WINNER-TAKE-ALL BATTLES REVISITED: INFLUENCE DECAY, BATTLE DURATION, AND BARGAIN-THEN-RIP-OFF STRATEGY

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ABSTRACT: In winner-take-all markets, where network effects lead to battles for dominance, popular wisdom holds that firms should pursue a get-big-fast strategy. Often implicitly assumed is that the battle will be over quickly, even though exceptions to this have been observed. We develop the concept of influence decay — a reduction in the relative influence of earlier vis-à-vis new adopters in shaping subsequent adoption choices. Using a computational model, we find that rapid battles are only a special case of low influence decay. A slight increase in influence decay may bring about a dramatic rise in battle duration. When the battle is prolonged, a firm following popular wisdom must sustain unexpectedly large losses, but it garners a hidden benefit — the likelihood of victory increases sharply.

1. INTRODUCTION

Many industries are characterized by network effects, which refer to user benefits arising from increasing adoption of a product or service (e.g., Adner, Chen and Zhu 2020, McIntyre and Srinivasan 2017, Farrell and Klemperer 2007). Strategies leveraging network effects have become highly visible not only in information technology industries (e.g., social media) but also in a wide range of service industries (e.g., see Iansiti and Strojwas 2003 for semiconductor manufacturing services and Chung, Zhou and Ethiraj 2023 for ride-sharing). A well-known strategic implication of network effects centers around the idea that a firm should get big fast. This idea became prominent during the first dot-com boom, with the logic of the bargain-then-rip-off (BTRO) strategy, in which the firm sets its price lower (often to zero) than its rival's until it monopolizes the market (Ferrell and Klemperer, 2007). These strategies, described as "blitzscaling" by Paypal and LinkedIn co-founder Reid Hoffman (Hoffman and Yeh, 2018), remain a mainstay of Silicon Valley thinking.

We revisit this prominent view of how to compete in winner-take-all markets. In doing so, we highlight a critical condition that limits the merits of the BTRO strategy. The strategic implications of network effects have been the subject of substantial research. Arthur's (1989: p. 116) pioneering work sparked interest in these implications by proposing that if there is positive feedback, increasing adoption magnifies user benefits, and "a technology that by chance gains an early lead in adoption" will corner the market via a success-beget-more-success process. Arthur's theoretical work points to a *rapid* winner-take-all (WTA) process that results from network effects when incompatible technologies compete. If a winner can emerge *quickly*, the BTRO strategy may well be a successful approach.

The extant literature, however, has overlooked a critical question in WTA markets — how long will the battle for dominance last? Consider, for example, a firm that attempts to get big fast with a BTRO strategy. The firm must bear substantial early losses in order to attract customers and build a large installed base, often at prices that are well below cost. After winning the battle, the firm can harvest rewards by raising its price dramatically. The calculus of this strategy is straightforward if the duration of the WTA battle is short, as assumed in the literature.

The literature has been relatively silent on the question of battle duration. This is, in part, because Arthur's (1989) theoretical work points to a simple, black-and-white world, where competition between incompatible technologies quickly leads to a WTA outcome in the presence of network effects. In their absence, however, competition results in a shared-market outcome in which a WTA tendency is completely subdued. In this black and white world, there seems to be little room for the discussion of the duration of the WTA battle. Subsequent theoretical work has echoed, more or less, this kind of dichotomous imagery of a rapid WTA versus a shared market outcome (e.g., Lee et al. 2006, Lee et al. 2016, Zhu and Iansiti 2012, Zhu et al. 2021).

In this paper, we consider the gray area that lies between the WTA regime and the shared market regime (i.e., no WTA outcome). Adoption dynamics may be more complex than the simple dichotomy suggests, and the literature has begun to recognize the need to shed theoretical light on such a gray area (McIntyre and Srinivasan 2017). A key to understanding this gray area is to revisit the prevailing view on the concept of an installed base in which an installed base established in the past will be continuously valued by new users. The computer/typewriter keyboard industry, with over a century of dominance of the QWERTY design, suggests that this view of the installed base is valid (David 1985). However, anomalies to this prevailing view have been observed. In certain industries, new users do not value an established installed base. A prominent example is a recent slowdown in the adoption of Facebook when the TikTok generation did not value the installed base built by Facebook. Likewise, more than a decade earlier, the Facebook generation did not value the installed base built by MySpace. Zhu and Iansiti (2012) also challenged the view by empirically showing that the value of an established installed base in the video game industry (e.g., numerous old game titles) became increasingly less valued by new gamers.

To understand the relationship between these anomalies and battle duration, we introduce the concept of *influence decay*, which we define as a reduction in the relative influence of earlier adopters vis-à-vis new adopters in shaping subsequent adoption choices. We develop a computational model of WTA dynamics by building on the canonical Arthur (1989) model of competition between incompatible technologies. We extend the model by considering the effects of various levels of influence decay to represent a wide range of possibilities across industries. The model allows us to probe how influence decay impacts the rich dynamics of the winner-take-all battle in the gray zone, where the duration of the WTA battle changes.

Our findings show that a rapid WTA outcome is only a special case among many possible WTA battles. Less well-understood in the literature are prolonged WTA battles, the lengths of which vary widely depending on the level of influence decay. In particular, a slight increase in influence decay in the gray area brings about a dramatic increase in battle duration. When influence decay is neither too low nor too high (this is characteristic of the gray area), there are two countervailing forces pushing adoption dynamics in opposite directions — as in a tug-of-war between evenly matched factions. On the one hand, the cumulative effects of a larger installed base tend to propel the market system to the WTA outcome. On the other hand, influence decay tends to wash out those cumulative effects, thereby pushing the system to maintain incompatible technologies persistently. Since these forces are in a delicate balance, a success-beget-success process is seemingly at work, but lock-in to one technology does not happen quickly. Instead, the dynamics exhibit a dramatically protracted period of contestation during which an observer of the market sees no clear-cut WTA outcome, even though one technology will corner the market eventually.

Our key findings offer more nuanced strategic implications. Adoption dynamics in the gray area are analogous to a war of attrition. A firm pursuing the BTRO strategy but neglecting the impact of influence decay is prone to strategic mistakes. The firm may well believe that the WTA battle will be over soon. But influence decay may cause the battle to extend far beyond what the firm anticipates, resulting in far larger costs of pursuing the strategy. Moreover, the firm may give up early if it misinterprets a prolonged battle duration as the nonexistence of WTA phenomena. Interestingly, however, if the BTRO firm can manage the costs and avoid such mistakes, it may garner an unexpected benefit from influence decay — the likelihood of victory with the BTRO strategy increases sharply with a slight increase in influence decay.

2. THEORETICAL BACKGROUND

In this section, we consider how influence decay shapes the duration of the winner-take-all battle. The relationship between influence decay and battle duration is an important missing piece in the discussion of the costs and benefits of get-big-fast strategies. To appreciate why this missing piece matters, we first review the received view on network effects and their strategic implications.

2.1. Network Effects and Incompatibility

Network effects are defined as user benefits arising from compatibility among users of certain products or services (Farrell and Klemperer 2007). Network effects may derive from either direct or indirect user benefits (Katz and Shapiro 1985). In the former, user benefits come directly from interactions among users in the form of sharing information, files, photos, or videos. In the latter, user benefits arise indirectly from complementary products or services available to users.

Network effects are strategically important not only in information technology industries but also in a wide range of service industries. For example, Uber has built user benefits by offering a service that acts as a liaison between users and drivers who are in the same area. As more drivers join Uber's service network, the more useful Uber's service is to users who need rides, encouraging more people to join the service network. Likewise, using artificial intelligence, the data generated from users could also serve as a source of network effects. For example, Adner et al. (2019: p. 258) note that for "modern speakers such as Amazon Echo or Google Home…As they accumulate more data from each user, they become more intelligent and, hence, attract more usage and more users, enjoy higher scalability, and gain larger market shares."

In the presence of network effects, a firm faces a strategic choice regarding whether or not its technology will be compatible with those of its rivals. Such a decision depends on the returns arising from that decision. Suppose that all firms decide to make their technologies compatible with those of rivals. Then, users or complementary service providers do not have to worry about which technology to adopt, and the basis of their adoption choices will be on price or other conventional factors. Consequently, network effects will not be a source of firm-specific advantage. For example, Chung et al. (2022) provide evidence for this possibility in the context of rideshare services in New York. Uber built its driver network with freelancers. Given that Uber cannot have exclusive contracts with these drivers, its rival, Lyft, can also access them to provide services to their users.

Unless regulatory mandates or other restrictions force firms to maintain compatibility, they may try to pursue incompatibility. Farrell and Klemperer (2007: p. 2048) illustrate this possibility with historical examples, noting that "the dominant Bell system declined to interconnect with upstart independents in the early post-patent years of telephone competition in the U.S., …WordPerfect (a dominant player in the word processing market in the 1980s and the early 1990s) sought compatibility with the previously dominant WordStar, but then fought compatibility with its challengers."

2.2. Winner-Take-All Dynamics without Influence Decay

Before introducing the concept of influence decay, let us briefly review the received view on the installed base and its underlying assumptions in the literature on network effects. When firms choose to compete with incompatible technologies, the choices of earlier adopters may influence the technology adoption decisions of later adopters. In particular, a technology that has been chosen by the majority of earlier adopters tends to build a larger installed base, making new users align their choices with earlier ones. On the theoretical front, the possibility of winner-take-all outcomes has garnered substantial attention. This stream of research was pioneered by Arthur (1989), who argued that if network effects are strong, increasing adoption magnifies user benefits such that the technology that gains an early lead will likely monopolize the market. Subsequent theoretical work has examined boundary conditions under which the WTA outcome, such as innovation (e.g., Schmalensee 2000, Lee, Song and Yang 2016), strength of network effects (e.g., Zhu and Iansiti 2012), demand heterogeneity (e.g., Cennamo and Santalo 2013, Rietveld and Eggers 2018), and the structure of user networks (e.g., Lee, Lee and Lee 2006, Afuah 2013).

In considering WTA dynamics, the taken-for-granted view is that "history matters" for user adoption choices. This expression implies that a technology with a larger installed base accrues more user benefits and that the influence of early adopters remains as important as that of recent ones in shaping future adoption choices between incompatible technologies. For example, Farrell and Klemperer (2007: p. 2034) noted that because "early adoptions affect later ones, long-term behavior is driven by early events, whether accidental or strategic." The implicit assumption in this view is that the installed base built in the past will continue to be valued by new users. The keyboard industry, with over a century of dominance of the QWERTY design, more or less supports this view (David 1985). A key strategic implication is that a market leader with a larger installed base is better positioned not only for protecting its position but also for further increasing its market share.

2.3. Influence Decay and Duration of the Winner-Take-All Battle

The received view, however, does not always represent adoption dynamics in real-world industries — a larger installed base may not always act as a bulletproof shield against the rise of rivals. A case in point is the demise of Atari when the Nintendo Entertainment System quickly gained popularity after its introduction in 1996. Although Atari built up a large installed base with many game titles, it did not help the firm protect its market position from the entrant's attack. Shapiro and Varian (1999: p. 235-236) noted: "Atari's second-generation equipment, the Atari 7800, could play games written for Atari's dominant first-generation system, the Atari 2600. Unfortunately for Atari, *these older games held little appeal for a new generation of boys* entranced by the superior games available on Nintendo's system" (Italics added).

Such a lack of enthusiasm for an established installed base in the social media market has also been observed among new generations of adopters. Recently, a slowdown in the adoption of Facebook was observed when the TikTok generation did not value the installed base built by Facebook. Likewise, more than a decade earlier, the Facebook generation did not value the installed base built by MySpace. What matters in the game of network effects for this market is to keep attracting new users, who may be influenced by new fads or trends different from those of earlier generations of adopters. If a leader loses such new users to other rivals, its future may not be promising because these users do not share much of value across cohorts. Even when network effects are strong within the older cohort, its large installed base may not serve as a bulletproof defense as the new generation grows in size.

Little theoretical attention has been paid to this kind of anomaly and its relation to battle duration. To fill this void, we introduce the concept of influence decay, which we define as a reduction in the relative influence of earlier adopters vis-à-vis recent adopters in shaping subsequent adoption choices. With this concept, we consider the effects of various levels of influence decay to represent a wide range of decay possibilities across industries. This theoretical lens allows us to see adoption dynamics in a far more nuanced way than has previously been done. For example, the statement, 'history matters,' begs the following questions: Should one account for all parts of history or only some parts? If one part of history carries more weight, which one does so and to whom?

Imagine competition between two incompatible technologies, A and B, as shown in Figure 1a. At every time step, one adopter enters the market and chooses between the two. In the literature, the value of an installed base for a given technology has been measured as a cumulative number of previous adopters. The implicit assumption here is that each adopter makes an equal contribution to the value of the installed base regardless of whether the adopter is dead, old, or young. Figure 1a represents this received view, where the size of each adopter's contribution is equal. When there is influence decay, however, each adopter's contribution diminishes over time. Consequently, an earlier adopter carries less and less weight over time compared to that of a new adopter, as illustrated in Figure 1b.

< Insert Figure 1 about here >

Another way of considering the same issue is from the perspective of marginal contribution. Suppose that each adopter's influence lasts for a long period of time, for example, 250 periods. Then, a new adopter's marginal contribution is rather small in percentage terms. This situation is more akin to the received view in that the influence of an earlier adopter lasts a sufficiently long time. In contrast, if each adopter's influence lasts for only 25 periods, a new adopter's marginal contribution becomes larger in percentage terms. In this case, earlier adoption choices are less influential than recent ones.

Consider what might happen to a dominant technology if past adoption choices are less influential than more recent ones in shaping future adoption choices. With such influence decay, market leadership changes are more likely. One scenario is that once a market leader loses its position, it may never recover, as was the case with Atari. Another scenario is that leadership changes become more frequent if the former leader has the willingness and ability to fight back. In this scenario, while the success-beget-more-success process may be apparent with strong network effects, adoption dynamics may not quickly lead to the WTA outcome. Given these conflicting signals, even a seasoned observer of the market finds it difficult to predict who will win eventually.

Indeed, anecdotal evidence suggests that such confusing, mixed dynamics do exist in reality. For example, Shapiro and Varian (1999: p. 174) observed: "As Wintel's share of the personal computer market grew, users found the Wintel system (computers compatible with Microsoft's Windows and Intel's CPUs) more and more attractive. Success begat more success, which is the essence of positive feedback." Given this apparent positive feedback process (i.e., strong network effects), Shapiro and Varian (1999: p. 174) predicted the fall of Apple by saying: "the Apple Macintosh will *shortly* become the Sony Beta of computers" [Italics added]. More than a decade later, however, Zhu and Iansiti (2012: p. 102) observed the rejuvenation of Apple, providing detailed reasons why the established installed base did not drive out its rival as follows:

> In the 1990s, consumers' reliance on third-party software was much higher than it is today. Consumers had to install many software packages such as music players, CD makers, and zip utilities. Today, most of these functionalities are provided by the operating system platform or are accessible over the Web through a Web browser. As a result, consumers are less sensitive to application variety [the value of the established installed base].

This historical evidence suggests that competition between incompatible technologies may not quickly lead to a WTA outcome. That is, the duration of the WTA battle may be prolonged, but this type of dynamics and their strategic implications have not been well-understood in the extant literature. Thus far, the literature has focused largely on the rapid WTA process, neglecting the possibility of prolonged battle duration. For example, Arthur's theoretical work points to a simple, black-and-white world, where competition between incompatible technologies quickly leads to a WTA outcome in the presence of strong network effects. In their absence, however, competition results in a shared-market outcome with never-ending incompatibilities. Subsequent theoretical work has, more or less, echoed this dichotomous imagery (e.g., Cennamo and Santalo 2013, Lee, Lee and Lee 2006, Lee, Song and Yang 2016, Zhu and Iansiti 2012, Zhu et al. 2021). McIntyre and Srinivasan (2017) point out that reality is far more complex than this simple dichotomy would suggest, calling for more theoretical work to shed light on dynamics in the gray area.

In the next sections, we develop a model to elucidate dynamics in the gray area by conceptualizing influence decay. In this area, influence decay is conceptualized to be neither too low nor too high. Unlike the simple, black-and-white dynamics, *gray-area dynamics* are characterized by a mixture of two properties: (1) A success-beget-success tendency is seemingly at work; but (2) no rapid, clear-cut WTA outcome happens. This kind of peculiar dynamics is equivalent to what physicists call 'phenomena near the critical point' (Christensen & Moloney 2005; Newman & Barkema 1999; Stanley 1987).

In our framework, the critical point is a watershed point that divides the WTA regime from the shared market regime. The gray area lies in the neighborhood of the critical point from the side of the WTA regime. Here, two countervailing forces are clashing like a tug-of-war with one end of the rope being pulled toward the WTA outcome and the other toward persistent technology incompatibilities. That is, on the one hand, the cumulative effects of a larger installed base tend to propel the market system to the WTA outcome. On the other hand, influence decay tends to wash out those cumulative effects, thereby pressing the system to maintain technology incompatibilities. Since the countervailing forces near the critical point are in a delicate balance, lock-in to one technology will not happen quickly. As influence decay approaches toward the critical point bit by bit, battle duration is prolonged exponentially.

2.4. Prolonged Battle Duration near the Critical Point Allows Challengers to Win

Strategic implications in this uncharted area have not been well-understood in the literature. The received view, in general, is that a challenger seeking a minor advantage cannot beat a leader with an installed-base advantage as long as network effects are strong (e.g., Farrell and Saloner 1985; Farrell and Klemperer 2007; Katz and Shapiro 1992; Lee et al. 2016; Shapiro and Varian 1999). In particular, Farrell and Klemperer (2007: p. 4) noted: "When there are benefits to compatibility… that can be categorized as network effects, a single product would tend to dominate in the market. Moreover, this product would enjoy its privileged position whether or not it was the best available." To win the battle for dominance in the market for network effects, Shapiro and Varian (1999: p.19) emphasized the merits of the BTRO strategy as follows: "[Y]ou need to be aggressive early on to build an installed base of customers...*Pricing below cost is a common tactic* to build an installed base" (Italics added). These implications may remain useful if influence decay is in the WTA regime but not in the gray area.

However, the strategic implications seem paradoxical when the market system is in the gray area, and participants are prone to make strategic mistakes. Consider a firm pursuing the get-big-fast, BTRO strategy while neglecting the impact of influence decay. This firm may well believe that the WTA battle will be over soon. But influence decay may cause the battle to extend far beyond what the firm anticipates, resulting in far larger costs of pursuing the strategy. Alternatively, the firm may give up early when it misinterprets a prolonged battle duration as the nonexistence of WTA phenomena. A longer battle duration, however, has a counter-intuitive, second-order effect — it increases the likelihood of victory with the BTRO strategy. Moreover, influence decay in the gray area may help a challenger with the BTRO strategy (i.e., a minor price advantage) overtake an incumbent with an installed base advantage. In the next sections, we develop computational models to validate the strategic implications discussed above.

3. BASELINE MODEL

We develop a computational model to confirm our argument that the rapid WTA battle in the Arthur (1989) model is a special case of more general WTA phenomena, which also includes a wide range of prolonged battles. In this section, we first describe the essential features of the classic Arthur model. Building on and extending this model with a new construct, influence decay, we develop our baseline model to confirm the wide possibilities of WTA battles. Then, we develop extended models with financial variables, such as price and cost, to derive implications of influence decay for the BTRO strategy. In the interest of brevity, we postpone the description of these extended models to Section 4.2.

3.1. Arthur Model

The Arthur (1989) model was the beginning of the formal analysis of winner-take-all phenomena. It is considered the foundational model in the field. This model is both parsimonious and dynamic in that through a simple extension, we can elucidate a role of influence decay in WTA dynamics. In particular, this dynamic nature allows us to apply powerful tools from statistical physics to understand richer possibilities of prolonged WTA battles, which happen in the gray area, or the area near a critical point (Christensen & Moloney 2005; Newman & Barkema 1999; Stanley 1987).

In the Arthur model, there are two incompatible technologies, A and B, and two types of users, R and S. In each period t, only one of either type enters the market with a probability of 0.5 and chooses a technology.[1] Each adopter's payoff for choosing either technology A or B is shown in Table 1 (in the Arthur model, $\delta = 0$). Let $N_i(t)$ denote an installed base (the number of adopters) for technology i at time t for $i \in \{A, B\}$. R's payoff for choosing A is $\alpha + \theta N_A(t)$, whereas her payoff for choosing B is $\beta + \theta N_B(t)$. Likewise, S's payoff for choosing A is $\beta + \theta N_A(t)$, whereas her payoff for choosing B is $\alpha + \theta N_B(t)$. We assume that $\alpha > \beta$, such that user R has an inherent preference for A, whereas user S has for B.

< Insert Table 1 about here >

The parameter θ describes how important an installed base is to user benefits (or payoffs). In the absence of network effects (i.e., $\theta = 0$), the basic feature of the model is a random walk (Arthur 1989). In other words, R-type adopters choose A, while S-type adopters B. In this paper, we only consider dynamics when there is positive feedback such that $\theta > 0$, where θ biases the random walk to gravitate toward the history-dependent dynamics.

< Insert Figure 2 about here >

The rapid WTA process results from adoption dynamics with a history-dependent tendency that crosses an absorbing barrier in a short time. Consider R-type adopters who, in the absence of network effects, prefer technology A. As long as $\theta(N_B\text{-}N_A) < \alpha - \beta$, they will choose technology A. However, once $\theta(N_B\text{-}N_A) > \alpha - \beta$, technology B will cross its absorbing barrier. Then, even R-type adopters will choose technology B. So once the market share of either technology A or B reaches

[1] In the model, n is the number of adopters at time t. Since only one adopter is assumed to enter the market in each period, $n = t$.

its respective absorbing barrier, that technology eventually corners the market, driving out the other alternative. For example, in Figure 2a, we plot the adoption dynamics for the Arthur model (with settings of $\alpha = 10$, $\beta = 1$, and $\theta = 2$). The horizontal axis represents time, and the vertical axis represents the difference in the installed base between the two technologies (e.g., above the zero point on the horizontal axis, technology A leads). When these dynamics cross the absorbing barrier, lock-in to a technology occurs.

There are two implicit assumptions in the Arthur model, which we will relax in later analysis. First, this model assumes that the influence of an adopter does not decay — earlier adopters are as influential as more recent adopters in shaping subsequent adoption choices. Second, there is no cost and price in the model. In other words, profit is implied by the installed base, and as a consequence, there is no explicit financial variable. In the Result Sections 4.2 and 4.3, we introduce extended models with these financial variables to allow the examination of the implications of the BTRO strategy.

3.2. Baseline Model with Influence Decay

We now introduce our baseline model, which is built upon the Arthur model with a new construct, influence decay. As described earlier, the Arthur model is characterized by history-dependent dynamics with a biased tendency toward the WTA outcome if $\theta > 0$. In our model, increasing influence decay plays the role of a countervailing force in washing out this WTA tendency. Specifically, we define a degree of influence decay δ:

$$\delta = 1 - \frac{influence\ of\ an\ adopter\ at\ t-1}{influence\ of\ an\ adopter\ at\ t}, \tag{1}$$

where $t \geq 1$ and $0 \leq \delta \leq 1$. If $\delta = 0$, there is no influence decay in that all previous adoptions are equally important in determining subsequent adoption decisions. When $\delta > 0$, however, the influence of previous adopters decays. That is, the effects of more recent adoption choices carry more weight in shaping future adoption choices. With δ, we can calculate $N_i(t, \delta)$ as an exponentially weighted sum of the installed base for technology i at time t, where influence decay is tuned by the parameter $\delta \in [0, 1]$:

$$N_i(t, \delta) = \sum_j (1 - \delta)^j I_i(t - j) . \quad (2)$$

Note that $1 \leq j \leq t-1$, and $I_i(x)$ is an indicator - which is 1 if x^{th} user chooses technology i, otherwise 0. With the decay parameter δ, we can describe the continuum between two theoretical extremes: adoption dynamics with complete influence decay (i.e., $\delta = 1$) and the Arthur model with no decay (i.e., $\delta = 0$). For example, suppose that technology A was chosen in periods 1, 2, and 3, and technology B was chosen in period 4. If $\delta = 0$, the values of the installed bases for A and B at the end of $t = 4$ can be calculated as follows: $N_A(t = 5 \mid \delta = 0) = 1^3 + 1^2 + 1^1 = 3$ and $N_B(t = 5 \mid \delta = 0) = 1^4 = 1$. Thus, earlier adopters are as influential as more recent ones for incoming users. In contrast, $\delta = 0.6$, their values are $N_A(t = 5 \mid \delta = 0.6) = (1 - 0.6)^4 + (1 - 0.6)^3 + (1 - 0.6)^2 \approx 0.25$ and $N_B(t = 5 \mid \delta = 0) = (1 - 0.6)^1 = 0.4$. Here, choices made by new adopters in recent periods become more important in shaping future adoptions. In sum, as influence decay increases, early adopters become less influential vis-à-vis recent adopters.

4. RESULTS

We show that the rapid WTA process (i.e., short battle) in the literature is only a special case among many possible WTA battles. Less well-understood is prolonged WTA battles, the lengths of which may vary widely depending on the extent of influence decay (δ), given that network effects are strong ($\theta > 0$).

In the analysis that follows, we begin with the baseline model and demonstrate that as influence decay approaches the critical point, battle duration increases dramatically. There is a protracted period of contestation during which an observer of the market sees no clear-cut WTA outcome, even though one technology will corner the market eventually. We then report the results of the models with financial variables, which are necessary for specifying the BTRO strategy. In particular, we show that the merits of the BTRO strategy depend on the level of influence decay. Influence decay may cause the battle to extend far beyond what the firm anticipates, resulting in far larger costs of pursuing the strategy. But a longer battle duration has a counter-intuitive, second-order effect — it increases the likelihood of victory with the BTRO strategy. Finally, we analyze the mechanism underlying these results.

4.1. Baseline Model

Our key argument is that the rapid WTA battle in the literature is only a special case of WTA dynamics. The broader range of WTA dynamics including prolonged battles can occur when adopter influence decays over time. The main results are in Figure 3. The vertical axis here represents the average time to reach a steady state.[2] The model parameters are described in Table 2. The qualitative patterns of the results below are not sensitive to changes in these parameters, as we show later in the sensitive analysis.

< Insert Figure 3, and Table 2 about here >

[2] We assume that the system has reached a steady state if all subsequent adopters choose the same technology regardless of their types, *R* and *S*. We take the average value of realized steady-state outcomes from 10,000 simulations.

If $\delta = 0$, (this represents the Arthur (1989) model, where adopter influence does not decay over time), WTA dynamics reach a steady state very quickly — that is, the battle finishes very quickly. This result is shown at the far left in Figure 3. In Figure 2, we plot typical runs of the simulations across different levels of influence decay, and Figure 2a corresponds to the setting for $\delta = 0$. When adopter influence is allowed to decay over time (i.e., $\delta > 0$), battle duration increases substantially. For example, when $\delta = 0.1$, the battle duration increases by a factor of 10 from the zero-influence decay result. Typical simulation runs for $\delta = 0.1$ are in Figure 2b. If influence decay is $\delta = 0.18$, we observe a more prolonged battle. As shown in Figure 3, the average time to steady state is 1,000,000 times that at $\delta = 0$. Typical simulation runs for $\delta = 0.18$ are illustrated in Figure 2c. On the surface, the impact of increasing influence decay on the length of the battle might seem rather gradual. Surprisingly, the impact turns out to be quite abrupt.

Our model with influence decay exhibits a threshold-like behavior at the critical point, which reveals a sudden transition from the WTA regime to the shared-market regime. In Appendix 1, we show numerically and analytically that there is a critical point, which is $\delta_c \simeq 0.182$ for the current model parameterization. For $\delta < \delta_c$, the WTA outcome always occurs. On the other hand, if $\delta > \delta_c$, adoption dynamics are characterized by a shared market regime in which the two incompatible technologies coexist indefinitely. Typical simulation runs of this condition are also shown in Figure 2d.

The key finding is that influence decay has a non-linear impact on battle duration. This pattern implies that a slight increase in influence decay near the critical point (or in the gray area) leads to an exponential increase in battle duration. In the next section, we consider the strategic implications of influence decay and battle duration.

4.2. Strategic Implications of Influence Decay for Bargain-then-rip-off Strategy

In our discussion above, we showed that battle duration is a nonlinear function of influence decay. In this section, we examine why a narrow focus on the *rapid* WTA process could blind firms to a potential danger (or opportunity) associated with a *prolonged* WTA battle. In particular, we consider the bargain-then-rip-off (BTRO) strategy in which a firm seeks to increase its installed base quickly by giving away its products or services for free. We show that battle duration has two implications for the BTRO strategy. The first (somewhat trivial) implication is that the longer the battle, the greater the losses the firm must be able to sustain. The second implication is that the longer the battle, the more likely the BTRO strategy will win if the firm pursuing the BTRO strategy has the willingness and resources to stay in the longer battle.

Below, we proceed as follows. First, we describe the setup for the extended model. Second, we consider the simultaneous entry case, where two firms enter the market together and compete with different pricing strategies, which we will specify below. Third, we consider the sequential entry case, where the incumbent starts first by building an installed base with a non-BTRO strategy, and a BTRO firm enters later.

4.2.1. Extended Model for BTRO Strategy

In the extended models, we investigate the implications of the BTRO strategy by adding financial variables: (1) price, (2) cost, and (3) profit. In particular, we consider competition between two firms in a WTA battle. Cumulative profit or loss is defined by $\sum_{t=1}^{T} \pi_t = \sum_{t=1}^{T} (I_t p - C)$, where C is a fixed cost for maintaining or upgrading the firm's operation at time period t. For simplicity, we assume that $C > 0$ for all firms, whereas their marginal cost is 0. These two assumptions are considered the key characteristics of the digital economy (e.g., Shapiro and Varian 1999). We denote I_t as an indicator function. If a user chooses a focal firm's technology at t, $I_t = 1$; $I_t = 0$, otherwise. During a WTA battle, the BTRO firm gives away its product or service (i.e., $p_{bargain} = 0$) for free in the hope of building a large installed base quickly. The other firm pursues a more financially prudent strategy by setting its price to break even during the battle duration (i.e., $p_{high} = 2C$). Once the battle is over, the BTRO firm will make profits by raising its price (i.e., p_{ripoff}) up to the point where the firm can still attract all new users, $p_{ripoff} = \beta - \alpha + \theta N_A(t, \delta) - \theta N_B(t, \delta) + p_{high}$. The details of the payoff functions modified to incorporate this competition are described in Table 3. Other than the inclusion of the price and the cost, all the other model parameters are unchanged.

< Insert Table 3 about here >

4.2.2. Simultaneous Entry Case

We first consider the simultaneous entry case, where two firms enter the market together and compete with the different pricing strategies described above. Figure 4 highlights the danger of a prolonged WTA battle for the BTRO strategy — the larger the value of influence decay, the longer the battle, and the greater the accumulated losses before the battle is won by the BTRO firm. In the figure, the horizontal axis is time in log (of base 10) scale, and the vertical axis is cumulative profits or losses until the end of the battle. The lines represent single realizations of the model at different levels of influence decay, δ, under conditions in which the BTRO firm wins the battle. In early time periods, the lines are all downward sloping, indicating that losses are accumulated by the BTRO firm. The inflection points occur when losses stop and growth in profits begins. After the BTRO firm wins the battle, it changes its price from the bargain price, $p_{bargain}$, to the ripoff price, p_{ripoff}. The firm accumulates profits, thereby offsetting prior losses.

Our typical simulation results show that the BTRO strategy becomes far more costly with increasing δ in the gray area, which is near the critical point. When there is no influence decay (i.e., $\delta = 0$), the duration of the WTA battle is short, and the BTRO firm's cumulative losses are relatively small. Near the critical point (i.e., $\delta \rightarrow \delta_c$), however, the duration of a battle is exponentially prolonged. Consequently, the BTRO firm suffers from larger cumulative losses. For example, when $\delta = 0$, the BTRO firm faces losses of 13.5 monetary units during the battle period of 27. As influence decay increases to $\delta = 0.1$, the losses reach 103. If $\delta = 0.18$, the BTRO firm takes the period of 2,327 (about 86 times those for $\delta = 0$) to win the battle, thereby increasing the cumulative losses of 1,163 monetary units during the battle. Note that we are not interested in the parameter range for $\delta > \delta_c$ because it represents the shared market regime, where no firm will become a monopolist. In this regime, the BTRO strategy becomes unreasonable.

< Insert Figure 4 about here >

Although a higher level of influence decay near the critical point increases the cost of pursuing the BTRO strategy, the strategy also increases the probability that the BTRO firm will win the battle in the long run. In Figure 5a, we plot the winning probability for the BTRO firm. The winning probability is measured as a fraction out of 10,000 independent simulation runs. The fraction represents how many times the BTRO firm wins the market at the end of the battle period. First, we assume that both firms have unlimited financial resources to endure losses during the battle period. In the curve with closed squares, we show results with this assumption.

The figure shows that as influence decay increases, so does the probability of winning for the BTRO firm. As δ approaches δ_c, the winning probability for the BTRO firm approaches 1.

Now, we relax the assumption that the BTRO firm is unconstrained in its ability to carry losses in pursuit of winning the market. In particular, we examine the success probability of the BTRO firm under three finite resource scenarios: (a) low resource availability to carry a loss up to 10; (b) medium resource availability to carry a loss up to 100; (c) high resource availability to carry a loss up to 1000. The results of these scenarios are shown in all the other curves in Figure 5a. When the level of financial resources available to the firm is low, the winning probability declines in most ranges of increasing influence decay. In general, our results show the inverted U-shaped relationship between influence decay and the winning probability for the BTRO firm. That is, the winning probability increases initially at some intermediate ranges of influence decay, but the probability drops eventually because at a higher level of influence decay, the firm is more likely to run out of resources. This implies a danger of pursuing the BTRO strategy when a firm with limited resources believes that the WTA battle will be finished quickly.

< Insert Figure 5 about here >

4.2.3. Sequential Entry Case

Now, we consider the sequential entry case. In this setting, an incumbent begins first and thus has an established installed base when an entrant arrives. Here, we assume that the incumbent is a de facto monopolist, thereby pursuing the non-BTRO strategy, whereas the entrant pursues the BTRO strategy. We vary two parameters across simulations: (a) variation in the size of the installed base for the incumbent (0, 5, 10, and 100) and (b) level of influence decay.

Our analysis in Figure 5b reveals the conditions under which an entrant pursuing the BTRO strategy can flip the game — i.e., capturing the entire market previously dominated by an incumbent with an existing installed base. Near the critical point (i.e., $\delta \rightarrow \delta_c$), the winning probability for the incumbent approaches zero regardless of the size of its installed base. That is, the entrant can flip the game with probability one in the long run. Thus, influence decay is an important determinant of whether an entrant can dethrone the established incumbent. The implication of this strong determinant, especially when influence decay is near the critical point, has not been well understood in the literature on sequential entry.

On the other hand, if $\delta << \delta_c$, our results are not surprising in light of the extant literature. The results show that the size of the incumbent's initial installed base matters. If this installed base is sufficiently large, the incumbent's winning probability becomes one. That is, the entrant has a zero chance to flip the game. If the incumbents' installed base is sufficiently small, however, there is a non-zero probability for the entrant to flip the game. The smaller the incumbent's installed base, the higher the flipping probability.

4.3. Mechanics behind Surge of Winning Probability for BTRO Strategy in the Gray Area

To understand the impact of influence decay on battle duration, one must first recognize that influence decay, δ, and the strength of network effects, θ, are functionally distinct. They impact adoption dynamics in very different ways. In this section, we analyze how increasing influence decay near the critical point increases both (a) the winning probability for the BTRO firm and (b) the frequency of leadership changes during the battle. We then show the mechanism underlying these results.

4.3.1. Probability of Winning the Battle for BTRO Strategy

Influence decay and the strength of network effects differ greatly in how they impact the BTRO firm's winning probability. In Figure 6, we consider how a change in influence decay and a change in the strength of network effects impact the probability that the BTRO firm will win the battle, given that the BTRO firm does not face resource constraints. In particular, decreasing θ in Figure 6a (from right to left) has little effect on the BTRO firm's winning probability, given that $\theta > 0$. At the parameter settings in the present paper, the BTRO firm has approximately 55% chance of winning, whereas the non-BTRO firm has about 45% chance. That is, out of 10,000 independent simulation runs, approximately 5,500 cases show that the BTRO firm monopolizes the market, whereas 4,500 cases show that the non-BTRO firm corners the market. In the absence of the BTRO strategy in the baseline model, both firms would have had a 50% chance of winning. The small difference between 50% in the baseline case and 55% in the BTRO case reflects the minor price advantage the BTRO firm obtains by giving away its product or service for free.

< Insert Figure 6 about here >

In contrast, increasing influence decay δ in Figure 6b (from left to right) leads to a large increase in the winning probability for the BTRO firm from 0.55 to 1.0. The quantum jump in this probability near the critical point (i.e., $\delta \to \delta_c$) clearly suggests that the firm's minor price advantage becomes a major winning advantage in this parameter range. However, as influence decay goes beyond the critical point, the winning probability sharply falls to zero as the regime changes from winner-take-all (δ below the critical point) to a shared market regime (δ above the critical point).

4.3.2. Leadership Changes During the Battle

The strength of network effects, θ, and influence decay, δ, differ also in their impact on the frequency of leadership changes during the battle. We plot the number of leadership changes in the first 100 periods in Figure 7. In Figure 7a, we vary the strength of network effects while fixing influence decay at $\delta = 0$. We observe that changing the strength of network effects, θ, has little impact on the number of leadership changes. We see that in this experimental setup, there are, on average, three leadership changes during the first 100 periods. In contrast, in Figure 7b, we vary the influence decay δ, while setting the strength of network effects fixed at $\theta = 2$. We see a very different pattern for the effects of varying influence decay. When influence decay is $\delta = 0$, we observe 3 leadership changes on average, as was the case in Figure 7a. As influence decay approaches the critical point, however, the number of leadership changes increases substantially.

< Insert Figure 7 about here >

4.3.3. Why Does Influence Decay Function Differently from a Decrease in Network Effects?

We now address the questions of why these parameters function so differently in impacting leadership change and why influence decay near the critical point dramatically increases the BTRO firm's winning probability.

To see why such qualitatively distinct impacts arise, we must recall the essence of the adoption dynamics in our model. As described in the model section, the essential feature of the baseline model is a random walk in the absence of network effects ($\theta = 0$). When $\theta > 0$, this parameter pushes the adoption dynamics toward a history-dependent process, where leadership changes do not occur frequently as all future adopters will eventually lock into the winning technology.[3]

In contrast, increasing influence decay has substantial impacts on the frequency of leadership changes because it alters the marginal contribution of a new adopter in comparison with that of an old adopter. One can think of influence decay as a factor that determines the time window over which a prior adopter influences the decisions of subsequent adopters. In Figure 8, we plot the time window as a function of influence decay at the model parameterization used here.[4] The time window refers to the number of time steps during which an adopter has a nontrivial impact on future adoption choices. When $\delta = 0$, each adopter's influence lasts infinitely. When $\delta = 0.02$, each adopter's influence lasts for 228 periods (assuming a time window based on a 99% reduction in influence). In this scenario, the marginal contribution of the next new adopter in shaping future adoption choices is rather small in percentage terms. In contrast, when $\delta = 0.15$, the time window of the adopter's influence is substantially reduced to only 28 periods, and the next new adopter's marginal contribution looms much larger in percentage terms in shaping subsequent adoption choices.

< Insert Figure 8 about here >

4.3.4. Why Does Influence Decay near the Critical Point Dramatically Increase the BTRO Firm's Winning Probability?

A high frequency of leadership changes means that no firm takes a sufficient installed base lead for the system to lock into a winner. In Arthur's (1989) model ($\delta = 0$), the lock-in to one

[3] Analytically, when $\theta > 0$ and $\delta = 0$, leadership changes are independent of θ — they are only a function of only α and β.
[4] Time window in Figure 8 is based on a 99% reduction in influence based on Equation 1. That is, we assume that in calculating the values of time window, the adopter's influence is considered negligible when it is less than 1% of that of a new adopter (i.e., $TW(\delta) = \log_{1-\delta} 0.01$).

firm's technology is a function of the difference in the installed bases. A small "chance event" can tip the market towards one of the technologies. In this regard, Arthur noted: "a technology that by chance gains an early lead in adoption may eventually 'corner the market' of potential adopters." Such a chance event in the model stems from the assumption that in each time period, only one of either a *R*-type (preferring tech *A*) or an *S*-type adopter (preferring tech *B*) enters the market with a probability of 0.5 and chooses a technology. While these adopters arrive with a 50/50 chance from the statistical standpoint, it is not impossible to see a realization in which four *S*-type adopters enter the market in a row (which has a 0.0625 probability). This kind of a chance event can tip the market towards locking in to one of the technologies, thereby driving out the BTRO firm despite the fact that it has a price advantage.

We now go back to the question of why influence decay near the critical point dramatically increases BTRO firm's winning probability. Recall that (per Figure 6) when there is no influence decay (i.e., $\delta = 0$), the winning probability for the BTRO firm is 0.55, while the probability that chance events drive out the BTRO firm is 0.45. However, when influence decay is near the critical point, this probability increases to 1. That is, the role of chance events is sharply reduced to 0 near this point.

So, what is going on near the critical point? Two countervailing forces, installed-base advantage and influence decay are at work – they are clashing like a tug-of-war, with one end of the rope being pulled toward the WTA outcome and the other toward persistent technology incompatibilities. On the one hand, the cumulative effects of a larger installed base tend to propel the market system to the WTA outcome. On the other hand, influence decay tends to wash out those cumulative effects, thereby pressing the system to persistent technology incompatibilities. Our analysis reveals that these forces near the critical point are in a delicate balance. As influence decay approaches toward the critical point bit by bit, the tug-of-war prolongs the battle duration exponentially. The closer to the critical point, the longer the battle duration, and the larger the BTRO firm's winning probability.

In sum, the two parameters θ and δ are functionally quite different with respect to leadership changes. Variation in θ has little impact on the frequency of leadership change insofar as $\theta > 0$, whereas the increasing value of δ elevates this frequency. Near the critical point, leadership changes become more frequent as a new adopter's marginal contribution in shaping future adoption choices becomes larger in percentage terms. Furthermore, as influence decay washes out the cumulative effects of a larger installed base, adoption choices also become more susceptible to a minor advantage, which comes from the lower price in the BTRO strategy. This minor advantage would have had little impact on the adoption choices of new users *had influence decay not washed out some of the cumulative effects of the larger installed base*. The upshot is that near the critical point, the susceptibility to this type of minor advantage ensures the BTRO firm will win the battle eventually.

Prior theoretical work without consideration of influence decay has examined whether or not a challenger can dethrone a leader with installed-base advantage (e.g., Farrell and Klemperer 2007, Farrell and Saloner 1985, Katz and Shapiro 1992, Lee et al., 2016). The prior work has shown that if the leader has already built up a huge installed base, a challenger with this kind of minor advantage cannot beat the leader. Our finding here suggests that in the gray area, influence decay acts as a strong determinant for flipping the game. As long as the diversified challenger can fund the cost of pursuing the BTRO strategy from other businesses, it can beat the established leader eventually.

4.4. Additional Results and Sensitivity Analysis

4.4.1. Switching to Non-BTRO Strategy

In this section, we compare the effects of the two different scenarios in which a BTRO firm competes with a non-BTRO firm. In the base scenario (i.e., the model from Section 4.2), the BTRO firm sticks with its strategy indefinitely. In the switching scenario, the firm starts the game playing the BTRO strategy against a non-BTRO firm for a given period of time and then switches to the non-BTRO strategy. Here, we vary the timing of switching. This may reflect the fact that the firm does not know the level of influence decay *ex ante*, but has a trial period to learn about how the battle could unfold in the future. We also assume that both firms enter the market at the same time and the BTRO firm is not resource-constrained. The question we ask here is: At what point should the BTRO firm switch to the non-BTRO strategy?

The model setup and results, which are available in Appendix 2, suggest that adoption dynamics near the critical point are analogous to a war of attrition in which participants are prone to make strategic mistakes. One key type of mistake is that the firm believes that the battle will be over soon, when in fact, it will be prolonged dramatically. The interesting findings, again, occur in the gray area (i.e., near the level of 0.18). If the BTRO firm learns that influence decay is close to the critical point, the results suggest that the firm should stay with the BTRO strategy as long as they have the financial resources to withstand it. Switching early is a mistake. It is because the firm's winning probability is close to one if it can stay for 10^5 periods. In contrast, if the BTRO firm with constrained resources learns that influence decay in their market is at δ = 0.14, they would be well served by switching to the non-BTRO strategy at 10^3 periods. Doing so will provide them with a relatively high probability of winning while potentially saving a lot of costs for pursuing the BTRO strategy. At this level of influence decay, the probability of winning if one switches at 10^3 is very close to that at 10^4 and 10^5 — approximately 0.9.

4.4.2. BTRO versus BTRO Competition

In our main models, we considered competition between a BTRO firm and a non-BTRO firm. Here, we extend the model to have two firms simultaneously pursue the same BTRO strategy. The results are in Appendix 3. When both firms pursue the identical BTRO strategy, the winning probability of either of BTRO firms stays around 0.5, which drops from 0.55. Note that this probability (i.e., 0.5) is what one expects from the baseline model, where neither of the firms has an advantage over the other.

To understand why this happens, we analytically scrutinized the payoff functions between the two cases. The extended BTRO model with the financial variables and more detailed assumptions became isomorphic to the baseline model (i.e., the one with no financial variables) when both firms pursued the same BTRO strategy. This is because the effects of those financial variables tend to cancel out in long-term dynamics when the two firms pursue the same BTRO strategy.

4.4.3. Sensitivity Analysis

We examine the sensitivity of our results to alternative model specifications. First, we examine alternative functional forms of influence decay. In our baseline case, we model influence decay as the exponentially weighted sum of the installed base. In Appendix 4a, we consider a linear decay model. When the linear decay parameter is set at 0.1, the adopter influence decays by 0.1 with each subsequent period until the adopter influence reaches zero. We find that the distinguishing characteristic of our model — threshold behavior with the critical point — appears to be rather robust to the functional form of influence decay.

Second, we examine different parameter settings in our baseline model, varying the values of α, β, and θ. The results are in Appendix 4b-4d. Although the details of the dynamics change with different parameter values, the generality is that there is a critical point and that battle duration increases exponentially as influence decay approaches this point.

5. DISCUSSION

We develop computational models of WTA dynamics to understand the strategic implications of the BTRO strategy. We analyze the impacts of influence decay, which we define as a reduction in the influence of earlier adopters relative to new adopters in shaping subsequent adoption choices. We find that there is a critical point, in the vicinity of which a slight increase in influence decay brings about a dramatic increase in battle duration. Near the critical point, or in the gray area, a success-beget-success process is at work, but locking into one technology does not happen quickly. Instead, the dynamics exhibit a greatly protracted period of contestation during which an observer of the market sees no clear-cut WTA outcome, even though one technology will corner the market eventually.

5.1. Rapid WTA Process as a Special Case

Our findings show that the rapid WTA battle in the literature is only a special case of more general WTA phenomena. Less well-understood are prolonged WTA battles. In the literature, the length of battle duration has received little attention because it has been taken for granted that a large installed base built in the past will continue to be valued by new users (e.g., Arthur 1989).

This view is often violated (e.g., Zhu and Iansiti 2012). By relaxing this hidden assumption in our model, we are able to shed new light on the relationship between influence decay and battle duration. In particular, our findings highlight that if influence decay is near the critical point, where it is neither too low nor too high, a tug-of-war between installed base advantage and influence decay prolongs the battle duration exponentially.

5.2. Battle Duration and BTRO Strategy

Our key findings also speak to the literature on the BTRO strategy, in which firms give up short-term profits in order to build an installed base faster. This strategy has largely been viewed as a winning strategy in WTA markets (e.g., Cennamo and Santalo 2013, Clements and Ohashi 2005, Farrell and Klemperer 2007, Shapiro and Varian 1999). Our findings suggest that the calculus of this strategy is valid if the duration of the WTA battle is short with a lower level of influence decay. The short duration allows the BTRO firm to afford the cost of pursuing its strategy while harvesting rewards by raising its price after winning the battle.

If influence decay is near the critical point, however, the duration for a WTA battle increases exponentially, and strategic implications are paradoxical. Here, the firm pursuing the BTRO strategy will suffer from larger losses, but its winning probability increases sharply. Prior theoretical work with sequential entry situations has examined whether or not a challenger can dethrone a leader with installed-base advantage. The dethroning possibility has been understood as contingent on the timing of the challenger's entry or the size of the leader's installed base (e.g., Farrell and Klemperer 2007, Farrell and Saloner 1985, Katz and Shapiro 1992, Lee et al., 2016). Therefore, it seems reasonable for the challenger not to enter if the leader has already built up a huge installed base. Our finding suggests that the role of these contingency factors is far less important than expected if influence decay is near the critical point – influence decay acts as a strong determinant in flipping the game. As long as the diversified challenger can fund the cost of pursuing the BTRO strategy from other businesses, it can beat the established leader eventually. This possibility has been less well-understood in the literature.

5.3. Limitations and Future Research

Although our findings are robust to the selected model specifications, we made several simplifying assumptions. First, influence decay is exogenously given in our model. It is possible that a firm may intentionally shape influence decay either to enhance its user benefits or to reduce those associated with its rivals' products and services. Second, we assume that the focal firm in our model is able to pursue either of the WTA strategies above by ignoring the details of how it can finance its business operations. Future research may relax some of these simplifying assumptions and further enrich our understanding of WTA strategies. We believe there are promising opportunities for further extending our work.

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TABLES AND FIGURES

Table 1. Payoff Functions

	Technology *A*	Technology *B*
User *R*	$\alpha + \theta N_A(t, \delta)$	$\beta + \theta N_B(t, \delta)$
User *S*	$\beta + \theta N_A(t, \delta)$	$\alpha + \theta N_B(t, \delta)$

Table 2. Model Parameters

Parameter	Remarks	Range of parameter values analyzed
α	*R*'s inherent preference for *A* and *S*'s inherent preference for *B*	[Figures 2-7]: 10
β	*S*'s inherent preference for *A* and *R*'s inherent preference for *A*	[Figures 2-7]: 1
θ	Strength of network effects	[Figures 2-5, 6b, 7b]: 2 [Figures 6a, 7a]: 0~2
p_A	Price of *A*	[Figures 2-4, 7]: 0 [Figures 5 and 6]: 0 for the bargain period; $\beta - \alpha + \theta N_A(t) - \theta N_B(t) + p_B$ for the ripoff period
p_B	Price of *B*	[Figures 2-4, 7]: 0 [Figures 5, 6]: 1
δ	Influence decay	[Figure 2, 6b, 7b, 8]: 0-1 [Figure 3]: 0, 0.1, 0.1, 0.18 [Figure 4]: 0, 0.1, 0.15, 0.18 [Figure 5]: 0-0.18 [Figure 6a, 7a]: 0

Note: All simulation results involve 10,000 runs.

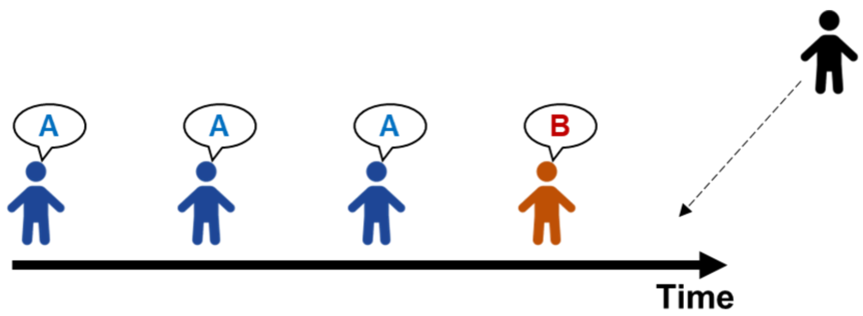
Table 3. Payoff Function with BTRO Competition

	Technology A	Technology B
User R	$\alpha + \theta N_A(t, \delta) - p_{BTRO}$	$\beta + \theta N_B(t, \delta) - p_{high}$
User S	$\beta + \theta N_A(t, \delta) - p_{BTRO}$	$\alpha + \theta N_B(t, \delta) - p_{high}$

Note: In our analysis, we set a fixed cost at 0.5 and thus $p_{high} = 1$. p_{BTRO} consists of $p_{bargain}$ and p_{ripoff}. In the bargain period, $p_{bargain} = 0$. In the ripoff period, it raises its price up to the point where it should be able to attract all new customers (i.e., $p_{ripoff} = \beta - \alpha + \theta N_A(t, \delta) - \theta N_B(t, \delta) + p_{high}$).

Figure 1. Illustration of Adoption Dynamics with or without Influence Decay

(a) Adoption process without influence decay



(b) Adoption process with influence decay

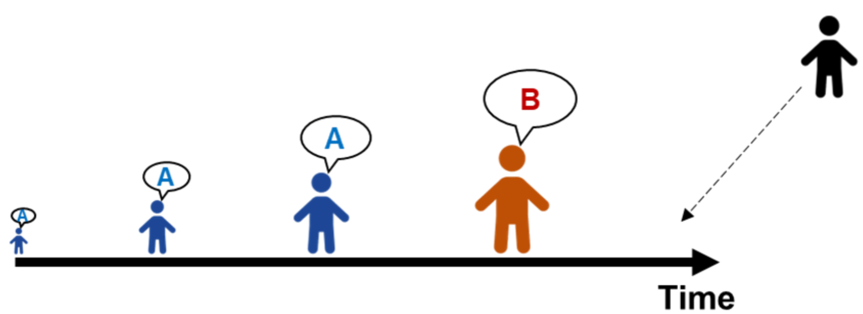


Figure 2. Typical Simulation Runs across Levels of δ

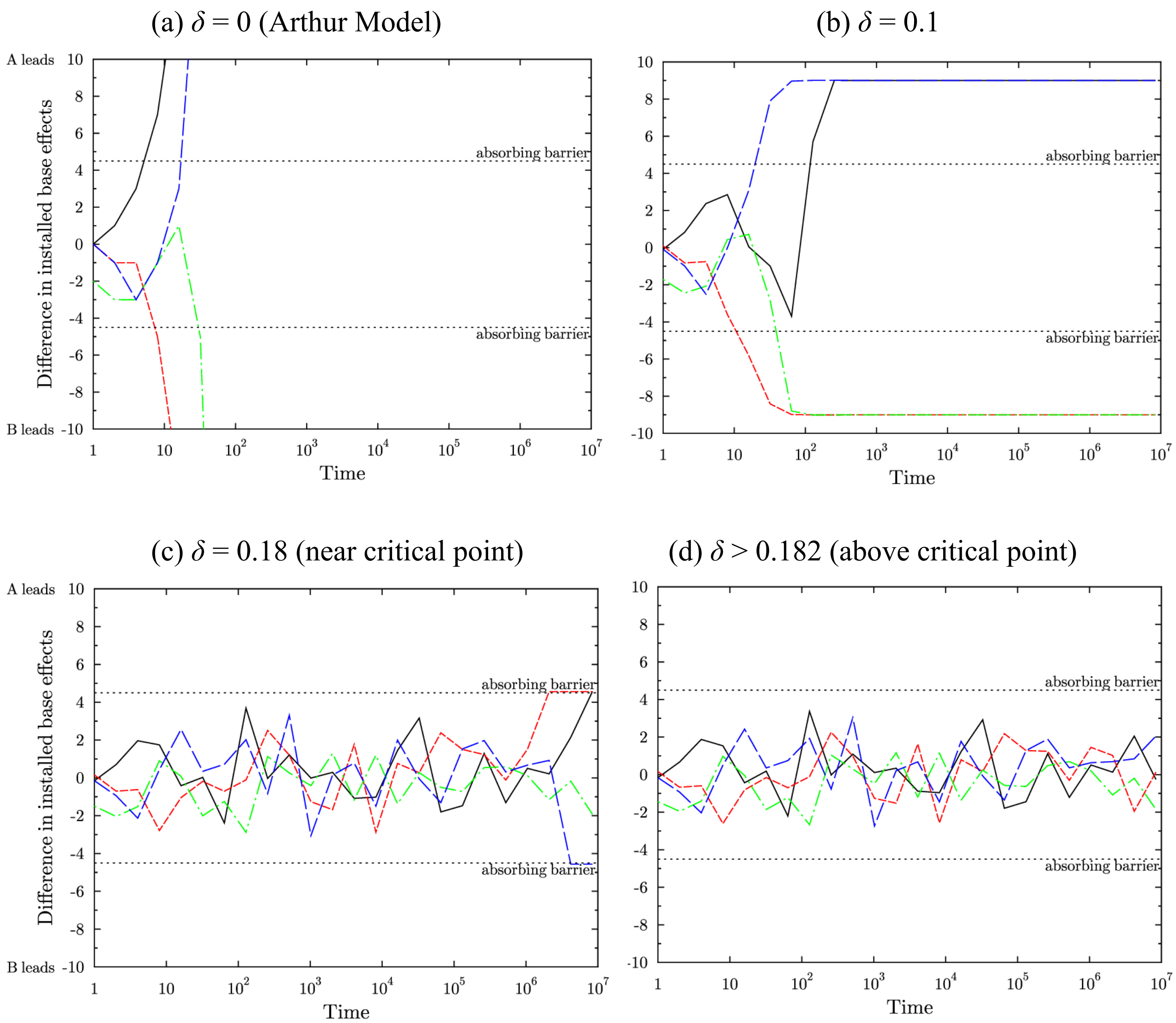


Figure 3. Duration of Winner-Take-All Battle with Influence Decay

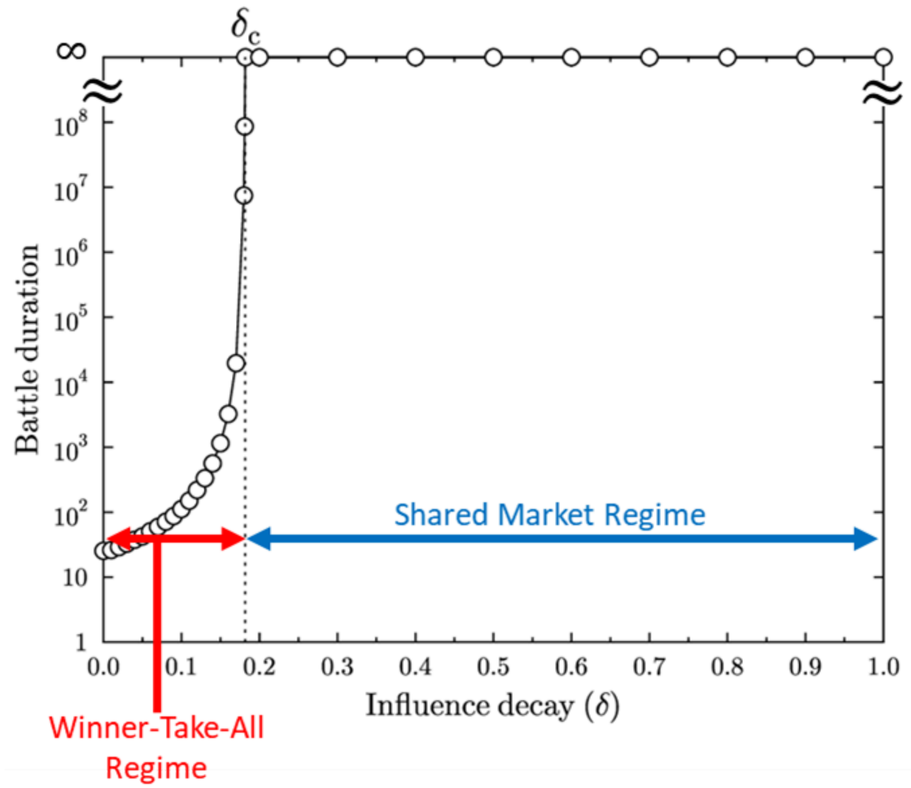


Figure 4. Cumulative Profits (Losses) for BTRO Firm by Influence Decay

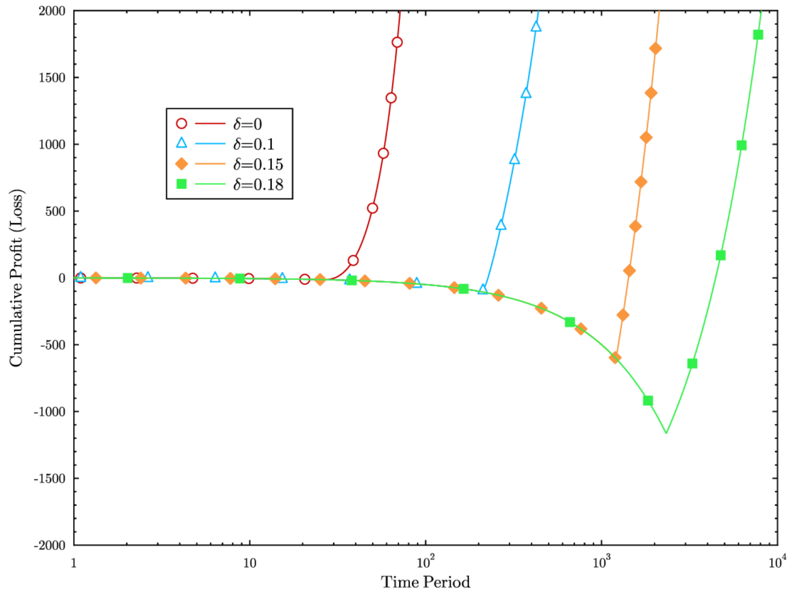
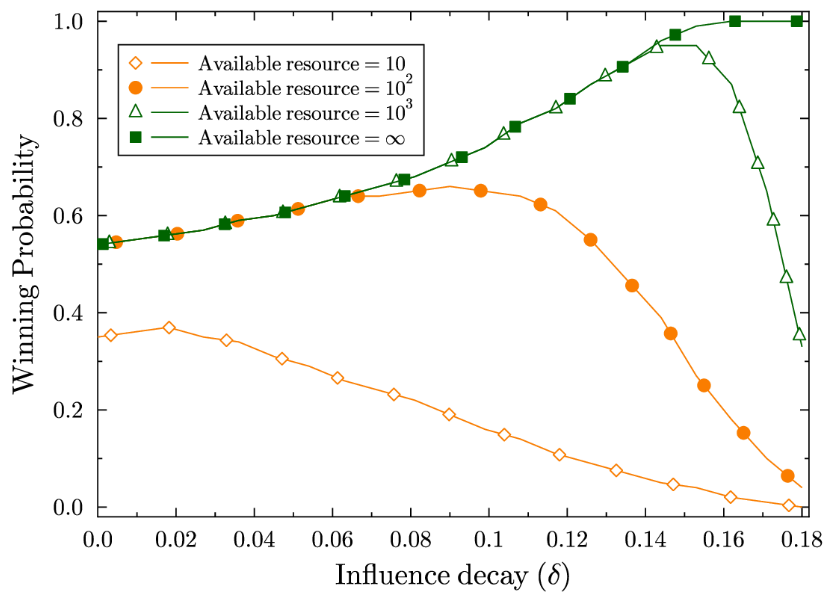


Figure 5. Winning Probability for BTRO Firm

(a) Simultaneous entry



(b) Sequential entry with unconstrained resources

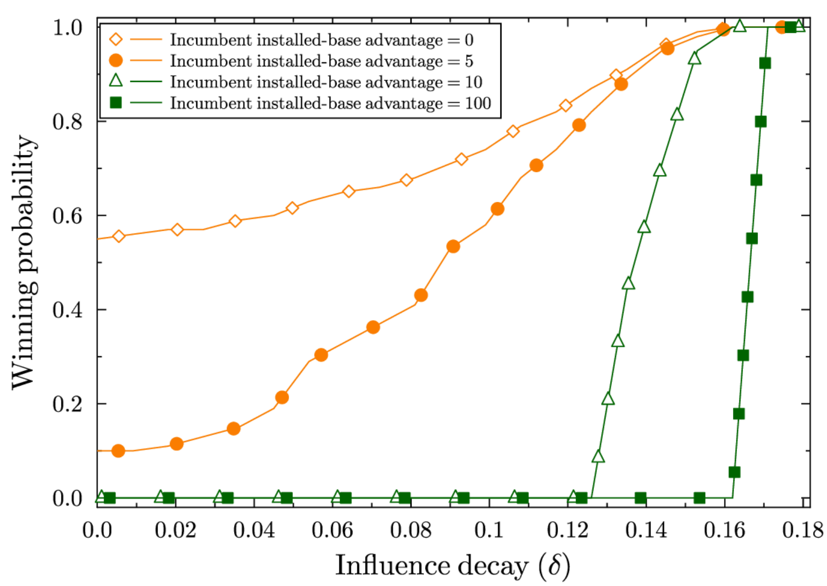
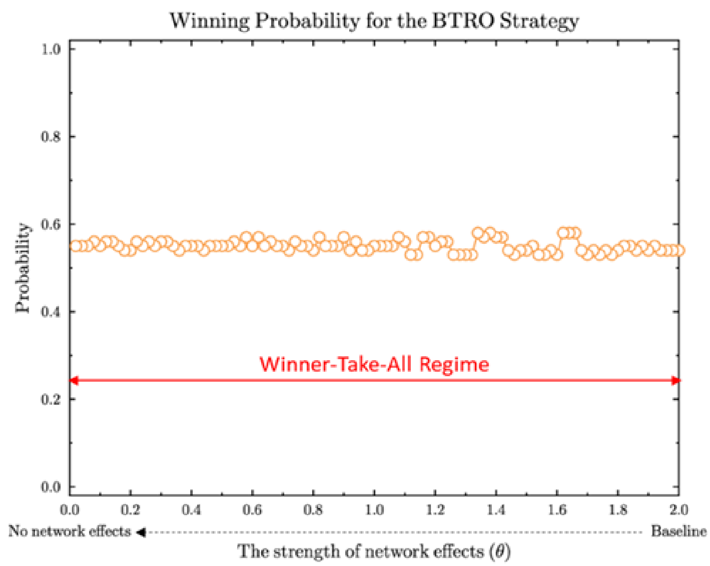


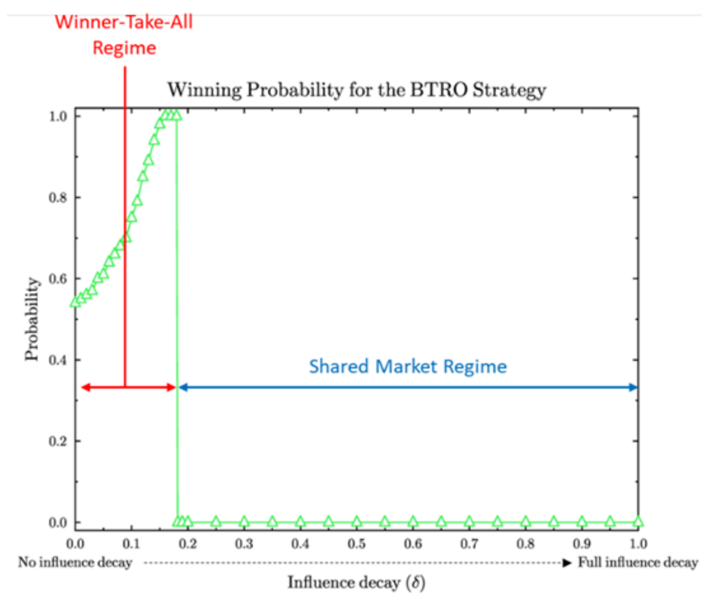
Figure 6. Implications of Difference between Influence Decay and Strength of Network Effects in terms of BTRO Firm's Winning Probability

(a) Effects of decreasing θ on winning probability for the BTRO firm



Note: In this figure, we assume that there is no influence decay ($\delta = 0$).

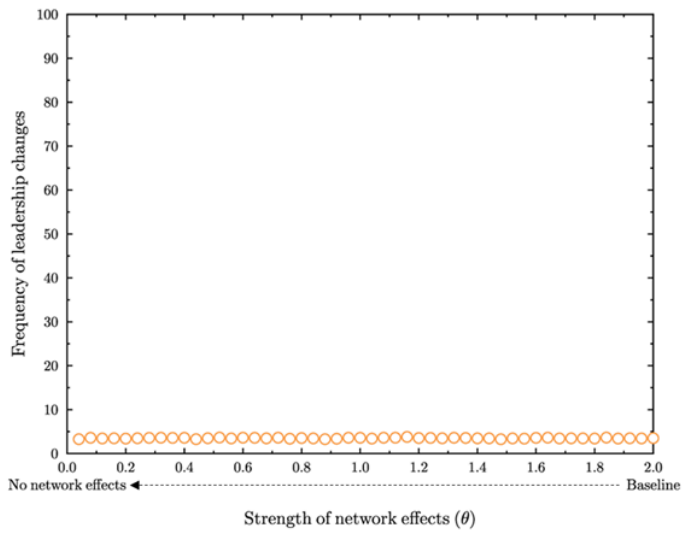
(b) Effects of increasing δ on winning probability for the BTRO firm



Note: In this figure, we assume a constant strength of network effects ($\theta = 2$).

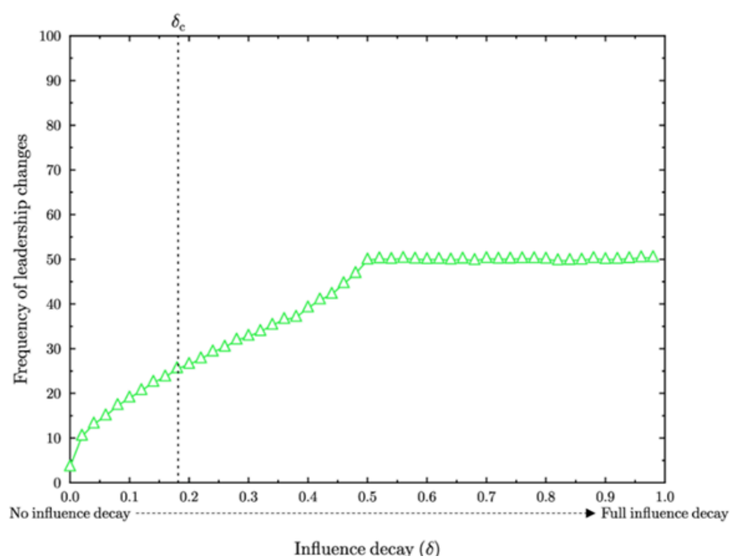
Figure 7. Strength of Network Effects vs. Influence Decay for Leadership Changes

(a) Effects of decreasing θ on the number of leadership changes for first 100 periods



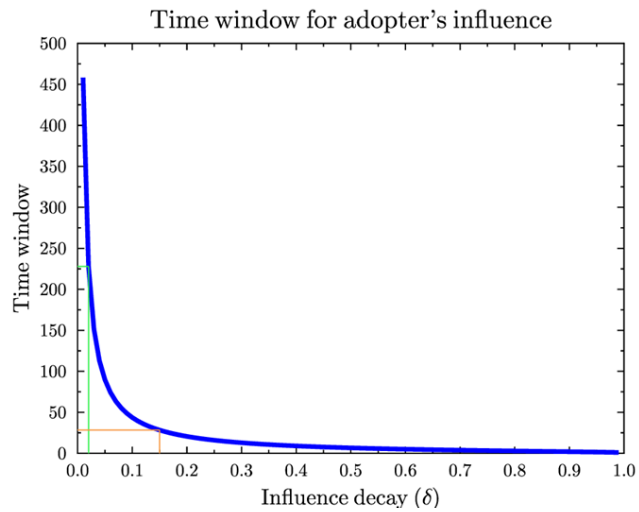
Note: In this figure, we assume that there is no influence decay ($\delta = 0$), and the frequency of leadership changes is measured during the battle period. The result is generated from the baseline model.

(b) Effects of increasing δ on the number of leadership changes for first 100 periods



Note: In this figure, we assume a constant strength of network effects ($\theta = 2$), and the frequency of leadership changes is measured during the battle period. The result is generated from the baseline model.

Figure 8. Relationship between δ and Time Window for the Adopter's Influence



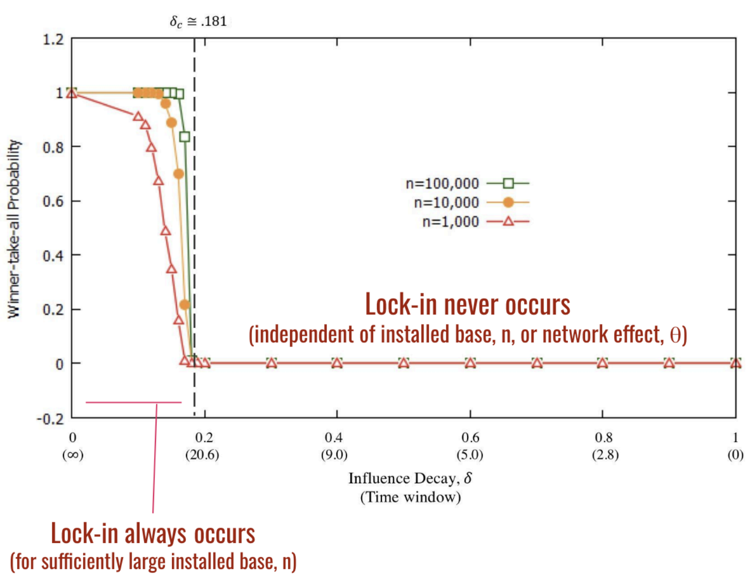
Note: Time window is based on a 99% reduction in influence based on Equation 1. That is, we assume that in calculating the values of time window, the adopter's influence is considered negligible when it is less than 1% of that of a new adopter (i.e., TW(δ) = $log_{1-\delta}0.01$).

APPENDICES

Appendix 1: Numerical and Analytical Results for the Critical Point

One might assume that the impact of increasing influence decay on the length of the battle is rather gradual, but it turns out to be quite abrupt. In Figure A1, we examine the range of δ to understand this abrupt change. At each level of δ, we calculate the WTA probability by examining the outcomes of 10,000 simulation runs. In each run, we check whether one technology monopolizes the market at a given market size (i.e., n = 1,000, 10,000, and 100,000 adopters). If it happens, we then count this as an instance of the WTA outcome. For example, if the probability is estimated as one in a test at n = 10,000, then all 10,000 independent runs generated the WTA outcomes. In contrast, when the probability is estimated as zero, none generated that outcome. Thus, the figure demonstrates that the model with influence decay produces a phase transition at the critical point δ_c.

Figure A1. Transition to the Winner-Take-All Regime by System Size



We can analytically derive the critical point δ_c. In our model, the positive feedback process initiates when the difference in installed base between technology A and B exceeds what Arthur (1989: p. 121) called " absorbing barriers,"

$$|N_A - N_B| > \frac{\alpha-\beta}{\theta}. \tag{A1.1}$$

Given δ, we can derive the maximum possible difference between N_A and N_B at time t. In the adoption dynamics, it is possible that users of the same type repeatedly choose a technology at every step until period t. For instance, only users of type R may repeatedly enter and choose A. The maximum difference in installed base between A and B is represented by

$$Max\,|N_A(t,\,\delta) \;-\; N_B(t,\,\delta)| \;=\; \sum_{k=1}^{t} (1 \;-\; \delta)^k. \tag{A1.2}$$

Given decaying influence ($\delta > 0$), the maximum difference in the limit of large t can be represented by the sum of geometric sequence as follows:

$$\lim_{t\to\infty} Max\,|N_A(t,\,\delta) \;-\; N_B(t,\,\delta)| \;=\; \frac{1-\delta}{\delta}. \tag{A1.3}$$

The critical value of $\delta = \delta_c$ in equation (A1.3) should be equal to the absorbing barrier in equation (A1.1), yielding $\frac{1-\delta_c}{\delta_c} = \frac{\alpha-\beta}{\theta}$. Solving for δ_c , we get the critical point

$$\delta_c = \frac{\theta}{\alpha-\beta+\theta}. \tag{A1.4}$$

Given the parameter values in the paper, $\alpha = 10$, $\beta = 1$, and $\theta = 2$, we get $\delta_c = 0.1818\ldots \simeq 0.182$.

Appendix 2: BTRO Firm Switching its Strategy

We can compare the effects of the two different scenarios in which a BTRO firm competes with a non-BTRO firm, given that both enter the market at the same time. In the base scenario, which is reported in Section 4.2, the BTRO firm sticks with its strategy indefinitely. In the switching scenario, the firm initially pursues the BTRO strategy for a period of time before switching to the non-BTRO strategy. We assume that during this trial period, the BTRO firm learns the market conditions to foresee how the battle could unfold in the future. In our simulation experiments, we vary the timing of switching.

The lines in the figure represent different switching times. For example, the circle-marked line shows the results for the BTRO firm that switches to the non-BTRO strategy at period 1000. The interesting findings occur in the region near the critical point (i.e., near the level of 0.18). Imagine a firm that starts the game playing a BTRO strategy (against a non-BTRO firm). Assume that the firm does not know the level of influence decay, δ, ex ante, but can learn about it over time. Then a question is: At what point should the BTRO firm switch to the non-BTRO strategy? Recall that influence decay drives battle duration.

If the BTRO firm learns that influence decay is close to the critical point of influence decay (near 0.18) then the results in Figure A2b suggest that they should stay with the BTRO strategy as long as they have the financial resources to withstand it. It is because their probability of winning is near one if they can stay for 10^5 periods. In contrast, if the BTRO firm learns that influence decay in their market is at $\delta = 0.14$, they would be well served by switching to the non-BTRO strategy at 10^3 periods. Doing so will provide them with a relatively high probability of winning, while potentially saving a lot of costs of pursuing the BTRO strategy (see Figure

A3a). In Figure A2b, we see that at this level of influence decay, the probability of winning if one switches at 10^3 is very close to that at 10^4 and 10^5— approximately 0.9.

Figure A2a. Switch-timing and cumulative costs for BTRO firm

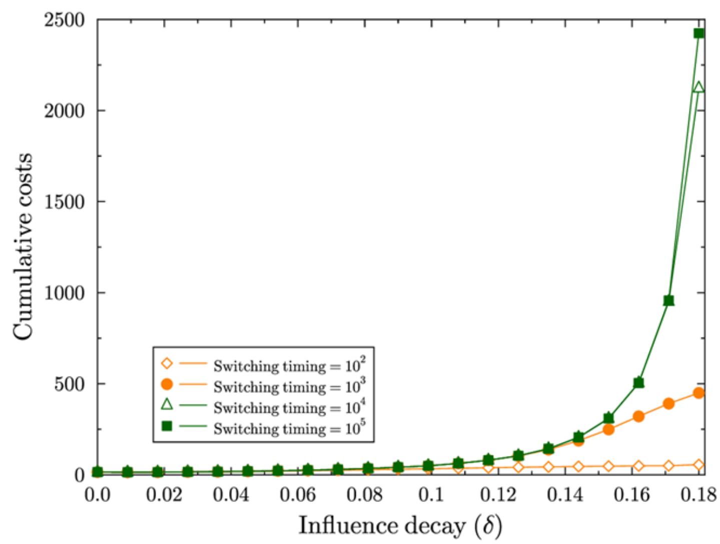
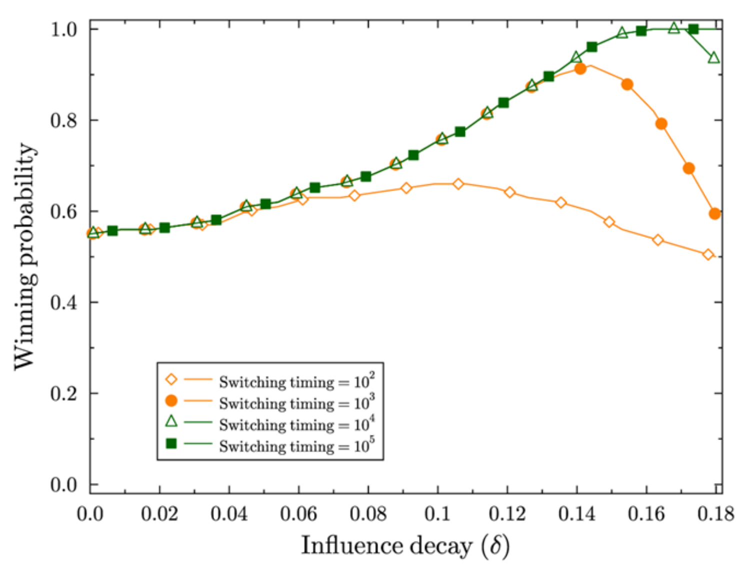


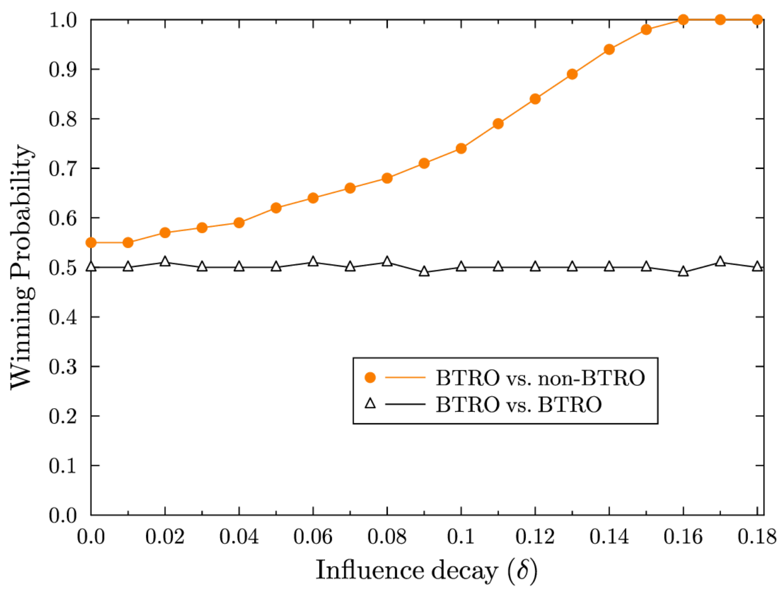
Figure A2b. Switch-timing and winning probability for BTRO firm



Appendix 3: BTRO versus BTRO

In our main models, we considered competition between a BTRO firm and a non-BTRO firm. Here, we extend the model to have two firms simultaneously pursue the same BTRO strategy. When both firms pursue the identical BTRO strategy, the winning probability of each firm stays around 0.5. Note that this probability (i.e., 0.5) is what one expects from the strip-down, baseline model where neither firm has a competitive advantage over the other. As in the original Arthur model, simulations of the extended model show that which firm will win depends purely on chance, and a lucky firm will corner the market.

Figure A3a. Winning Probability for the BTRO firm

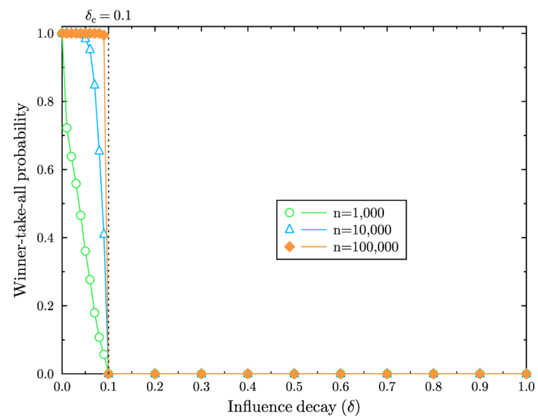


Appendix 4: Sensitivity Analysis

In the baseline model, we adopt an exponential decay model for influence decay with a specific set of parameters (i.e., $\alpha = 10$, $\beta = 1$, $\theta = 2$). Here, we show that our key findings remain robust to these specifications. In Figure A6a, we adopt a linear decay model in which the influence of adopters decreases by δ at each time step. In Figure A7b-d, we examine different parameter sets with an exponential decay model.

Figure A4a. Linear decay model

(a) Transition to the winner-take-all regime by system size



(b) Duration of winner-take-all battle with influence decay

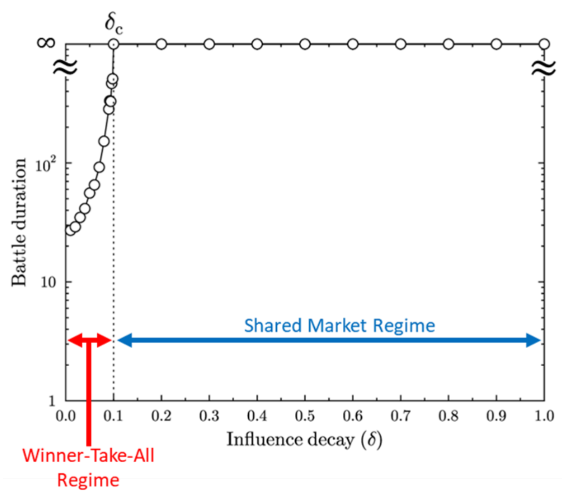
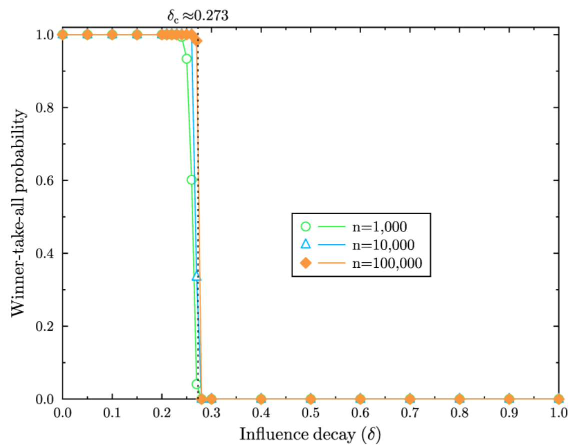


Figure A4b. Exponentially weighted sum with α = 5, β= 1, θ = 1.5

(a) Transition to the winner-take-all regime by system size



(b) Duration of winner-take-all battle with influence decay

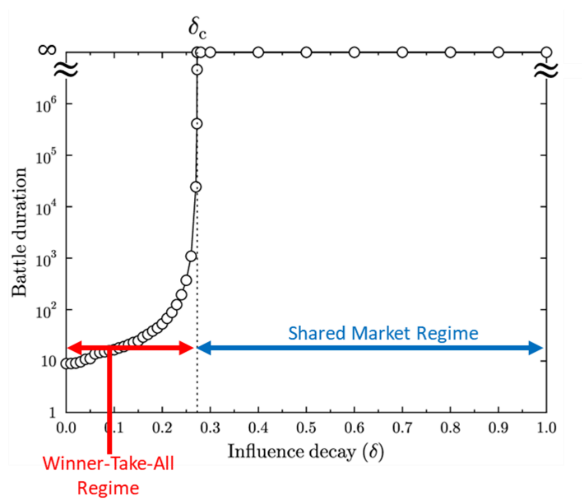
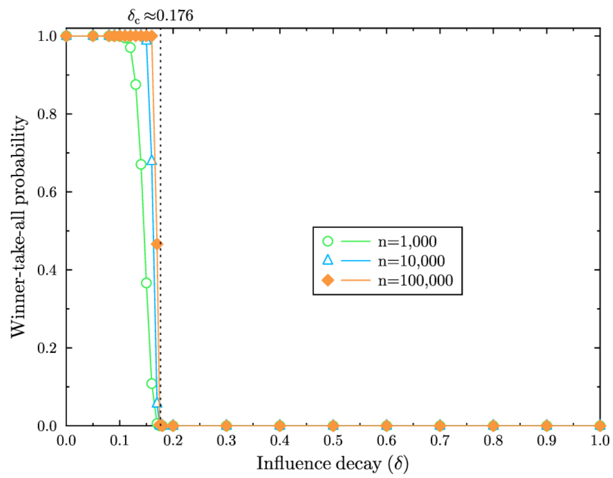


Figure A4c. Exponentially weighted sum with $\alpha = 15$, $\beta = 1$, $\theta = 3$

(a) Transition to the winner-take-all regime by system size



(b) Duration of winner-take-all battle with influence decay

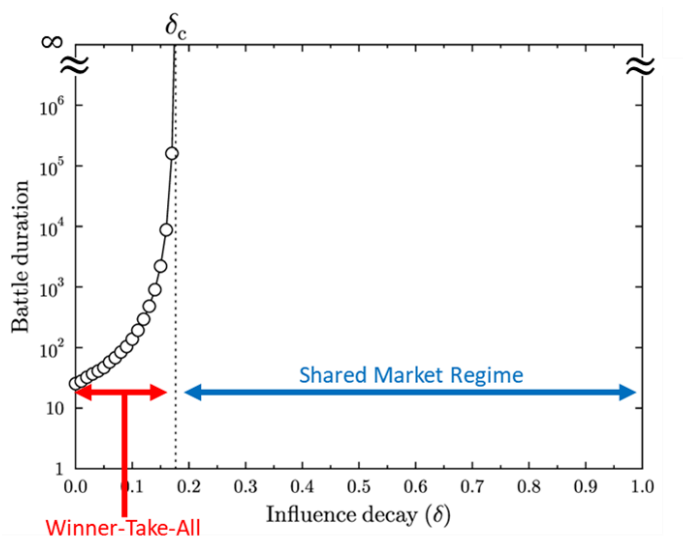
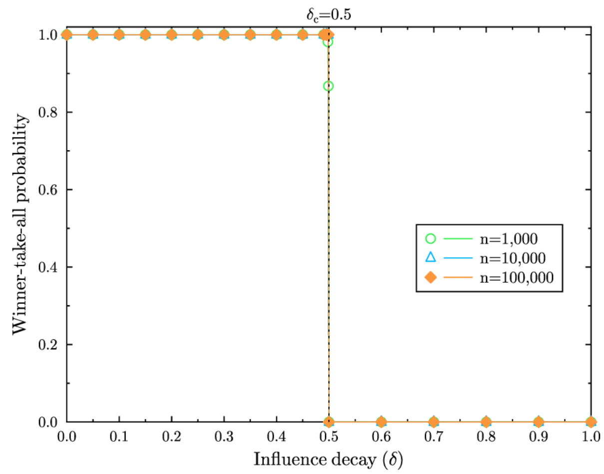


Figure A4d. Exponentially weighted sum with $\alpha = 5$, $\beta = 2$, $\theta = 3$

(a) Transition to the winner-take-all regime by system size



(b) Duration of winner-take-all battle with influence decay