bar{x}_{jt}$, based on the estimated β_{jt} and β_{jt-1}, respectively. The corresponding Laspeyres-type price index for period t relative to period $t-1$ is computed by

$$p_{t,t-1}^{LAS} = \frac{p_t(\hat{\beta}_{jt}, \bar{x}_{jt-1})}{p_{t-1}(\hat{\beta}_{jt-1}, \bar{x}_{jt-1})}. \tag{3}$$

Once the price imputation measures are computed between two adjacent periods, the quality-adjusted price between the base period 0 and period t is computed by "chaining", i.e., by successive multiplication of indexes between periods 0 and 1, 1 and 2, $\cdots, t-1$ and t. In general, though, the Laspeyres-type index and the Paasche-type index do not coincide, diverging to the degree that the average characteristics change over time. So, both types of indexes should be computed and be combined with each other using, for example, the geometric mean (i.e., a Fisher-type price index).

The time dummy hedonic indexes approach, on the other hand, uses the fact that the coefficient of the dummy variable represents the quality-adjusted price change between the base period and a subsequent period. This method has been popular because of its simplicity. One usually pools cross-sectional data of period t and subsequent periods, say $t+1, t+2, \cdots, t+K$, and estimates a variant of the regression model (1) with time dummy variables: for $s = t, t+1, \cdots, t+K$,

$$\log(p_{is}) = \alpha_t + \sum_{k=1}^{K} \alpha_{t+k} D_{t+k} + \sum_{j=1}^{J} \beta_{jt} x_{ijs} + \varepsilon_{ijs}, \tag{4}$$

where D_{t+k} is a dummy variable that takes one only when the period is $s = t+k$. We assume that the coefficient β_{jt} is constant during the pooled periods between $s = t$ and $s = t+K$. Then the quality-adjusted price of a handset between periods t and $t+K$ is computed from the estimates of the coefficients of the time dummy variables through the following formula:

$$p_{t,t+K}^{TIME} = \exp(\hat{\alpha}_{t+K}). \tag{5}$$

4.2 Empirical Strategy

Which one of the above two hedonic approaches should we use to compute the quality-adjusted prices of mobile phone handsets? In the case of the Japanese mobile communication industry, we find that the time dummy hedonic indexes approach seems preferable to the hedonic imputation indexes approach because the latter suffers from the "new characteristics problem" that was pointed out by Triplett (2004).

To understand this, consider a situation where a new binary characteristic, say Truetone, is introduced to a new mobile phone handset in period t, while it is not available on any handset for periods 0 to $t-1$. In this situation, it is impossible to compute the Paasche-type index (2), because the estimate of the coefficient of the characteristic, or equivalently, the implicit price of the characteristic, is not available for the previous period $t-1$. One may compute the Laspeyres-type index (3) by using the weight of the characteristic as zero at period $t-1$. Yet, this can introduce serious bias to the quality-adjusted price because this ignores the value added by the arrival of the new characteristic (Triplett 2004, p.85). One can thus conclude that the hedonic imputation indexes approach is inappropriate for estimating the quality-adjusted price of mobile phones in Japan where new mobile phone handset characteristics have been introduced continuously.

The price index based on the time dummy hedonic indexes approach, on the other hand, does not suffer from the introduction of new characteristics. It is common for old handset models without some new characteristic to continue to be sold, at a substantial price discount, in the market for some time after new models with the characteristic have been released. This implies that the time dummy variables in the hedonic regression are not collinear with the dummy variable that represents a newly introduced characteristic. Thus, the time dummy hedonic regression model (4) can be estimated from our data. Taking all these points into consideration, we therefore base our analysis of the quality-adjusted price of mobile phone handsets on the time dummy hedonic regression method in the following empirical analysis.

Of course, as is frequently pointed out in the literature, the assumption of time dummy hedonic regression regarding parameter stability across pooled periods is unrealistic and restrictive. Whenever a new characteristic is introduced in the market, a new non-trivial variable is added to the set of independent variables in the hedonic regression so that the structure of the regression changes.

In order to address this issue, we set up a recursive test procedure to examine the stability of the slope coefficient over time: we start the F test from two adjacent quarters of period 0 and 1, and if the null hypothesis of no structural break is not rejected we repeatedly expand the periods by adding a new period until the null hypothesis is rejected by the F test. Once the null hypothesis is rejected at, say, period t' (≥ 2), we conclude that periods from 0 to t' should be pooled for the hedonic regression, and we restart the F test from the subsequent two adjacent quarters of period t' and $t' + 1$, recursively.

The results of the recursive F test procedure suggest that no more than two adjacent periods should be pooled for the aggregated carrier data.[14] In many cases, structural breaks occur due to the introduction of new characteristics. But in other cases where characteristics are unchanged over consecutive periods, the null hypothesis that coefficients are stable is rejected at the 5% significance level for *any* pooled periods.

We therefore opt for pooling *only two adjacent* quarterly periods, and run the regression for each pair of combined adjacent periods. Then the hedonic regression model is given by

$$\log(p_{is}) = \alpha_t + \alpha_{t+1} D_{t+1} + \sum_{j=1}^{J} \beta_{jt} x_{ijs} + \varepsilon_{ijs}, \tag{6}$$

for the two adjacent periods $s = t$ and $t + 1$. Requena-Silvente and Walker (2006) call this type of hedonic regression *adjacent period regression*. Given the estimates of the adjacent period hedonic regressions, the quality-adjusted price between the base period 0 and period t is computed by the following chaining rule:

$$\widehat{QAP}_t = \prod_{s=1}^{t} \exp(\hat{\alpha}_s). \tag{7}$$

It should be noted that the adjacent hedonic regression (6) we implement here is not "weighted". Because the product share information of each handset model, in either sales or revenues, was not available, we could not adjust the hedonic regression by quantity or expenditure weights. Although the computation of quality-adjusted prices based on unweighted hedonic regression is common in the literature (e.g., Berndt et al. 1995; Berndt and Rappaport 2001), the interpretation needs some qualification in terms of the representativeness of the data: quality-adjusted prices between the base period and reference periods based on unweighted hedonic regression are interpreted as price changes of the average handset model rather than the price change of an average transaction.[15]

[14] The results are not reported but are available upon request.

[15] Only the shipment share of handsets by manufacturer was available, so we implemented hedonic regressions weighted for manufacturer quantity. Based on the weighted least squares estimates, we

The last issue of concern with the hedonic regression is the possible existence of price markups due to imperfect competition on the supply side of the market. In a perfectly competitive market, which is assumed in the traditional hedonic regression model, the estimated coefficient of the hedonic regression can be interpreted as the consumers' marginal evaluation of each characteristic of the good (Rosen 1974). On the other hand, in an imperfectly competitive market, where the price exceeds the marginal cost, the hedonic regression may provide a biased estimate of the consumer's implicit price for the characteristic, as Feenstra (1995) pointed out. Therefore, the hedonic regression should be modified in order to take into account the difference between the price and the marginal cost.

Recently, this matter was challenged by Pakes (2003).[16] He argued that, in the Bertand equilibrium of (differentiated) oligopolistic markets, the hedonic regression represents the expectation of the marginal cost of a producer plus a market power function of the distribution of consumers' preferences and the characteristics of competing products. So, the coefficients have "no obvious interpretation in terms of economic primitives" (Pakes 2003., p.1581).

In this paper, we follow Pakes, and do not worry about the "coefficient bias" of the estimated hedonic regression. We thus interpret the hedonic regression estimating the conditional expectation of marginal cost and markup given the characteristics, which is approximated in the sense of minimizing mean squared error by the linear combination of characteristics with appropriate transformation of the dependent variables (prices) and the independent variables (characteristics).

Given this view of hedonic regression in "reduced form", the focus is not on the estimated coefficients but on the price indexes generated by the hedonic regression. Even if there are large markups in the markets, an unbiased estimate of price indexes can be obtained from the hedonic regression, although the coefficients are not interpreted as measures of either consumers' marginal evaluations or producers' marginal costs.

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computed the quality-adjusted price of mobile phone handsets and found that the results do not change much when the quantity weight is included. The results are available from authors upon request.

[16] See Anstine (2004) for an excellent discussion of this matter. In a more general context, Benkard and Bajari (2005) proposed the use of factor analysis methods to correct the bias due to unobserved characteristics.

5 Estimation Results

5.1 Hedonic Regression

Table 3 presents the estimation results of the aggregated carriers for some main characteristics. Prices are deflated by the Japanese GDP deflator (base period = the first quarter of 2002). (See Watanabe et al. 2009 for the entire estimation results.) As indicated by the sign change, estimates of some coefficients (those of camera resolution and age) are stable over time while the estimates of other coefficients (those of speed, screen, and battery duration) are unstable. For example, the transmission speeds have a significant positive impact on handset prices in the earlier periods but their effect starts to vary after around 2005. Although not presented in the table, the estimated coefficients of the binary variables are also unstable (sign reversals).

Table 3: Regression Results: All Carriers for Selected Variables

Periods	log(speed)	log(camera)	log(screen)	log(duration)	age	time dummy	N	$\bar{R}^2$
02Q1 –02Q2	**0.197**	**0.040**	-0.109	−−	**-0.040**	-0.006		
	(0.024)	(0.017)	(0.133)		(0.006)	(0.007)	338	0.959
02Q2 –02Q3	**0.425**	0.003	**-0.545**	**0.936**	**-0.072**	**-0.025**		
	(0.060)	(0.048)	(0.143)	(0.215)	(0.006)	(0.007)	463	0.889
02Q3 –02Q4	**0.197**	**0.054**	**0.142**	0.081	**-0.057**	**-0.085**		
	(0.030)	(0.023)	(0.034)	(0.049)	(0.006)	(0.008)	662	0.733
02Q4 –03Q1	**0.067**	**0.059**	**-0.054**	0.030	**-0.103**	**-0.045**		
	(0.011)	(0.016)	(0.022)	(0.051)	(0.006)	(0.009)	895	0.595
03Q1 –03Q2	**0.054**	**0.042**	**-0.038**	**0.150**	**-0.079**	**-0.059**		
	(0.013)	(0.013)	(0.019)	(0.061)	(0.006)	(0.008)	1005	0.664
03Q2 –03Q3	**0.111**	**0.039**	-0.011	**0.575**	**-0.068**	**-0.079**		
	(0.012)	(0.009)	(0.013)	(0.067)	(0.004)	(0.006)	1311	0.798
03Q3 –03Q4	**0.131**	**0.060**	-0.004	**0.560**	**-0.062**	**-0.021**		
	(0.007)	(0.007)	(0.009)	(0.050)	(0.003)	(0.005)	1676	0.776
03Q4 –04Q1	**0.077**	**0.058**	**0.026**	-0.027	**-0.074**	**0.013**		
	(0.007)	(0.009)	(0.010)	(0.054)	(0.004)	(0.006)	1704	0.705
04Q1 –04Q2	**0.076**	**0.089**	**0.090**	**-0.285**	**-0.086**	**-0.090**		
	(0.006)	(0.007)	(0.010)	(0.044)	(0.003)	(0.005)	1816	0.765
04Q2 –04Q3	**0.071**	**0.079**	**0.056**	**-0.199**	**-0.078**	**-0.040**		
	(0.006)	(0.006)	(0.010)	(0.038)	(0.003)	(0.006)	2246	0.718
04Q3 –04Q4	**0.043**	**0.031**	-0.020	**-0.084**	**-0.065**	**-0.037**		
	(0.005)	(0.007)	(0.012)	(0.037)	(0.003)	(0.006)	2324	0.648
04Q4 –05Q1	**0.018**	**0.019**	**-0.029**	**-0.080**	**-0.046**	**0.008**		
	(0.006)	(0.007)	(0.014)	(0.036)	(0.003)	(0.006)	2245	0.629
05Q1 –05Q2	**-0.031**	**0.067**	**-0.038**	**-0.142**	**-0.046**	**-0.041**		
	(0.008)	(0.009)	(0.019)	(0.038)	(0.004)	(0.006)	2168	0.646
05Q2 –05Q3	**-0.002**	**0.129**	**0.141**	**-0.139**	**-0.055**	**-0.048**		
	(0.009)	(0.010)	(0.023)	(0.035)	(0.003)	(0.005)	2293	0.679
05Q3 –05Q4	**0.050**	**0.132**	**0.249**	**-0.291**	**-0.065**	**-0.040**		
	(0.007)	(0.009)	(0.025)	(0.033)	(0.003)	(0.005)	2423	0.682
05Q4 –06Q1	**0.039**	**0.140**	**0.448**	**-0.269**	**-0.076**	**-0.057**		
	(0.007)	(0.010)	(0.037)	(0.042)	(0.003)	(0.006)	2480	0.596
06Q1 –06Q2	**0.039**	**0.140**	**0.448**	**-0.269**	**-0.076**	**-0.057**		
	(0.007)	(0.010)	(0.037)	(0.042)	(0.003)	(0.006)	2480	0.596
06Q2 –06Q3	**-0.029**	**0.131**	-0.004	**0.255**	**-0.082**	-0.002		
	(0.007)	(0.008)	(0.017)	(0.037)	(0.002)	(0.004)	3392	0.640
06Q3 –06Q4	**-0.030**	**0.088**	**-0.056**	**0.251**	**-0.057**	**-0.033**		
	(0.007)	(0.009)	(0.015)	(0.036)	(0.002)	(0.005)	3324	0.545
06Q4 –07Q1	**0.014**	**0.053**	**-0.107**	**0.152**	**-0.039**	**-0.057**		
	(0.006)	(0.009)	(0.029)	(0.026)	(0.003)	(0.006)	3364	0.475
07Q1 –07Q2	**-0.003**	**0.053**	0.008	**0.055**	**-0.042**	**0.014**		
	(0.005)	(0.008)	(0.020)	(0.016)	(0.002)	(0.004)	4004	0.505

NOTE: Robust standard errors are in parentheses. Boldfaced values are significant at .05.

Following the argument of Pakes, however, the instability and reversals of signs of the estimated coefficients are "neither unusual results for hedonic regression nor a particular source of worry" (Pakes 2003, p.1587). As presented, in an imperfectly competitive market, the coefficient of a characteristic no longer represents an implicit price; instead, it represents a marginal cost function plus a markup function that resulted from the optimization behavior of consumers and producers in a market with product differentiation. In what follows, therefore, we opt for not interpreting the coefficients of characteristics.

Given that our interest is in the price index generated by the hedonic regressions, we need to take into account its mean and variance. We focus on the adjusted R-squares of hedonic regressions, because they are closely associated with the mean squared error of the price prediction. Table 3 shows that the adjusted R-squares have average $\bar{R}^2 = 0.68$, so the model is generally well specified using the standards of previous studies of hedonic price indexes.[17]

One concern is that the goodness-of-fit measure in the adjusted R-square declines from 0.96 to 0.48, and this might suggest misspecification may arise.[18] To account for the possibility of unobserved characteristics, we allow for carrier-specific heterogeneity in the hedonic regression.[19] For this purpose, we start by examining whether data should be aggregated or disaggregated over carriers. We first implement an F test of the null hypothesis that the coefficients of the hedonic regressions are all equal *across* carriers. F tests are carried out for the all-period-pooled hedonic regression and for each adjacent period hedonic regression. In all cases, we found that the null hypothesis is rejected at the 5% significance level.

We further implement a recursive F test, as described above, to examine the stability of the coefficients of the hedonic regression over time. Because the test results above implied that the sample should be disaggregated by carrier, the recursive F tests were implemented for each sample of carriers, NTT, KDDI, and SoftBank respectively. Again, we found that no more than two adjacent periods are pooled for any of the three carriers. All these tests indicated that hedonic regressions for each carrier should be estimated by pooling two adjacent periods.

Table 4 reports the adjusted R-squares for the aggregated and disaggregated carrier samples. As presented, the goodness-of-fit measures improve substantially

[17] For example, Pakes (2003) examined many functional forms in the hedonic regression and reported $\bar{R}^2$s for PCs that ranged from 0.26 to 0.52.

[18] We included in our estimation as extensive a set of handset characteristics as possible given the information available to us. Nontheless, there might be unobserved characteristics that correspond more directly to the subscribers' individual preferences that may cuase the declining tendency of the adjusted R-square. For example, it is hard to quantify the "design" of a handset as a variable in our estimation given the information available. Such factors may be important for consumers' determination of whether or not to purchase a handset, and thus they can be incorporated in the handset prices.

[19] We also took care of manufacturer-specific unobserved factors in the hedonic regressions by adding dummy variables for all 22 manufacturers.

Table 4: Adjusted R-squares for Hedonic Regressions

Periods	All Carriers	NTT	KDDI	SoftBank
02Q1-02Q2	0.96	0.86	0.87	0.91
02Q2-02Q3	0.89	0.83	0.64	0.90
02Q3-02Q4	0.73	0.75	0.89	0.87
02Q4-03Q1	0.60	0.67	0.84	0.84
03Q1-03Q2	0.66	0.72	0.73	0.74
03Q2-03Q3	0.80	0.81	0.70	0.79
03Q3-03Q4	0.78	0.76	0.67	0.80
03Q4-04Q1	0.70	0.74	0.77	0.88
04Q1-04Q2	0.76	0.84	0.71	0.83
04Q2-04Q3	0.72	0.89	0.66	0.73
04Q3-04Q4	0.65	0.86	0.59	0.66
04Q4-05Q1	0.63	0.87	0.54	0.85
05Q1-05Q2	0.65	0.83	0.65	0.82
05Q2-05Q3	0.68	0.86	0.48	0.74
05Q3-05Q4	0.68	0.83	0.63	0.80
05Q4-06Q1	0.60	0.78	0.57	0.85
06Q1-06Q2	0.60	0.85	0.64	0.83
06Q2-06Q3	0.64	0.82	0.56	0.90
06Q3-06Q4	0.55	0.79	0.46	0.70
06Q4-07Q1	0.47	0.59	0.66	0.53
07Q1-07Q2	0.51	0.51	0.50	0.66
Average	0.68	0.78	0.65	0.79

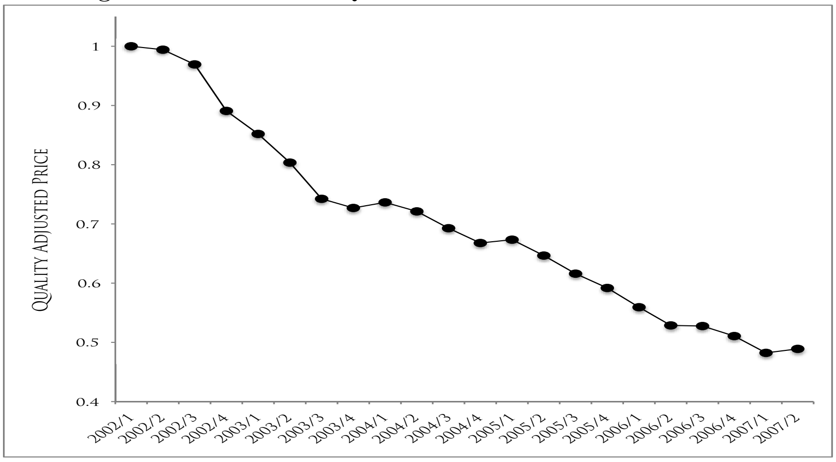
for NTT and SoftBank, with averages 0.78 and 0.79, respectively, while those for KDDI become slightly worse, with an average of 0.65, compared to those for aggregated carrier data, which have an average of 0.68. This suggests that we may not have controlled for some important factors that determine the prices of a handset, especially for KDDI handsets.

For example, we cannot control "design" as a determinant of the handset price. It is hard to quantify such a factor given the information available, but the factor may be important for consumers' determination of whether to purchase a handset. According to a business anecdote, KDDI was successful in the mid-2000s in attracting new subscribers, in particular teenagers, by headhunting competent industrial designers and creating elegantly designed mobile phone handsets. We are thus obliged to acknowledge that missing factors may bias the quality-adjusted prices of handsets, especially for those of KDDI.

5.2 Carriers' Strategies on QAPs

Fig. 3 presents the estimated QAPs of the mobile phone handsets sold in Japan between 2002 and mid-2007. It is clear that the QAP decreased steadily during this period. The consistent decrease in the QAP contrasts remarkably with the widely fluctuating average handset price depicted in Fig. 1.

Figure 3: Estimated QAPs of Handsets for All Carriers



The classic explanation for a decreasing trend in QAP is the *obsolescence effect* on the values of existing products due to technological progress: The introduction of new models with higher functions and quality lowers the value of the monopolist carrier's old models.[20] To give a theoretical foundation for this explanation, Fishman and Rob (2002) endogenized technological progress as a monopolist's decision problem on its dynamic R&D investment.

In oligopolistic markets, however, the introduction of such new models lowers the value of rivals' models as well. The QAP given by (7) is not suitable for capturing this *business stealing effect*, because it is not directly comparable across carriers but only measures the *relative* change in QAPs of the same carrier's handsets. Thus, we examine another measure, the *absolute* QAP, which explicitly allows for the initial price difference among carriers in the base period.

Denote by $\bar{p}_0^k$ the average price of carrier k's handsets in the base period $t = 0$ and by $\hat{\alpha}_s^k$ the estimated coefficient of the dummy variable D_s in hedonic regression (6) for carrier k. The absolute QAP of carrier k's handsets in period t is defined by

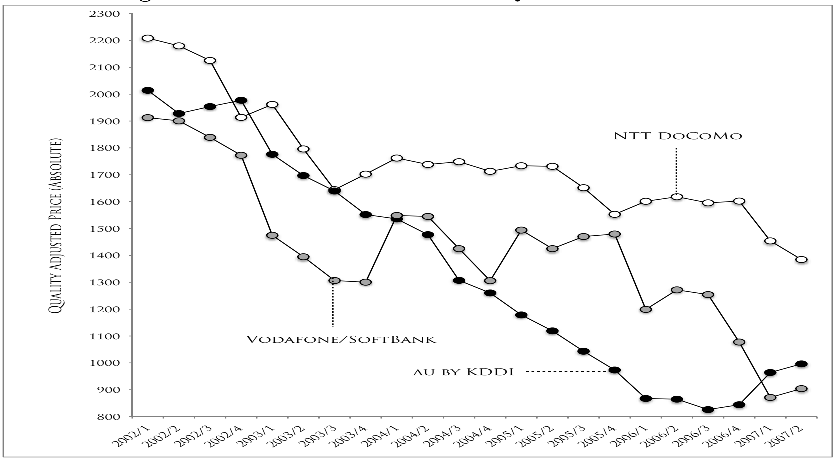
$$\widehat{AQAP}_t^k = \bar{p}_0^k \prod_{s=1}^{t} \exp(\hat{\alpha}_s^k). \tag{8}$$

For the remaining part of this subsection we will refer to the absolute QAP as simply the QAP.

The decreasing trend in estimated absolute QAP can be seen in Fig. 4. The QAPs of NTT handsets were more expensive than those of KDDI and SoftBank handsets. NTT has nevertheless retained a remarkably large market share, more

[20]We measure the "age" of a handset to capture the obsolescence effect on its price. See Table 2.

Figure 4: Estimated Absolute QAPs of Handsets



than 50% of subscribers, throughout the study period. From 2003 to 2005 the KDDI QAPs decreased from quarter to quarter, enlarging the difference in QAPs between NTT and KDDI handsets.[21] During this period, KDDI gained many more subscribers and NTT lost market share.[22] NTT might have been reluctant to decrease the QAPs of its handsets due to the profitability of having the largest market share.

The QAPs of both KDDI and SoftBank handsets decreased more rapidly than that of NTT handsets. This is understandable because, as well as against NTT with its remarkably large market share, these two smaller carriers were fiercely competing against each other to gain the remaining share. We can observe in Fig. 4 the different overall patterns and the asynchronous timing of these two carriers' decisions to make large decreases in their QAPs.

A carrier can gain more subscribers by the business-stealing effect of large reductions of QAP relative to that of a fiercely competing rival. Accordingly, a large decrease in QAP by a carrier roughly simultaneous with a large decrease by such a rival will not much affect its relative subscriber share, and thus may not be the best strategy for either carrier, particularly if the introduction of higher-performing models requires considerable development cost, in addition to the cost of advertising the new lower QAP.

Large asynchronous decreases in QAP generate a clear *turnover cycle* in QAPs between KDDI and SoftBank handsets, the first turnover occurring in the first quarter of 2004, and the second one occurring in the first quarter of 2007. The QAP

[21] KDDI started various new services in December of 2002 and had completely shifted to the 3G mobile communication system by the end of 2005. See footnote 7 for details.

[22] The market share fell below 50% in March 2008.

Table 5: Granger-causality Tests for First Differenced absolute QAPs

Null Hypothesis	Critical Probability
KDDI does not Granger-cause NTT	0.0900 (rejected)
SoftBank does not Granger-cause NTT	0.5411 (accepted)
NTT does not Granger-cause KDD I	0.1274 (accepted)
SoftBank does not Granger-cause KDDI	0.0740 (rejected)
NTT does not Granger-cause SoftBank	0.6597 (accepted)
KDDI does not Granger-cause SoftBank	0.5313 (accepted)

NOTE: The Toda-Yamamoto's augmented Granger-causality tests are carried out based on the VAR model of absolute QAPs with four lags, where $k = 3$ and $d_{max} = 1$. Critical probabilities are provided. The rejection of null hypothesis is based on 10% significance level.

gap between the two carriers' handsets grew larger from the third quarter of 2002 to the fourth quarter of 2003, and then started to shrink. After the first turnover, the QAP gap again grew continuously larger in the first quarter of 2005, and then started to shrink in the fourth quarter of 2006.

To investigate the strategic interaction of carriers' QAPs, we implemented Granger-causality tests. The pre-tests of unit roots (augmented Dickey-Fuller and Phillips-Perron) consistently suggested that all the QAPs are integrated of order one, $I(1)$.[23] As is known in the literature (e.g., Toda and Phillips 1993), if the endogenous variables are integrated, the standard Granger-causality test based on level vector autoregression (VAR) is invalid. We thus use a variant of the Granger-causality test proposed by Toda and Yamamoto (1995), which is robust to the integration or cointegration properties of the process.[24]

Toda and Yamamoto's augmented Granger-causality test is carried out by the following steps: (1) the lag length k of the VAR of endogenous variables and the maximal order d_{max} of integration are determined, (2) a level VAR of the variables is estimated with a total $p = k + d_{max}$ lags, and (3) the standard Granger-causality test is implemented based on the estimated VAR with p lags.

For the system of the carriers' QAPs, the Consistent AIC proposed by Bozdogan (1987), a small-sample corrected AIC, suggests that $k = 3$, up to four lags, for the sample size in 22 periods.[25] Given that the unit root tests suggested $d_{max} = 1$, we

[23]The results are not reported but are available upon request.

[24]The vector error correction model, VECM, is an alternative method. VECMs, however, need more degrees of freedom, and thus we could not choose it, faced with the limited sample size of QAPs.

[25]Due to the small sample size relative to the number of model parameters, we use the Consistent AIC, which imposes a greater sample size penalty on the log-likelihood than the original AIC criterion, and therefore tends to favor more parsimonious models. The small-sample corrected AIC was first proposed by Sugiura (1978) as c-AIC, and revised by Hurvich and Tsai (1989). Bozdogan

estimated the VAR model of the QAPs with $p = 4$ lags, and implement the standard Granger-causality tests.[26]

The results of the Toda-Yamamoto's augmented Granger-causality test, shown in Table 5, suggest that the QAPs of a carrier's handsets should be influenced by those of the carrier that is next lower ranked in the market share. If SoftBank's share exceeds KDDI's in the future, the direction of causality may become reversed. Then we could say that the reversal statistically confirms the complete turnover cycle between KDDI and SoftBank's QAPs.

6 Final Remarks

A decreasing trend in QAP has been reported for new cars (Griliches 1961), software packages (Gandal 1994), personal computers (Nelson et al. 1994; Berndt et al. 1995), mainframe computers (Brown 2000), and PDAs (Chwelos et al. 2008). Faced with limited sample sizes, these empirical studies all examined the whole market, and found that QAP decreases rapidly during the early stages of the introduction of a new product, and then the rate decrease tapers off, or that the faster new products are introduced, the faster the rate of decrease in their QAPs. Our larger data set allowed us in this study to consider the strategic interactions among carriers in view of changes in the QAPs of their mobile phone handsets.

In this paper we confined our analysis to the changes in QAPs of handsets, yet there are many other aspects of carriers' strategies in need of examination, for example, the service contents, regulations, and pricing systems. Grzybowski (2005) reported that the introduction of mobile number portability has a negative impact on prices of mobile communication services in the EU countries.[27] According to Lambrecht and Skiera (2006) and Lambrecht et al. (2006), complicated pricing systems will bias consumers' choices of services. These aspects are all closely connected to carriers' product and marketing strategies.

Finally, it would be interesting to evaluate how new pricing systems recently established by carriers influenced the QAPs of their mobile phone handsets in Japan. As noted in Sect. 2, the Ministry of Internal Affairs and Communications recommended that mobile phone carriers lessen their heavy dependency on price subsidies by 2010, and the carriers started establishing new pricing rules; they first reduced base call charges by half in September 2007. This is left for future research.

(1987) proposed the Consistent AIC as another correction and showed the theoretical and empirical advantages of the Consistent AIC over the AIC in small samples.

[26] The results are not reported but are available upon request.

[27] In Japan, mobile number portability was introduced in October 2006.

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