CSoHS Voice Capacity in HSPA networks with realistic overhead channel modeling

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***Abstract*—In this paper, we analyze the capacity of Circuit Switched Voice over High Speed Packet Access (HSPA) (CSoHS), using a Release 7 HSPA system that supports Continuous Packet Connectivity (CPC). On the Downlink (DL), we modeled the power consumption of the Fractional Dedicated Physical Channel (F-DPCH) and the Enhanced DCH Hybrid ARQ Indicator Channel (E-HICH). On the uplink (UL), we modeled the overhead channels, High Speed Dedicated Physical Control Channel (HS-DPCCH) and Enhanced DCH Dedicated Physical Control Channel (E-DPCCH). Our results show voice capacity gains that are achievable with CPC. We also show the gains in downlink voice capacity that are achievable by using the MAC-segmentation feature, introduced in Release 7.**

***Index Terms*—CSoHS voice, HSDPA, HSUPA, F-DPCH, E-HICH, DTX, DRX, HS-DPCCH, E-DPCCH, MAC Segmentation.**

I. Introduction

High speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA) have been standardized by the Third Generation Partnership Project (3GPP) in Release 5 and Release 6 respectively. Release 6 HSPA introduced and Release 7 further optimized support for the Fractional Dedicated Physical Channel (F-DPCH), in order to reduce code consumption for TPC bits on the downlink. Release 7 also introduced support for battery saving features for the user equipment (UE); Discontinuous Reception (DRX) on the Downlink (DL) and Discontinuous Transmission (DTX) on the Uplink (UL), together referred to as Continuous Packet Connectivity (CPC). In addition to battery saving, CPC also reduces Noise Rise on the uplink by gating UE transmissions.

In [1], the authors presented the capacity of UL and DL CSoHS voice in Release 6 and Release 7 HSPA networks. However, in [1], the power consumption of the DL overhead channels (F-DPCH, E-HICH) was assumed to be fixed ([2]), at 10% of the total cell power. In this paper, we model the power consumption of F-DPCH and E-HICH realistically. We find that the fixed power assumption in [1] over-estimates DL CSoHS voice capacity. Our DL voice capacity simulations consider UEs with a single receive antenna as well as UEs with two receive antennas. Single receive antenna UEs constitute the majority of UEs today, while UEs with two receive antennas are beginning to be introduced in some smartphones.

For uplink capacity simulations, we model the power consumption due to the overhead channels, Enhanced DCH Dedicated Physical Control Channel (E-DPCCH) and High Speed Dedicated Physical Control Channel (HS-DPCCH). We also present DL and UL CSoHS voice capacity results with the use of CPC, as well as DL voice capacity results when using downlink MAC segmentation. MAC segmentation, introduced in Release 7, allows a voice packet to be split into two or more payloads, if the power available at the Node-B is not sufficient to transmit it. This reduces the probability that a packet is stuck at the Node-B during channel down-fades and improves voice packet error rates, particularly for cell edge users.

The rest of the paper is organized as follows. In Section II, we explain our simulation model. In Section III, we explain system settings and the modeling of overhead channels. In Section IV, we present CSoHS voice capacity results, with realistic modeling of overhead channel power. We present conclusions in Section V.

II. Simulation Model

We used system simulations to evaluate the voice capacity of CSoHS on the UL and DL. We dropped users uniformly in a 57-cell system with wraparound ([2], [3]).

The CSoHS voice source is based on the AMR 12.2 vocoder ([4]). A full rate voice frame is generated every 20 ms when the vocoder detects speech ("speech period"), while a Silence Indicator (SID) is generated every 160 ms when the vocoder detects silence ("silence period"). Figure 1 shows the two state model with transition probabilities. The speech and silence durations are exponentially distributed. The mean speech and silence duration for these transition probabilities is 3 seconds ([1]).

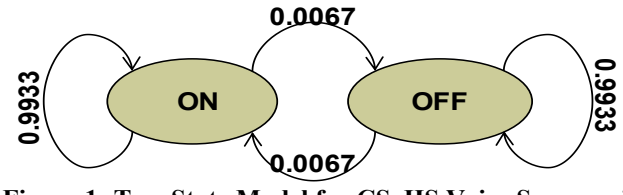

Figure 1: Two State Model for CSoHS Voice Source with Transition Probabilities.

For the 12.2 AMR full-rate frame , the CSoHS packet on the uplink consists of 244 bits of AMR payload, 4 bits for octet-

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alignment, 8 bits for PDCP header (to carry CS Counter, which provides functionality equivalent to the RTP timestamp), 8 bits of RLC UM header (carrying the RLC sequence number, which provides functionality equivalent to the RTP sequence number) and 24 bits of MAC-i/is header, for a total of 288 bits. On the downlink, the MAC-ehs header (24 bits) is used instead of the MAC-i/is header.

We used a delay bound of 100 ms at the NodeB scheduler for CSoHS voice packets. Any packet that waits for its first or subsequent HARQ transmissions at the scheduler for a delay greater than this bound is discarded. Any packet that arrives at the UE with a delay greater than this bound is also discarded.

A UE is defined to be in outage if its Packet Error Rate (PER) is higher than 3%. PER computation includes packets dropped over-the-air, packets dropped at the Node-B and the UE due to the delay bound criterion. On the DL, the system is said to have reached capacity if 5% of the UEs are in outage. On the UL, an additional stability condition is imposed while defining capacity: the Noise Rise should not exceed 7 dB more than 1% of the time.

On the DL, we used a proportional fair scheduler with both channel sensitive and delay sensitive terms, similar to [1]. As a packet's delay approaches the delay bound, its priority increases. On the UL, CSoHS transmission uses non-scheduled grants. This eliminates the overhead of assigning scheduled grants every 20 ms to voice UEs.

The rest of the simulation assumptions are listed in Table 1.

Table 1: System Simulation Assumptions

Parameter	Value
ISD	1 km
Path Loss (dB)	$128.1 + 37.6 \text{ Log}_{10}(D_{km})$
Std-Dev of Log-Normal Shadowing	8 dB
C-PICH Ec/Ior	-10 dB
Total Cell Ior	43 dBm
F-DPCH + E-HICH Ec/Ior	Fixed Case: -10 dB Realistic: Time Varying
Channel Model	3GPP Mix 30:30:20:20 PA3:PB3:VA30:VA120
Number of HARQ Processes	8 on UL, 6 on DL
Max No of Transmissions	6 on DL, 4 on UL
Outer Loop (UL)	UL: 1% Residual BLER after 4 HARQ Tx
HS-PDSCH Outer Loop Margin	0.5 dB
UE Receiver Type	LMMSE: 1 Rx and RxD
Node-B Receiver	RxD, Rake w/MRC

III. System Settings And Overhead Channel Modeling

In the following sub-sections, we describe the modeling of the overhead channels as well as other system settings.

A. F-DPCH

The F-DPCH channel on the downlink carries the power control bit for the UE's UL Dedicated Physical Control Channel (DPCCH) ([5]) in every slot (2560 chips). This channel is carried on a Spreading Factor (SF) 256 code. Given 2560 chips per slot, each SF-256 code can support 10 F-DPCH symbols.

The UE's UL DPCCH is power controlled by all cells in its active set. So, for UEs in Soft Handover, F-DPCH is sent from all the cells in the UE's active set. Depending on the number of UEs per cell and the soft handover factor, F-DPCH occupies a certain number of SF-256 codes per cell.

Figure 2 explains how we modeled the power consumption for "N" SF-256 codes that carry F-DPCH per cell. For each UE, the F-DPCH power requirement may be different. For each 256 chip period (covering one F-DPCH symbol), the F-DPCH power is summed up across all the N F-DPCH codes. This gives the required power per 256-chips. Note that the required power for F-DPCH may change every 256 chips.

Figure 2 also identifies the maximum power taken by F-DPCH over a slot. This power cannot be allocated to the High Speed Downlink Shared Channel (HS-DSCH), since we do not allow HS-DSCH power to vary every 256 chips.

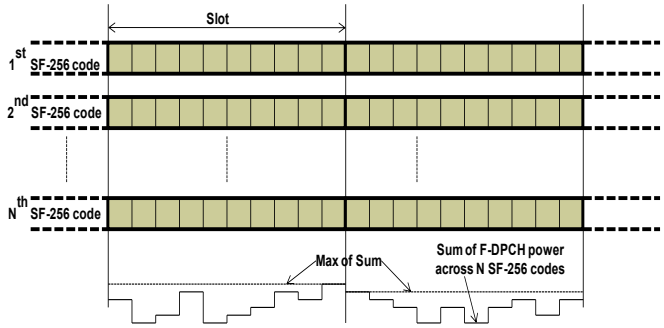

Figure 2: Power Consumption for F-DPCH channels transmitted by a cell

The F-DPCH channel is power controlled by the TPC bits sent on the UL DPCCH. We assumed a 2 slot delay for this power control, so as to account for transmission and decoding. For the purpose of DL simulations, we assumed an i.i.d 4% error rate on the TPC bit sent on the uplink. For UEs in Soft Handover, F-DPCH powers were balanced every 20 ms, by equating F-DPCH power from the non-serving cells to that from the serving cell. Power balancing is commonly used in CDMA-based systems to prevent the power transmitted to a UE from its soft handover legs from drifting; such drift might happen due to decoding errors on power control bits transmitted on the uplink. We also imposed a peak Ec/Ior of -16 dB per user per cell for F-DPCH.

When DTX is enabled, the UE wakes up for UL DPCCH transmission 2 slots before the TTI in which it can transmit UL data (E-DPDCH and E-DPCCH) and stays awake for 1 slot following this TTI. Figure 3 shows the transmission duration for F-DPCH and UL-DPCCH assuming a DTX cycle of 4 TTIs. As F-DPCH "follows" TPC bits transmitted on the UL, the UE listens to F-DPCH for 6 out of 12 slots in this example.

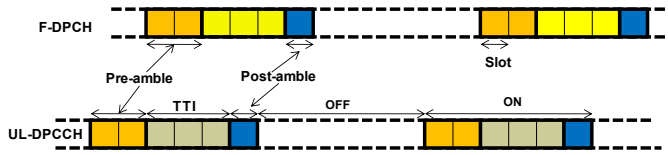

Figure 3: F-DPCH and UL-DPCCH When DTX is enabled

B. E-HICH

The E-HICH channel carries the ACK/NAK information on the DL for a packet transmitted by the UE on the UL. This channel is transmitted on an SF-128 code. There are 40 signatures which are used for E-HICH and E-RGCH channels. The E-RGCH channel is used by the Node-B for sending relative grants to the UEs. In this paper, since we assume UL transmission of CSoHS voice happens through non-scheduled grants, we allocate all 40 signatures to E-HICH. So, 1 SF 128 code can be shared by 40 UEs ([5]). E-HICH On-time depends on UL TTI length. For 2 ms TTI on UL (our assumption), E-HICH is ON for 2 ms on the DL.

For Soft Handover UEs, UL data is decoded by all the cells in the UE's active set. So, E-HICH may be sent to the UE from all these cells. From the serving cell, E-HICH is sent whether the packet is decoded successfully (ACK) or not (NAK). From the non-serving cells, however, E-HICH is sent only in case the packet successfully decoded (ACK). As shown in Table 1, we target 1% block error rate (BLER) after 4 transmissions on the uplink. From simulations, we find that the average number of transmissions per uplink packet is 2.5. Thus, from the serving cell, the UE receives:

- During Speech Period: 2.5 E-HICHs every 20 ms or 10 TTIs
- During Silence Period: 2.5 E-HICHs every 160 ms or 80 TTIs
- Mean No. of E-HICHs per TTI = 2.5*(1/10+1/80)*0.5 = 0.141
  - The factor of 0.5 accounts for speech and silence occurring with equal probability.
- Frequency of E-HICH transmission = 1/0.141 ~ 1 in 7 TTIs

Users in Soft Handover also receive E-HICH from the non-serving cell. However, E-HICH is transmitted from the non-serving cell only in the case of an ACK. Thus, from the non-serving cell, the UE receives:

- During Speech Period: 1 E-HICH every 20 ms or 10 TTIs
- During Silence Period: 1 E-HICH every 160 ms or 80 TTIs
- Assume equal probability of decoding at the serving and non-serving cells (the non-serving cell is likely weaker, so this assumption leads to an upper bound in number of E-HICHs transmitted from the non-serving cell).
- Mean No of E-HICHs per TTI = 1*(1/10+1/80) * 0.5 * 0.5 = 0.028
  - The first factor of 0.5 accounts for speech and silence occurring with equal probability.
  - The second factor of 0.5 accounts for equal probability of decoding at the serving and non-serving cells.
- Frequency of E-HICH transmission = 1/0.028 ~35 TTIs

In summary, we assume the following frequencies of E-HICH transmission:

- From the serving cell: 1 out of 7 TTIs
- From the non-serving cell: 1 out of 35 TTIs.

The two main metrics to consider when evaluating the performance of the E-HICH channel are the Probability of False Alarm (FA), i.e., P(DTX->ACK), and the Probability of Missed Detection (MD), i.e., P(ACK->DTX).

The event DTX->ACK occurs whenever the Node-B transmits a DTX on the DL and this is decoded as an ACK at the UE. The Node-B transmits DTX only when it misses the E-DCH Dedicated Physical Control Channel (E-DPCCH) on the UL. In the case of a CSoHS system, this event leads to increased packet error rate, since the UE thinks the Node-B has successfully decoded the packet, and does not retransmit the packet. So, the probability of this event needs to be kept to a very low value.

The ACK->DTX event occurs when the Node-B has successfully decoded a packet, but the ACK sent by the Node-B is mis-decoded as a DTX by the UE. In the case of a CSoHS system, this leads to reduced capacity on the UL, since the UE retransmits packets that have been successfully decoded by the Node-B.

To keep the impact to UL capacity small, we targeted a probability of 0.2% for false alarm and 5% for missed detection (note that since the average number of transmissions on the uplink is ~2.5, 5% missed detection leads to 5%/2.5 = just 2% increased retransmissions). This gives a C2P of -9 dB for E-HICH from serving cell for Non-SHO UEs. For UEs in soft handover, the same considerations lead to -6 dB C2P for E-HICH from serving cell and -4 dB C2P for E-HICH from non-serving cell.

C. HS-DPCCH (ACK Channel)

As in the case of E-HICH, the two main metrics to consider when evaluating the performance of the HS-DPCCH ACK channel are P(FA), and P(MD).

The event DTX->ACK occurs whenever the UE transmits a DTX on the UL and this is decoded as an ACK at the Node-B. The UE transmits DTX only when it misses the High Speed Shared Control Channel (HS-SCCH) on the DL. The probability of missing the HS-SCCH is typically 1% or lower. Thus, to meet a 0.1% probability for the false alarm event, we target a probability of 10% for the DTX->ACK event.

The ACK->DTX event leads to reduced capacity on the downlink, since the Node-B retransmits packets that have been successfully decoded by the UE. To keep the impact to downlink capacity small, we targeted a probability of 1% for

missed detection.

We performed link simulations to evaluate the performance of the ACK channel under various fading channels, as well as under conditions where the UE has a single link or is in soft handover (with varying degree of imbalance between serving and non-serving cells).

For the non-SHO scenario, with a T2P of 6dB for the full-rate AMR frame, an ACK C2P of 0dB meets (or is close to the 1% ACK->DTX target) for all the considered fading channels. For the case of SHO with equal serving and non-serving links (i.e., imbalance of 0 dB), an ACK C2P of 2dB is required to meet the ACK->DTX target. For other imbalance scenarios, which are likely to occur less frequently, some degradation of the probability of mis-detection is seen, but the probability is within a few percent.

Based on these results, we chose C2P of 0 dB for non-SHO and 2 dB for SHO, when 6 dB is the T2P for the payload of the full-rate AMR frame. Note that when T2P for the full-rate AMR payload is 8 dB or 10 dB (corresponding to lower pilot setpoints), the C2P for HS-DPCCH is increased by 2 dB and 4 dB respectively.

D. HS-DPCCH (CQI Channel)

Errors on the CQI channel may lead to a wrong choice of transport block size at the base station scheduler. The HSDPA CQI, however, has unequal error protection : the MSB has ~1 dB more protection than other bits. Thus, the probability that CQI errors cause a big change in the SNR information is small. In addition, CQI reports are usually filtered by the base station scheduler. These two points make the HSDPA system quite robust to errors on the CQI channel. Our simulation results (not included here due to lack of space) show insignificant degradation in system capacity with up to 5% errors on the CQI channel. To meet this 5% error target, our link simulation results show that a good choice of C2P for the CQI channel is -2 dB (when not in SHO) and 0 dB (when in SHO), when 6 dB is the T2P for the payload of the full-rate AMR frame.

E. E-DPCCH

For the E-DPCCH channel, the two metrics that one needs to consider are (i) the probability of false alarm P(FA), which is the probability that the Node-B mistakenly detects E-DPCCH without the UE transmitting, and (ii) the probability of missed detection P(MD), which is the probability of the Node-B missing an E-DPCCH transmitted by the UE. E-DPCCH false alarm can lead to increased pilot setpoint, since the NodeB expects an E-DPDCH transmission, attempts to decode and sees a failed CRC. E-DPCCH missed detection leads to wasted E-DPDCH transmissions, since the E-DPDCH will not be used for decoding if E-DPCCH decoding fails.

In our simulations, the RNC uses a MAC-layer based outer loop setpoint adjustment algorithm. Using this algorithm, the RNC increases the setpoint only if it sees a "hole" in the received TSN sequence. This algorithm ends up being insensitive to E-DPCCH False Alarm, since the setpoint responds only to an actual missing TSN. We, thus, focus on the other metric, i.e., P(MD). Based on link simulations, when using a T2P of 6 dB for the full-rate AMR frame, the C2P required for E-DPCCH to meet P(MD) of 1% is 0 dB.

Note that when T2P for the full-rate AMR payload is 8 dB or 10 dB (corresponding to lower pilot setpoints), the C2P for E-DPCCH is increased by 2 dB and 4 dB respectively.

F. Continuous Packet Connectivity (CPC)

We ran DL simulations with DRX cycle of 4 TTIs and DTX cycle of 4 TTIs. For UL simulations, we assumed DTX Cycle-1 of 4 TTIs and DTX Cycle-2 of 8 TTIs. Note that the UE is typically in DTX Cycle-2 during silence periods. The CPC feature also includes the use of preamble and postamble, which are pilot transmissions before and after the DTX "on" times. These are used to help channel detection and estimation at the NodeB. We assumed that the preamble and postamble are 2 slots and 1 slot respectively.

G. Traffic To Pilot (T2P) Ratios

For the payload of the full-rate AMR frame, we used different values of T2P (6 dB, 8 dB and 10 dB). The T2P for the payload carrying the SID frame was ~3 dB lower than that for the full-rate frame. The T2Ps were chosen to cover a range of pilot setpoints. In general, lower pilot setpoints reduce the overhead due to pilot, leading to higher capacity, but also cause higher error rates for TPC bits sent on the uplink.

H. UL DPCCH Formats

Two uplink DPCCH formats were simulated: the (8, 2) format, meaning 8 pilot bits and 2 TPC bits, and the (6, 4) format, meaning 6 pilot bits and 4 TPC bits. The (6, 4) format helps to improve performance of TPC bits.

IV. CSoHS Voice Capacity

A. Downlink Capacity

In this section, we present capacity results for the DL. We assumed that NodeBs can use 100% power; if power were lower to allow some margin for the Power Amplifier (PA), the capacity may be lower. We present capacity results for the cases of: (a) 10% fixed power for F-DPCH and E-HICH without DRX/DTX, (b) realistic modeling of F-DPCH and E-HICH (based on details presented in Section II) without DRX/DTX, (c) realistic modeling of F-DPCH and E-HICH with DTX enabled, DRX disabled and (d) realistic modeling of F-DPCH and E-HICH with both DTX and DRX enabled. Table 2 shows the capacity results for a system consisting of Single Rx Antenna UEs. We assume a Rake receiver with Pilot Weighted Combining for the F-DPCH channel; the HS-DSCH channel is equalized.

Assuming a fixed power of 10% for F-DPCH+E-HICH causes capacity to be overestimated by 23% (81 versus 66).

Table 2: Capacity Numbers with 1 Rx Antenna UEs

Scenario	Capacity
Baseline (10% Ec/Ior for F-DPCH+E-HICH)	81

(No DRX/DTX)	
F-DPCH+E-HICH Realistic (No DTX, No DRX)	66
F-DPCH+E-HICH Realistic (DTX, No DRX)	69
F-DPCH+E-HICH Realistic (DTX, DRX)	63

The use of DTX and DRX has the following impacts:

- DTX saves F-DPCH power on the DL (as mentioned in Section III.A) and increases the DL capacity. It also allows for UE battery life gains.
- DRX allows for additional UE battery life gains on top of DTX. However, DRX reduces the number of UEs available for scheduling per TTI. This leads to loss in multi-user diversity and hence loss in voice capacity.

With DTX and DRX enabled, the voice capacity is 63 users/cell, while enabling DTX and disabling DRX leads to 69 users/cell.

In Figure 4, we show the power consumption for the F-DPCH channel per user across all of its serving cells, as a function of the channel model. We see that PA3 consumes the least amount of power.

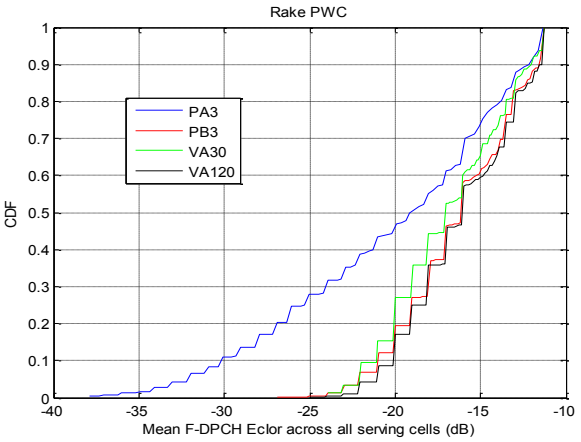

Figure 4: Mean F-DPCH power consumption per user across all of its serving cells with DTX

MAC segmentation on the DL allows the full-rate packet to be segmented, if, based on the CQI, there is not enough power to support it (this benefits the PA3 channel, in particular). We found the capacity with MAC-segmentation to be 77 users/cell, with realistic modeling of F-DPCH and E-HICH with DTX enabled and DRX disabled.

Table 3 shows the capacity results for a system where UEs have Receive Diversity (RxD). Again, note that assuming a fixed power of 10% for F-DPCH+E-HICH causes capacity to be overestimated. Unlike in the single Rx Antenna case, here the overestimation is much more significant. The reason is that with RxD, the baseline capacity increases ~3 fold. So, if we realistically model the power consumption of F-DPCH and E-HICH, they consume a larger proportion of cell power, thereby reducing capacity to 180 users/cell (without DRX or DTX).

Table 3: Capacity Numbers with RxD

Scenario	Capacity
Baseline (10% Ec/Ior for F-DPCH+E-HICH) (No DRX/DTX)	260
F-DPCH+E-HICH Realistic (No DRX, no DTX)	180
F-DPCH+E-HICH Realistic (DTX, No DRX)	217
F-DPCH+E-HICH Realistic (DTX, DRX)	190

Similar arguments for impacts of DTX and DRX hold for UEs with two receive antennas, as for UEs with single receive antenna. With DTX and DRX enabled, the capacity for UEs with RxD is 190 users/cell.

The gains from MAC segmentation are likely to be lower for RxD UEs compared to single rx UEs, since the probability of such UEs being CQI-limited is lower.

B. Uplink Capacity

In this section, we present results on uplink CSoHS capacity. As mentioned in Section II, the UL capacity is also limited by the Noise Rise criterion (noise rise does not exceed 7 dB more than 1% of the time). When Interference Cancellation (IC) is enabled, we consider the Effective Noise Rise (after interference cancellation), as the capacity limiting factor. Our IC implementation is based on the design principles defined in [6] and is described in more detail in [1]. The IC efficiency is a function of the pilot SNR at the Node-B.

Table 4 presents the UL capacity for a few values of T2Ps and slot formats, with and without DTX and IC.

Table 4: UL Capacity

Full-Rate Frame T2P	Slot Format (Pilot, TPC)	No DTX, No IC	No DTX, IC	DTX, No IC	DTX, IC
6dB	(8,2)	71	90	102	137
8dB	(8,2)	82	105	110	152
	(6,4)	76	100	102	142
10dB	(8,2)	88	116	110	154
	(6,4)	81	110	102	145

We see that T2P=10dB and the (8, 2) slot format provides the highest capacity, but this comes at a significant TPC error rate of ~18%. We think that T2P=8dB and the (8, 2) slot format provides a good trade-off between TPC error rate and system capacity.

V. Conclusions

In this paper, we presented DL and UL CSoHS capacity results with realistic modeling of overhead channel resource consumption. On the DL, we performed system simulations with realistic modeling of F-DPCH and E-HICH. On the UL, we modeled the power consumption of HS-DPCCH and E-DPCCH. In addition, the T2Ps for E-DPDCH and slot formats of UL DPCCH were chosen so as to reduce the error rate on the TPC bits, which power control the F-DPCH on the DL.

Our simulations showed that with DTX and DRX enabled and no MAC segmentation, the capacity for single antenna UEs is 63 users/cell, and for dual antennas UEs is 190 users/cell. Note that maximum battery life gains for the UE are realized when both DTX and DRX are enabled. With MAC-segmentation, the capacity with single antenna UEs improves by ~10%.

On the UL, with 8 dB T2P for the AMR full-rate frame and the (8, 2) slot format for UL DPCCH, our simulations showed the capacity to be 110 users/cell with DTX and 152 users/cell with DTX and IC.

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