Control and Data Signaling in SC-FDMA Communication Systems

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1. Introduction

The disclosed invention considers the transmission of positive or negative acknowledgement signals (ACK or NAK, respectively) and channel quality indicator (CQI) signals in a single-carrier frequency division multiple access (SC-FDMA) communications system as it is known in the art and is further considered in the development of the 3GPP E-UTRA long term evolution (LTE). The invention assumes the uplink (UL) communication corresponding to the signal transmission from mobile user equipments (UEs) to a serving base station (Node B). The ACK/NAK and CQI signals may also be referred to as the physical uplink control channel (PUCCH) or simply the control channel. The invention further assumes that ACK/NAK or CQI signals are transmitted together with data signals carrying the service information.

The ACK or NAK signal is in response to the correct or incorrect, respectively, data packet reception in the downlink (DL) of the communication system which corresponds to signal transmission from the serving Node B to a UE. The CQI signal transmitted from a reference UE is intended to inform the serving Node B of the channel conditions for channel-dependent scheduling of DL data. Either or both of the ACK/NAK and CQI signals may be transmitted simultaneously with or separately from the data signal. As previously mentioned, the disclosed invention considers the former case. This case may also be referred to as data-associated transmission of the ACK/NAK and/or CQI signals.

The UEs are assumed to transmit control and/or data signals over a transmission time interval (TTI) corresponding to a sub-frame. **Figure 1** shows the sub-frame structure assumed in the disclosed invention. The sub-frame has duration of one millisecond and comprises of two slots. Each slot further comprises of seven symbols and each symbol further comprises of a cyclic prefix in order to mitigate interference due to channel propagation effects as it is known in the art. Furthermore, the middle symbol in each slot carries the transmission of reference signals (RS), also known as pilots, which are used to provide channel estimation and allow coherent demodulation of the received signal (DM RS).

The transmission bandwidth (BW) is assumed to comprise of frequency resource units which will be referred to as resource blocks (RBs). Each RB in a symbol is assumed to comprise of 12 sub-carriers and UEs are allocated a multiple N of consecutive RBs for the data transmission. Nevertheless, the above values are only illustrative and not restrictive to the embodiment of the disclosed invention.

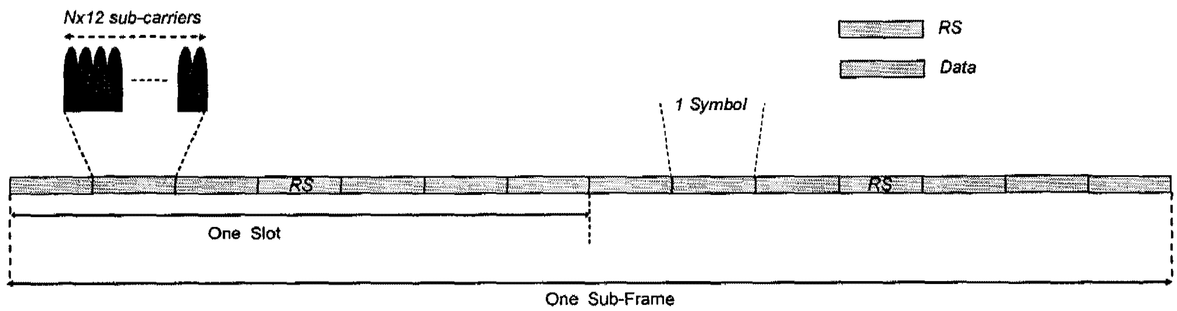

Figure 1: Structure of the UL Sub-Frame.

An exemplary transmitter structure for SC-FDMA signaling is shown in **Figure 2**. In order to transmit the control (ACK/NAK and/or CQI) bits, certain data bits (such as, for example, the parity bits in case of turbo coding) may be punctured and replaced by the control bits in order to maintain the single-carrier property. The discrete Fourier transform (DFT) of the combined bits is then obtained, the sub-carriers corresponding to the assigned transmission bandwidth are selected, the inverse fast Fourier transform (IFFT) is performed and finally the cyclic prefix (CP) and filtering are applied to the transmitted signal. This time division multiplexing (TDM) between the control (ACK/NAK and or CQI) and data signals prior to the DFT is necessary to preserve the single carrier property of the transmission.

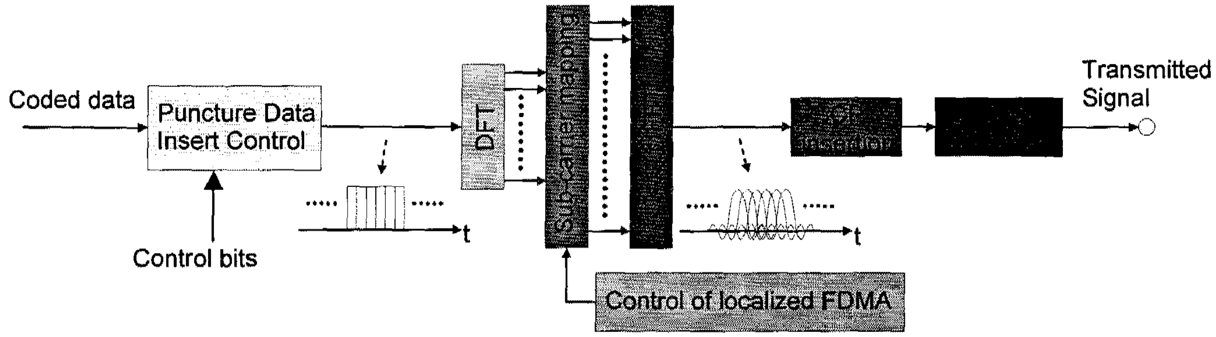

Figure 2: Multiplexing of Control and Data Signals

2. Placement of Data-Associated ACK/NAK and CQI Signals

The main object of the invention is the placement in the UL sub-frame of the ACK/NAK and CQI signals by considering aspects related to their reception performance and other general SC-FDMA communication system requirements. Another object of the invention is the enhancement of the overall reception reliability for the data signal.

A first observation for the UL sub-frame structure in **Figure 1** is that the demodulation RS (DM RS) exists only in the middle symbol of each slot. In case of high speeds, this results to substantially degraded channel estimate for symbols located further away from the DM RS (that is, for symbols near the beginning and end of each slot). This may be acceptable for data transmission which is coded, has typically a relatively large target block error rate (BLER) of 10% or above, and can benefit from retransmissions though a conventional HARQ process. Conversely, the CQI and particularly the ACK/NAK have much stricter performance requirements.

The second observation relates to the transmission of a sounding RS (SRS) in synchronous systems. The SRS has a wideband nature and is transmitted by UEs in order to serve the purposes of UL frequency domain channel dependent scheduling, timing estimation for synchronous operation, and power control as it is known in the art. **Figure 3** illustrates the concept of SRS transmission. The SRS typically has larger transmission bandwidth than the data and the DM RS. It is transmitted periodically in one of the symbols of the UL sub-frame (in the example of **Figure 3**, the SRS is transmitted in the first symbol and once every two sub-frames).

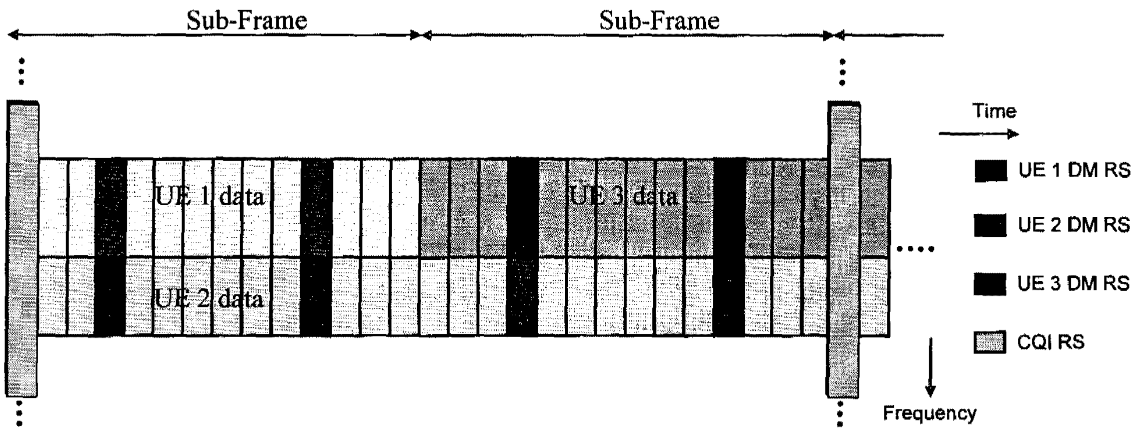

Figure 3: Multiplexing of Control and Data Signals

Because the DM RS is assumed to have a contiguous spectrum, the SRS cannot be transmitted at the middle symbol of each slot because it will create mutual interference with the DM RS (clearly, the DM RS transmission is necessary for the data demodulation and cannot be omitted). Distributing the CQI and ACK/NAK signals substantially over the entire UL sub-frame will either severely restrict the placement of the SRS or introduce additional complexity and performance loss in the reception of ACK/NAK and/or CQI signals as puncturing will be dynamically needed in a symbol depending on whether or not the SRS is transmitted in that symbol. Having as many as possible locations for the SRS transmission is desirable in synchronous systems because, for proper UL CQI and power control measurements, the SRS should capture interference from data transmission and not from other SRS transmission, that is, SRS transmission from neighboring cells and Node Bs should not coincide.

Subsequently, a brief set of simulation results for the raw bit error rate (BER) is provided to illustrate the impact of inaccurate channel estimation on the data reception quality as a function of the symbol position in the slot and the UE speed. **Table 1** provides the simulation assumptions which provide the most optimistic setup for the performance loss of symbols further away from the DM RS because:

a) Transmission bandwidth is 1 RB. This maximizes power per sub-carrier.
b) Channel frequency selectivity is large and there are 2 uncorrelated receiver antennas. This maximizes the slope of the raw BER curve.
c) Operating signal-to-interference and noise ratio (SINR) is large. This minimizes the impact of inaccurate channel estimation.

Table 1: Simulation Assumptions

Parameters	Assumptions
Operating Bandwidth @ Carrier Frequency	5MHz @ 2.6 GHz
Modulation Scheme	QPSK
Data Transmission Bandwidth (BW)	1 RB
UE Speed	3, 30, 120 and 350 kmph
Transmission Type	Localized (at same RB) over the sub-frame at 3, 30 Kmph Frequency Hopping Between Slots at 120 and 350 Kmph
Channel Model	GSM - TU6
Number of Receive Antennas	2
Number of Transmit Antennas	1

Figure 4 presents the raw BER. At symbol locations symmetric to the DM RS, the BER is typically the same. At 120 Kmph and 350 Kmph, the transmission in the first slot is assumed to occur at a different BW than the one in the second slot (frequency hopped transmission per slot). As only 1 DM RS per slot is available for channel estimation, the BER is the same at symbols symmetric (equidistant) to the DM RS. At low speeds, such as 3 Kmph, this is also the case because the channel does not change over the sub-frame. Some variability does exist for medium UE speeds, such as 30 Kmph, but, for simplicity, the average BER of symbols equidistant to the DM RS is shown in **Figure 4**.

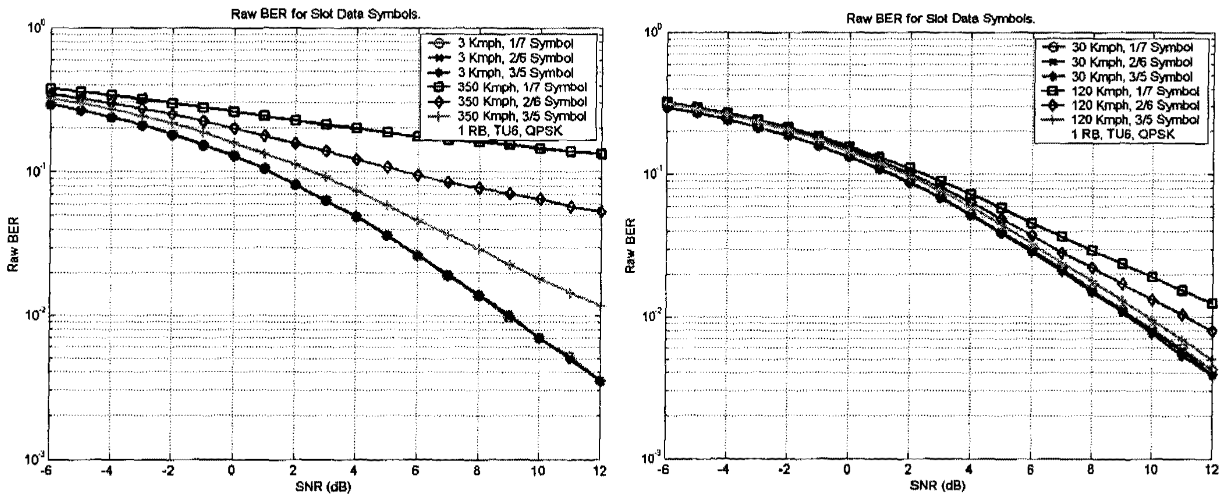

Figure 4: Raw BER as a Function of the Slot Symbol and the UE Speed.

Even under the previous, most optimistic, assumptions for the raw BER degradation at symbols further away from the DM RS, at 350 Kmph, the BER saturates at the $1^{st}/7^{th}$ and $2^{nd}/6^{th}$ symbols. However, the impact on the BER of the $3^{rd}/5^{th}$ symbols is rather contained and saturation is avoided (the difference relative to the BER at 3 Kmph is also partly due to the fact that the latter uses both RS in the sub-frame for channel estimation, that is, channel estimation is operating with 3 dB more SINR). The BER at 120 Kmph, relative to the one of the $3^{rd}/5^{th}$ symbols at about 1% BER, is also degraded by about 3 dB for the $1^{st}/7^{th}$ symbols and by about 1.5 dB for the $2^{nd}/6^{th}$ symbols. Obviously, due to the flattening of the BER curves for the $1^{st}/7^{th}$ and $2^{nd}/6^{th}$ symbols, the degradation will be much larger for operating points below 1% as needed for the NAK reception.

Based on the results in **Figure 4** it becomes apparent that the data-associated PUCCH transmission should be placed immediately next to the DM RS. **Figure 5** shows an example for such placement when a UE transmits both ACK/NAK and CQI during a sub-frame by applying TDM with data.

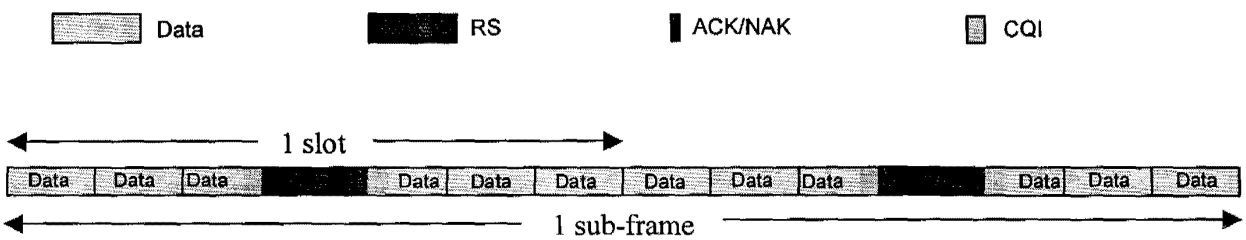

Figure 5: Placing of ACK/NAK and CQI Transmission

Figure 6 shows an example for such placement when the UE transmits only ACK/NAK bits together with the data signal during a sub-frame while **Figure 7** considers the case of only CQI and data transmission.

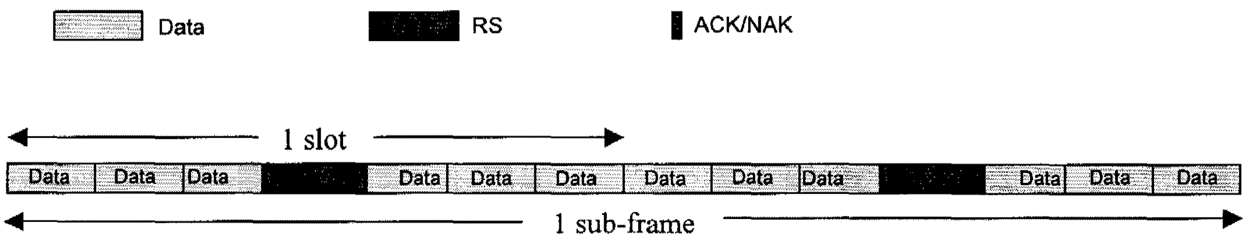

Figure 6: Placing of ACK/NAK Transmission

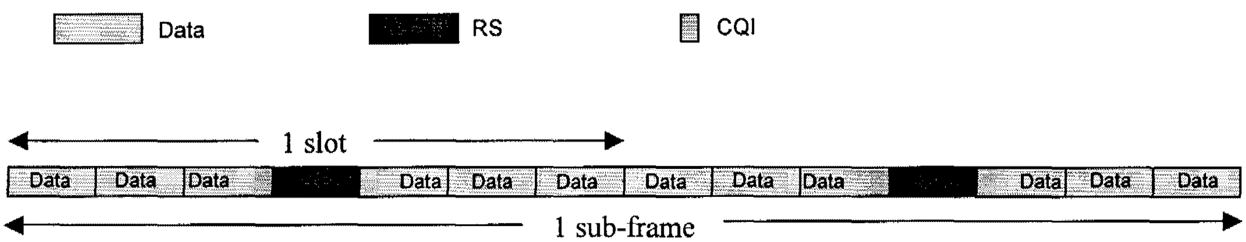

Figure 7: Placing of CQI Transmission

To minimize channel estimation losses, the ACK/NAK should be placed with priority in the symbol after the first DM RS. Notice that this does not impact demodulation latency as a channel estimate is available only after the first DM RS (clearly, there is no use from earlier transmission with respect to latency).

Subsequently, to address low SINR or coverage issues, the ACK/NAK can be placed in the symbol before the second DM RS. The reason is that for medium UE speeds, this second ACK/NAK placement benefits from improved channel estimation and time diversity while for high UE speeds, it benefits from frequency and time diversity. The tradeoff is the increased latency which however is not critical for the ACK/NAK transmission. Typically, data non-associated PUCCH transmission is assumed to be over the entire sub-frame and therefore, the resulting latency for the proposed data-associated PUCCH transmission is not larger. Moreover, CQI and ACK/NAK performance targets are similar for all UE speeds while they are most challenging to achieve for high UE speeds.

Provisioning for ACK/NAK transmission in the number of sub-carriers over 2 symbols is typically comfortably adequate to achieve the desired BER for the ACK reception even for the lowest SINRs and transmission only over 1 RB (corresponding to the fewest number of available sub-carriers). Nevertheless, since the NAK reception has lower BER requirements, it is appropriate for robustness and to achieve time and frequency diversity, to have the ACK/NAK transmission over the number of sub-carriers in 1 symbol in each slot.

If further ACK/NAK transmissions are needed, because of low SINR or coverage issues, or for some interference randomization in asynchronous systems, the other symbols next to the RS in the 2 slots

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