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User state-based notification volume optimization: A novel approach

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Abstract

Notification volume optimization presents a significant challenge in modern digital environments where user engagement must be balanced against notification fatigue. Traditional approaches employ uniform strategies across diverse user populations, failing to account for inherent behavioral differences between high and low activity users. The state-based notification volume optimization framework addresses this limitation by implementing segment-specific objective functions that align with natural engagement patterns. By differentiating between high-activity users who interact with platforms daily and low-activity users who engage on a weekly basis, digital platforms can more effectively allocate fixed notification resources. This differentiated approach applies Daily Active User (DAU) optimization for high-activity segments and Weekly Active User (WAU) optimization for low-activity users, respecting their distinct engagement rhythms. Implementation involves dynamic segmentation methodologies, segment-specific machine learning models, and asymmetric notification distribution while maintaining constant overall notification volumes. The framework consistently demonstrates superior performance across multiple metrics, including enhanced engagement rates, improved retention, reduced opt-outs, and more efficient resource utilization. Through strategic alignment of notification strategies with natural user behavior patterns, digital platforms can significantly improve engagement outcomes while simultaneously reducing notification fatigue and associated negative consequences.

Keywords: Notification Optimization; User Segmentation, Engagement Patterns; Multi-Objective Optimization; Personalized Communications

1. Introduction

The optimization of notification volume represents a critical challenge for digital platforms seeking to maintain user engagement while avoiding notification fatigue. Traditional approaches have typically employed a one-size-fits-all strategy, utilizing a single machine learning model to predict engagement probability and optimize for a universal objective function—either Daily Active User (DAU) or Weekly Active User (WAU) engagement. This paper proposes a more nuanced framework that recognizes the heterogeneity of user behavior patterns and implements a segmented approach to notification volume optimization. By differentiating between high and low activity users and applying distinct objective functions to each segment, we demonstrate that platforms can achieve superior engagement outcomes while maintaining a constant overall notification volume. This user state-based approach represents a significant advancement in the field of engagement optimization, offering a more sophisticated and effective methodology for digital platforms to enhance user retention and interaction.

Recent research by Nwaimo et al. reveals that modern smartphone users receive between 65-89 notifications daily, with engagement declining proportionally as volume increases beyond 72 notifications per day. Their comprehensive analysis of user interaction patterns across five major social platforms identified distinct behavioral segments, with approximately 31.4% classified as "high-engagement users" who interact with applications multiple times daily, while 68.6% fall into lower engagement categories with weekly or less frequent interaction patterns. The study further

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demonstrated that notification response rates vary dramatically between these segments, with high-engagement users demonstrating 2.7x higher click-through rates for similar notification content compared to occasional users (Nwaimo et al., 2024) [1].

Implementation of segmented notification strategies requires sophisticated machine learning approaches that can effectively balance multiple competing objectives. Zakaria et al. explored this challenge in their seminal work comparing single-objective versus multi-objective optimization frameworks. Their research demonstrated that multi-objective approaches consistently outperformed single-objective models across 17 different test cases, with average performance improvements of 23.8% when applying specific objective functions to distinct system components. The researchers emphasized that "complex systems with heterogeneous elements fundamentally require optimization approaches that respect their inherent diversity" and that forcing diverse components to conform to a single optimization function inevitably produces suboptimal results. Their mathematical modeling conclusively demonstrated that maintaining separate objective functions for distinct system elements allowed for 31.7% more efficient resource utilization while simultaneously improving overall system performance by 19.4% (Zakaria et al., 2012) [2].

When applied specifically to notification optimization, these principles suggest substantial benefits from segment-specific modeling. By maintaining distinct objective functions—DAU optimization for high-activity users and WAU optimization for low-activity users—platforms can more effectively allocate their fixed notification budget. This approach acknowledges the fundamental differences in user engagement patterns and optimizes accordingly, rather than forcing all users into a single engagement paradigm. The resulting improvement in notification efficiency represents a compelling case for adopting state-based optimization approaches across digital platforms seeking to enhance user engagement while respecting individual usage patterns.

Table 1 Comparison of notification response rates between high and low engagement user segments [1]

User Segment	Percentage of User Base	Click-Through Rate Multiplier	Daily Engagement Frequency	Notification Response Time (min)	Uninstall Risk Factor
High-engagement users	31.40%	2.7x	5.8	12.3	0.7x
Low-engagement users	68.60%	1.0x	1.2	47.8	1.4x
Weekend users	41.20%	1.8x	2.3	31.5	0.9x
Dormant users	18.30%	0.4x	0.3	124.7	2.3x
New users	14.50%	2.1x	3.9	8.2	1.1x

2. Traditional Notification Optimization Approaches and Their Limitations

Current industry practices predominantly rely on a single machine learning model to predict user engagement probability with notifications. These models typically optimize for one universal metric—either DAU or WAU engagement—regardless of individual users' activity patterns or engagement preferences. This approach fails to account for the significant variability in user behavior and can lead to suboptimal outcomes: over-notification of already active users and under-engagement with less active users who might require different stimuli to maintain connection with the platform. Furthermore, this uniform approach may contribute to notification fatigue among certain user segments while missing opportunities to re-engage dormant users through more strategically timed communications.

Liu et al.'s comprehensive market segmentation research provides critical insights into the limitations of unified modeling approaches when applied to heterogeneous user populations. Their analysis of customer behavior across digital platforms demonstrated that single-framework approaches consistently underperform compared to segment-specific strategies. Their study examined 27,354 customers across multiple sectors and found that homogeneous treatment of heterogeneous segments reduced prediction accuracy by 34.7% and diminished optimization effectiveness by 28.3%. Their proposed segmentation methodology yielded seven distinct customer archetypes, each demonstrating significantly different response patterns to similar stimuli. The researchers concluded that "the aggregation of disparate

consumer segments into a unified framework inherently compromises performance" and that segment-specific modeling approaches "significantly enhance both predictive power and strategic implementation effectiveness." Their findings demonstrated a 41.6% improvement in engagement metrics when segment-specific optimization replaced universal approaches, highlighting the fundamental limitations of traditional notification strategies (Liu et al., 2012) [3].

Table 2 Notification timing effectiveness and retention impact [4]

Metric	High-Activity Users	Low-Activity Users	Mixed Approach	Control Group	Optimal Distribution
Peak engagement rate - perfect timing	38.70%	17.20%	24.50%	13.80%	32.10%
Poor timing engagement rate	4.20%	2.10%	3.50%	3.10%	3.80%
Weekend vs weekday effectiveness	1.3x better on weekends	2.17x better on weekends	1.56x better on weekends	1.21x better on weekends	1.73x better on weekends
90-day retention improvement	41.30%	41.30%	37.20%	Baseline	43.70%
Uninstall rate	12.70%	21.40%	18.20%	26.50%	11.30%

Dwivedi's extensive analysis of push notification effectiveness across various digital platforms reveals critical insights into notification optimization challenges. Her research, encompassing data from over 1,000 applications and 763 million notifications, found that traditional single-model approaches to notification timing resulted in dramatically different outcomes across user segments. High-activity users demonstrated optimal engagement when receiving notifications during specific micro-moments throughout the day, with engagement rates peaking at 38.7% for perfectly-timed communications but plummeting to just 4.2% for poorly-timed notifications. Conversely, low-activity users showed fundamentally different engagement patterns, with weekend notification effectiveness outperforming weekday communications by 217%. The research identified severe consequences of notification misalignment, with 61% of users reporting they had uninstalled applications specifically due to irrelevant or excessive notifications. Perhaps most significantly, Dwivedi found that applications employing adaptive, segment-specific notification strategies achieved a 41.3% higher user retention rate over 90 days compared to those utilizing uniform notification approaches. These findings conclusively demonstrate that one-size-fits-all notification strategies fundamentally fail to accommodate the diverse engagement patterns exhibited by different user segments (Dwivedi, 2023) [4].

2.1. User Segmentation Methodology

Table 3 Advantages of dynamic over static segmentation approaches based on Optimove [5]

Metric	Improvement Percentage	Implementation Cost Factor	Maintenance Complexity	Update Frequency (days)	Data Requirements
User responsiveness to targeted communications	37.40%	1.6x	Medium	14	High
Notification engagement rates	28.90%	1.4x	Medium-High	14	Medium-High
Reduction in notification opt-outs	23.60%	1.3x	Medium	30	Medium
User segment transition accuracy	31.80%	1.7x	High	7	Very High
Seasonal variation handling	42.30%	1.5x	Medium-High	14	High

The proposed framework begins with the classification of users into distinct segments based on their activity patterns. Primary segmentation divides users into "High activity users" and "Low activity users" through analysis of historical engagement data, session frequency, session duration, feature utilization, and interaction patterns. This classification can be implemented through unsupervised clustering techniques or rule-based thresholds determined by platform-specific benchmarks. The segmentation process must be dynamic, allowing for users to transition between segments as their engagement patterns evolve over time. This ensures that the notification optimization strategy remains responsive to changes in individual user behavior.

Research on dynamic customer segmentation has revealed substantial advantages over static approaches in notification optimization contexts. According to Optimove's comprehensive analysis, dynamic segmentation methodologies have demonstrated a 37.4% increase in user responsiveness to targeted communications compared to traditional fixed segmentation approaches. Their research across multiple digital platforms found that 31.8% of users naturally transition between engagement categories over a typical 60-day period, with significant seasonal variations affecting up to 42.3% of the user base during holiday periods. The implementation of real-time segmentation recalibration led to a 28.9% improvement in notification engagement rates and a 23.6% reduction in notification opt-outs. Perhaps most critically, their analysis revealed that high-activity users (representing approximately 24.7% of the typical user base) demonstrated fundamentally different notification response patterns, with engagement rates peaking at different times of day and with different frequency thresholds compared to occasional users. The researchers emphasized that "static segmentation approaches inevitably lead to misclassification over time" and that "the dynamic nature of user behavior necessitates equally dynamic segmentation methodologies" to maximize engagement [5].

Recent advances in machine learning-based segmentation techniques have further enhanced notification optimization capabilities. RapidCanvas's analysis of modern segmentation algorithms applied to digital engagement demonstrates that supervised clustering techniques incorporating recency, frequency, monetary value, and engagement depth features can achieve classification accuracy of 91.7% when validated against ground-truth engagement patterns. Their research found K-means clustering with optimal feature selection outperformed other approaches, correctly identifying high-engagement users (characterized by 6+ weekly sessions) with 93.4% accuracy and low-engagement users (0-2 weekly sessions) with 89.2% accuracy. Their longitudinal analysis of 4.2 million users across 17 applications revealed that 21.6% of users shift between engagement segments in any given month, with significant seasonal variations affecting up to 34.8% of users. Implementation of their ML-based segmentation approach with bi-weekly recalibration improved notification engagement rates by 32.7% compared to traditional segmentation methods. The researchers emphasized that "machine learning algorithms enable organizations to move beyond simplistic RFM models to incorporate nuanced behavioral signals" which proved "particularly valuable for optimizing time-sensitive communications like push notifications" [6].

3. Dual-objective function optimization

The core innovation of our approach lies in the implementation of distinct objective functions for different user segments. For high activity users, the optimization model prioritizes DAU engagement, recognizing that these users exhibit a pattern of frequent interaction with the platform. Conversely, for low activity users, the model optimizes for WAU engagement, acknowledging that these users engage with the platform on a less frequent basis and require a different notification cadence to maintain connection without inducing notification fatigue. This dual-objective function approach allows for more refined targeting that respects the natural engagement rhythms of different user types.

Venkatesh's comprehensive analysis of push notification effectiveness provides compelling evidence for segment-specific objective functions. His research spanning 42 mobile applications with a combined user base of 18.7 million demonstrates that high-activity users and low-activity users fundamentally differ in their notification response patterns. The study found that high-activity users (representing approximately 31.2% of the average application's user base) demonstrated optimal engagement when notifications aligned with their daily usage patterns, with response rates decreasing by 47.3% when notifications arrived more than 2.8 hours outside their typical usage window. The implementation of DAU-optimized algorithms for this segment increased retention by 28.6% compared to generic approaches. Conversely, low-activity users (68.8% of users) showed dramatically different patterns, with notifications timed to their weekly engagement cycles improving response rates by 42.9%. When applications implemented dual-objective optimization – applying DAU optimization to high-activity users and WAU optimization to low-activity users – overall engagement metrics improved by 34.7% while maintaining identical notification volumes. Perhaps most significantly, the research found that misaligned notification strategies were the primary driver of uninstalls among 41.3% of churned users, highlighting the critical importance of respecting natural engagement rhythms (Venkatesh, 2023) [7].

Kvasnevska's extensive research on push notification segmentation strategies further validates the efficacy of dual-objective approaches. Her analysis of 27 e-commerce and content platforms with 23.4 million combined users revealed that segmentation-based notification strategies incorporating distinct optimization objectives for different user types outperformed unified approaches by 38.2% in terms of engagement and 26.5% in terms of 60-day retention. The study documented that high-activity users (approximately 29.3% of users) demonstrated consistent daily engagement windows averaging 78 minutes in duration, during which notification response rates were 5.3x higher than outside these windows. Low-activity users (70.7%) exhibited starkly different patterns, with engagement typically occurring in 2–3-day clusters separated by 4–6-day periods of inactivity. When notification strategies aligned with these natural rhythms through segment-specific objective functions, the average application experienced a 31.7% increase in notification effectiveness with no increase in overall notification volume. The research conclusively demonstrated that "segment-specific optimization represents the single most impactful improvement possible for notification systems" and that "the alignment of optimization objectives with natural user behavior patterns produces dramatically superior outcomes compared to one-size-fits-all approaches" (Kvasnevska, 2023) [8].

Table 4 Effectiveness of segmentation-based notification strategies with distinct optimization objectives [8]

Metric	Improvement Percentage	Time to Implementation	Technical Complexity	Organizational Challenges	Maintenance Requirements
Engagement vs unified approaches	38.20%	45 days	Medium-High	Medium	Bi-weekly updates
60-day retention improvement	26.50%	45 days	Medium-High	Medium	Bi-weekly updates
Notification effectiveness increase	31.70%	30 days	Medium	Low-Medium	Weekly updates
User satisfaction scores	29.30%	60 days	Medium	Medium-High	Monthly surveys

4. Implementation and Resource Allocation

With the total notification volume held constant as a system constraint, the implementation of this framework requires strategic allocation of notifications across user segments. The proposed approach distributes a higher proportion of notifications to high activity users, where the probability of immediate engagement is greater. Conversely, low activity users receive fewer but more carefully timed notifications optimized for weekly engagement. This asymmetric distribution is facilitated by the deployment of two separate machine learning models, each trained on segment-specific data and optimized for its respective objective function. The implementation requires careful monitoring of the balance between segments to ensure that overall system goals are met while respecting the distinct optimization criteria for each user group.

Wei et al.'s research on multi-objective optimization for resource allocation provides valuable insights applicable to notification systems. Their comprehensive study demonstrating the effectiveness of the Non-dominated Sorting Genetic Algorithm II (NSGA-II) framework showed performance improvements of 37.6% compared to traditional single-objective approaches when balancing competing goals under constrained resources. The researchers found that a Pareto optimal solution set consistently outperformed single-objective optimization, with average performance improvements of 29.3% across all system metrics. Their analysis of optimal resource distribution demonstrated that asymmetric allocation strategies, which distributed resources according to anticipated performance impact rather than equally across all system components, improved efficiency by 41.8%. When applied to communication systems with heterogeneous endpoints, their findings suggest that distributing 67.2% of resources to high-priority components and 32.8% to secondary components maximized overall system effectiveness while maintaining the same total resource expenditure. Their novel Pareto-based approach eliminated the need for predetermined weighting of competing objectives, instead allowing the system to identify optimal tradeoffs dynamically based on real-time performance data (Wei et al., 2021) [9].

Ashwini's comprehensive analysis of event-driven architectures for product-led growth optimization provides critical implementation insights for segment-specific notification systems. His research across 12 major SaaS platforms

demonstrated that real-time event processing architectures outperformed batch-processing approaches by 43.7% in terms of notification timeliness and relevance. Implementation of dual-stream processing frameworks, which maintained separate analytical pipelines for different user segments, improved engagement rates by 28.9% compared to unified approaches. The deployment architecture required careful consideration, with his analysis showing that Apache Kafka-based event streaming with segment-specific consumer groups provided optimal performance, processing 12,500+ events per second with average latency under 178ms even at peak loads. His implementation guidelines emphasized the importance of separate machine learning pipelines, with segment-specific model training improving prediction accuracy by 41.3% compared to unified models. Resource requirements for this dual-stream approach increased computational needs by only 11.7% while delivering performance improvements exceeding 30%. Ashwini's longitudinal analysis demonstrated that dynamic resource allocation between segments, which adjusted notification distribution ratios approximately every 14 days based on evolving engagement patterns, maintained optimal performance despite seasonal variations in user behavior (Ashwini, 2024) [10].

5. Conclusion

The state-based notification volume optimization framework represents a significant advancement in digital engagement strategies by recognizing and accommodating natural variations in user behavior patterns. Traditional unified approaches consistently underperform when applied across heterogeneous user populations, failing to account for fundamental differences in engagement rhythms between high and low-activity users. By implementing segment-specific objective functions—DAU optimization for high-activity users and WAU optimization for low-activity users—digital platforms can substantially improve engagement metrics while maintaining identical notification volumes. The implementation architecture, leveraging dynamic segmentation methodologies and asymmetric notification distribution, allows for optimal resource allocation based on expected engagement probabilities. Critical to success is the application of segment-specific machine learning models trained on relevant data and optimized for distinct objective functions. This approach acknowledges that user engagement is not a monolithic phenomenon but rather consists of diverse behavioral patterns that require tailored communication strategies. The consistent performance improvements documented across multiple studies and platforms—including enhanced engagement rates, improved retention, reduced notification fatigue, and more efficient resource utilization—provide compelling evidence for the effectiveness of state-based notification optimization. By aligning notification strategies with natural user behavior patterns rather than attempting to force diverse user segments into a single engagement paradigm, digital platforms can create more meaningful user experiences while simultaneously achieving superior business outcomes.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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