論 文 の 内 容 の 要 旨

論文題目 A Physical-layer Investigation on Concurrent Transmission for Wireless Networks
（同時送信型無線ネットワークの物理層に関する研究）

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Multi-hop networks are expected to play an important role in the upcoming Internet-of-Thing (IoT) era. Concurrent transmission (CT) is a revolutionary multi-hop protocol that significantly improves the MAC- and network-layer efficiency by allowing synchronized packet collisions. Although its superiority has been empirically verified, there is still a lack of comprehensive physical-layer investigation on how the receiver survives such packet collisions, particularly in the presence of the carrier frequency offsets (CFO) between the transmitters. In this work, we undertake this task. The main contributions are threefold.

Analyses of the CT characteristics: By utilizing the similarity between the CT and the wireless multi-path fading channel, we present an equivalent channel model of the one-hop behavior of CT. Next, we provide actual measurement numbers to show that the CFO is the dominating factor in the CT channel, and the beating effect resulting from the CFO affects the receiver performance significantly. In view of the importance of the beating signal, we further theoretically derive the closed form of the average fading duration (AFD) of the beating in terms of the transmitter number and the standard deviation of the CFO, and prove that the derived AFD is an effective indicator to quantify the receiver performance degradation resulting from the beating. Our derivation theoretically shows that the AFD can be reduced by increasing the deviations of CFO and the number of transmitters that joins the CT. Finally, we estimate the AFD in real systems by measuring the CFO of a large amount sensor nodes.

Evaluations of CT on IoT standards: We evaluate the results for IEEE 802.15.4, IEEE 802.15.4g, and a recently popular low-power-wide-are (LPWA) standard - the LoRa system. We distinguish our evaluation from the previous ones by the extensive CT effect modeling, discerning metrics, and accurate and reproducible evaluation platform. The main findings from our evaluations are as follows. For the IEEE 802.15.4 system, we show that the adopted direct sequence spread spectrum (DSSS) scheme plays the key role in combating the beating effect.

However, due to the limited length of DSSS, the receiver still suffers from the beating if the fading duration is too long. On the other hand, we also show that the basic M-ary FSK mode of IEEE 802.15.4g is vulnerable to CT due to the lack of error correcting mechanism. We also prove that is a proper error correcting mechanism is implemented, CT can still be applied to the IEEE 802.15.4g system. For the LoRa system, we find that, due to the time-domain and frequency-domain energy spreading effect, LoRa is robust to the packet collisions resulting from CT. We further show that the receiver performance under CT can be further improved by introducing timing offsets between the relaying packets.

Proposal of novel CT-enabled applications: The third contribution is the proposal of two novel CT-enabled applications using the insight obtained from the theoretical analysis and comprehensive evaluations. The first proposal is the multiple-building-area networks (MBAN), which is a wireless network consisting of only indoor low-power devices while providing a wide coverage over several buildings. In view of that the 2.4~GHz multi-hop networks suffer from the weak penetration power, we strive to construct a CT-based sub-GHz LoRa network (CT-LoRa). Thanks to the analyses and evaluations in the previous chapters, we have learned that introducing timing offsets can improve the reliability of LoRa receiver under CT. Toward this, we propose a timing delay insertion method, the offset-CT method, that adds random timing delay before the packets while preventing the timing offset from diverging over the multi-hop network. Moreover, we conduct proof-of-concept experiments to demonstrate the feasibility of CT-LoRa. Secondly, we propose to apply CT to the distributed antenna system (DAS). Specifically, in the conventional DAS, sophisticated cooperations are adopted to prevent fading. However, such cooperation also significantly restrict the real-time capability. On the other hand, CT can realize real-time DAS but with the risk of introducing fading. Since we have learned that the fading duration can be improved by having more antennas and higher CFO deviation, we proposed to adopt the CT in the DAS system with massive antenna as well as large random frequency offset to guarantee both real-time capability and reliability.