Experience: Rethinking RRC State Machine Optimization in Light of Recent Advancements

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ABSTRACT

Broadband mobile networks utilize a radio resource control (RRC) state machine to allocate scarce radio resources. Current implementations introduce high latencies and cross-layer degradation. Recently, the RRC enhancements, continuous packet connectivity (CPC) and the enhanced forward access channel (Enhanced FACH), have emerged in UMTS. We study the availability and performance of these enhancements on a network serving a market with a population in the millions. Our experience in the wild shows these enhancements offer significant reductions in latency, mobile device energy consumption, and improved end user experience. We develop new over-the-air measurements that resolve existing limitations in measuring RRC parameters. We find CPC provides significant benefits with minimal resource costs, prompting us to rethink past optimization strategies. We examine the cross-layer performance of CPC and Enhanced FACH, concluding that CPC provides reductions in mobile device energy consumption for many applications. While the performance increase of HS-FACH is substantial, cross-layer performance is limited by the legacy uplink random access channel (RACH), and we conclude full support of Enhanced FACH is necessary to benefit most applications. Given that UMTS growth will exceed LTE for several more years and the greater worldwide deployment of UMTS, our quantitative results should be of great interest to network operators adding capacity to these networks. Finally, these results provide new insights for application developers wishing to optimize performance with these RRC enhancements.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication; C.4 [**Performance of Systems**]: measurement techniques, performance attributes

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Keywords

UMTS; RRC state machine; radio resource optimization

1. INTRODUCTION

The UMTS and LTE RRC state machine implementations play an important role in determining mobile application performance [30]. The purpose of the RRC state machine is to efficiently allocate network radio resources among a multitude of mobile devices. An additional goal is to minimize the utilization of energy intensive resources on the mobile device. The RRC state machine places wireless devices into one of several defined states that determine the amount of control, mobility management, and radio resources allocated. State changes incur a high cost, with delays up to several seconds. Minimizing state changes in the packet flow is required for good performance. A competing requirement is minimizing use of the resource intensive DCH state.

The impact of the RRC state machine on application performance has been studied in detail for CDMA, UMTS, and LTE networks [24,30,32]. Huang *et al.* [21] find TCP performance is affected by the longer delays and delay variability present in mobile wireless networks. TCP typically utilizes less than 50% of the available network bandwidth. Multiple studies investigate the impact of the RRC state machine implementation on device energy consumption. Tail time has been identified as a large contributor to poor power efficiency [20, 27]. While much is now understood about root cause, effective solutions remain elusive.

Existing RRC optimization methods have proved inadequate to resolve the issue, causing many current applications to experience unnecessary latency or excessive energy consumption. Currently, optimization requires trading off energy consumption for reduced performance by either shortening or extending state tail times. Qian *et al.* [27] found that optimization of RRC parameters for any specific class of traffic negatively impacts the majority of other traffic types. These limitations were found to be inherent in the state machine design.

As a solution, the industry organization that sets the technical specifications for LTE and UMTS mobile networks (3GPP) included RRC state machine enhancements in 3GPP Release 7 and 3GPP Release 8. Release 7 introduced *CPC* and *Enhanced FACH*. CPC allows HSPA users in the DCH state to operate without a dedicated control channel and utilizes discontinuous transmission and discontinuous reception. This results in reduced mobile device energy consumption and increased system capacity. Enhanced FACH defines use of the high speed downlink shared channel (HS-DSCH) for the FACH state (HS-FACH). 3GPP Release 8 further improves Enhanced FACH with a shared enhanced uplink channel (EUL-FACH) and DRX for the FACH state (E-FACH DRX).

While the recent growth of LTE subscribers is impressive, we note that increasing the capacity and performance of UMTS networks remains a priority for 3GPP participants. Over the next few years, global subscriber growth for UMTS / HSPA is forecast to exceed that of LTE. In 2019, UMTS subscriptions are forecast to exceed LTE subscriptions by 2.9 Billion [9, 11]. To address these needs, 3GPP has introduced numerous UMTS / HSPA enhancements [8,10], many of which are implemented as software upgrades. The need for operators to quantitatively assess these enhancements and decide which features to implement motivates our research of recent UMTS state machine improvements.

The key contributions of our paper are as follows:

- **The first measurement of UMTS RRC state machine enhancements in the wild.** We study an operational network serving a large metropolitan area with a population in the millions. We measure the availability of devices supporting the 3GPP Release 7 and 8 optional features. From our measurement study, we found that only a subset of the features are well supported. Specifically 14% of the devices support CPC, 4.5% support HS-FACH, while EUL-FACH and E-FACH DRX were not supported.

- **A new measurement method for assessing the performance of CPC** (§4.1). We use an RF spectrum analyzer to monitor the RF envelope of mobile device transmissions. This provides accurate identification of when a mobile device utilizes CPC DTX with millisecond granularity.

- **A detailed study of UMTS RRC state machine enhancements: CPC and Enhanced FACH** (§4 and §5). We find that CPC reduces device energy consumption during DCH tail time by 25%. This improvement in energy efficiency allows network operators to extend DCH tail times, improving application performance. Enhanced FACH measurements reveal that lack of EUL-FACH support severely limits the potential benefits of this technology. The existing uplink channel for FACH (RACH) is a low bandwidth channel and exhibits high latency. Even with these limitations, we found devices supporting Enhanced FACH reduced 200 byte ping round trip times (RTT) by 26%. We also find that the HS-FACH channel reduces latency of control signaling messages.

- **Analysis of the enhanced RRC state machine performance with popular mobile applications** (§6). We found that for audio and video streaming applications, CPC DTX is active up to 90% of the time during track downloads. This reduces energy consumption by 23%. For a popular social media application, we find that background transfers use the DCH state 13.7% of the time and the energy consumption is reduced by 21% in the DCH state. We also find that HS-FACH offers only limited improvements to the popular applications we studied, but with full implementation of Enhanced FACH, there is potential for improved FACH performance.

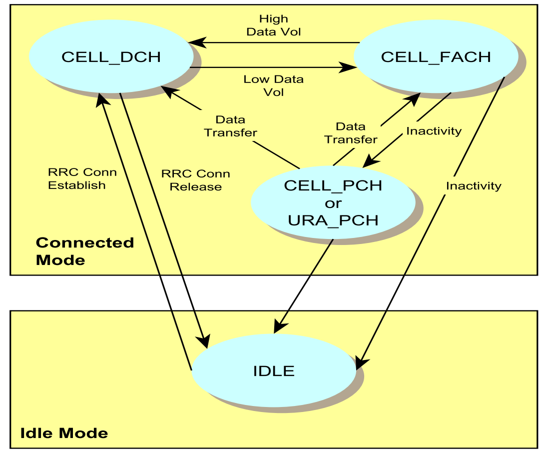

Figure 1: The UMTS RRC state diagram.

Summary: we learned that current RRC state machine enhancements narrow the performance gap between UMTS and LTE. We identified that pre-standard implementations of Fast Dormancy circumvent these enhancements. Further, Release 7 Enhanced FACH is limited in performance by reliance on the legacy RACH channel. Release 8 EUL-FACH is required for an effective Enhanced FACH implementation. Finally, we note FACH requires further improvements to provide needed capacity for developing Machine to Machine and Internet of Things applications.

2. BACKGROUND

Mobile wireless networks use an RRC state machine to allocate shared radio resources and minimize mobile device energy consumption. RRC state machines are implemented in GPRS, EVDO, UMTS, and LTE Networks [25].

We begin by reviewing the UMTS implementation. The state machine is shown in Figure 1. The basic RRC state machine consists of three states: IDLE, DCH, and FACH. These states are maintained simultaneously by the mobile device and the Radio Network Controller (RNC). The RNC provides control functions and radio resource management for the cellular base stations (NodeBs). A basic description of each state is given [19]:

- **IDLE** minimizes the use of network resources and device energy; only occasional monitoring of the network Broadcast channel (BCH), Paging channel (PCH), and Pilot channel (CPICH) are performed in this state.

- **FACH** requires an RRC connection to the RNC and minimizes use of radio resources by utilizing a slow speed shared channel with a bandwidth limited to aproximately 32 kbps. FACH has lower device energy consumption than DCH, and FACH to DCH promotions require less signaling overhead than IDLE to DCH promotions.

- **DCH** utilizes dedicated radio resources and provides a high bandwidth transport channel, however radio energy consumption is high.

3GPP Enhancement	Short Name	Release
Cont. Packet Conn.	CPC	7
Enhanced FACH	HS-FACH	7
	EUL-FACH	8
	E-FACH DRX	8

Table 1: Summary of RRC Enhancements.

Prior work covers operation of the RRC state machine [13, 24, 26, 27]. Optimization requires trading off state promotion delays and signaling load with increased energy consumption and radio resource utilization. Maximizing use of the IDLE state minimizes device energy consumption and radio resource usage. The benefits provided in the IDLE state are at the cost of increased state promotions and demotions. State promotions from IDLE incur signalling load, and delays, in the order of several seconds. In many networks, the optional PCH state is used as an intermediate state between IDLE and the other states to improve performance. When the amount of data in the mobile device or RNC transmit buffers exceeds a defined threshold, a state promotion to DCH is triggered [24]. State demotions from DCH to FACH are triggered when link throughput is below a defined threshold for a specified time. State demotion from FACH to IDLE is triggered by inactivity on the uplink and downlink [19].

3. MEASUREMENT METHODOLOGY

In this section, we first introduce the details of the CPC and Enhanced FACH features shown in Table 1. The RRC enhancements are optional features. Therefore, we determine which features are widely available across the target network. The target network is comprised of 3 RNCs, controlling approximately 280 wireless base stations (NodeBs). The network serves an area with a population in the millions. All of our experiments were conducted over a 5 month period commencing in May 2014. We protect end user privacy by only collecting statistical metadata and signaling messages, without subscriber identifying information.

In section (§3.2), we present the measurement study used to identify mobile devices supporting CPC and Enhanced FACH. As a result of our study, we find that only the Release 7 capabilities (CPC, HS-FACH) are well supported. Regarding the Release 8 features, we note implementation work beginning in late 2012 [17], and note several recent announcements of their availability [18, 29, 31]. Using our data and these announcements, we infer that mobile devices supporting all four features are just now entering the market place. Consequently, our experiments are limited to CPC and HS-FACH.

3.1 RRC State Machine Enhancements

We now describe the RRC enhancements introduced in 3GPP Release 7 and 8 [4, 5], which are shown in Table 1. CPC defines DTX and DRX capabilities for the DCH state physical channels. CPC capable mobile devices utilize discontinuous transmission in the uplink. On the network under study, CPC utilizes a 20 sub-frame DTX cycle, with a burst of typically one or two subframes every 20 subframes [2,8]. An HSPA subframe is 2 ms and the 20 subframe DTX cycle appears as transmit pulses every 40 ms.

The benefits of CPC are best realized if the DCH tail time is increased to minimize the number of state demotions and promotion between bursts of user data. Our tests show that DCH tail times can be extended significantly with only modest increases in radio resource consumption and no additional energy consumption. Another capability of CPC is DRX. DRX allows the mobile device receiver to power off when there is no downlink data. When using DRX, the mobile device no longer monitors the down link high speed shared control channels (HS-SCCH). Alternatively, it monitors the HS-DSCH directly and uses a specific DRX pattern and transport format to identify down link data. This mode of operation is comparable to the micro sleep capability of LTE [20].

The next RRC enhancements we consider are the HS-FACH and EUL-FACH features. The FACH RRC state uses common or shared channels, eliminating dedicated radio resource assignments for each mobile device connected to the network. FACH provides an uplink and downlink transport channel for mobile devices transmitting small amounts of data, such as periodic heartbeat messages or screen clicks. Energy consumption in the FACH state is lower than the standard DCH state, and by using shared resources FACH provides network connectivity and capacity for a larger number of devices than DCH. Research on the current FACH implementation shows poor performance, as FACH is unable to carry significant data volumes [27]. Rosen et al. [30] show that FACH buffers are set to trigger state promotions for packets as small as 200 bytes. This limits FACH traffic to low values, triggering frequent FACH to DCH state changes with high signaling delays.

In contrast, HS-FACH utilizes the HS-DSCH transport channel, which is the same channel used for HSPA downlink in the DCH state. HS-FACH supports a maximum bit rate of 1 Mbps nearly 30 times the rate provided by the existing R99 downlink FACH channel. The higher bandwidth allows for faster promotion to DCH [15].

3GPP Release 8 further improves FACH with DRX and EUL-FACH. E-FACH DRX lowers energy consumption, allowing mobiles to remain in FACH for extended periods. To support extended FACH connection times, new FACH tail timers are specified for use with E-FACH DRX [7]. The EUL-FACH feature provides a set of common enhanced uplink channels (EDCHs) that are shared among supporting mobile devices. The EDCH transport channel provides much greater bandwidth, and unlike the RACH channel, the mobile device can transmit consecutive protocol data units (PDUs). RACH, however, limits each transmission to one PDU. After each PDU transmission on RACH, the mobile device must repeat the channel access procedure, which greatly limits FACH performance.

3.2 CPC and Enhanced FACH Support

While CPC and Enhanced FACH have been defined in the 3GPP standards for some time, they have been introduced rather slowly [6]. To determine adoption of the CPC and Enhanced FACH features, we monitor the number of RRC Connection Complete Messages sent over the network from May to September 2014. The RRC Connection Setup Complete message includes information elements identifying support for the features [7]. In Figure 2, we find that CPC and HS-FACH capable devices represent over 10,000 mobile devices. Conversely, we found limited support for E-FACH DRX and EUL-FACH. These features were supported on less than 0.5% of mobile devices. As a consequence, mea-

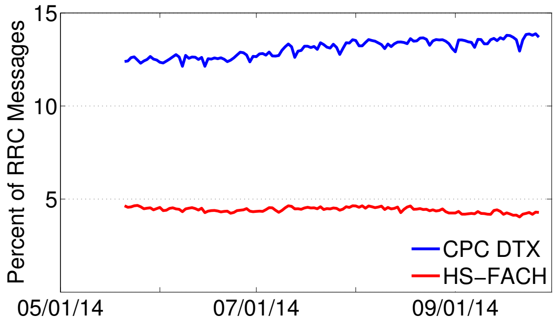

Figure 2: CPC DTX and HS-FACH support.

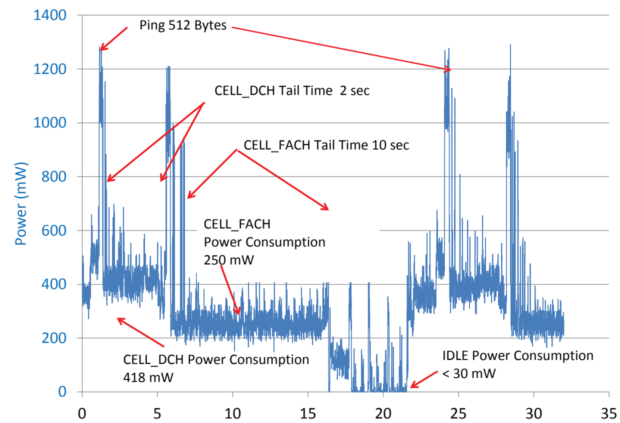

Figure 3: State transitions with noisy power measurements.

surements for these features were not conducted. Further, we observed an increase in low end smartphones supporting CPC, but not HS-FACH, while observing high end smartphones were starting to support 3GPP Release 8 features. Based on multiple supplier announcements, regarding full support HS-FACH and EUL-FACH, we expect the small decline in HS-FACH to reverse [18, 29, 31].

Next, we present our method for measuring CPC (§4) along with data from experiments on extending DCH tail time (§4.2).

4. CPC AND DCH PERFORMANCE

Identifying CPC DTX operation requires monitoring the transmitted RF envelope simultaneously with device energy consumption. By correlating these measurement, we accurately model the reduction in energy consumption. After identifying CPC energy savings, new values for the DCH tail timers are determined. In section (§4.2), we implement revised DCH tail timers on two RNCs in the network representing 65% of the cells, and measure the subsequent effect on RRC state changes and radio resource utilization.

4.1 CPC Power Reduction Measurements

CPC improves performance by minimizing the energy consumption of DCH. A major industry chipset company reported that CPC reduces the RF modem energy consumption 30% to 40% [29]. To measure these benefits, we develop a new measurement method that identifies state transitions and when CPC DTX is active. The measurements were made using an Alcatel One Touch 995S smart-phone running Andriod 4.0.4 (Ice Cream Sandwich). This phone supports HS-FACH and CPC, but does not support EUL-FACH nor E-FACH DRX.

In prior work, researchers have relied on mobile device power measurements to identify RRC state transitions and state machine parameters [20, 26, 27, 33]. In practice, there is a large amount of noise on the power measurements. This requires making multiple measurements and averaging results to clearly identify RRC states.

CPC complicates RRC state identification as it increases power measurement noise. After running multiple experiments, we were not able to clearly identify when CPC was active in the DCH state. To solve this problem, we develop a new measurement method. Our method monitors over-the-air transmissions from the mobile device. We use an Agilent 4402B spectrum analyzer for over-the-air measurements. The spectrum analyzer is configured in zero span mode. In this mode, the analyzer acts as a fixed tuned receiver measuring received signal power from a test antenna [22]. The test antenna is tightly coupled to the mobile so that the received signal is measured between -40 and -50 dBm.

Without CPC, the mobile device transmits continuously when in DCH. Whenever DTX is active, the device transmits a specific DTX pattern that causes the transmitter to pulse at the rate of the DTX cycle. These pulses occurred every 40ms and allowed clear identification of CPC DTX. To measure power reductions, the over-the-air measurements were synchronized with the battery current measurements.

IDLE mode baseline measurements are conducted with the phone screen, Bluetooth, WiFi, camera, and GPS accessories turned off. This leaves the cellular RF modem as the primary consumer of battery power. The energy consumption measured with all radio interfaces off established the baseline measurement. The energy consumption baseline is 25.7 mW. This is the same power measured in the IDLE state, allowing clear identification of this state.

CPC power measurements. Power measurements were then made with CPC disabled and enabled. In Figure 3, the measurement noise and the current spikes present create an ambiguity in identifying state changes. To overcome this, our additional measurement of received RF power is overlaid onto the battery current measurements. RF power measurements provide a graph of the received signal strength, which we refer to as the *RF envelope*. Transitions in the RF envelope identify the transition from one RRC state to the next.

To correlate RF power measurements with battery current measurements, we used the method described earlier. Shown in Figure 4 is the trace of two 512 byte pings sent 23 seconds apart. The time interval is set to allow for the state promotion delays, state demotion delays, DCH tail time, and FACH tail time to complete before the next ping is initiated. The red trace is triggered by the rising edge of the RF envelope. The rising edge corresponds to the mobile device's first access attempt on the RACH channel. A spike in battery current (blue trace) is observed when transmission of user data occurs. This spike is 1.2 seconds after the mobile starts transmitting, and the delay is caused by the state promotion from IDLE to DCH. There is then a 2

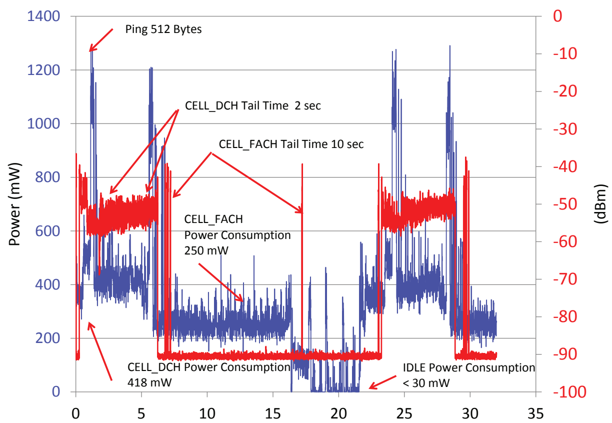

Figure 4: State transitions with RF envelope.

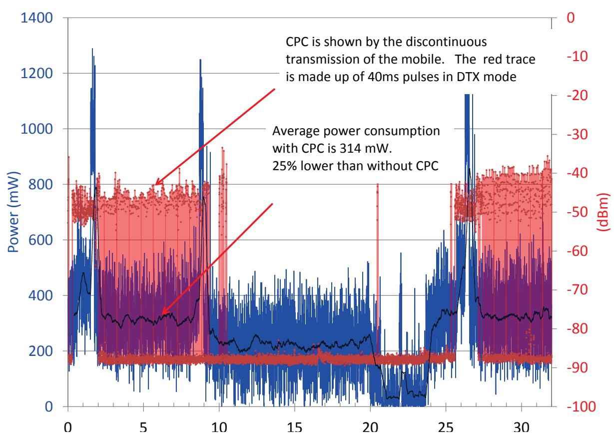

Figure 5: CPC DTX RF envelope.

second DCH tail, where no user data is transmitted. Another spike in battery current is observed just as the mobile device transitions from DCH to FACH. After the DCH to FACH demotion delay, there is 10 seconds of FACH tail then a short TX burst as the mobile device returns to IDLE. The measurements were then repeated with CPC.

The RF envelope clearly identifies the CPC DTX mode. The effects of CPC DTX are seen in Figure 5. During the DCH tail, the pulsed RF envelope of DTX is easily identified. The RF envelope allows for unambiguous identification of when DTX is active and accurate measurement of energy consumption.

DCH tail energy consumption with CPC averages 314 mW and achieves a 25% reduction in power. Our complete results are shown in Table 2, along with measurements reported in prior studies [27, 33].

4.2 Extending DCH Tail Time

In this section, we measure the impact on network capacity of increasing DCH tail time by analyzing the consumption of two key radio resources, NodeB TX power and RRC connections. We note, some operators may prioritize increasing mobile device battery life and will not increase existing DCH tail times. The priority for other operators is reducing latency, excess state transitions, and subsequent signaling load. The performance trade offs between longer

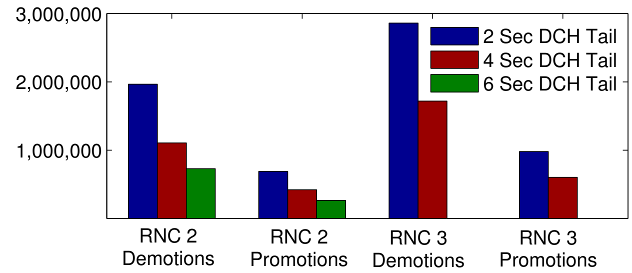

Figure 6: State change improvements.

DCH tail time, decreased battery life, and increased radio resource consumption are well documented in the literature [14, 23, 24, 32]. However, the impact on radio resources of increased tail times has only been discussed analytically. Our experiments provide a set of quantitative results from an operational network.

We extend DCH tail time from 2 to 4 seconds in the first measurement run. The tail time was extended on two different RNCs and the number of state promotions and demotions measured over a period of two weeks. A second run for RNC 2 is made with DCH tail extended to 6 seconds. The increase in DCH tail time results in a 44% and 40% reduction in demotions for RNC 2 and RNC 3 respectively. The number of promotions from FACH to DCH is also reduced by 39% for RNC 2 and RNC 3.

Longer DCH tail times require increased radio resources to maintain the dedicated connections with the NodeB. As we increase DCH tail time, we observe the effect on DCH connections, FACH connections, and Node B TX power. In Figure 7, we measure the 24 hour summation of hourly average DCH and FACH connections. As expected, there is an increase in DCH connections 10% on RNC 2 and 13% on RNC 3 for the 4 s DCH tail. RNC 2 increases an additional 12% for the 6 s DCH tail.

A decrease in FACH connections occurs as DCH tail time increases. There are two possible causes for the reduction in FACH connections, first the longer DCH tail will cause a portion of packet flows to remain in DCH rather than transition to FACH and back to DCH when the flow resumed. This occurs when the gap in the flow t_1 is such that $\alpha_1 < t_1 < \alpha_2$. Where t_1 is the interpacket time, and α_1, α_2 are the original and extended DCH tail times. We also note, in some cases Fast Dormancy was a contributor to decreases in FACH connections. Fast Dormancy is a capability that terminates RRC connections using mobile device control [16]. When the RRC connection is terminated, the mobile device bypasses FACH and returns directly to IDLE or in some network implementations PCH. The timer used to terminate the connection is dependent on the mobile device. When the timer t_f is such that $\alpha_1 < t_f < \alpha_2$, then DCH demotions bypass FACH, reducing FACH connections, where α_1 and α_2 are the original and extended DCH tail times.

Next we examine NodeB TX power. The increased number of DCH connections observed potentially increases the NodeB TX power. To determine this impact, data was collected from two different network RNCs on TX power utilization. Power measurement were collected 2 weeks prior and 2 weeks after the implementation of longer DCH tail times. Transmit power utilization was averaged for all effected cells and the CDF of this usage is presented in Fig-

RRC State	Alcatel 995	Alcatel 995 with CPC	TyTN*	Nexus One*	HTC Dream**
DCH	418 mW	314 mW	800 mW	600 mW	570 mW
FACH	248 mW	224 mW	460 mW	450 mW	401 mW
IDLE	30 mW	32 mW	0	0	10 mW

*Reported in [27], ** Reported in [33]

Table 2: Summary of mobile device power measurements.

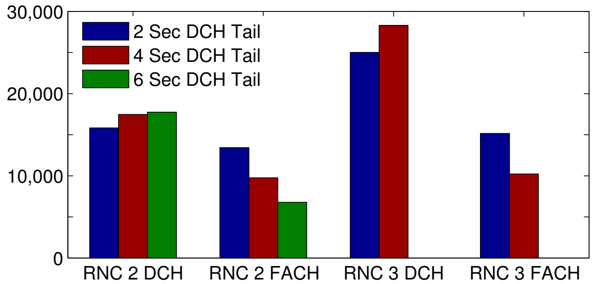

Figure 7: FACH and DCH connections.

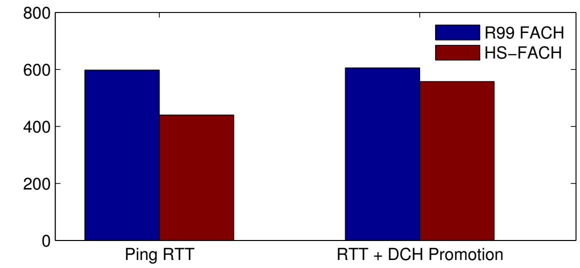

Figure 9: HS-FACH RTT.

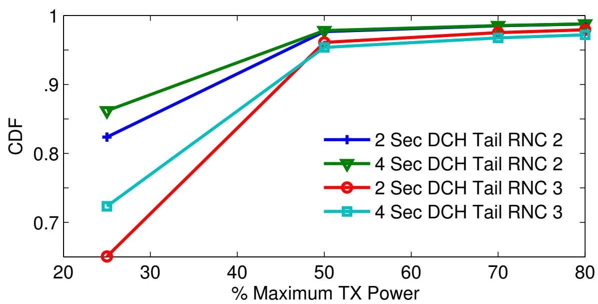

Figure 8: TX Power Resource Utilization.

ure 8. The lower probabilities correspond to higher TX power use. The probability that TX power is less than 25% of maximum actually increases for both RNCs despite the increase number of DCH connections. By examining overall trends in network traffic, we observe the small decreases in NodeB TX power were due to small changes in network traffic, and there is no measurable increase in power from the longer DCH tail.

The NodeB TX power increase is small and we conclude that the longer DCH tail has a negligible effect on overall consumption of available transmission power. Overall, significant reductions in promotions and demotions along with the subsequent delays were obtained with limited increases in the use of other radio resources.

5. ENHANCED FACH

In this section, we assess the performance of the feature HS-FACH. As noted, the majority of mobile devices supporting Enhanced FACH implement only the HS-FACH downlink capability and not the corresponding EUL-FACH uplink enhancement.

5.1 HS-FACH

To measure HS-FACH performance a simple ping test was performed, a packet size of 200 bytes was chosen, as packet sizes larger than 256 bytes trigger a promotion from FACH to DCH. Figure 9 shows the measurement results. Average ping round trip times (RTT) decreased from 600 ms to 440 ms, an improvement of 26%. While significant, the improvement in FACH is much less than expected. It is believed that the RTTs are dominated by the slower RACH channel and the power ramping procedure that is used to access the RACH channel. RACH uses a contention based access method and open loop power control that requires the mobile device to send an identifying preamble at a power level estimated from the received signal strength of the serving base station [1, 19]. If the mobile device does not receive a response, it ramps up the power and sends the preamble again. This continues until the mobile device receives a response. The process must be repeated for each transmission over the RACH channel and greatly limits the possible throughput of this channel, consequently limiting performance in the HS-FACH state.

HS-FACH improves promotion times from FACH to DCH. The HS-FACH channel allows for faster transmission of signaling messages and corresponding reductions in promotion times. To measure the improvement, RTT measurements were made for 300 byte pings. The 300 byte packet size triggers a promotion from FACH to DCH. Data for several hundred runs were conducted using both FACH and HS-FACH on the same mobile device. The results in Figure 9 show a 48 ms reduction in average RTT times, which is attributed to the reduction in promotion time from FACH to DCH.

In order to obtain an additional assessment of the throughput and performance capability of HS-FACH, throughput on the HS-FACH channel was measured using statistical counters present in the RNC. These counters are samples of the HS-FACH throughput made every 100 ms. If the channel throughput is 0 kbps, the sample is discarded. The samples are then averaged providing a measure of HS-FACH throughput on an hourly basis. Unfortunately, statistical counters for the conventional R99 FACH channel were not available. This necessitated using other throughput measurements. For comparison, the same average throughput data was collected for the 64 kbps DCH channel.

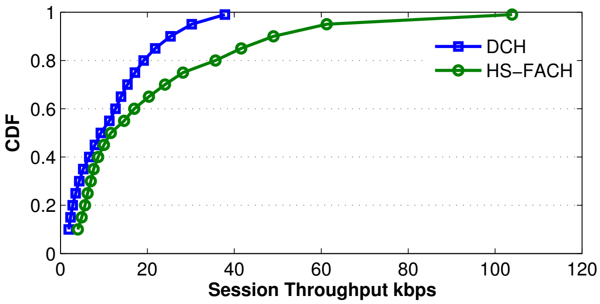

Figure 10: HS-FACH vs. R99 DCH throughput.

The 64 kbps DCH channel has twice the bandwidth of the traditional FACH channel and is a dedicated channel not shared among multiple users. The 64 kbps DCH provides much higher performance than is available on the traditional FACH channel. Statistical data for several days was collected for both channels, and their distributions are shown in Figure 10. HS-FACH consistently provides better throughput than the 64 kbps DCH channel, with the 50th percentile HS-FACH speeds exceeding 11.6 kbps as opposed to 9.3 kpbs for 64 kbps DCH. These results indicate that HS-FACH performance over FACH is qualitatively substantial. As a result, we conclude that HS-FACH provides a significant increase in downlink FACH channel performance. However, the lack of support for the EUL-FACH channel limits mobile application benefits.

5.2 Fast Dormancy and FACH interactions

Fast Dormancy is a mobile device capability introduced to reduce DCH tail energy. Device manufactures introduced this capability outside the 3GPP standardization process, creating unanticipated problems [16]. When invoked, the Fast Dormancy procedure demotes a mobile device in DCH directly to the IDLE state. This bypasses both the FACH and PCH states.

Bypassing the PCH state circumvents it benefits. The PCH state retains the RRC connection with a mobile device and reduces the promotion delay to the DCH state. PCH has low energy requirements similar to IDLE. To correct this problem, 3GPP Release 8 includes an improved Fast Dormancy procedure that transitions the mobile device from DCH to any lower power state IDLE, PCH, or FACH [7, 16]. The new procedure includes an additional information element, "UE Requested PS Data session end", sent by the mobile device when invoking Fast Dormancy. When received, the network moves the mobile device to one of the more battery efficient states; FACH, PCH, or IDLE. The state selected is configured by the network operator.

6. APPLICATION CASE STUDIES

Understanding the benefits of CPC and HS-FACH on application performance motivates us to conduct a series of case studies. For our analysis, we use a widely available application performance optimizer, ARO [12]. From our results, we conclude streaming applications that remain in DCH for extended periods of time use significantly less power with CPC. The benefits of HS-FACH were mixed. The bandwidth of current VoIP applications, such as Skype, are higher than what can be reasonably be met by the Enhanced FACH channels, however VoIP applications with bandwidths of 32 kbps or less should be able to utilize HS-FACH, increasing network capacity and reducing device energy consumption.

6.1 Streaming Media Applications

Pandora is a popular audio streaming application widely used on mobile devices. Both CPC and HS-FACH potentially offer improvements in radio resources utilization. The ARO application analyzes packet flow dynamics to allow tuning of network parameters for the desired behavior. ARO analysis provides a graphical display of the packet flow dynamics including RRC state. Figure 11 shows the dynamics of a captured Pandora session.

Analysis of the captured traces reveal that audio content is received in chunks of 8000 bytes spaced at one second intervals. With overhead the downlink throughput is less than 72 kbps when averaged over several seconds, well within the bandwidth of the HS-FACH channel. However, the dynamics of each chunk include a high bandwidth initial burst that quickly exceeds the downlink RLC buffer threshold, triggering a promotion to DCH. This leads us to conclude that track downloads will quickly up switch to DCH and remain there, and it is not practical for audio streaming applications of this class to use the HS-FACH channel.

The analysis reveals CPC is quite beneficial in minimizing energy consumption. There is minimal uplink traffic during track download. For this flow, the mobile device is transmitting only TCP ACKs and no data payload. Consequently, CPC switches from continuous transmission to DTX immediately after the mobile device's TX buffer is emptied. Without CPC, the transmitter is powered continuously for the duration of the track download. Examination of the uplink flow dynamics shows that the TX is idle more than 90% of the time during the track download. As a result, CPC reduces device energy consumption by 94mW during track download, corresponding to a power reduction of 22%.

YouTube shares similarities with the Pandora application, we observed the same chunk download dynamics that were present for Pandora. Using the 640x360 video format for our downloads, the average bit rate for YouTube content was 1 Mbps, and data was downloaded in blocks of 65,536 bytes. The block size was very consistent, with negligible variance. The blocks were downloaded at 484 ms intervals. The download time per block averaged 82 ms, which shows that the TX is idle 82% of the time, reducing device energy consumption 85 mW during track download.

6.2 Voice over IP

Common voice over IP (VoIP) applications consist of a UDP packet flow with small payloads. Packet loss, delay, and jitter are the first order determinants of application performance. Skype is a popular VoIP, video chat, and messaging application for personal computers and mobile devices. We limit our examination of this application to the VoIP functions. We examined the packet flow of this application with ARO to understand the dynamics of the flow and how the application interacts with CPC and HS-FACH.

Packet flow analysis. On the mobile device downlink, UDP packets with average payload of 104 bytes are received at a rate of 50 packets per second, or one packet per 20 ms. This constitutes an audio stream with a bit rate of 42 kbps.

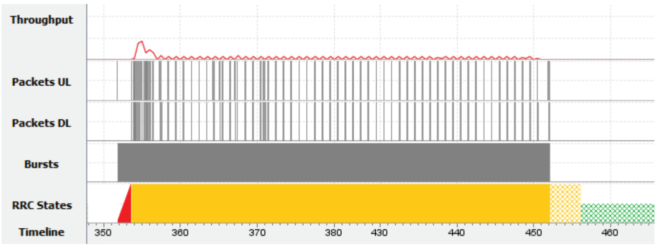

Figure 11: Pandora packet flow analysis with ARO.

The packet payload and bit rate for the uplink were 73 bytes and 30 kbps respectively, however no audio was transmitted on the uplink. The uplink data rate did not change when using an open microphone with background noise or a muted microphone. The packet rate on uplink was also 50 packets per second.

CPC and HS-FACH do not benefit the VoIP packet flow. Based on the packet flow dynamics of Skype, we conclude that CPC will not benefit this application, as the CPC DTX cycle is based on a 20 subframe or 40 ms period, and the packet rate used by Skype precludes use of the CPC DTX cycle. We also note that the application consumes additional power by sending an uplink stream of significant bandwidth, even during periods of silence or with a muted microphone. The inter-packet timing of this stream exceeds the capability of RACH, precluding the possibility of the mobile device utilizing HS-FACH. Optimization of the stream would provide substantial benefits in bandwidth and energy reduction for this application.

6.3 Social Media

We studied the packet flow dynamics of the popular social media application Facebook. While running in the background, Facebook intermittently exchanges information in small to medium sized bursts. In our data set, 46% of the bursts were less than 1 kB, and these small bursts consume substantial energy during the DCH and FACH tail times. Both CPC and Enhanced FACH provide alternative solutions for the handling of small bursts.

DCH was active for 13.7% of the time during our traces. For most of the time in DCH, no data was transmitted and CPC was active. For our traces, CPC is active greater than 82% of the time while in DCH, and reduces radio energy consumption 21%. We also observe that the small transfers are within the capability of the Enhanced FACH state. The enhanced FACH state lowers energy consumption even further than CPC. However, for the FACH channel to be of benefit, the RRC state machine would need to be configured so that promotions from IDLE to DCH first transition to FACH. On many networks including the target network, promotions are from IDLE to DCH and do not pass through the FACH state. Based on the limitation of HS-FACH and its reliance on the RACH channel for uplink, we do not recommend implementing an RRC state machine that would use FACH as an intermediate state for promotions from IDLE or PCH. Consequently, we conclude that performance gains with HS-FACH alone are limited, and the full implementation of Enhanced FACH including EUL-FACH is required to further improve the performance of typical social media applications.

7. RELATED WORK

Perala *et al.* showed significant variations in timer values and the inability to accurately predict state machine operation without network measurements [24]. RRC state machine parameters are often measured by monitoring mobile device battery current [13,20,21,26,27,33]. These measurements are plagued by noise. Our contributions provide a new measurement method, greatly improving identification of RRC states and modes such as CPC DTX.

Energy consumption is studied in [23,32] using simulation and then developing analytical expressions for application in network design. Chua *et al.* [14] uses simulations to identify optimum state machine timing for web browsing. Rosen *et al.* [30] provides a comprehensive study of promotion and demotion delays, showing that in specific circumstances, these delays can be long and create additional degradation of user experience. Researchers have also shown that periodic transfers, inefficient content prefetching, random bursts triggered by user actions, and other common application behaviors use radio network resources inefficiently [25–27]. They created software tools that allow developers to analyze application performance and previously hidden cross-layer interactions [12]. By applying similar techniques, our work shows that recent RRC enhancements address past limitations. Additional timers and RRC parameters are introduced allowing energy efficient mobile devices to remain in high performance states for extended periods of time. Further, we observe prior techniques used to minimize mobile device power can interfere with these improvements [16]. Finally, we note that further RRC state machine enhancements are planned [3,28], and the techniques we develop in this paper are useful for optimization and implementation.

8. CONCLUSIONS

In this paper, we have characterized the performance of recently available RRC state machine enhancements in the wild. Our results show that CPC provides significant reduction in device energy consumption, particularly for streaming applications. CPC reduced energy consumption by 25% during the DCH tail. Based on the measured energy savings, we conclude extending the DCH tail time is generally beneficial, offering improved application performance. We also find that the HS-FACH channel has greatly improved bandwidth. However, limited support of the EUL-FACH uplink channel greatly limits the improvements that can be realized for many of the applications we tested. Our work provides further insight into how new RRC state machine enhancements interact with applications and require developers and operators to update their optimization tools and strategies accordingly.

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