# Modeling and Characterizing User Experience in a Cloud Server Based Mobile Gaming Approach

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***Abstract*****—With the evolution of mobile devices and networks, and the growing trend of mobile Internet access, rich, multi-player gaming using mobile devices, similar to PC-based Internet games, has tremendous potential and interest. However, the current client-server architecture for PC-based Internet games, where most of the storage and computational burden of the game lies with the client device, does not work with mobile devices, constraining mobile gaming to either downloadable, single player games, or very light non-interactive versions of the rich multi-player Internet games. In this paper, we study a cloud server based approach, termed Cloud Mobile Gaming (CMG), where the burden of executing the gaming engines is put on cloud servers, and the mobile devices just communicate the users' gaming commands to the servers. We analyze the factors affecting the quality of user experience using the CMG approach, including the game genres, video encoding factors, and the conditions of the wireless network. Based on the above analysis, we develop a model for Mobile Gaming User Experience (MGUE), and develop a prototype for real-time measurement of MGUE that can be used in real networks. We validate MGUE model using controlled subjective testing, and then use it to characterize user experience achievable using the CMG approach in wireless networks.**

## I. INTRODUCTION

Internet video games, played on PC and notebook clients over primarily wired DSL and cable networks, has seen tremendous popularity and growth in the last few years, At the same time, there has been significant interest and growth in the use of mobile devices for data services, starting with enterprise applications like emails, but more recently spreading to more mainstream consumer spaces like Internet access, and Mobile Video/TV. For example, recent market research by Nielsen Mobile [1] in July 2008 shows more than 40 million mobile subscribers in the US (15.6% of mobile subscribers), and hundreds of million more globally, access the web through their mobile devices every month. So the obvious question is: what are the prospects of video gaming using mobile devices and mobile networks?

Clearly, there is tremendous interest and promise of growth in mobile video games. According to a recent report from comScore [2], the number of mobile game downloads hit 8.5 million in November 2008, a 17 percent increase from November 2007. However, despite the interest, mobile video games and the gaming experience remain constrained in two ways: 1) unlike the richness and interactivity of Internet/PC games, current mobile video games are very light-weight, both in terms of graphics/features supported, as well as the content in the case of mobile versions of Internet games; and 2) unlike the multi-player capability, and the associated social networking, that made Internet/PC video gaming so popular, current mobile video games are primarily single player games. To achieve the popularity and growth of Internet PC games, mobile gaming will have to address and eliminate the above two handicaps, enabling mobile users, using mobile devices and wireless networks, to play the same popular Internet video games, and with similar gaming experiences.

However, there are two significant challenges to achieving the above goal. The first challenge pertains to the inherent constraints of a mobile device, which largely inhibits the current practice of Internet PC games: installing the game engine on the PC, and letting each PC client perform the main gaming tasks, with the gaming server primarily used for maintaining the game database and synchronizing the multi-player PCs. The game engine of a typical Internet PC game requires huge disk storage, and takes up significant memory and processing resources during run-time. For instance, the most popular Multiplayer Online Role-Playing Game (MMORPG), World of Warcraft (WOW), with over 10 million subscribers, needs up to 1 GB storage space to install, and requires about 500 MB memory and over 1000 MIPS during run-time, resources that would be difficult to spare even in the current and future high-end mobile devices. Moreover, the modern Internet PC games, including World of Warcraft, require sophisticated graphics processing, which is not currently available in mobile devices. While we can expect future mobile devices to have more storage, memory, processing and graphics capabilities, the gap between the growing requirements of Internet video games and the capabilities of mobile devices may not come close any time soon, at least for the vast majority of small footprint, battery constrained mobile devices.

The second challenge relates to the characteristics of mobile wireless networks. As opposed to wireline DSL and cable networks used by Internet gamers, most mobile networks are bandwidth and capacity constrained, and the wireless medium is characterized by various types of interference and noise sources, leading to significant packet losses at times, even at the application layer. While 3G and 4G networks are significantly adding to available bandwidth and capacity, the fundamental challenges of bandwidth fluctuations, latency and packet loss, will remain.

To address the above challenges, we study the feasibility of a cloud server [3] [4] based approach to enable rich, multi-player mobile video gaming: Cloud Mobile Gaming (CMG). This approach alleviates the need to install and execute gaming engines on a mobile device. Instead, the CMG server hosts the gaming engines. During a gaming session, the game control

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commands are sent from the mobile device to the CMG server, which executes the appropriate gaming engine, and compresses and streams the resulting video frames to the mobile devices in real time. Though the CMG approach addresses the first challenge in enabling rich mobile gaming by eliminating the need for game engines to be installed and executed on mobile devices, we need to determine how it will cope with the second challenge - the variable and unpredictable nature of wireless media – in delivering satisfactory end user experience.

To answer the above question, we need to have a way of measuring the quality of user experience of mobile multiplayer gaming. There have been several approaches that have been developed to model the quality of experience [5] [6] [7] of streaming video [8]. There have been also efforts to understand and model the effect of wireless networks on video delivery [9] [10]. However, video quality metrics and tools, like PSNR and VQM [11], cannot be directly applied to measure the quality of user experience in gaming, which is a highly interactive application, and where the round-trip response time has a significant impact on user experience, as opposed to the one-way nature of video. There has also been some work to analyze factors affecting user experience in gaming [12] [13] [14] [15]; however, they focus on conventional PC games, and do not apply to the cloud server based mobile gaming approach that is the subject of this paper.

In this paper, we formulate a model to quantitatively measure the user experience of mobile gaming using the CMG approach. We validate the model using controlled subjective testing, and then use the model to characterize Mobile Gaming User Experience (MGUE) in various tests and commercially deployed wireless networks. The remainder of the paper is organized as follows. Section II provides a high-level description of the architecture of the CMG system. Section III analyzes the factors that affect MGUE, and introduces GMOS as a way to model and measure MGUE. Section IV derives the MGUE model, as well as introduces a software MGUE prototype for measuring the factors and calculating the corresponding GMOS score during live mobile gaming sessions. In section V, we validate the MGUE model, and characterize and assess the feasibility of the Cloud server based Mobile Gaming (CMG) approach, with both emulated and real wireless networks. Section VI summarizes our findings and points out the future work.

## II. Cloud Mobile Gaming: A System Overview

In this section, we present the Cloud Mobile Gaming (CMG) approach, including an overview of the CMG server, and the overall control-data flow between mobile clients and the CMG server. Fig. 1 shows the overall CMG approach. In a conventional Internet multiplayer game server, game content server is the key component that runs the fundamental game logic in a single process, and maintains the game database. Besides, it holds the connections for the users, delivers the interactive messages as well as updates the active users' game data simultaneously. To support mobile gaming on thin clients, in CMG system we extend the conventional game server with two key components, game engine server and game streaming server. When a player accesses the game server from a mobile device, the connection will be first confirmed by the game content server. Subsequently, it initializes a game engine server and a game streaming server for this mobile device/user. The game engine server then loads the client's account information and game data from game content server, and starts to process the game logic and user data to render the raw game video. The generated raw game video is encoded by the game streaming server, and finally sent to the mobile client via the wireless connection. On the other hand, the mobile user's inputs are delivered to CMG server, and accepted by the game content server directly. Fig. 1 shows the control flow (green) and data/video flow (red) for a CMG video game session.

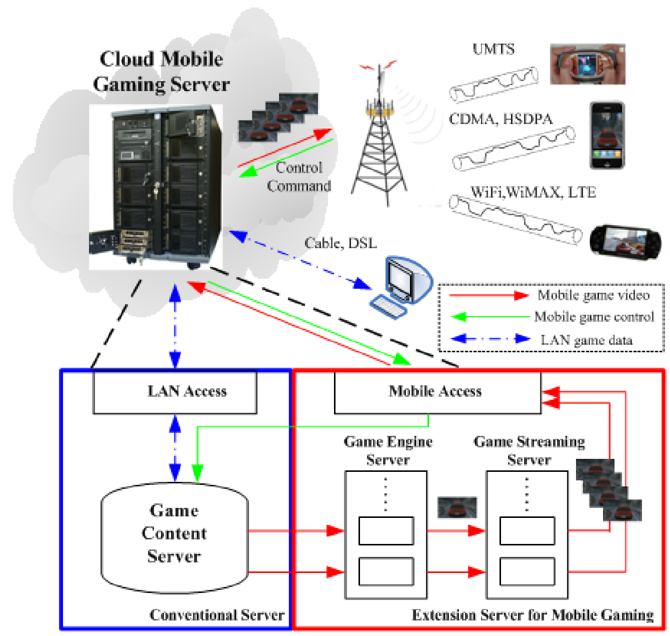


Figure 1. Overview of CMG architecture and data/control flow

Though the CMG approach addresses the first challenge to rich mobile multi-player gaming described in the Introduction, by enabling users to play rich Internet games, on any mobile device without having to download the game engines, the second challenge, that of the wireless network, remains. The fundamental question arises: how good will the user experience be using the cloud server based mobile gaming approach, considering the user control data has to be transmitted uplink from the mobile devices, and streaming video data transmitted downlink from the server, all through the challenges of a wireless network? To answer the above question, in the following sections, we first analyze what affects gaming user experience in the CMG approach, and develop a model which can quantitatively measure Mobile Gaming User Experience.

## III. Quantitative Measurement of MGUE

In this section, we start by identifying and analyzing the various factors affecting the Mobile Gaming User Experience. Next we develop a quantitative MGUE model. The functions in this model will be derived in section IV.

### A. *Factors Affecting the MGUE*

As shown in Fig. 2, the MGUE would mainly depend on the subjective factors: response time and received video quality. The game response time refers to the total delay from the user control command occurring to the corresponding video frame displaying

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on the mobile device, while the received game video quality is influenced by the image quality in each frame and the smoothness of all the frames.

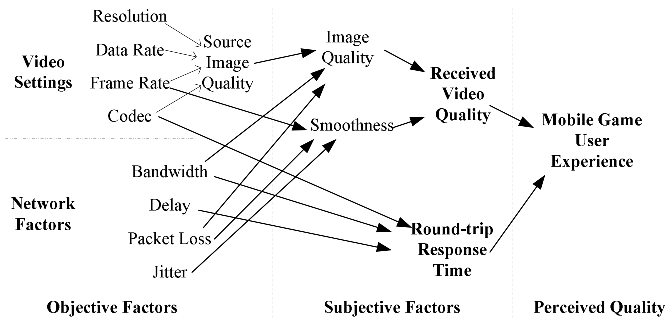


Figure 2. Objective and subjective factors affecting CMG user experience

The subjective factors are affected by a number of objective factors shown in Fig. 2, which can be categorized into two groups: video settings and network parameters. All these objective factors affect the game response time and game video quality in a complex manner. As shown in Fig. 2, the factors affecting the user perceived game video quality come from both the source video settings and the network.

For instance, the quality loss in the image perceived by the user occurs during the compression process from the source. The loss could also happen in the congested network. The smoothness of the video is decided by the source frame rate, the network packet loss rate, and the delay jitter. The game response time typically consists of the codec delay, caused by video encoding and decoding, the network round-trip delay and the client's play out buffering delay. It should be noted that in the remainder of this paper, whenever we use term delay, it implies the network round-trip delay.

Besides the factors shown in Fig. 2, game genre is also an important factor that determines the contributions of all the other factors in determining the MGUE. For instance, in some games (e.g. racing games) fast response time is more crucial in determining the MGUE, while in some other games (e.g. MMORPG) being able to clearly see the objects, and hence sufficient video quality, is more crucial in determining the MGUE.

### *B. Mobile Gaming User Experience Model*

One of the significant contributions in this paper is to develop a quantitative model for measuring the perceived quality of MGUE. In audio and video services, Mean Opinion Score (MOS), a subjective score that ranges from 1 (unacceptable) to 5 (excellent), has been widely used to measure the perceived quality. Similarly, we introduce the Game Mean Opinion Score (GMOS) as a measure for MGUE, and later in the paper, go on to develop a MGUE model to quantitatively measure GMOS.

As shown in Fig. 2, the GMOS of MGUE directly depends on the subjective factors: the exact game response time and the received video quality in the client. The exact response time can be measured from the video obtained from recording the entire visual progress when the user played the game. The received video quality needs to be measured from the off-line comparison of the video displayed in the client and the reference video in the server. However, both measurements for subjective factors are time consuming and costly. To ensure feasibility, we decided to formulate the GMOS based on the objective factors in Fig. 2.

However, it is hard to integrate all the objective factors to determine the model, thus we present the following analysis which allows us to reduce the complexity of the model by reducing the number of factors. First, since the codec, resolution and frame rate factors are given when the video streaming starts, we group these factors together in a *Config* parameter. Second, the video streaming bit rate determines the video quality, but is conditional on the codec and video content. Therefore, it is hard to study and determine its impact in determining the MGUE. Instead, we use Peak Signal to Noise Ratio (PSNR), the most commonly used distortion metric, to measure the quality of compressed video. Third, delay jitter affects the smoothness of the video. This effect can be eliminated by a data buffer and video play-out delay. However the play-out delay cannot be too long as that might affect the gaming response time. We assume that the buffer size and the play-out delay are appropriately adjusted in the mobile device, such that delay jitter does not affect the quality of the gaming experience. Hence, we do not consider explicitly the effects of delay jitter in modeling MGUE. Finally, the effect of the constrained bandwidth will lead to the delay as well as packet loss. Hence it could be represented by these two factors. Based on the above discussion, we formulate the GMOS to:

$$GMOS = f(Game, Config, PSNR, Delay, Loss)\,. \qquad (1)$$

Since formulation in (1) is a complex function, we attempt to derive simple individual functions from it according to the framework of ITU-T E-model [16] for transmission planning. Although this E-model was originally proposed for the audio transmission planning, the framework of transmission rating factor R is helpful for any transmission planning because it makes the quality judgments for *Good or Better* (GoB) and *Poor or Worse* (PoW) in a good statistical mapping, hence can be applied in our study. The function of MOS formulated by R can be found in [16], we duplicate this relationship in our GMOS formulation:

$$GMOS = 1 + 0.035R + 7\times10^{-6}R(R-60)(100-R)\,. \qquad (2)$$

The R-factor ranges from 0 to 100 and is related to GMOS through a non-linear mapping. We then formulate the R-factor with individual Impairment Functions, $I_C$, $I_P$, $I_L$ and $I_D$:

$$\begin{aligned} R = 100 - I_C(Game, Config) - I_P(Game, PSNR) \\ - I_D(Game, Delay) - I_L(Game, Loss) \end{aligned}\,. \qquad (3)$$

While $I_C$ includes the effect of the initial streaming video *Config* (codec, resolution, frame rate); $I_P$ represents the impairment caused by source streaming video quality *PSNR*; $I_D$ indicates the impairment caused by *Delay*; $I_L$ covers the impairment caused by packet *Loss*. Therefore the GMOS can be evaluated by the *Game*, initial video *Config* and measureable factors: *PSNR*, *Delay* and *Loss*. The remaining work for MGUE model (2) and (3) is to determine the Impairment Functions, which will be completed in next section through subjective quality assessment experiments.

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## IV. DERIVATION OF IMPAIRMENT FUNCTIONS

In this section, we describe the approach we use to derive the Impairment Functions, $I_C$, $I_P$, $I_D$, and $I_L$. As a first step, we set up a controlled test environment, where each of the factors, *Config*, *PSNR*, *Delay*, and packet *Loss*, can be varied independently without affecting the settings of the other factors. Next, we conduct a series of MGUE subjective tests using a study group, where each test constitutes playing a game under a particular setting of one of the factors. Each study group participant provides an assessment of his/her gaming experience for each subjective test using a GMOS score. Subsequently, we use linear regression analysis to derive the Impairment Functions.

We start by describing the subjective testing process. Next, we describe how we derive the Impairment Functions to complete the MGUE model. In the next section, we show how we experimentally validate our MGUE model.

### A. Subjective Quality Assessment Experiments

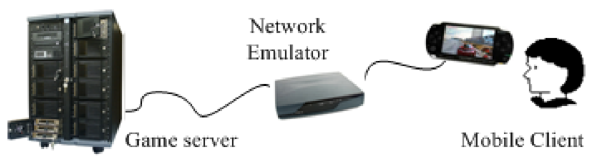


Figure 3. Experiment framework

To study the effect of each of the factors on MGUE, we set up a controlled environment as shown Fig. 3. We connect the client, which will be used by the study group participants, to a CMG server, directly via a network emulator, which we can use to control the network factors, *Delay* and packet *Loss*. We can vary the *Config* factor by changing the resolution and frames per second settings on the encoder used by the CMG server. Similarly, we can change the *PSNR* values used by appropriately changing the compression factor of the encoder used by the CMG server.

TABLE I. EXPERIMENTAL PARAMETERS

| | |
|---|---|
| Game | WOW(MMORPG), NFS(Racing), PES(Sports) |
| Config{Codec, Resolution, FPS} | {WMV9,VGA,25}, {WMV9,VGA,15} {WMV9,QVGA,25}, {WMV9,QVGA,15} |
| PSNR (dB) | [26: 0.5: 38] |
| Delay (ms) | [40:40:800] |
| Packet Loss (%) | 0, 0.5, 1, 2, 3, 4, 6, 8 |

Table I shows how the different factors are varied to derive the subjective tests. We select three games to represent three different genres: a MMORPG "World of Warcraft (WOW)", a racing game "Need for Speed (NFS)", and a sports game "Professional Evaluation Soccer (PES)". Windows Media Video (WMV) 9 [15] is selected as the video codec. As shown in Table I, we use four different configurations in our tests, with two different resolutions (QVGA and VGA), and two different frame rates (15 and 25). For each type of game, and each configuration, we derive a test by varying one of the other factors, *PSNR*, *Delay*, and packet *Loss*, to one of the settings shown in Table I. The *PSNR* settings are from 26 dB to 38 dB, in steps of 0.5 dB. *Delay* settings are from 40ms to 800ms, in steps of 40ms. Packet *Loss* settings are from 0 to 8%. Note when we vary the setting of one of the factors, we keep the other factors at the "best" values, so a single test can determine the effect of only of the factors independent of the other factors. For example, when we vary the *Delay* setting, we keep the *PSNR* and packet *Loss* values to their best, that is, 38dB and 0% packet loss.

TABLE II. GMOS RATINGS AND "R" VALUES

| GMOS | R | Description |
|---|---|---|
| 4.5—5.0 | 100 | Excellent game, no impairment at all |
| 4.0—4.5 | 80-100 | Minor impairment, will not quit game |
| 3.0—4.0 | 60-80 | Impairment noticeable, might quit the game |
| 2.0—3.0 | 40-60 | Clearly impairment, usually quit the game |
| 1.0—2.0 | 0-40 | Annoying environment, definitely quit. |

The study group was comprised of 21 students and staff at UCSD, who have prior experience of playing the selected games. Each study group participant played each of the three games under each of the test conditions described above, and provided assessment of their Mobile Gaming User Experience using a GMOS score rating system shown in Table II. Finally, the results of the study group were tabulated for further analysis and derivation of the Impairment Functions.

### B. Derivation of Impairment Function $I_C$

To determine $I_C$, we consider the results of the subjective tests where only the *Game* and *Config* are changed, keeping all the other three factors at their best values, such that there is no impairment caused by them. For a given *Game* type, and a *Config*, we get the average GMOS score of all the participants, and use it to get the value of R from (2), and subsequently the value of $I_C$ using (3), where the other Impairment Functions $I_P$, $I_D$ and $I_L$ are all 0 (as they do not cause any impairment). Table III shows the values of $I_C$ for each of the *Config* used for each *Game* type.

TABLE III. VALUE OF $I_C$

| Game | {VGA,25} | {VGA, 15} | {QVGA,25} | {QVGA,15} |
|---|---|---|---|---|
| WOW | 3 | 3 | 10 | 10 |
| NFS | 0 | 0 | 3 | 3 |
| PES | 0 | 3 | 5 | 7 |

It should be noted that the value of the Impairment Function indicates how much the impairment affects the user perceived quality. From Table III, we find that the game WOW demands high resolution, as the value of $I_C$ increases dramatically (and hence MGUE suffers) as resolution is reduced from VGA to QVGA. However, it is not sensitive to changes in frame rate. The game PES is sensitive to both resolution and frame rate, while the quality of the game NFS is not affected significantly by the video configurations.

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### C. Derivation of Impairment Functions $I_D$, $I_P$ and $I_L$

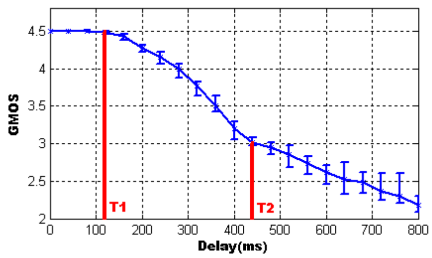


Figure 4. Subjective test results of Delay versus GMOS for WOW

To determine $I_D$, we use the results from the subjective tests, where only *Delay* is varied and all the other factors are kept at their best values. Fig. 4 shows the GMOS scoring by the study group for the game WOW. As expected, the GMOS score goes down when the delay increases. We define two delay points, $T_1$ and $T_2$. $T_1$ denotes the delay when the GMOS score starts to decrease below 4.5 (R=100), and $T_2$ denotes the delay where GMOS hits 3.1(R=60). Then $T_1$ and $T_2$ divide network delay into three segments. In the first segment ($T_1$>Delay), GMOS keeps at a constant value of 4.5, which implies the user experience remains unimpaired. Consequently, for this segment, the value of impairment function $I_D$ should be 0. In the second segment ($T_2$>Delay>$T_1$), GMOS decreases from highest 4.5 to 3.1 (minimum acceptable GMOS), while R-factor decreases from 100 to 60, which implies the value of $I_D$ increases from 0 to 40. After $T_2$, the value of $I_D$ keeps increasing from 40 with a slower slope, denoted by α. Then we derive the $I_D$ using linear regression analysis to:

$$I_D = \begin{cases} 0 & (T_1 > Delay > 0) \\ 40\times[(Delay - T_1)/(T_2 - T_1)] & (T_2 > Delay > T_1) \\ 40 + \alpha\times(Delay - T_2) & (Delay > T_2) \end{cases} . \quad (4)$$

Similarly, to derive the impairment function $I_P$, we analyze the GMOS scores of the corresponding subjective tests (where only *PSNR* is varied, keeping other factors at their best values). We notice similar trends like displayed by the *Delay* factor, except that the GMOS score increases with increasing *PSNR*. We derive $I_P$ as:

$$I_P = \begin{cases} 40 + \beta\times(P_1 - PSNR) & (P_1 > PSNR > 0) \\ 40\times[(P_2 - PSNR)/(P_2 - P_1)] & (P_2 > PSNR > P_1) \\ 0 & (PSNR > P_2) \end{cases} . \quad (5)$$

From the subjective tests corresponding to packet *Loss*, we see a different trend on how it affects user experience. We notice that even low packet Loss tends to affect the quality and smoothness of the video received by the end device and perceived by the subject. And increasing packet *Loss* will lead to a continuous drop in GMOS. We use linear regression to estimate the effect caused by packet *Loss*:

$$I_l = \gamma \times Loss . \quad (6)$$

The values of $T_1$, $T_2$, $P_1$, $P_2$, and coefficients α, β and γ, shown in Table IV, are determined by applying (4) (5) (6) to the subjective test results. This completes the derivation of the Impairment Functions in (3).

TABLE IV. THE VALUE OF METRICS IN EQUATIONS (4) TO (6)

| Game | α | β | γ | $P_2$ | $P_1$ | $T_2$ | $T_1$ |
|---|---|---|---|---|---|---|---|
| WOW | 0.05 | 5 | 8 | 34 | 30 | 440 | 120 |
| NFS | 0.08 | 6 | 13.5 | 33 | 29 | 320 | 80 |
| PES | 0.12 | 9 | 20 | 36 | 33 | 240 | 80 |

Equations (2) - (6), together with the Tables III-IV, provides the complete MGUE model, which can be used to quantitatively measure the quality of gaming experience over wireless networks using the CMG approach. Note that the values in Tables III and IV apply to the three game genres considered in this study, and the codec (WMV9) used. However, they can be easily extended to other games genres and codecs by repeating the approach (subjective study, regression analysis) outlined in this section.

### D. Prototype to Measure Delay/Loss and Calculate GMOS

We have also developed a client-server software MGUE prototype to automatically measure the objective factors (*PSNR*, *Delay*, and packet *Loss*) during a mobile gaming session, and calculate the corresponding GMOS score, using the model proposed above.

The key component of the MGUE measurement prototype is a network probing mechanism which collects the values of *PSNR*, *Delay* and packet *Loss*, during a mobile gaming session. The mobile client periodically sends a TCP probe to the CMG server, which includes the probe send out time and probe sequence number. The CMG server puts the information of the video compression settings being used, and the video source *PSNR*, into the received probe, and sends it back to the client through the UDP connection. The accurate *Delay* can be obtained at the client by comparing the probe send out time and receive time. The packet *Loss* rate can be calculated by checking the received probe sequence number. The packet size of the probe is 100 bytes, and the probing interval is 100ms. Hence, the associated overhead of the network probes is 8kbps, which is relatively small compared to the application bit rate used by the CMG approach, as will be described later.

Once the value of *PSNR*, *Delay*, and packet *Loss* are known, the GMOS score can be calculated using (2) - (6), and the values of $I_C$ (Table III) and $T_1$, $T_2$, $P_1$, $P_2$, α, β, γ (Table IV) as appropriate for the type of *Game* being played, and the *Config* used.

## V. MGUE MODEL VALIDATION AND MOBILE GAMING USER EXPERIENCE CHARACTERIZATION

In this section, we first validate the accuracy of the MGUE model. Next, we apply the MGUE prototype to characterize the Mobile Gaming User Experience in both controlled network conditions and wireless mobile networks. Consequentially, the feasibility of the CMG approach is assessed.

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### A. MGUE Model Validation

Having derived MGUE model to quantitatively measure the value of GMOS, we next validate the model by conducting another set of controlled experiments. We use the same experimental framework presented earlier (Section IV A), but a different study group consisting of 15 participants. Also, the test cases are different than in Section IV. As opposed to testing the effect of individual factors, we want to consider the effect of simultaneously varying all the factors. Hence, 213 subjective tests were created as combinations of parameters in Table I. The GMOS scale used by the participants to score MGUE for each test condition is the same as described in Table II.

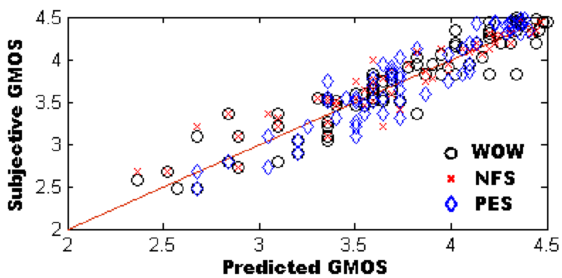


Figure 5. Relationship between predicted and subjective GMOS

Fig. 5 shows the relationship between the GMOS scores predicted by the MGUE model (x-axis) and the subjective GMOS score by the participants (y-axis). The correlation between predicted and subjective user experience was 0.92. The mean of the 95% confidence interval (MCI) for subjective GMOS was 0.23, while the root mean square error (RMSE) was 0.19. The evaluation error of the MGUE model is less than the statistical ambiguity of the subjective score (RMSE < MCI). The results demonstrate the accuracy of our MGUE model in quantitatively measuring the Mobile Gaming User Experience of a user, given the *Game*, *Config* used, *PSNR* used, and the *Delay* and packet *Loss* experienced during the gaming session.

Having established the accuracy of the MGUE model, we can now use it to characterize Mobile Gaming User Experience under different network conditions typical in a mobile network. Note that this characterization is valid for a CMG based mobile gaming system described in Section II.

### B. Characterizing MGUE in controlled networks

First, we apply MGUE prototype to various controlled networks to measure the Mobile Gaming User Experience. The streaming bit rate (related to *PSNR*) is varied at the server, and the *Delay* and packet *Loss* are controlled by the network emulator, while the MGUE prototype simultaneously computes the user experience in terms of GMOS.

Fig. 6 presents the GMOS as a function of *Delay* and packet *Loss* for three WOW game video streams: I) 500kbps VGA game (good video quality, PSNR is above 34); II) 300kbps VGA game (medium video quality, PSNR is around 32) and III) 200kbps QVGA game (good video quality, PSNR is above 34). For each video stream, there is a surface representing the user experience, given a certain network condition. The two horizontal planes with constant GMOS values (4.0 and 3.0) separate the quality of user experience into three levels: good (above 4), medium (3 to 4) and poor (below 3). The points on each surface represents a good gaming experience for the corresponding stream under those network conditions (in particular, *Delay* and *Loss*) where the surface lies above the (GMOS=4) plane. In other words, for any given application, Fig. 6 shows the network circumstances under which a CMG-based system can provide a user experience of good quality. In the same way, we could also find out the minimum network requirements for the acceptable (medium) quality, and those network conditions that will lead to poor user experience. For instance, consider a network condition where delay is 200ms and packet loss is 1%. A, B and C are the corresponding points for each of the three video streams. In this network condition, the figure shows that only 500kbps VGA can provide a good gaming experience, while the other two can only provide a medium quality experience.

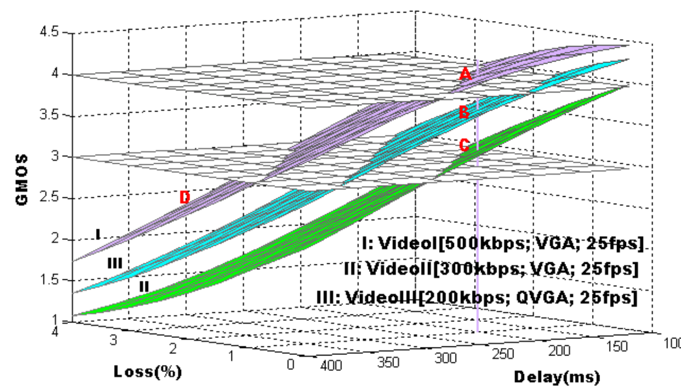


Figure 6. User experience characterization in different network conditions

It should be noted that a higher application bit rate (better source video quality) does not always guarantee a better gaming quality, although the surface for 500kbps always lies above the 300kbps in Fig. 6. This is because increasing the application bit rate in a particular network may also affect the *Delay* and packet *Loss*, especially when the application bit rate exceeds the network bandwidth. Therefore, in the figure, moving the operating point from one surface to another may also require a change in the loss and delay values, and ultimately result in a lower GMOS. To illustrate this, we again consider the network delay (200ms) and packet loss rate (1%) from our previous example, but with the additional constraint that network bandwidth is 350kbps. Now, trying to select an application bit rate of 500kbps will move the operating point from point A to D, where the delay is 300ms and packet loss is 4%. However, an application bandwidth of 300kbps will not alter the Delay or Loss rate, so it can remain at point C which has a higher GMOS than point D. In this case, sending the video at 300kbps will lead to a better quality of gaming experience than at 500kbps.

We can also obtain the other mappings of applications for different games and video settings by applying our GMOS model. These mappings can help people characterize the Mobile Gaming User Experience under any network conditions.

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### C. *Characterizing MGUE in Mobile Wireless Networks*

Next, we apply the MGUE prototype to measure the Mobile Gaming User Experience in real wireless networks. This also helps assess the feasibility of the CMG approach to deliver the desired gaming experience in today's wireless networks.

We have conducted experiments with two types of networks: an 802.11g WLAN network deployed in the UCSD campus, and a commercially available cellular HSDPA network. The game server is located in our lab in the UCSD campus, while we roam with the Wi-Fi client in several parts of the campus, and with the HSDPA client inside and outside the campus.

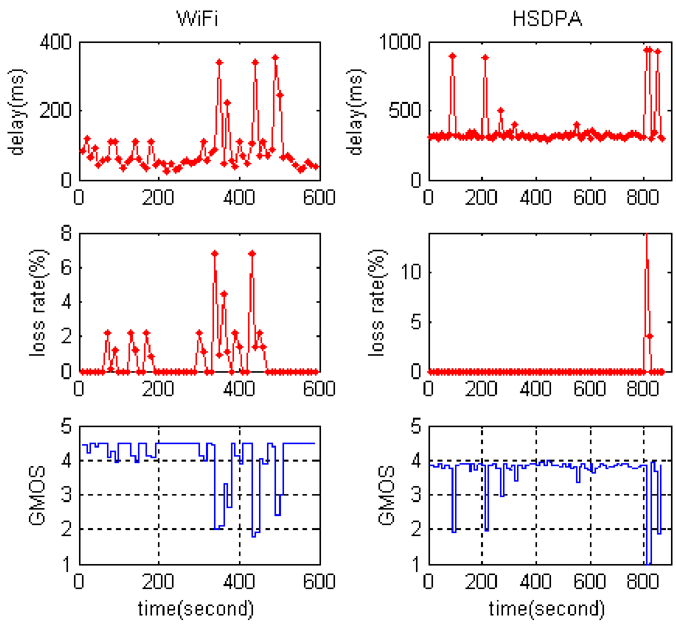


Figure 7. Test results for [WOW; VGA; 25fps] with streaming video bit rate 500kbps (a) in WiFi network (left) (b) in HSDPA network (right)

Fig. 7 shows a representative sample of the data collected from numerous gaming sessions on both Wi-Fi and HSDPA networks. The selected experiment game is WOW, and the video *Config* setting is {VGA, 25 fps}. The average streaming video bit rate in the tests is 500kbps, which provides good source video quality to the clients. To ensure accuracy of the MGUE measurements, we initialize our network prober and the mobile gaming session simultaneously. We make the following observations from our experiments:

- On an average, the CMG approach can provide the minimum acceptable user experience (GMOS>3.0) in both HSDPA and Wi-Fi networks.
- In the Wi-Fi network tested, while we can achieve very good quality gaming experience (GMOS>4.0), there can be periods of great instability, at which times the user experience can become unacceptable (GMOS ~ 2).
- In the HSDPA network tested, the mobile gaming experience is relatively stable compared to Wi-Fi. However, the user experience achieved was not very good, staying around a GMOS score of 3.8. Also, though the user experience did not deteriorate for long periods, there are some noticeable fluctuations, with GMOS score dipping to less than 2.0 at times.

## VI. CONCLUSION

In this paper, we study a Cloud server based Mobile Gaming (CMG) approach which can enable mobile users to play rich multiplayer games comparable to those available to PC users. To assess its feasibility, we develop and validate a quality of experience MGUE model to quantitatively measure the Mobile Gaming User Experience. The MGUE prototype enables us to characterize MGUE for different game genres in simulated networks as well as real wireless networks. Our study shows that while it is possible to achieve good quality gaming experience over wireless networks using the CMG approach, there are several network conditions in which the CMG based gaming experience may be unacceptable. In the future, we will investigate techniques to enhance the CMG approach to address the challenges imposed by the wireless medium. We will also enhance the MGUE model to address cloud server latency and scalability issues that may be faced in real deployment scenarios with significant number of mobile game players. We believe that the MGUE model introduced in this paper will serve as a very useful tool in future attempts to enable Cloud server based Mobile Gaming.

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