On Economic Models of Network Technology Adoption, Design, and Viability

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1 Research Interests

The potential for both economic and technological growth offered by networked systems have attracted the attention of researchers and entrepreneurs, and allowed for convergence of ideas from various fields like computer science, economics, and operations research. As the demand for data continues to rise and new Internet protocols and technologies are invented to meet these growing needs, the role of interdisciplinary research in creating holistic analytical and experimental frameworks is becoming ever more important. My own research interests in this area arises partly from my doctoral research [9] done in collaboration between the Electrical engineering school and the Wharton School of business of the University of Pennsylvania, followed by my postdoctoral research in Electrical engineering at Princeton University during which I focused on transforming many of these theoretical ideas into experimental testbeds. As an Assistant Professor of Information & Decision Sciences at the Carlson School of Management in the University of Minnesota, I continue to investigate these three research themes that will be of interest to the IAB's ITAT workshop:

1. *Adoption of Network Technologies:* What factors affect the success or failure of network technology adoption? How economic and technological factors impact the outcome of competition between entrant and incumbent technologies? How pricing and quality can impact the interaction between a base and a supplementary network technology? When and how much seeding of the market is desirable?

2. *Network Infrastructure Design Decisions:* How to decide on whether to deploy new technologies and services by sharing resources of existing incumbent infrastructure or to create a dedicated infrastructure for the entrant technology? What is the right amount of functionalities to build into a network platform, and whether certain characteristics of costs incurred by third-party developers to contribute to the platform can favor a functionality-rich platform over minimalist design choice?

3. *Pricing Networks for Economic Viability:* How to provision for demand growth of the Internet technologies and use pricing as a mechanism to regulate network congestion? How can smarter pricing schemes be adopted for the Internet and what engineering and regulatory support are needed to realize them? How can technology and pricing modify adoption and usage behavior of Internet users?

The results from some of my works on these topics are discussed in additional details in the following sections.

2 Research Works

2.1 Network Technology & Protocol Adoption

The success of any new network technology, standard, or protocol depends largely on the outcome of its competition against an incumbent. An operator's actions, in terms of seeding the market, pricing the new technologies, providing compatibility etc., can have significant impact on the eventual outcome. These considerations are important even when the new technology is meant to provide supplementary benefits to the users of an existing technology. In this section we discuss some of our research works that address these issues.

2.1.1 Competition between Incumbent and Entrant Network Technologies

Network technologies (e.g., services, platform architectures, protocols etc.) often have to compete against formidable incumbents for adoption. An entrant's success hinges not only on technical superiority but also on several other factors. In the past, we have witnessed many Internet technologies, e.g., IP multicast, QoS solutions, IPv6 etc., which were successful in meeting their technical goals but failed to get wide adoption due to factors like high costs, lack of demand, weight of incumbency etc. Understanding how these different factors can potentially impact the adoption of competing technologies is of much interest to the networking community. With networking researchers exploring new experimental architectures and mechanisms that can eventually replace the existing Internet architecture and address many of its shortcomings [3, 6, 7], this discussion is very relevant today.

A large installed base can give an incumbent an edge even if a new (entrant) technology is technically superior. The traditional networking approach to this problem has been converters (a.k.a. gateways) to ease migration from one technology to another. This is not unique to networks, but converters are particularly important in network settings where "communication" is the primary function, and its benefits grow with the number of users that can be reached, e.g., as in Metcalfe's Law. Since converters allow users of one technology to connect with users of another, they are an important tool in the adoption of network technologies. However, developing, deploying, and operating converters comes at a cost, one that often grows as a function of the converter's quality. Further, converters can play a directionally ambiguous role. On one hand, a converter can help the entrant overcome the advantage of the incumbent's large installed base by allowing connectivity to it. On the other hand, the converter also helps the incumbent technology by mitigating the impact of its users migrating to the newer technology. Understanding the impact of converters on network technology adoption is, therefore, a topic that deserves further scrutiny.

To understand these issues, we develop a modeling framework to study adoption dynamics of entrant and incumbent technologies in the presence of network externalities [4]. Specifically, we introduce a model for the utility derived by an individual user from a communication network, and use it to build an aggregate model for technology adoption that is consistent with individual rational decision-making. We apply the model to study the role that converters can play in the adoption of network technologies [13]. Our main findings are:

- The adoption process can exhibit multiple steady state outcomes (equilibria); each associated with a specific region of initial adoption levels for the two technologies. For example, an entrant technology may succeed only if the incumbent is not already well entrenched.

- Converters can help a technology improve its own standing, e.g., market share, and even ensure its dominance while it would have entirely disappeared in the absence of converters. For example, a low-quality but low-cost technology may thwart the success of a better but more expensive competitor by preserving the ability of its users to access adopters of the pricier technology, whose usage would then be limited to a few "techno-buffs."

- Improving converters' efficiency can at times be harmful. They can result in lower market shares for an individual technology or for *both*. For instance, high market penetration may depend on the combination of a cheap but low-end technology with a high-end but more expensive one to adequately serve the full spectrum of user preferences. A situation where converters allow the better technology to gain market share at the expense of the lesser technology may result in low-end users of that technology dropping out altogether; thereby contributing to a lower overall market penetration.

- While in the absence of converters technology adoption always converges to a stable steady-state equilibrium, this need not be so when converters are present. Boom-and-bust cycles in which users switch back-and-forth between technologies can arise when technologies are asymmetric in the externality benefits they offer.

We further show in [12] that these behaviors remain present across a wide range of utility models that include nonlinear externality functions, non-uniform distribution of user preferences, user heterogeneity in both standalone and network benefits and switching/learning costs. Our model is generic enough to be applicable to a wide range of scenarios in competing network technologies, protocols, and standards. Similar models for the diffusion of network technologies within a user population under different user utility functions and the effect of seeding on the adoption outcome were also studied [?, 8].

2.1.2 Role of Supplementary Network Technologies

Successful technologies are often followed by other supplemental technologies, which when combined with the original enhance its features and quality. In the context of networks, one could think of femtocells enhancing 4G speeds or 3G traffic being offloaded to WiFi networks. Upon introducing an additional access cost for users of the supplemental technology, one can then study the adoption of the supplemental and base technologies in an economic framework. Yet considering network access technologies also requires accounting for network externalities. For example, as more users adopt a technology like 3G or 4G, congestion on the network increases, which can in turn reduce users' utility from using that technology.

The presence of negative network externalities affords network operators an opportunity to improve services on their base technology by offloading users onto a supplemental technology. Indeed, ISPs are already beginning to exploit such opportunities: for instance, in the United States, Verizon has begun to offer femtocells in order to supplement its 4G network capacity, while AT&T has deployed WiFi hotspots in New York to manage persistent 3G congestion. In light of rapid growth in the projected demand for mobile data, Internet service providers (ISPs) are likely to continue using such supplemental networks to curb network congestion [19]. Indeed, as mobile demand keeps growing, ISPs may soon begin to charge consumers for access to these supplemental networks. Already, T-Mobile and Virgin Mobile respectively charge their subscribers an extra $20 and $15 a month for WiFi access. Given these developments, there is a need for economic models that can help determine how to price access to such base and supplementary technologies and the implications of those pricing decisions.

Our work is inspired by two research areas: the study of user technology adoption and that of network offloading. Though both areas have separately received considerable attention from economics and networking researchers, our contribution lies in incorporating user adoption models to study technology subscription dynamics and the tradeoffs between deployment costs and offloading benefits for a supplementary technology. We seek to understand user adoption decisions between a generic base technology and a bundled offering of a base plus supplemental technology; users may adopt the base technology, no technology, or the bundle of both technologies. In particular, our work [5] explores the following example scenarios:

- Will increasing the coverage of a supplemental network lead to more traffic being offloaded on the network? Suppose that an ISP wishes to expand its WiFi network to offload more 3G data traffic, but cannot change its pricing plan due to exogenous factors, e.g., the presence of a competitor. We derive conditions under which increased WiFi coverage can decrease WiFi adoption: at the new equilibrium, increased congestion induces some users to drop the bundled service and only subscribe to 3G. In fact, we show that this decrease may occur even when the ISP offers revenue-maximizing prices.

- Will increasing the base technology's access price reduce its adoption? Consider an ISP trying to induce heavy users to leave its 3G network by increasing the access price. We show that this may actually increase 3G user adoption: increasing the price of 3G and the 3G & WiFi bundle by the same amount can lead some users to drop their bundled subscriptions and adopt only 3G.

Given these adoption behaviors, we then consider an ISP's optimal operating point. In our framework, the ISP may influence user adoption with three variables: the access prices of the two technologies, and the coverage area of the supplementary technology (e.g., supplementary WiFi access may not always be available). We first consider a generic model of ISP revenue and derive analytical expressions for the revenue-maximizing prices and coverage of the supplemental technology. We then focus on the scenario of offloading 3G traffic to WiFi, estimating the offloading benefits and deployment costs with empirical usage data. We consider the following questions:

- What is the optimal coverage area of a supplemental network? Suppose that an ISP seeks to optimize its revenue with respect to WiFi coverage and 3G and WiFi access prices. We show that revenue is maximized under full WiFi coverage, and that the total adoption of 3G and the 3G & WiFi bundle will increase with WiFi coverage as long as some users adopt only 3G.
- How do deployment costs affect the optimal coverage and resulting adoption of the base & supplementary bundle? We consider an ISP offering 3G and WiFi plans and show that the WiFi adoption may increase with WiFi deployment costs, even under the profit-maximizing prices and WiFi coverage area.

The results from this work as well as the generic framework is useful in the study of technology adoption and pricing in the presence of supplementary network technologies and standards which can alter the quality of experience for the end-users depending on the relative benefits afforded by different positive and negative externalities that may arise from such coexistence.

2.2 Models for Network Infrastructure Design Decisions

The successful adoption of new Internet technologies also depend on the economic considerations involved in determining a deployment/seeding strategy as well as the infrastructure/platform design choices made to support these new network services. We explored these issues along the following themes:

2.2.1 Evaluating Shared versus Dedicated Infrastructure Design Choices

Over the years, the Internet's growth has been driven largely by its ability to support a the number of innovative services (e.g., P2P, Social networks, IPTV) that being offered on it. For the providers of these new services, the Internet served both as a shared platform for easy and inexpensive deployment as well as a driver for their successful adoption. But in recent times, the convergence of voice, video, and data services has led to questioning whether using a shared platform for services with disparate service level requirements is recommended or not. This is because although sharing helps to save on infrastructural expenses, deploying multiple services on a shared network comes at the cost of increased complexity in operation, manageability, security, and troubleshooting. As these shortcomings of shared solutions become more evident, many service providers are now opting for dedicated platforms with built-in functionalities for their own services. Therefore, a natural question that arises is whether deploying a new network service on dedicated infrastructure is better than a shared solution, and to determine when and why this is the case or not. The question has become even more relevant with the advent of new technologies such as software-defined networking and virtualization, which can further facilitate the deployment of new network "slices" dedicated to an individual new service.

Such trends are not limited to the Internet. As networking and communication technology continue to improve and new service sectors get network-enabled, e.g., health-care, infrastructure monitoring, surveillance, etc., the question of whether to create a shared or a dedicated network becomes important. For instance, the emergence of green buildings results in a facilities management infrastructure that relies upon networked sensors and actuators to monitor and control building operation. This can be realized either by piggy-backing the existing IT infrastructure of a building, or by creating a dedicated facilities management network, and neither shared nor dedicated network choice emerge as an obvious winner. These examples point to a need for a coherent framework to evaluate the underlying trade-offs between the network design choices instead of undertaking ad-hoc decisions by operators.

Besides the economic factors (e.g., resource pooling, hedging against uncertainty, and (dis)economies of scope in costs), the complexity of such decisions is further enhanced by technological factors like virtualization. While virtualization allows better resource sharing on a platform by minimizing interactions among the deployed services, it also allows for easier on-demand reprovisioning of network resources. The impact of the latter ability on the network choice is rather unclear, and our research showed that this factor alone can play an important role in the network choice [10,20]. Our framework in [1] also help to understand these design tradeoffs and to identify operational metrics, such as gross profit margin and return on capacity, that influence the choice of shared or dedicated infrastructures for deployment of new network services.

2.2.2 Minimalist versus Functionality-rich Platform Design

The success of new technologies and services also depend on the functional capabilities provided by the underlying platforms on which they are deployed. The Internet started out with a minimalist design but has since evolved from a physical infrastructure into a broader ecosystem of software and web services that serve as a platform between two market segments, application developers and consumers. The realization of services like the Amazon web services, Google App Engine, social network platforms etc, bear witness to the progress made in the creation of that ecosystem. A question that therefore arise is whether the minimalist design principle of Internet is still relevant and suitable in today's world of complex interconnected systems and infrastructures. Answering what is the right level of functionalities that a platform should offer calls for evaluating the cost-benefit trade-offs between choosing a functionality-rich and a minimalist design.

Platforms provide foundations on which services or products can be developed that deliver value to both their users and the providers that develop them. In general, platforms succeed based on their ability to "connect" *consumers* of applications and services to the *developers* of those applications and services. The Internet and Android offer two recent examples of (network and operating system) platforms whose success largely comes from their ability to connect users and service/application providers. Platforms are, therefore, commonly studied within the framework of *two-sided markets*. The platform is the 'market' and customers and applications/services developers are the 'two sides' of the market. The analytical framework we develop [11] follows in this tradition, and the specific issue our work is concerned with is the level of *functionality* that the platform should offer.

A platform typically provides a set of capabilities through built-in APIs, modules, tools, etc., which make it easier for developers to innovate new applications and services of interest/value to consumers. This, however, comes at a cost to the platform, and this cost grows with the number of features offered. The question for the platform provider is then to determine the number of features that maximizes profits. A minimalist platform has a low cost but makes developing services and applications more complex, which limits the number of application developed for the platform. This makes the platform less attractive to consumers and lowers revenues. Conversely, a functionality-rich platform is expensive to build, but this cost may be offset by facilitating the development of more applications, therefore attracting more consumers. This trade-off arises in many environments and properly assessing it can have far-reaching consequences. For example, many attribute the Internet initial success to its minimalist design principles. However, as it matures and transforms from a "physical" network platform to a broader ecosystem of software and web services, the question of whether or not to abandon this minimalist principle is increasingly being raised. The focus of this work is to explore the decision problem faced by a monopolist platform provider seeking to select the level of functionality the platform should offer.

The investigation identifies the ratio of the *rate of change* in the cost (to the platform) of adding new features and the cost of developing applications given a number of platform features, as a key factor in determining the optimal (for the platform) number of features to offer. This optimal choice is, however, highly sensitive to small relative changes in these two costs, with minor differences producing drastically different outcomes, i.e., shifting the optimal operating point from a minimalist to a functionality-rich platform. This negative result not-withstanding, the model provides a framework for reasoning about the impact of introducing more features to a platform. In addition, in cases where the costs of developing new features and their benefits in lowering application development costs can be estimated, the model offers quantitative tools that can assist decision makers.

2.3 Designing and Pricing for Long-term Economic Viability

In the design and deployment of new network technologies, an operator must also have built-in provisions for sustaining growth in the demand for that technology. For example, the doubling of demand for data from bandwidth-hungry mobile devices is a serious challenge faced by operators today, and new mechanisms are needed to cope with it. Internet Service Providers (ISPs) are turning to using pricing as the ultimate congestion management tool [19]. This changing landscape is evidenced by the elimination of flat-rate plans in favor of \$10/GB usage based fees in the US, and several variants of dynamic pricing and app-based pricing mechanisms in both European and Asian markets. These pricing schemes, broadly categorized as

Smart Data Pricing (SDP), can refer to (a) time/location/app/congestion dependent dynamic pricing, (b) usage based pricing with throttling/booster, (c) WiFi offloading/proactive caching, (d) two-sided pricing, (e) quota-aware content distribution, and any combination of the above. SDP can help create happier consumers and enterprise users, less congestion, and better Quality of Experience, lower CapEx/OpEx, higher revenue/profit margin, less churn, more consumption and ad revenue to content/app providers. But it also requires developing smart pricing models that capture the interplay between technical and economical factors, better interfaces among pipe providers and content/app providers, effective user interface designs, new accountIng and billing protocols, and new policies [18].

As Internet Service providers explore new pricing plans to match their revenues to costs, networking researchers need to identify potential bottlenecks and solutions to increase flexibility of Internet's pricing and QoS mechanisms. The coming decade will likely see several pricing innovations, including the introduction of dynamic *time-dependent pricing* (TDP) for mobile data [17]. TDP adjusts the discounts in less-congested periods to incentivize users to shift their usage from peak to off-peak periods. In fact, many applications today, e.g., movie and software downloads, cloud data synchronization etc., which have an inherent time elasticity of demand can be deferred to low usage periods if proper incentives are provided. Working with our partner ISPs' data, we found that the difference in demand between peak and valley hours is more than a factor of 10, and that even within 10 minutes there is often a factor of 2 difference in capacity demand. TDP can leverage this traffic pattern to help ISPs reduce the cost of peak-load provisioning for their network, while also providing consumers with more options of saving money by choosing the time of their usage. Implementing such a TDP plan requires architecting and prototyping a fully functional system that can help ISPs to offer prices that are acceptable to both ISPs and users. Additionally, it requires developing simple and intuitive GUIs that let users easily view and respond to the offered prices. In [2, 16], we present a first-of-its-kind design, implementation, consumer survey, and pilot trial evaluation of TUBE (Time-dependent Usage-based Broadband price Engineering) system, a dynamic TDP architecture that meets these challenges in the pricing of mobile data. Our trial results indicate that TDP can indeed flatten out demand temporally and reduce peak demand, while increasing bandwidth usage in the off-peak periods.

But to implement flexibility with pricing schemes both regulatory and engineering aspects need to be accounted for. In 2010, the US FCC recognized "importance of business innovation to promote network investment and efficient use of networks, including measures to match price to cost." As for the engineering aspects, there are several other proposals for managing network congestion, such as the M3I (Market Managed Multi-service Internet) collaboration that has proposed an architecture for market management of the Internet's QoS and demonstrated new business models that it can enable. The core of the QoS problem tackled by the M3I project is to solve the fast control problem to avoid QoS degradation during short-term congestion. In doing so, the M3I architecture requires network providers to deploy ECN (Explicit Congestion Notification) on all routers so that the congestion experienced field in the IP packet header can be set with a probability related to the current network load, allowing prices to adapt to the congestion conditions in the network. Issues in adoption of such mechanisms by operators is an interesting problem to study in itself.

The engineering aspects also need to focus on how to evolve these mechanisms and protocols to address new developments, such as the Shared Data Plans [15] and Sponsored Content, which create several implementation issues since these plans require real-time rating and charging for all subscribers, and users need new mechanisms to allocate and control the shared data caps. Today, wireless ISPs' current billing systems (including 2G, 3G, and 4G) heavily depend on the RADIUS (Remote Authentication Dial In User Service) protocol, which supports centralized Authentication, Authorization, and Accounting (AAA) for users or devices to use a network service (RFC 2865). In particular, RADIUS accounting (RFC 2886) is well suited to support usage-based pricing, since it can keep track of the usage of individual sessions belonging to each user. Yet individual session lengths are often quite long, making it difficult to retrieve usage at the smaller timescales needed for dynamic pricing.

RADIUS account sessions are initiated by the Network Access Server (NAS) when a user first attempts to connect to the network: the NAS sends a user's login credentials to the RADIUS server, which compares the credentials to a secure database. The RADIUS server then authenticates the session and authorizes it to access different functionalities on the network. Once this session has been initiated, a start record is created in the RADIUS logs. Interim accounting request messages can be sent periodically to update the usage information. When the end user terminates the connection, the NAS sends a stop message to the RADIUS server and a stop record is created that stores the total usage volume of that session. Since these RADIUS sessions can have very long durations, up to several hours, RADIUS logs cannot be used to calculate usage at smaller timescales.[1] Moreover, the RADIUS log has no information on the type of application(s) corresponding to each session. While one session may encompass usage from multiple apps used in parallel, in some cases individual apps initiate new sessions; thus, the concept of a "session" cannot be definitively tied to an individual app (RFC 2886).

Changing the RADIUS protocol to deliver usage estimates at a smaller time granularity would require significant overhead in both control signaling and storing RADIUS records. A perhaps easier alternative would be to record usage at the network edge, i.e., on client devices–such functionality already exists, but this approach would be vulnerable to users' deliberately falsifying the usage recorded on their device. Similarly, RADIUS logs do not contain any information on per-application usage, but client devices can easily obtain this information. Thus, application-specific pricing could also benefit from usage tracking functionalities on the end user devices. Some verification procedures could be implemented to guard against user tampering, e.g., comparing the total monthly usage measured by RADIUS servers and client devices, but would require careful design and might not be completely secure. As the Internet grows and its pricing practices evolve, networking researchers have to start tackling these issues within an interdisciplinary framework with inputs from managers, economists, regulators, and HCI researchers [14].

Biography

Soumya Sen received the B.E. (Hons.) in Electronics and Instrumentation Engineering from BITS-Pilani, India, in 2005, and both the M.S. and Ph.D. in Electrical and Systems Engineering from the University of Pennsylvania in 2008 and 2011, respectively, where he conducted research in collaboration with Moore School of Engineering and The Wharton School of Business. He conducted his postdoctoral research in the Department of Electrical Engineering at the Princeton University between 2011-2013. He is currently an Assistant Professor in the Department of Information & Decision Sciences at the Carlson School of Management of the University of Minnesota. His research interests are interdisciplinary and focuses primarily on Internet economics, communication systems, and e-commerce.

Soumya has published several research articles on these topics in ACM SIGCOMM, ACM SIGCHI, ACM CCR, ACM Computing Surveys, IEEE INFOCOM, IEEE/ACM Transactions on Networking, IEEE JSAC, IEEE Communications Magazine, NetEcon, WITS, ICWSM, WOSN etc. His works have been received media coverage in Wall Street Journal, MIT Technology Review, Politico, TechCrunch etc., and he won the BITSAA International 30 under 30 Award for contributions to academia, research & development. His work on broadband pricing was a finalist at the 2011 Vodafone Wireless Innovation competition and he won the Best Paper Award at IEEE INFOCOM 2012.

He is a co-founder of DataMi, a startup that provides incentive-based network congestion management solutions. He is a founder and organizer of the Smart Data Pricing (SDP) Forum, which promotes industry-academic interaction on broadband pricing research, and served as a General Co-chair of the Workshop at SDP 2012 (Princeton) and SDP 2013 (Turin). Since 2011, the SDP Industry Forum and SDP workshops have attracted large participation from the operators (e.g., AT&T, Verizon, Telcordia, Comcast), vendors (e.g., Cisco, Microsoft, Alcatel-Lucent, Niksun), regulators and trade organizations (e.g., FCC, NECA), and faculties from Engineering, Economics, Information Systems & Decision Sciences, Operations Research, and Mathematics. He has also contributed a chapter on SDP to ACM SIGCOMM's eBook on "Recent Advances in Networking" and is an editor of a forthcoming book on Smart Data Pricing, published by John Wiley & Sons. He has been an invited speaker at WITE 2012, Annual Exposition of US National Exchange Carrier Association in 2011 and 2012, the Princeton Keller Center for entrepreneurship in 2011 and 2012, the Allerton Conference in 2013, and the 2013 INFORMS Annual Conference.

[1] Note that interim update messages are sent periodically when a session joins the system, and hence, the time interval for interim updates should be kept low to support sending time-of-day usage, which may introduce significant control overhead.

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