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RESEARCH ARTICLE

Measurement and analysis of online gaming services on mobile WiMAX networks

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ABSTRACT

Online games have been played mainly in desktop computers over wired networks because of high speed and intensive computation requirements. The advances in mobile devices and ever increasing wireless link bandwidth motivate us to study whether players can enjoy online gaming over broadband wireless networks such as mobile Worldwide Interoperability for Microwave Access (WiMAX). In this paper, we carry out comprehensive measurements of the World of Warcraft (WoW) over the mobile WiMAX in Seoul, Korea, and analyze the network performance focusing on two aspects: (1) network layer dynamics such as round trip time, jitter, and packet loss and (2) WiMAX link layer statistics such as the radio signal strength, handovers, and piggyback mechanism. From the empirical data, we set up performance models and evaluate the performance of WoW over WiMAX. We also discuss how to improve the service quality of online gaming over WiMAX. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS
online gaming service; mobile WiMAX; measurement

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Over the last decade, the online games have become one of the most popular and profitable applications on the Internet. So far, people have enjoyed various gaming experiences in virtual worlds mostly over the wired Internet, which offers stable connection with short delays and small jitter. Recently, more and more people choose to play games via wireless and mobile networks [1,2], which has opened the new era of online entertainment services of the Internet. Over the recent few years, Worldwide Inter-operability for Microwave Access (WiMAX) network based on the IEEE 802.16(e) standard [3] has gained substantial attention as an IP-based wireless access technology for *mobile* users. As mobile WiMAX supports handovers (HOs) and mobility management, which potentially provides continuous IP-compatible Internet services, more and more mobile users are likely to use it to play online games, particularly in a bus or metro [4].

The world's first successful WiMAX network was deployed and commercialized in Seoul, Korea, by Korea Telecom (KT) in 2006, being referred to as Wireless Broadband (WiBro) [5]. WiBro, the Korean version of WiMAX[†], operates at 2.3 GHz bands with a 10 MHz channel bandwidth, adopting time division duplex between downlink and uplink [5]. For flexible bandwidth allocation among users, the orthogonal frequency division multiple access is employed for multiple access. A base station (BS) offers an aggregate throughput of 30 to 50 Mbps theoretically and covers a radius of 1 to 5 km, supporting mobility up to 120 km/h [6]. To keep the continuous Internet connectivity, when a subscriber station (SS) moves across the boundaries between cells, the SS performs an HO that incurs processing delay, which potentially impairs the network latency. Being affected by the HO and other link level characteristics, it is desired to assess the performance of

[†]In this paper, we use WiMAX to indicate the KT's WiBro network in which we carried out measurements.

various Internet applications via WiMAX, like VoIP [7], BitTorrent [8,9], and online gaming.

For years, there have been many studies on network support for games. Several works have evaluated online game performance via various last-mile access networks, for example, Wireless Local Area Network (WLAN) [10] and general packet radio service (GPRS) [11]. Also researchers have investigated how multi-variable network dynamics (latency, jitter, packet loss, etc.) impacts the gaming experience, such as [12] and [13]. Designing proper network environments for online games is also challenging; for instance, Chen *et al.* [14] and Griwodz and Halvorsen [15] carried out empirical studies on how TCP affects games, and proposed to design new efficient protocols for online games. As online gaming has become a representative real-time application utilizing TCP mostly, investigating the performance of real-time TCP over WiMAX is becoming important. However, no work has yet investigated how well (or badly) WiMAX networks support TCP-based online games.

In this paper, we carry out extensive measurement and evaluation of the performance of World of Warcraft (WoW) over a mobile WiMAX network, including the analysis of network layer dynamics and link layer characteristics. Also, we evaluate its performance using the models of mean opinion score (MOS) [13] and departure ratio [12]. To the best of our knowledge, this is the first study that comprehensively measures and evaluates the performance of online gaming over a mobile WiMAX network. We highlight our contributions as follows:

(1) We comprehensively measure online gaming performance over WiMAX. We make our collected network layer traces publicly available[‡] for researchers interested in extending or validating the work.
(2) We measure and evaluate the performance of online gaming via WiMAX considering two aspects: (i) the characteristics of online gaming traffic at network layer, such as delay, throughput, and packet loss, and (b) link layer dynamics specific to WiMAX networks, such as signal quality, HO, multi-user service, and piggyback bandwidth request. Our findings from the measurement experiments include the following: (i) the average round trip time (RTT) between a WoW client and its server over WiMAX is around 122 ms, which reflects the TCP's delayed acknowledgement (ACK) mechanism and relatively long uplink transmission delay; (ii) radio signal quality impacts the performance significantly, and HOs seriously degrade the performance by triggering undesired packet losses and large delays; (iii) from our empirical measurement of HOs, we found that the inter-arrival times of HOs approximately follow the normal distribution in the subway setting and exponential distribution in the bus setting, which provides models for future research such as simulator design; (iv) the best-effort (BE) (scheduling) service of WiMAX BSs performs poorly for delay sensitive gaming traffic, particularly when the BSs are saturated with multiple concurrent flows; and (v) the piggyback mechanism in WiMAX improves the uplink transmission delay moderately and hence reduces the RTT.
(3) We adopt the MOS metric proposed by [13] and the departure ratio method proposed by [12], to quantitatively evaluate the performance of online gaming via the WiMAX network. From the results, WiMAX gaming has much lower MOS scores (around 1.2 to 2.5) compared with Ethernet (around 3 to 4), and also, the departure ratio in the bus case is much higher than that in other cases. The bad evaluation results are mainly because of the large jitter, which is caused by HOs and unstable WiMAX signal.
(4) We conclude that mobile WiMAX network is likely to be functioning well for online gaming from the perspective of continuous gaming experience in mobile situation and acceptable delay, but overall gaming performance evaluated by referring models is still limited compared with Ethernet. To offer a better online gaming environment via WiMAX, we suggest the following: (i) SSs should turn off the delayed ACK mechanism; (ii) game program should utilize piggy mechanism for a faster uplink transmission; (iii) BSs need to implement extended real-time polling service to schedule gaming packets better; (iv) HO processes should be optimized, and an appropriate transmission scheme with fast recovery functionality need to be designed; and (v) in the WiMAX network in Seoul, mobile users can enjoy the game better in the metro than in the bus because the network's BSs have been densely deployed considering the Seoul Metro system, but outdoor BSs cannot always guarantee strong and stable signal quality to the users in the bus, and also, the outdoor obstacles further impact the signal.

The paper is organized as follows: In Section 1, we review related work. In Section 2, we describe our methodology. Sections 3 and 4 present the measurement and analysis results. We further evaluate the networking performance of online gaming via the WiMAX by the MOS and departure ratio models in Section 5. Section 6 concludes the paper.

1. RELATED WORK AND MOTIVATION

Since the deployment of WiMAX in Korea, several studies have been carried out to evaluate its system performance. The measurement work in [16] focuses on low-layer details, in particular the evaluation of HO characteristics. Some papers specifically focus on delay [17]

[‡]http://crawdad.cs.dartmouth.edu/snu/wow_via_wimax; note that link layer traces are not shared, as requested by XROnet and KT.

and the bandwidth request mechanism with piggyback [18] in WiMAX. The performance of applications via WiMAX has been also evaluated, such as measurement of TCP/UDP transmission in [19], BitTorrent and VoIP measurement in [8] and [7], respectively. As the online gaming has become a representative real-time application mostly utilizing TCP, investigating the quality of real-time TCP performance over WiMAX is becoming increasingly important. However, very limited work [20,21] has yet investigated how well (or badly) WiMAX supports online game applications based on TCP.

Turning to the scope of online gaming research, substantial work has been carried out for the last 10 years. For instance, Chen *et al.* [22] analyzed the traffic of a massive multi-player online role-playing game (MMORPG) in detail to discover the traffic characteristics. The traffic of the *Lineage 1* and *Lineage 2* were measured and analyzed in [23] and [24], respectively. The modeling work in [25] adopted statistical models for the traffic of the WoW. The work in [26] empirically measured, analyzed, and characterized popular online games based on multiple server data traces.

Many researchers also have focused on how wireless access networks influence gaming experience; for example, the gaming traffic of Nintendo DS via WiFi has been measured in [10], and Wattimena *et al.* [13] evaluated the performance of first-person-shooter games in WLAN. Also, the GPRS has been tested to support online gaming in [11]. As TCP is the main transmission protocol of online gaming packets, Chen *et al.* [14] and Griwodz and Halvorsen [15] measured and analyzed the TCP performance for data transmission in online games. The evaluation works in [12,27] have discussed game playing times influenced by network Quality of Service (QoS) including the latency, jitter, and packet loss, concluding that the quality of online games essentially relies on the quality of network access. For multiplayer real-time games, Wattimena *et al.* [13] proposed a methodology to predict the perceived quality of a first-person-shooter game based on network performance, for example, delay and jitter.

We are motivated to comprehensively investigate and adequately utilize WiMAX for online gaming. We carry out measurement of online gaming played via the WiMAX network and analyze the packet-level traffic performance and low-layer details. Also, we score the overall performance by related evaluation methods.

2. MEASUREMENT METHODOLOGY

In this paper, we choose the most famous MMORPG, WoW [28], which has gathered more than 10 million players till now, as a representative online game for our measurement. The ever increasing number of MMORPG games and their players exhibit the popularity of MMORPGs. MMORPGs typically provide unique experiences for players to interact with others in a virtual world. As MMORPGs require less strict timely delivery of data than first-person-shooting games and real-time strategy games [13], it may be more suitable for people to play the games in wireless/mobile environments, which are more prone to delay and jitter. That is the rationale behind the selection of WoW for measurement of online games played in a WiMAX environment.

(a) WiMAX modem (b) XRONet diagnostor

Figure 1. Test environment. (a) WiMAX modem and (b) XRONet diagnostor.

Our measurement platform is an Apple Macbook Pro with Intel Core 2 Duo CPU T8300, 2 G RAM, and Nvidia 8800GT graphic card, running Windows XP sp4. This specification is fast enough to run WoW with the speed of at least 50 frames per second, so that the performance of playing WoW should not be limited by the hardware. We equip the Macbook with a USB dongle-based WiMAX network interface card, Samsung SWT-H200K, shown in Figure 1(a). We use the XRO7000 Diagnostic Monitor shown in Figure 1(b) from XRONet [29] in order to capture link layer behaviors. For higher-layer measurement, we use the tcpdump-based Wireshark [30] and TCPTrace [31].

In order to comprehensively evaluate WoW performance over WiMAX, we choose three routes: (1) *subway*: We take subway line 2, the most popular circular metro line in Seoul, where the portion from Jamsil station to Cityhall station is used for measurement. Also, we travel through parts of subway line No. 4 from Sadang station to Seoul station and subway line No. 3 from Seoul Education University station to Kyung-Bok Palace station for tests, as both are very popular city-crossing lines passing through the center of Seoul. The subway routes are shown in Figure 2(b). In the subway lines, one WiMAX BS is deployed at almost every subway station, and one or more repeaters are installed along the subway tunnels between adjacent stations to enhance the radio signal between SSs and BSs. Whenever a subway train moves across two BSs (or two adjacent stations), there is an HO. (2) *bus*: We take the bus No. 501 route from Seoul National University (SNU) to the city hall, along which a few university campuses, several apartment complexes, one tunnel, the Han River bridge, shopping malls, and so on are located. While the bus goes through the Seoul metropolitan area, the SS performs HOs among BSs. The bus route is shown in

(a) Route of bus test

(b) Route of subway test

(c) Route of campus test

Figure 2. Measurement routes. (a) Route of bus test, (b) route of subway test, and (c) route of campus test.

Figure 2(a). (3) *campus*: We measure the WoW performance inside the SNU campus, where only one BS and a few repeaters cover the entire area (around 4.3 km^2). Here, we carry out two sub-tests: (i) stationary: we fix the location of the laptop near the window in a dormitory and an office; and (ii) mobile: we move around the campus in a shuttle bus continuously. Figure 2(c) shows the route of the shuttle bus, and the pin marks show the fixed test points. Overall, we believe that these three routes can characterize the most typical usages on a mobile WiMAX network. Note that the length of the route paths and approximate travel time are also specified in Figure 2.

Even though a user participates in the same game (WoW), the game traffic patterns (i.e, the way in which packets are generated and exchanged between the SS and the WoW server via the WiMAX) can vary widely depending on what scenario and which place in the virtual world the player is playing at [22]. To reflect the effect of different traffic patterns, we investigate the three game scenarios: (1) *downtown*: Numerous players in WoW (and also in other MMORPGs) gather together at popular areas, for example, a main city, for the purposes of trading, chatting, refreshing, and so on. To this end, we make our avatar move in the Dalaran city in WoW. This scenario generates a low rate of uplink packets but a high rate of downlink packets because of high density of players. (2) *hunting*: In WoW, players always kill monsters to raise their in-game level and to obtain money and equipments. We control our own avatar to hunt monsters one by one continuously in an isolated map, Silithus. This scenario indicates the interaction between the player and the environment, so-called player versus environment. In hunting scenario, it does not require intensive operations of the avatar, and typically, a small number of surrounding monsters have limited behaviors, thus both uplink and downlink traffic will be relatively low. (3) *battlefield*: A player can experience an exciting fight when dueling with other players. In WoW, arenas offer fighting opportunities for groups, and some bigger battlefields support dozens or even hundreds of players to battle. We join the battlefields of Arathi Basin (15 people) and Wintergrasp (hundreds of people). This situation bears the active interaction among people, called player versus player, which exhibits both high uplink and downlink traffic, because avatars are trying their best to run and act for killing and surviving with intensive operations.

Each measurement result is obtained from tests repeated for more than five times, except the battlefield case by bus, which is tested three times because of the issue of laptop battery depletion. We capture WoW traffic with about 0.76 million packets, and because of security and privacy concerns, the tcpdump packet header traces only are publicly available at http://crawdad.cs.dartmouth.edu/snu/wow_via_wimax.

3. HIGHER-LAYER ANALYSIS

3.1. Round trip time

We first theoretically estimate the RTT as follows. WoW leverages TCP as the transport protocol, so the RTT is actually the duration of a round trip exchange of TCP data and its ACK packets, as illustrated in Figure 3. Initially, a TCP data packet containing the avatar's current action is sent to the WoW server, taking time of $T_{UL} + T_{sys1}$, where T_{UL} is the uplink delay over the air interface in the WiMAX network from the client (or SS) to the serving BS and T_{sys1} is the delay from the serving BS to the WoW server through the WiMAX backhaul and Internet backbone. We assume that the WoW server calculates the consequences

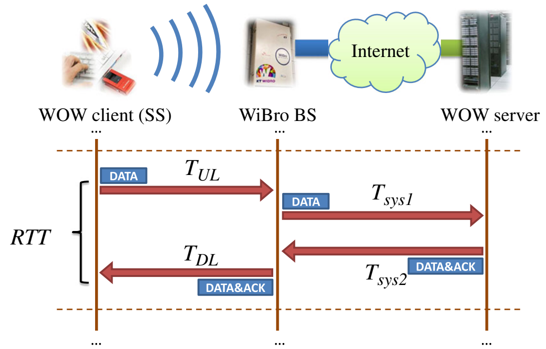

Figure 3. Round trip time in WoW via WiMAX.

Table I. Average round trip time with different scenarios (ms).

	Downtown	Hunting	Battlefield	Avg.
Bus	176.26	128.96	127.18	148.13
Subway	114.48	130.92	106.21	119.73
Campus	77.39	122.21	112.55	103.04
Avg.	124.26	129.62	117.73	121.87

Avg., average.

of the avatar's action instantly; that is, the server processing time should be negligible when comparing with the network delay. The WoW server returns the result to the client, which will arrive at the client after $T_{sys2} + T_{DL}$, where T_{DL} is the downlink delay from the WiMAX BS to the client and T_{sys2} is the delay from the WoW server to the SS's BS. Therefore, we estimate the RTT by calculation:

$$RTT_{est} = T_{UL} + T_{sys1} + T_{sys2} + T_{DL}$$

According to the previous report on one-way delay measurement in the same WiMAX network in Seoul [17], on average, T_{UL} is 80.1 ms, and T_{DL} is 25.5 ms, because of the asymmetric design of uplink and downlink access capacity and bandwidth allocation mechanism in WiMAX. When we trace the path of the packets by *tracert* command, $T_{sys1} + T_{sys2}$ is normally around 20 ms; thus, $RTT_{est} = 125.6$ ms.

On the other hand, we measure the average RTT of real WoW packets, RTT_{real}, from all the captured traces by TCP Trace, and the statistics are summarized in Table I. The overall average RTT_{real} is 121.87 ms, close to RTT_{est}. The most time-consuming part of the RTTs in the WiMAX network is the uplink delay, which is around 80 ms. This is mainly due to the bandwidth request mechanism of the WiMAX link layer, and we will investigate how piggyback mechanism can improve the uplink delay in Section 4.4.[§]

We make the cumulative distribution functions (CDFs) of the RTT values of all the scenarios as shown in Figure 4. Figure 4(a and b) shows the RTT distributions categorized by the types of routes and scenarios, respectively. In the downtown scenario, the campus case has the best performance because there is no HO and signal quality is relatively good. In the bus route, high RTT values take a much larger portion because there are frequent HOs, which often incur transmission errors and thus retransmissions inducing high delays; even in the absence of HOs, the WiMAX signal quality varies substantially because of the shadowing in outdoor environments due to buildings, hills, and so on. Note that in the subway route of the three scenarios, although HOs happen frequently, the RTT is actually small because of good signal quality (to be detailed in Section 4.1).

We further analyze the RTT values less than 1000 ms with dispersion box plots as shown in Figure 5. The box shows the boundary of 25% and 75% quartiles, and the red line shows the median. The whiskers are in black dash lines, and red crosses are individual outliers of RTT values.[¶] It is clearly shown that the RTT values in the subway and bus situations are higher than in the campus one. And also the hunting scenario has higher RTTs while downtown and battlefield have lower RTTs.

3.2. Jitter (round trip time variation) and lag

Players tend to be more sensitive to large delay variations than to large delays [12,32], so we compute the standard deviation of the RTTs (jitter) as shown in Table II. Clearly, the client (or SS) in the bus route suffers from high delay variations because of the dynamically changing signal quality and HOs, while the jitter of subway is smaller. In the campus stationary environment, there hardly exist sudden changes of the delay because of the stable signal.

In our measurements, there are often sudden occurrences of long delays, which we call *lags*. In order to obtain how often and how long the SS suffers from unacceptable lags, we define the lag as follows: We compute the average RTT of packets at the interval of a second. If the average RTT of a 1-s interval exceeds 200 ms, that is the start of a lag. (200 ms is often the threshold of unsatisfiable RTT values for players [12].) As soon as the RTT finally falls below 200 ms, that is the end of the lag.

We record the durations of lags and the inter-arrival times of lags; then, we calculate the portion of lags to the total measurement time as shown in Table II. The portion of lags in the bus case is almost 5%, which might hinder players' experience. Meanwhile, lags happen relatively infrequently in the campus and subway routes. Also, we

[§]In WiMAX, uplink transmissions always need to ask a BS for assigning bandwidth by a bandwidth request, which takes longer time; if there are continuous uplink packets being transmitted, an uplink bandwidth request can be piggybacked in the uplink packet to reduce the duration of the following uplink request and bandwidth allocation.

[¶]Values are plotted within the whisker if they are smaller than $q3 + w \cdot (q3 - q1)$ and larger than $q1 - w \cdot (q3 - q1)$, where q1 and q3 are the 25% and 75% percentiles, respectively, and w is set to 1.5. Extreme values that are out of the whisker's range are defined as outliers.

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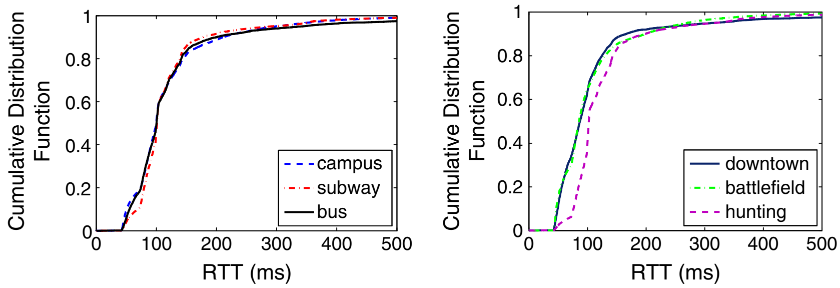
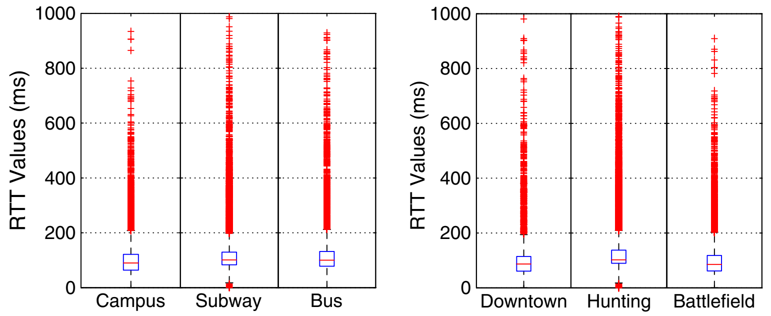


(a) RTT - various routes (b) RTT - various scenarios

Figure 4. CDF of RTTs. (a) RTT – various routes and (b) RTT – various scenarios.



(a) RTT Dispersion by Routes (b) RTT Dispersion by Scenarios

Figure 5. Dispersion of RTT values. (a) RTT dispersion by routes and (b) RTT dispersion by scenarios.

Table II. Round trip time standard deviation (ms) and lag.

	Bus	Camp. st.	Camp. mo.	Subway
RTT st. dev.	35.32	9.30	14.59	21.23
Portion of lags (%)	4.88	—	0.81	2.71
Avg. lag (s)	3.16	—	1.1	2.06

Camp. st., campus stationary; Camp. mo., campus mobile; RTT st. dev., round trip time standard deviation; Avg., average.

present the CDF of inter-arrivals of lags in Figure 6(a) and CDF of durations of lags in Figure 6(b). In the bus situations, lags happen frequently with shorter inter-arrivals, while the campus and subway situations have longer inter-arrival times, which means that the wireless links are more stable. The distribution of lag durations shows that lag durations are much shorter when we test in the campus and subway but are longest in the bus situation. Note that because of our definition of lag, the resolution of lags is at a second scale.

3.3. Delayed acknowledgement

Most of today's TCP implementations include the delayed ACK [33] mechanism, which postpones an ACK transmission for a specified period (typically 100 and 200 ms) to wait for the subsequent ACKs. Thus, an endpoint can transmit an accumulated ACK message to the other endpoint instead of frequent ACKs. This method is initially designed for efficient TCP transmission where a small delay of ACK packets is allowed, and it is turned on by default in Windows system [34]. We make the probabilistic distribution function (PDF) of the durations of the delayed ACKs from all the traces as shown in Figure 7. Most of the delayed ACKs fall between 100 and 200 ms, with the mean value of 144.58 ms. We observe that the probability around 200 ms takes the largest portion, which verifies the default setting of delayed TCP in Windows system registry [34]. Therefore, in fact, the delayed ACK mechanism brings large delays for uplink packets; if it is turned off, particularly when playing MMORPGs on a WiMAX network, the latency between game clients and servers will be reduced at the cost of more ACK packet transmissions.

3.4. Bandwidth consumption

From the WiMAX standards [3,6], the maximum aggregate bandwidth in each BS of WiMAX Wave 1 is 18.5 Mbps for downlink and 5 Mbps for uplink. The work in [19] empirically tested the average TCP throughput for a single SS as 2.45 Mbps for downlink and 1.77 Mbps for uplink. As we measure and show the bandwidth consumption in the three gaming scenarios in Table III, WoW is not a bandwidth-

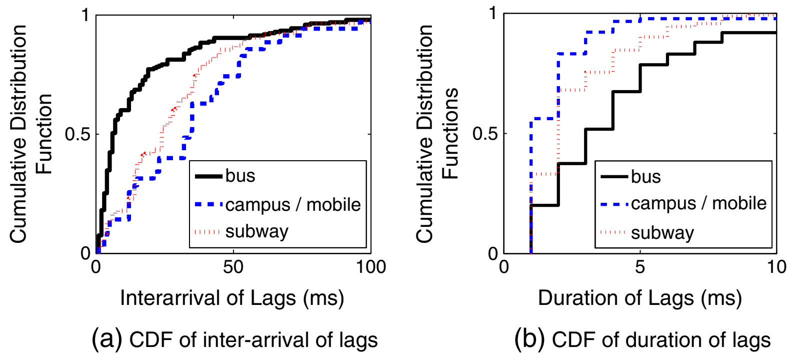


Figure 6. Evaluation of lags. (a) CDF of inter-arrival of lags and (b) CDF of duration of lags.

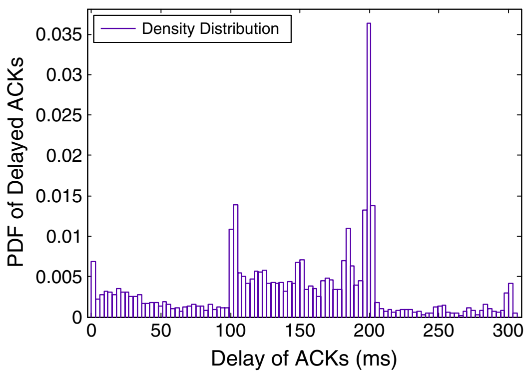


Figure 7. Distribution of delayed ACK.

Table III. Bandwidth consumption (Kbits per second).

	Avg. UL	Peak UL	Avg. DL	Peak DL
Downtown	3.42	64.23	13.12	344.31
Hunting	2.18	7.74	8.93	71.23
Battlefield	3.74	42.50	32.11	229.29

UL, uplink; DL, downlink; Avg., average.

hungry application. Also because of the global cooldown system of WoW [25,28], a player's avatar can perform only one action every 1 to 1.5 s, which keeps the uplink traffic under a relatively low level. On average, WoW only consumes 3 to 4 Kbps for uplink and less than 40 Kbps for downlink. The peak uplink and downlink traffic observed are 64.23 and 344.31 Kbps, respectively, both in the downtown scenario. In this regard, we conclude that WiMAX can support online games like WoW well as long as a serving BS is not saturated, which will further be discussed in Section 4.3.

3.5. Packet loss rate

Packet loss triggers retransmission of data packets and thus affects the game service quality [12]. So we measure the packet loss rate at the TCP layer by checking the retransmissions of TCP from the trace as shown in Table IV. We observe that the uplink has low packet loss ratio on average, but that of downlink often exceeds 2%, which may not be tolerable for the real-time online game service as discussed in [12,35]. Further investigation of the reason why the packet loss rates are different between uplink and downlink is left as future work. Also, we observe that the packet loss rate in the campus mobile is almost twice as high as that in the stationary case because of fluctuating link conditions and HOs. The relation between HO and packet loss will be further discussed in Section 4.2.

4. LOW-LAYER ANALYSIS

4.1. Carrier to interference and noise ratio

The carrier to interference and noise ratio (CINR) is one of the most important physical (PHY) layer parameters in WiMAX. Low CINR values will trigger an SS to change the PHY layer modulation and coding scheme to low PHY bit rate, or to carry out the HO to another BS with a higher CINR. Figure 8 shows the CDF of CINR values of the different routes. Clearly, the bus route exhibits the poorest CINR condition because the bus always moves around large buildings, hills, and even tunnels, and also the outdoor environment with many obstacles impacts the channel quality significantly because of the shadowing. In the subway case, as a BS is deployed almost at every subway station, and even in tunnels there are repeaters, the CINR is actually high; an SS always performs HOs to

Table IV. Packet Loss Rate.

	Bus	Camp./st.	Camp./mo.	Subway
UL	0.31%	0.19%	0.42%	0.40%
DL	2.85%	1.31%	2.42%	2.04%

Camp./st., campus/stationary; Camp./mo., campus/mobile; UL, uplink; DL, downlink.

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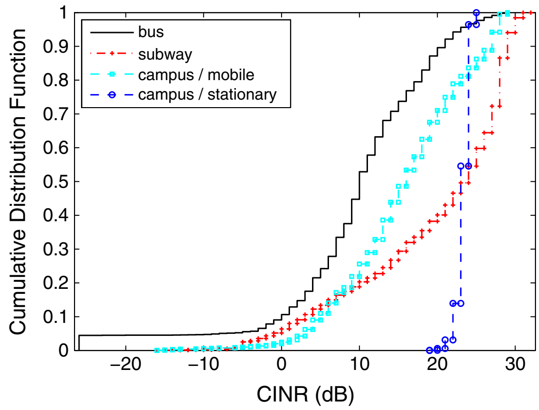


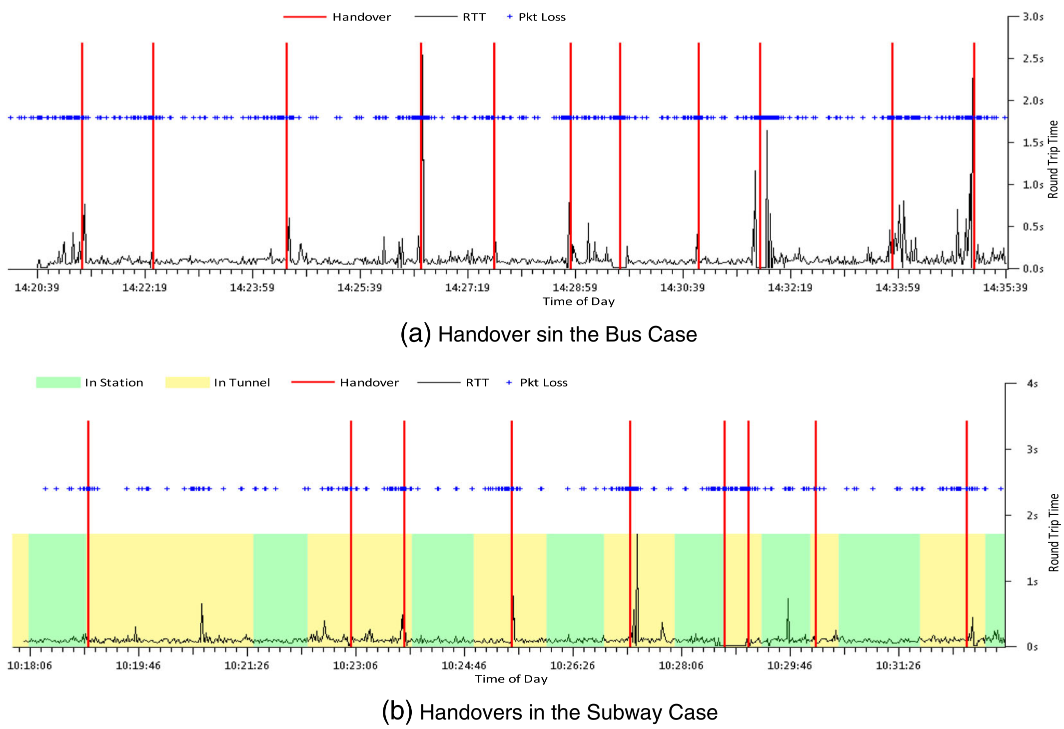
Figure 8. CINR values of different routes.

the next BS in the next station before the signal condition becomes bad. In the mobile case of the SNU campus, the CINR varies because the topography of trees and buildings always changes. Obviously, the radio signal stays almost constant when our device is stationary under a good channel condition.

4.2. Handover impact

An HO in WiMAX comprises several steps involving non-negligible delays, which affect the real-time online gaming services. We focus on the bus and subway cases to observe how HOs impact the network performance in terms of RTT and packet loss. Figure 9 plots the RTTs with the time of the day during the measurement, and the HO occurrences are indicated by red vertical lines, which are obtained by observing the MAC frame *MOB_MSHO_REQ_START* from the XRO7000 diagnostic monitor trace. Packet losses are plotted as blue crosses in the figures. The correlations between RTTs, packet loss, and HOs in the bus and subway routes are shown in Figure 9(a and b), respectively. In the latter, a green block shows a moment when the train is in a station, and a yellow block shows a period when the train is moving between two stations.

In both situations, RTT values fluctuate because of HOs or the changes of tunnel shapes like curvature, often surging to around 500 ms at the HOs, sometimes even over 1 to 2 s. In the subway situation, one or two HOs as well as RTT fluctuations always happen when the train runs in the tunnel because the SS performs an HO between the serving BS at the last station and the next BS at the coming station. We found that not every fluctuation exactly corresponds to an HO because the changes of tunnel shapes, such as curvature, may influence the signal quality. Also, HOs do not always induce sudden rises of RTTs because an HO in the subway case often takes place when the train moves into the next station, not because of poor signal strength. Therefore, an HO happens with a small delay under good signal conditions. In the bus situations, WiMAX BSs are not deployed as densely as they are in the subway route, so HOs happen mostly when the SS has quite poor signal



(a) Handover sin the Bus Case

(b) Handovers in the Subway Case

Figure 9. Impact of HOs on RTT and packet loss. (a) Handovers in the bus case and (b) handovers in the subway case.

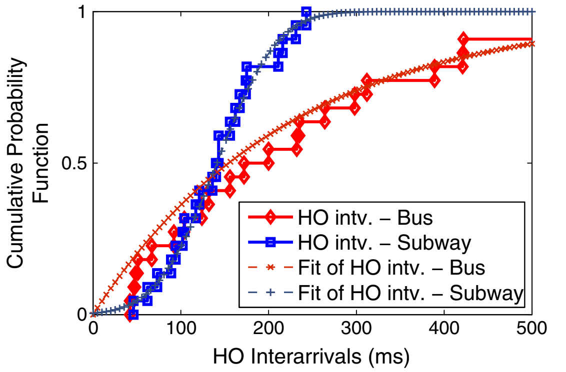


Figure 10. CDF of HO inter-arrivals with fitting; intv. is for interval.

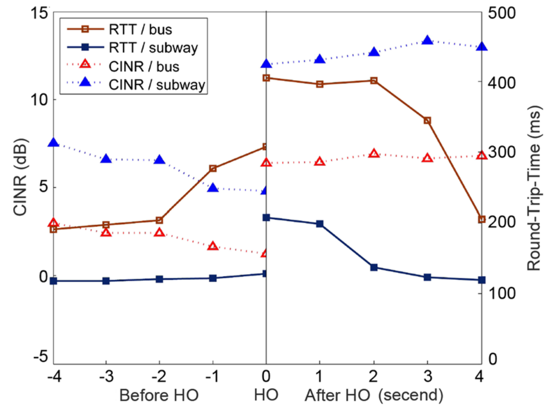


Figure 11. Handover and CINR and RTT.

quality with the current BS compared with other BSs; thus, an HO induces a longer delay as the transmission rate is low. The packet losses are often taking place in a burst right before and during the HOs, although some losses happen even without HOs. This phenomenon is worse in the bus case because of the unstable signal quality. Outdoor signal strength in the bus setting varies a lot, which causes the packet loss more frequently than in the subway.

We further investigate the pattern of HO occurrences by analyzing the inter-arrival times between every pair of adjacent HOs as shown in Figure 10. HO inter-arrivals in the bus case follow the exponential distribution with $\lambda = 222.864$ as shown by the red curves in Figure 10. The fitting PDF is given by

$$f(x) = \begin{cases} 222.864e^{-222.864x}, & x \geq 0, \\ 0, & x < 0 \end{cases}$$

However, the distribution of HO inter-arrivals in the subway case, shown as the blue curve, follows a normal distribution fitting with $\mu = 141.136$ and $\sigma = 54.036$ with fitting PDF as

$$f(x) = \frac{1}{\sqrt{2\pi}54.036} e^{-\frac{(x-141.136)^2}{2\times 54.036^2}}$$

Note that the HO inter-arrival values are in millisecond. The reasons why the distributions of HO inter-arrivals in the subway and bus cases are different could be the following: (i) The inter-station distances in the subway system are carefully designed to be within a limited interval considering the social requirements, which are not too long and also not too short. As almost every station implements one BS and an HO occurs between two neighboring stations, the distribution of HO inter-arrivals in the subway can be almost equivalent to the distribution of inter-station distances, which in nature follows a normal distribution. (ii) Although the inter-station distances in the bus system are also pre-planned in a similar manner to those in the subway system, WiMAX BSs have not been deployed along all the bus stations in Seoul but in a near-random manner. The HOs in the bus case occur whenever the CINR falls around 0 dB [16], and because of the BS-agnostic bus route and the significant influence of the shadowing effect caused by outdoor obstacles, the inter-arrivals of HOs are much more random; our fitting shows that the HOs in the bus case occur like a Poisson process. Our distribution fittings lay a groundwork for modeling HO inter-arrivals.

As HOs severely degrade RTTs, we plot the changes in the CINR and RTT around the HO occurrences. We trace all HOs by observing the two MAC frames, *MOB_MSHO_REQ* indicating the beginning of an HO and *HO_RNG_SUCCESS* indicating the end of the HO. We average the values of the CINR and RTT at 1-s intervals, from 5 s before the beginning of and after the end of an HO. These time-varying changes are shown in Figure 11.

In the bus case, the CINR values drop near 0 dB before HOs, which verifies that 0 dB CINR is the threshold of triggering HOs. Before HOs, the RTT keeps rising as the signal quality becomes worse and worse. Right before HOs, the RTT rises to over 300 ms. Even after them, the RTT still stays around 400 ms because of the route recovery and the slow start mechanism of TCP. We plan to investigate how the transmission is recovered as our future work. The RTTs fall back to an acceptable level around 200 ms, after 5 s of HOs.

In the subway case, the CINR values right before HOs are around 5 dB, relatively higher than those of the bus case, but still HOs take place. This tells us that relative CINR values of adjacent BSs determine the HOs as well. Before HOs, the RTT values hardly vary because of good link conditions. After HOs, the average RTT stays around 200 ms and gradually falls back to 110 ms as TCP congestion window catches up. Therefore, we can say that the negative impact of HOs on RTTs in the subway case is lighter than that in the bus case.

4.3. Best-effort service for multiple users

The WiMAX standards [3,5,6] specify that for the traffic of real-time applications with variable packet sizes on a periodic basis, the extended real-time polling service (ertPS)

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Table V. Performance of multi-user scenario.

No. of FTP users	Avg. WoW RTT (ms)	Avg. WoW Pkt. Loss (%)	Avg. FTP Thpt. (Mbps)
0	100.22	0.98	—
1	101.35	1.14	3.94
2	105.59	1.15	3.13
3	122.47	1.33	2.97

FTP, file transfer protocol; Avg., average; WoW, World of Warcraft; RTT, round trip time; Pkt., packet; Thpt., throughput.

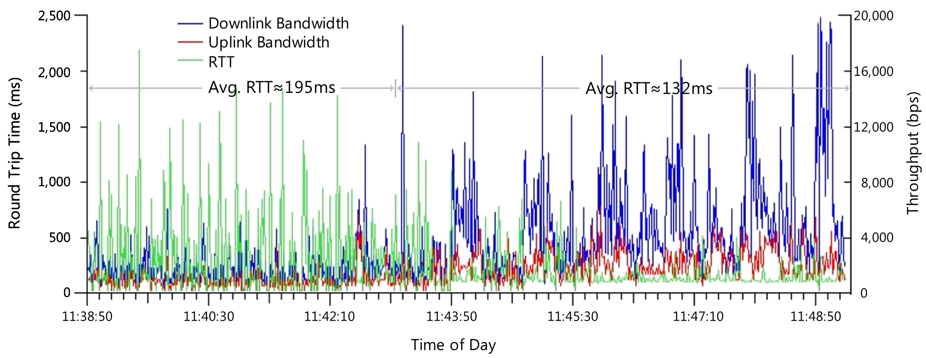

Figure 12. Impact of piggyback on RTT.

[3,6] should be implemented at BSs. However, currently, only the BE service is deployed in the WiBro network where we carry out the experiments, which means that all packets are treated equally in a BE manner by BSs. Therefore, when the aggregated traffic at a BS tends to be overwhelming, traffic flows from an online game application will be treated equally as other concurrent bursty flows such as those of FTP or P2P, thus making it difficult to satisfy the real-time requirements of online game services. Accordingly, the packet transmissions of the WoW flows may be delayed.

We carry out measurement using four laptops with WiMAX modems together fixed in the stationary location 3 in the campus near the BS, shown in Figure 2(c). While one SS keeps playing WoW, we start three FTP connections at the other three laptops one by one, around 3 min apart. When there is no other traffic, the average RTT of the WoW packets is 100.22 ms. As we turn on the first and second FTP flows (in the first and second laptops, respectively) in order, the first client achieves around 3.94 Mbps download throughput on average[‖], and then, the two concurrent clients obtain about 3.13 Mbps, respectively. The average RTT of the WoW traffic increases marginally to 101.35 ms and then to 105.59 ms. When we turn on the third FTP flow (in the third laptop), per-client average throughput drops to 2.97 Mbps, while the average RTT of the WoW flows rises to 122.47 ms. Also, we observe an increasing trend of the overall packet loss ratio (uplink and downlink together) as we add more and more FTP users.

All the average RTT, packet loss rate, and throughput results are shown in Table V, showing the trend that if there are more and more contentions from other bandwidth-consuming connections, the RTT and packet loss rate of a WoW flow will increase. So the BE scheduling may not service online gaming traffic effectively in the presence of multiple users contending for BS resources; the ertPS approach may have to be implemented for applications with real-time requirements, for example, online games or VoIP applications.

4.4. Correlation of uplink packet interval and round trip times

We also carry out experiments on how the uplink packet rate impacts RTTs. Initially, our avatar stands alone and takes no actions; after a while, it performs extensive actions to kill crowds of monsters in the same environment.

As shown in Figure 12, red and blue plots indicate uplink and downlink traffic rate, respectively, which are low when the avatar is idle at the beginning. The green plots indicating that the RTT values fluctuate intensively with the average value of 195 ms. When the avatar takes actions continuously and, thus, uplink packets are generated more frequently, the average RTT drops to around 132 ms. This phenomenon that higher rate of uplink traffic shortens RTT values is mainly due to the piggyback-based bandwidth request for WiMAX uplink transmissions [17,18]. Normally, every uplink transmission in the BE service should

[‖]This seems to be the upper bound of the throughput for each SS because of the scheduling policy in the BS.

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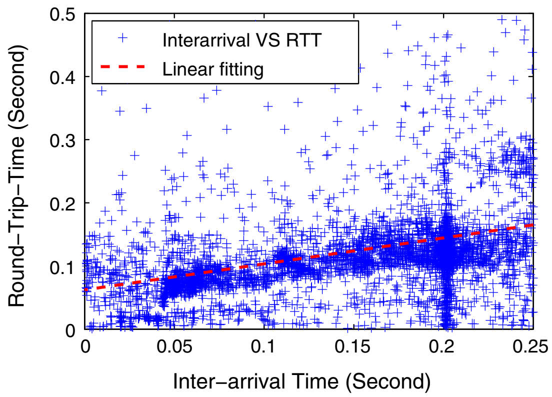

Figure 13. Relation of packet inter-arrival and corresponding RTT.

be requested to a BS, and then, the BS allocates slots in uplink bandwidth capacity, which may take considerable time before actual transmission. But if there are continual uplink packets being transmitted, such a bandwidth request can be piggybacked in the previous uplink packets. Therefore, higher uplink rates will shorten the RTTs.

In order to analyze how the piggyback mechanism can improve the uplink transmission delays, we observe the relation between the uplink packet inter-arrival time and the RTT of the corresponding packet. In Wireshark, the corresponding RTT value for each uplink packet can be easily calculated based on the arriving time of the corresponding ACK. The scatter plot is shown in Figure 13. Obviously, there is an increasing linear relation between RTTs and inter-arrival times of uplink packets, which is in line with [17,18]. However, the improvement is not very significant because of the delayed ACK mechanism and TCP congestion control. Note that two dense areas of scatters that fall in the x-axis are around 0.05 and 0.2 s, which highlight packet generation pattern of WoW [25].

5. THE MOS AND DEPARTURE RATIO EVALUATION

The effect of objective network factors such as delay (RTT), jitter, and packet loss on the game performance has been widely studied in [12] and [27] that measured the departure ratio as a QoS evaluation metric. Also, a user's subjective opinion on the experience of games is measured in terms of the MOS [13].

We first evaluate the MOS by the model from [13], where the MOS is evaluated based on the two quantities, ping delay (RTT), and jitter. The network impairment factor, X, which shows the weight of the network metrics of RTT and jitter on the impact of gaming performance, is given by

$$X = 0.104 \times RTT + Jitter$$

Then, the mapping for the MOS can be obtained by a polynomial fitting function as

$$MOS = -0.00000587X^3 + 0.00139X^2 - 0.114X + 4.37$$

Note that the highest score with no delay and no jitter is 4.37.

Another evaluation function is from [12] and [27], where they analyzed game session data and discovered the relation of the player's departure ratio r to the delay, jitter, and packet loss ratio as follows:

$$r = \mathrm{C} \cdot \exp(1.6 \times RTT + 9.2 \times Jitter + 0.2 \times \log(PacketLossRate))$$

The departure ratio is proportional to the exponent raised to the power of the weighted sum of network metrics. The weights reflect the effect of network impairments, and C is a proportional constant. A lower r means relatively a lower probability that a user leaves the game because of the unsatisfactory network QoS.

We calculate the MOS scores and departure ratio evaluation results in Table VI. The MOS results of WoW via the WiMAX network are with low values which means although the access network supports mobility and large coverage (compared to WiFi), the service quality of online gaming is not that satisfactory, particularly in the bus situation. The reason is mainly because the large jitter impacts the player's subjective experience more than the large delay does (e.g., [12]). From the MOS results, the campus/stationary case has the highest average MOS score, 2.651, and the bus case has the lowest MOS score, 1.397, because of its unstable outdoor signal quality and HOs. The average MOS in the subway case is 1.883, which exhibits the relatively good link quality despite HOs. According to [13], the gaming experience via the Ethernet achieves MOS around 3 to 4. Therefore, the relatively lower MOS values verify that the online gaming via the WiMAX network suffers from a poorer performance, particularly in

Table VI. Mean opinion score evaluation.

	Downtown	Hunting	Battlefield	Avg.
	MOS evaluation			
Bus	1.348	1.436	1.439	1.397
Subway	1.905	1.837	1.941	1.883
Camp. st.	2.767	2.533	2.635	2.651
Camp. mo.	2.599	2.316	2.373	2.432
Avg.	1.912	1.889	1.902	1.908
	Departure ratio evaluation with constant C			
Bus	1.359	1.260	1.256	1.299
Subway	1.058	1.086	1.043	1.066
Camp. st.	0.814	0.837	0.823	0.828
Camp. mo.	0.906	0.973	0.958	0.944
Avg.	1.023	1.042	1.022	1.027

Avg., average; MOS, mean opinion score; Camp. st., campus stationary; Camp. mo., campus mobile.

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mobile cases. From the departure ratio results, the campus/mobile case also has relatively low ratio (0.944C), but that of the bus case is 1.299C, which means that the probability that players in the bus will leave the game because of poor network condition is about 37.6% higher than that in the campus situation. The subway case has departure ratio (1.066C) close to the campus/mobile case, which verifies the similar performance of them. The campus/stationary case has the best performance in both the MOS score and the departure ratio evaluations.

6. CONCLUSIONS

In this paper, we measured and analyzed the performance of WoW, a representative online game, over a mobile WiMAX network in Seoul, Korea. We focus on both high-level packet statistics such as delay, jitter, bandwidth, and packet loss, as well as link level characteristics such as CINR, HO, BE approach, and piggyback mechanism. To measure the WoW performance in a comprehensive manner, we consider different test routes of bus, subway, and campus (stationary and mobile), with various gaming scenarios of downtown, hunting, and battlefield in the virtual space. Also, we evaluate the user experience of WoW over WiMAX by assessing the MOS and departure ratio models.

The mobile WiMAX network is likely to be functioning well for online gaming from the perspective of continuous gaming experience in mobile situation and acceptable delay. However, large lags and jitters degrade the quality of gaming experience significantly. Especially, the break-and-make type HOs in the WiMAX network affect the network performance substantially. The overall gaming performance evaluated by referring models is still limited compared with Ethernet. To reduce the delays, it is better to turn off the TCP-delayed ACK mechanism at the cost of more ACK packets, while the game program should be designed to utilize piggyback mechanism for a faster uplink transmission. Although the bandwidth consumption of a WoW flow is not so high, the BE approach at BSs supports online gaming poorly once concurrent flows make BSs saturated; therefore, the ertPS may support online gaming traffic better. HO processes should be optimized, and an appropriate transmission scheme with fast recovery functionality needs to be designed, which is considered as our future work [36].

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