Abstract of Ph.D. Thesis
"Uplink Timing Synchronization for Fifth Generation Communication Systems"
Mr. Alok Kumar Sinha (2015BSZ8005)

Fifth generation (5G) wireless communication systems have envisioned a communication utopia where every device and application will be served according to their need. This Herculean dream cannot be realised based on a single technology approach. Therefore the next-generation 5G wireless systems are a collective effort of many technologies such as massive multiple-input multiple-output (MIMO), millimeter wave (mmWave) communication, small cell network (SCN), device-to-device (D2D) communication, machine-to-machine (M2M) communication, etc. Area traffic capacity, network energy efficiency, latency, connection density, etc., are some of the key performance indicators of 5G. On the basis of requirements, the use cases of 5G are broadly classified into massive machine-type communication (mMTC), ultra-reliable and low-latency communication (URLLC) and enhanced mobile broadband (eMBB).

Uplink timing synchronization is the initial step of establishing a communication link between a base station (BS) and a user terminal (UT). For uplink timing synchronization, UTs advance their uplink time by their respective round-trip propagation delays so that the uplink signals from all UTs reach the BS simultaneously. In uplink timing synchronization, the BS estimates the round-trip propagation delay of a UT based on the random access (RA) preambles received from that UT in the uplink. The BS conveys this information back to that UT through random access response (RAR), and subsequently, the UT advances its uplink timing and attains uplink timing synchronization.

The uplink timing synchronization method in fourth generation (4G) long term evolution (LTE) systems is not robust to channel induced Doppler spread and cannot support simultaneous random access requests from a large number of UTs. Hence, the performance of the uplink timing synchronization method in 4G LTE degrades severely in high user density and high mobility scenarios. Since 5G systems are expected to operate in high user density and high mobility scenarios also, the 4G LTE uplink timing synchronization methods cannot be used in 5G systems. Therefore, in this thesis, we propose uplink timing synchronization methods for 5G systems, which are robust to mobility induced delay spread as well as high user density.

For high user density scenarios in 5G (e.g., mMTC, eMBB), we have proposed a novel uplink timing synchronization method based on massive

multiple-input multiple-output (MIMO). In massive MIMO systems, the BS is equipped with a large antenna array and can support multiple UTs in the same time-frequency resource, thereby enhancing connection density and traffic capacity. The RA preamble received at all the BS antenna is averaged so as to reduce the effect of AWGN and fast fading. This spatial averaging enables the successful detection of RA preambles even in scenarios where the same RA preamble is transmitted by more than one UT. It is noted that such collision scenarios will be more probable in high user density scenarios and will result in significant degradation of performance of uplink timing synchronization in 4G LTE systems. Also, the reduction in the effective noise variance makes the proposed method energy efficient. Detecting multiple UT on the same RA preamble and decreasing the preamble transmit power is not possible in 4G LTE. In 4G LTE, the random access response of each detected RA preamble is broadcast on a different downlink resource. As there is limited downlink resource for RAR broadcast, this limitation results in another bottleneck for uplink timing synchronization in 4G LTE. Therefore, in the proposed method we estimate the channel impulse response for each UT from the received RA preamble at the BS. This channel estimate is then used to beamform the RAR for more than one UT on the same downlink resource thereby enabling successful uplink timing synchronization for a large number of UTs in high user density scenarios. Beamforming of the RAR (instead of broadcasting it) also enables significant reduction in the downlink RAR transmission power.

In high mobility scenarios, the channel induced Doppler spread results in performance degradation in 4G LTE due to loss of orthogonality between its subcarriers. In this thesis, for high mobility scenarios we have proposed a novel RA preamble transmission waveform which is based on orthogonal time frequency space (OTFS) modulation. The proposed waveform is designed in the delay Doppler (DD) domain, which makes the estimation of the round-trip propagation delay almost invariant of the channel induced Doppler shift. For a given bandwidth constraint for the RA preamble waveform, we choose the delay domain width and the number of delay domain sub-divisions in such a manner so as to ensure accurate estimation of the round-trip propagation delay between a cell-edge UT and the BS and also a low peak-to-average power ratio (PAPR) of the RA preamble waveform. In OTFS modulation, the Doppler domain width is the inverse of the delay domain width and the number of Doppler domain sub-divisions is equal to the total time duration of the RA preamble waveform divided by the delay domain width. We study the probability of missed detection of this delay-Doppler domain RA preamble and also propose time-domain windowing of the received RA preambles so as to reduce interference between adjacent RA preambles along the Doppler domain. Our study reveals a trade-off between the number of allowed RA preambles and the Doppler domain width of each RA preamble. A large Doppler domain width of each RA preamble reduces the amount of interference between adjacent RA preambles, but then this also reduces the number of allowed RA preambles which increases the probability of two or more UTs transmitting the same RA preamble. Numerical simulations reveal that in high mobility scenarios, the probability of missed detection of the proposed DD domain RA preamble waveform is significantly smaller than that of the RA preamble waveform in 4G LTE systems.

In this dissertation, we have addressed two important challenges faced by current methods for uplink timing synchronization. We have proposed novel solution to these problems which will help in realizing the vision of 5G.