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Article

MCST Scheme for UAV Systems over LoRa Networks

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Abstract: In recent years, low-power wide-area network (LPWAN) has received widespread popularity with long-range and wide-area communication at low power for the Internet of Things (IoT) systems. Among many vendors of LPWAN, long-range low-power wireless communications, also called LoRa, is one of the competing standards and is well known in both academia and industrial communities as an emerging research area. Among the LoRa applications, unmanned aerial vehicles (UAV) systems are emerging with the benefits of extended battery life and a long communication range. In this paper, we investigate the network capacity with the mixture of concurrent and sequential transmission (MCST) scheme over LoRa networks. From the simulation results, it can be seen that MCST is suitable for implementation in the LoRa network. Specifically, MCST can achieve higher throughput with low transmission latency and energy consumption compared to the existing CSMA approach LoRa MAC. Besides, we also propose a modified MCST over the LoRa (mMCST/LoRa) scheme to mitigate the transmission latency further. The simulation results reveal a better performance in terms of throughput, latency and energy consumption, regardless of the frame payload size and the number of nodes in the network.

Keywords: basic relaying flow; MCST; MAC protocol; LoRaWAN; ad hoc networks

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1. Introduction

The evolution of today's wireless communication environment is heading to the 6G mobile communication system, which is also known as a fully digital and connected world with human-centric mobile communications. The networks in the 6G are expected to be highly reliable data-driven wireless networks with interconnected and intercommunicated devices, and the number of wireless devices is expected to increase dramatically. Nakamura [1] described that the technologies such as the Internet of Things (IoT), artificial intelligence (AI), robots, and big data would play a major technology in the future communication system. In the realisation of the IoT system, low-power wide-area network (LPWAN) is the emerging wireless network technology designed for the communication ability among low-power, especially battery-powered devices over long geographical areas [2]. Long-range low-power wireless communications, commonly known as LoRa, is one of the standards of LPWAN and is well known for low-cost design with long-range and low power communication. Since the sensors and end devices in the IoT system are mainly battery-based and power-limited communication devices, LoRa works as the solution to optimize the consumed energy of the end devices in the network. For example, Konstantinos et al. designed an access protocol based on the time-division multiple access (TDMA) principles for LoRa-based IoT systems [3]. In addition, as the application of LoRa in LPWAN, plenty of research has been done in sensor networks and unmanned aerial vehicle (UAV), which is also called drone, networks [4].

UAV is a flying vehicle without human pilots onboard, usually remotely controlled, and can be fully or partially autonomous. The UAV systems exhibit as an emerging technology with its benefits of line-of-sight link, dynamic deployment ability, link reliability and so on [5,6]. As an example of the UAV system, Shan et al. conduct the experiment of air-to-air communication by developing a drone location information sharing system over the LoRa network in [7]. Besides, they apply the machine learning technique in the model establishment for drone communication [8]. Similarly, Dong et al. [9] also employ UAVs to integrate with the machine learning technique for providing aerial services, i.e., communication service and edge computing service, in the 6G mobile communication system. A different scenario of the UAV system, in particular, a hybrid communication architecture for UAV swarms, is proposed by combining the long-range communication protocol and IEEE 802.11s protocol in [10]. In the other work, Saraereh et al. [11] evaluate the LoRa network performance with the UAV for disaster management. They proposed the decentralized topology control algorithm for the UAVs to ensure connectivity without being affected by node mobility. The authors in [12] also mention that the spectrum efficiency and energy efficiency of the communication can be significantly improved by utilizing UAV as the relay node to assist the cellular transmissions. Similarly, Xiong et al. [13] propose an energy-efficient data collection scheme over the LoRa network by employing the UAV as the gateway and show a significant improvement in energy consumption. However, UAV systems require low latency and high capacity transmission for resource sharing and performing mission-critical and time-critical applications. In this paper, we investigate the network capacity improvement when the mixture of concurrent and sequential transmission (MCST) scheme is used for remote identification and tracking of UAV system, which provides low-cost broadcast-based location information sharing between drones over the LoRa network.

2. LoRaWAN Network Architecture

LoRa is a physical layer or modulation technique for long-range low-power wireless communication. LoRa generally follows the standard of IEEE 802.15.4 for the low-rate wireless personal area network. LoRa is mainly used to feature low-power operation, low data rate, low cost and complexity, long communication range and long battery lifetime [14,15]. As shown in Figure 1, LoRa wide area network (LoRaWAN) is organized as a star network topology, in which the end devices connect to the network server through the gateway. The end device is the low-power end device, which supports the services or IoT applications. The gateway is the communication device that connects the end devices in the LoRa network to and from the server. The network server monitors the devices, i.e., the end devices and gateways, services, and applications in the network.

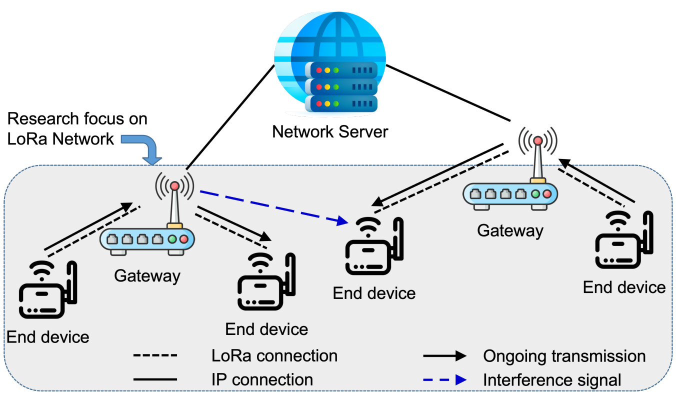

Figure 1. An example of LoRaWAN network architecture.

On top of the LoRa modulation, as illustrated in Figure 2, there are three classes of LoRaWAN medium access control (MAC) protocol that define how the end device proceeds with the communication. Class A is the baseline in which the end device performs the bi-directional communication which is a set of uplink transmissions from the end device to the gateway, and two short receive windows for downlink transmission from the gateway to the end device. The end device may initiate the transmission based on their need according to the random time basic ALOHA-type protocol. The gateway initiates the transmission through class B by sending the PNG packet as a ping message to the end device. Besides, the gateway sends a beacon every 128 s for synchronization purposes. With the synchronized beacon, different from random receive windows of class A, the end device opens the scheduled receive windows for downlink transmission. The end device in class C continuously opens the receive window until there is an uplink transmission. Therefore, the end device uses much more power than class A and class B.

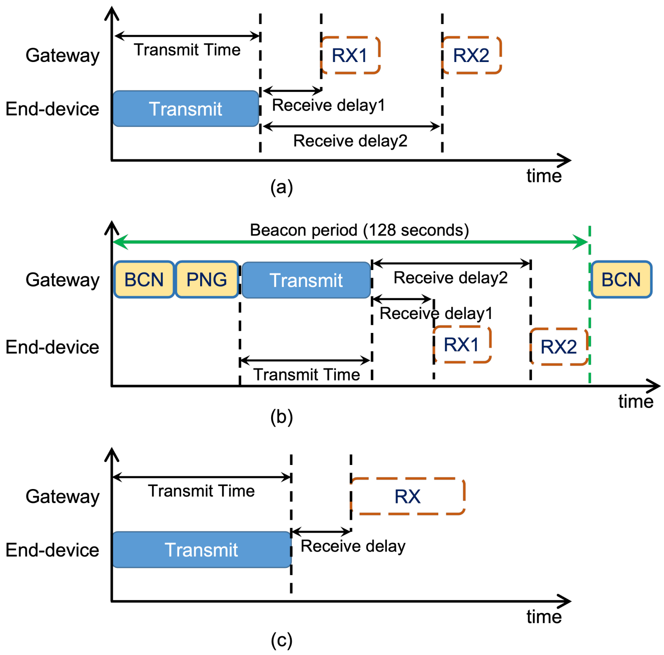

Figure 2. Three classes of LoRaWAN MAC; (**a**) Class A, (**b**) Class B and (**c**) Class C.

Plenty of research works have been proposed on LoRaWAN in different approaches [16–21]. LoRaWAN generally operates as the standard of pure-ALOHA protocol and has the drawback of a high packet loss rate due to collisions [16]. Therefore, Polonelli et al. applied the concept of slotted ALOHA and acknowledgment for successful transmission on the design of the LoRaWAN protocol in [17]. This work claims that the throughput gain can be achieved around six times compared to the standard LoRaWAN because of the highly successful transmission ratio. Generally, LoRaWAN cannot be implemented with the handshaking mechanism because the end device in the network does not always listen to the incoming transmission. They only wake up to transmit if they have DATA for uplink transmission. To overcome the high packet loss of the transmission, Ahsan et al. proposed the modified listen-before-talk mechanism in [18] and shows the improvement of channel utilization with energy consumption even in dense wireless networks. Similarly, the carrier-sense multiple access (CSMA) mechanism is considered in the design of LoRaWAN MAC for reducing the collision and optimizing the channel capacity in [19,20]. Among the different approaches of the LoRaWAN protocol, the authors in [21] showed that CSMA is scalable in terms of throughput and energy consumption. Similar research work to optimize the consumed energy of the LoRaWAN can be found in [22]. Moreover, the ever-increasing number of devices in the network and the growth of traffic still lead to capacity demand and energy consumption for better transmission performance. The existing research considered the approaches of proposing MAC to realize the transmission, minimize energy consumption and optimize the throughput in the network. The aforementioned research works show a lack of investigation into the approach of the transmission scheme over LoRa networks.

In this paper, we intend to investigate network capacity improvement with the mixture of concurrent and sequential transmission (MCST) scheme in the LoRa network. Only the LoRa network with the connection between the end devices and the gateway is considered for network capacity via the transmission scheme, which is different from the existing research approach in the LoRa network. Therefore, the objective is to study how the MCST scheme influences the performance of the LoRa network to maximize the throughput with minimum energy consumption. The scope of this research work is to focus on the performance investigation of the MCST scheme without considering the underlying physical layer of the LoRa network.

Our contributions to this paper are as follows:

1. It is possible to utilize the MCST scheme and the optimal throughput with minimum latency and energy consumption can be accomplished in the LoRa network.
2. The proposed modified MCST scheme over the LoRa network (mMCST/LoRa) further optimizes the performance of the MCST scheme regardless of the frame payload size and the number of nodes in the network.
3. The simulation result reveals that the performance of the LoRa network in terms of throughput, latency, and energy consumption can be optimized through the transmission scheme.

It should be noted that this paper is an updated version of [23] which was presented as a preliminary network capacity study of the MCST over the LoRa network. The structure of this paper is organized as follows. Section 3 describes the system model, and Section 4 discusses the MCST scheme. MCST scheme over the LoRa network is discussed in Section 5. Then, Section 6 describes the numerical simulations to describe the capacity improvement of the MCST scheme over the LoRa network, and the conclusion is drawn in Section 7.

3. System Model

In the LoRaWAN network architecture, we consider the LoRa network, network among the end devices and gateway, as illustrated in Figure 1. We only focus on a single relaying transmission flow in which one end device as a source node (S) connects to the other end device, which is assumed as a destination node (D) through the gateway in the network. We assume the gateway as a relay node (R) without considering the relaying strategies, i.e., decode-and-forward, amplify-and-forward, and so on, for simplicity. We simply define the transmission as a basic relaying flow (BRF) transmission, which is the combination of a source-relay (SR) transmission and a relay-destination (RD) transmission, by neglecting the time synchronization problem. Besides, there is no direct transmission between S and D since LoRaWAN does not support end-device to end-device communication [24]. We also assume that the end device and gateway are identical for theoretical purposes. It means that they have the same transmit power and channel bandwidth, and are operating with the same frequency channel in the network. Therefore, the term nodes in this paper simply represent the end device and gateway. Let $\mathbb{N} = \{1, \dots, n, \dots, N\}$ be the set of nodes where N is the total number of nodes. Each BRF transmission can be selected at most $F = N/3$ from the set of BRF transmissions, $\mathbb{F} = \{1, \dots, f, \dots, F\}$ in one network topology, where F is the total number of BRF transmissions. Besides, the selection of node combinations in a single BRF transmission is randomly performed in the network topology.

3.1. Channel Model

As the channel model for the transmission, the signal attenuation is based on the log-distance pathloss model with ITU recommendation [25]. The channel gain in decibel [dB] from transmitting node i to receiving node j of the ongoing transmission, where $i, j \in \mathbb{N}$, is given as

$$PL_{ij} = 10 \cdot \alpha \cdot \log_{10}(d_{ij}) + \delta + 10 \cdot \gamma \cdot \log_{10} \mathrm{F} + N(0, \sigma) \quad (1)$$

where α is the attenuation constant or coefficient associated with the increase of pathloss with distance, d_{ij} is the Euclidean distance between node i and node j in meter, δ is the coefficient associated with the offset value of pathloss and $\delta = 29.2$, γ is the coefficient associated with the increase of pathloss with frequency and $\gamma = 2.11$, F is the operating frequency [GHz], and $N(0,\sigma)$ is instantaneous fading, which is the zero mean Gaussian random variables with standard deviation σ. Then, the received power ratio between node i and node j is

$$G_{ij} = \frac{1}{10^{\left(\frac{PL_{ij}}{10}\right)}} \tag{2}$$

3.2. Interference Model

The interference model determines the interfering nodes from other concurrent transmissions and interference power on an ongoing transmission. In this paper, we assume the signal-to-noise ratio (SNR)-based interference model to define the interfering nodes set, i.e., $\mathcal{I}$, of the ongoing transmission as in [26]. As illustrated in Figure 3, the interfering nodes are decided according to the SNR of the ongoing transmission from node i to node j. Specifically, transmitting node k is defined as interfering node and $k \in \mathcal{I}$ if and only if $SNR_{ki} < SNR_{ij}$ and/or $SNR_{kj} < SNR_{ij}$. Then, the signal-to-interference-plus-noise ratio (SINR) at node j is given as:

$$SINR_{ij} = \frac{G_{ij} \cdot P_i}{\eta_j \cdot B + \sum_{k \in \mathcal{I}, k \neq i} G_{kj} \cdot P_k} \tag{3}$$

where P_i is the transmit power of node i, η_j is the noise level of node j, B is the channel bandwidth and k represents the interfering node to the ongoing transmission.

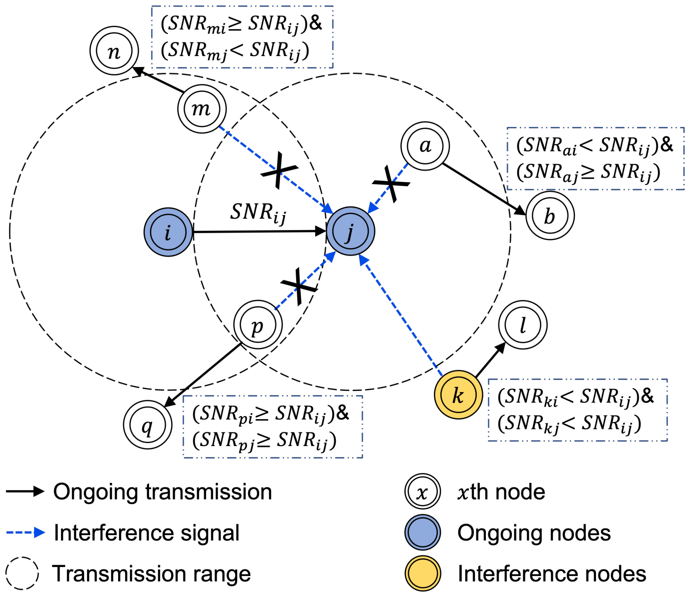

Figure 3. An example of SNR-based interference model.

3.3. Link Capacity Model

Then, the transmission rate [bit/s] from node i to node j is computed according to Shannon's capacity and is given as:

$$R_{ij} = B \cdot log_2\left(1 + SINR_{ij}\right) \tag{4}$$

With the assumed system model including the channel model, interference model and link capacity model, the capacity improvement of the LoRa network is investigated through the MCST scheme.

4. MCST Scheme

The mixture of concurrent and sequential transmission (MCST) scheme is a cooperative transmission scheme operated over the BRF transmission with the relaying node concept in multihop wireless networks. With the idea of TDMA in wireless networks, the transmissions are sequentially executed through the sequential transmission (ST) scheme in the half-duplex (HD) communication system. The ST scheme can give lower interference with limited network capacity. On the other hand, through the concurrent transmission (CT) scheme, several transmissions are executed concurrently in the same transmission medium via the help of potential techniques such as the full-duplex (FD) system. The CT scheme can achieve a higher network capacity. However, the interference issue becomes a considerable factor because of the concurrent transmissions. By applying the concept of the hybrid HD/FD system method, the MCST scheme combines both sequential transmission and concurrent transmission in a shared timeslot to obtain the highest transmission capacity with the least interference power level. For the BRF transmission, the transmission rates of SR and RD transmissions are different if the transmission scheme is operating as ST or CT. However, as the principle feature, MCST controls the time fraction to equal the transmission rates of SR and RD transmissions. Figure 4 illustrates an example of MCST operated over a BRF transmission, in which the SR transmission and RD transmission perform the sequential transmission in the time fraction of $(1 - \tau)$ as case 1 and case 2, respectively. Furthermore, for both cases, the time fractions for concurrent transmissions, i.e., τ_{SR} and τ_{RD}, are computed. Then, the transmission capacity for both cases is computed and MCST optimally selects the one that can give the higher transmission capacity. In this way, the MCST scheme optimizes the transmission capacity of the BRF transmission by optimally selecting the sequential transmission and time fraction of the concurrent transmissions. The MAC protocol to assist the MCST scheme was proposed in WLAN based on the basic access mechanism of distributed coordination function (DCF) in WLAN [26]. By keeping the originality of the MAC protocol with the MCST scheme, the paper designs the MCST scheme to operate over the LoRa network.

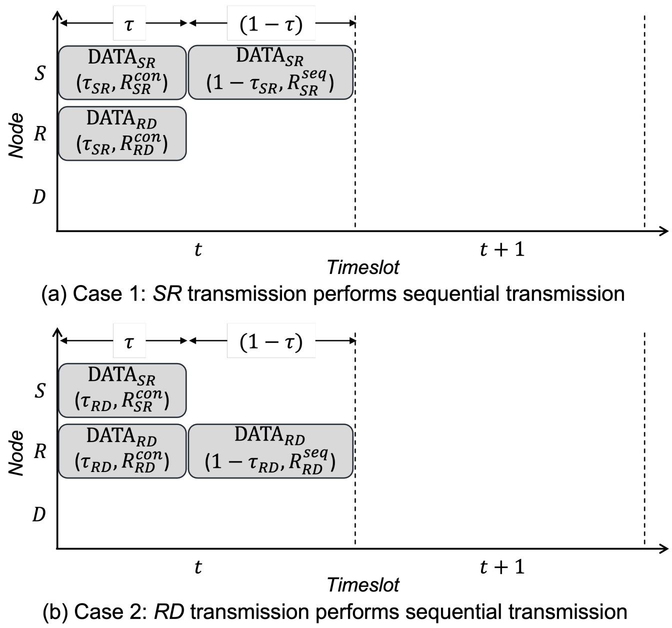

Figure 4. An example of MCST scheme for a BRF transmission.

5. MCST Scheme over LoRa Network

This section describes the design of the MCST scheme for optimizing the transmission performance in the LoRa network. We consider that the node in the LoRa network can perform concurrent transmission. We design the MCST scheme over the LoRa network

(MCST/LoRa scheme) via the drone-to-drone communication for the UAV system by integrating and modifying the three classes of LoRaWAN MAC, especially class A and class B, to enable the DCF mechanism in the MAC layer of the OSI model. Figure 5 shows an example frame exchange sequence for a BRF transmission through the MCST scheme in which the SR and RD transmissions perform the sequential transmission in the time fraction of $(1-\tau)$ for optimum transmission capacity as case 1 and case 2, respectively. As illustrated in the figure, the data transmission can be successfully completed with the four-way handshaking mechanism. Since we neglect the time synchronization problem in this paper, the order of operating sequential transmission and concurrent transmission does not matter in the MCST scheme for theoretical study. However, in the implementation of the real network scenarios, the MCST scheme performing the sequential transmission in the prior time fraction could be beneficial to time synchronization.

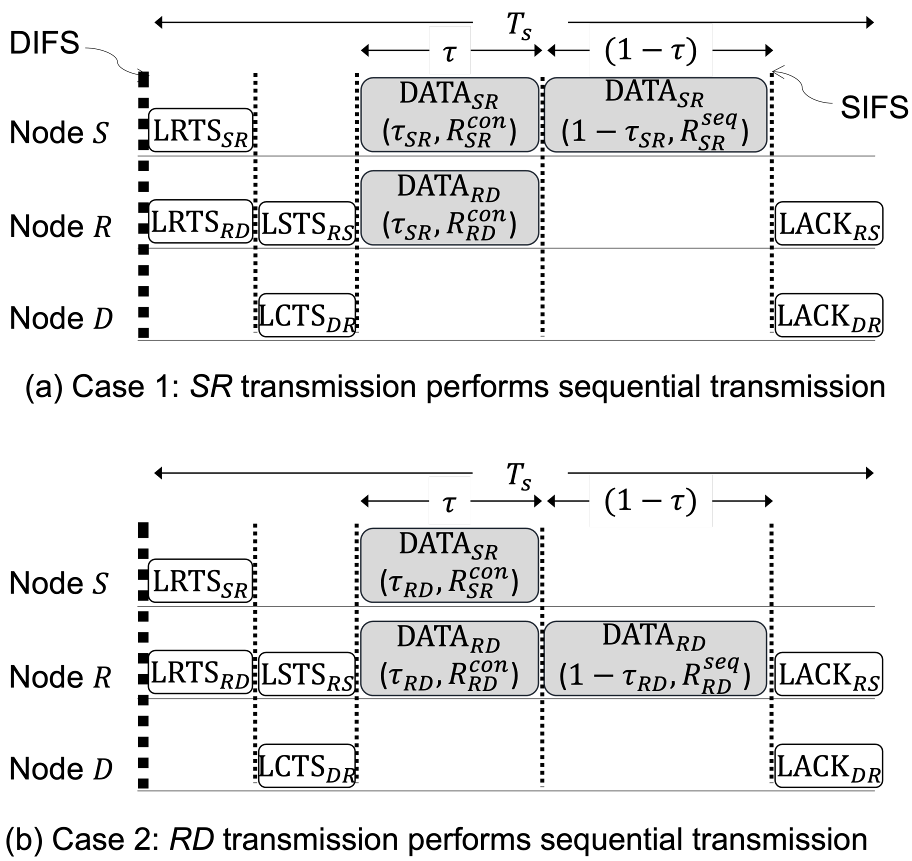

Figure 5. The frame exchanging sequence for successful BRF transmission through MCST over LoRa network (MCST/LoRa scheme).

Figure 6 shows the request-to-send/clear-to-send (RTS/CTS) message handshaking of the MCST/LoRa scheme over the LoRa network. As the figure represents, if the node wants to begin the transmission, it will first send the LoRaWAN request-to-send (LRTS) control frame set, which is a combination of request-to-send (RTS) control frame uplink transmission and LoRa answer (ANS) frame transmission from the gateway. Different from [17], this paper considers that the LoRaWAN-enabled end device in the network is in the acknowledged configuration; on the other hand, there is an answer from/to the gateway for the uplink/downlink transmission. Therefore, to follow the LoRaWAN standard of bi-directional transmission, the gateway will send the ANS frame in the receive window to indicate the reception of the uplink/downlink transmission [22]. We assume that the ANS frame transmission is a function of transmit power, transmission channel, and transmission rate of the uplink/downlink transmission and has a similar transmission time to the uplink/downlink transmission. If the receiving node is ready to accept the transmission, it will send the LoRaWAN clear-to-send (LCTS) control frame set, which is a combination of clear-to-send (CTS) control frame and ANS frame transmissions. Before processing the DATA transmission, the relay node sends the LoRaWAN set-to-send (LSTS) control frame set, which is a combination of set-to-send (STS) and ANS frame transmissions, to pass the MCST information, i.e., time fraction and transmission control for instructing the sequential transmission. After the DATA transmission is complete, the destination and relay nodes inform the transmission completion with the LoRaWAN acknowledgment (LACK) control frame set, which is a combination of acknowledgement control frame and ANS frame transmissions. For theoretical study purposes, this paper considers zero receive delay and only the first receive window with a simple ANS frame downlink/uplink transmission following each uplink/downlink transmission for both class A and class B LoRaWAN MAC.

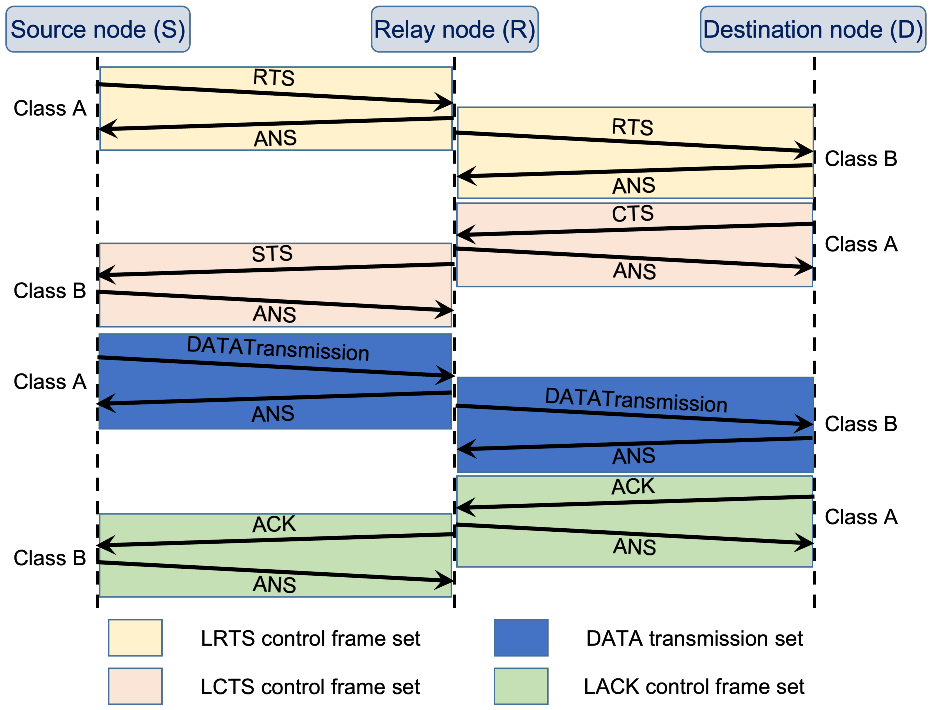

Figure 6. The message handshaking of MCST/LoRa scheme.

As mentioned in [22], the acknowledgment control frame transmission consumes the devices' energy. Therefore, we proposed a modified MCST over the LoRa network, namely mMCST/LoRa, following the LoRaWAN standard of bi-directional transmission as illustrated in Figure 7. In the proposed mMCST/LoRa, the control frames of the handshaking mechanism are reduced by considering the downlink transmission of the STS control frame from the relay node, the uplink transmission of the CTS control frame from the destination node, and the ACK control frame to indicate completion of DATA transmission as the transmission in the receive window of class A and class B LoRaWAN MAC. This way, the control frame transmission time and latency can be reduced, which could lead to the optimal BRF throughput and energy consumption. Figure 8 describes the frame formats of the control, i.e., RTS, CTS, STS, ACK, and DATA messages as the MAC payload frame of LoRaWAN format for MCST scheme with minor modification of LoRa specification [27].

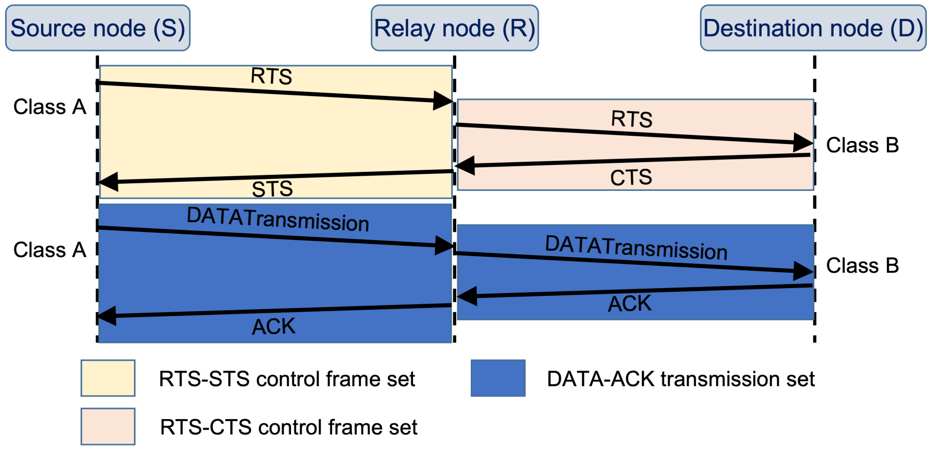

Figure 7. Proposed mMCST/LoRa scheme.

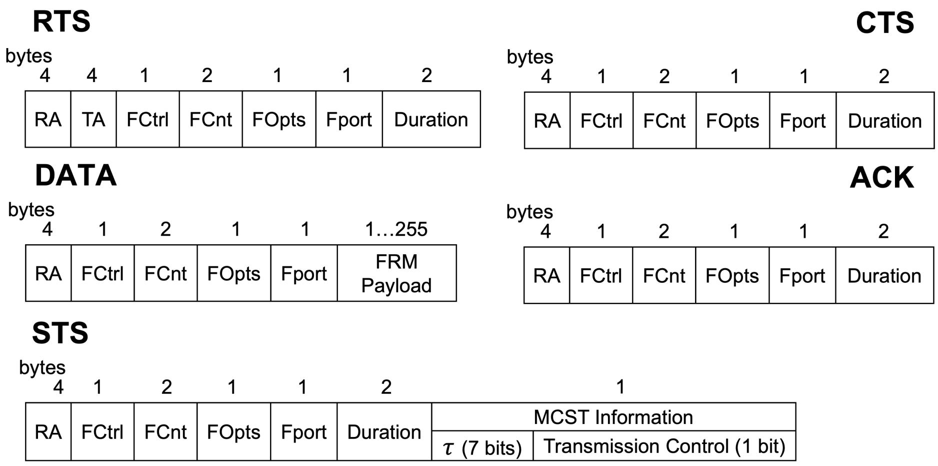

Figure 8. The frame formats of the control and DATA messages for MCST/LoRa.

6. Numerical Simulations

This section describes the performance evaluation of MCST/LoRa and mMCST/LoRa by comparing them with the CSMA/LoRa [19] in the LoRa network. By considering the remote identification and tracking of UAV systems for sharing the location information as the application case study, we perform a preliminary network capacity study of the MCST scheme over the LoRa network.

6.1. Simulation Scenarios and Settings

In this paper, the performance investigation is conducted through computer simulations using MATLAB R2022b. Here, we conduct the two simulation scenarios of performance study according to the frame (FRM) payload size in a 30-node random network topology with the fixed basic rate of 200 kbps and performance study according to the number of BRF transmissions in the network with fixed FRM payload size. The simulation parameters and settings are listed in Table 1 with the standard specification of the LoRa network, i.e., IEEE 802.15.4, for LPWAN [7,27]. In the simulation scenario, the wireless nodes are uniformly distributed in the coverage area with no node mobility model in the network. The node combination in a BRF transmission is randomly selected. We treat the log-distance pathloss model with ITU recommendation as the channel model. The attenuation constant is estimated from the network model of [7] using the particle filters algorithm. In addition, we also assume that all the wireless nodes always have an FRM payload of the same size for DATA transmission, i.e., $M_1 = M_2 = \cdots = M_f = M$. We consider only one transmission per DATA transmission for theoretical capacity study purposes. In our simulation, we focus on studying the performance of the MCST scheme over the LoRa network. Therefore, this paper only considers the transmission between end devices through the gateway and does not look into the performance of routing protocols. In the random topology scenario, 10,000 simulations are performed and averaged to obtain the performance metrics of achievable transmission latency, BRF throughput and energy consumption for a BRF transmission in the network.

Table 1. Simulation Parameters and Settings.

Parameter	Value
Network coverage size	1 km × 1 km × 150 m
Transmit power (P)	20 mW
Frequency (F)	920 MHz [8]
Channel bandwidth (B)	400 kHz [8]
Attenuation constant (α)	2.34 [8]
Shadowing parameter (σ)	5.06 dB [25]
RSSI, Basic rate (R_b)	−98 dBm, 200 kbps −117 dBm, 20 kbps [8]
RTS size	120 bits
CTS size	88 bits
STS size	96 bits
ACK size	88 bits
Preamble time	401.41 ms
Number of simulations	10,000 times

The achievable transmission latency (L_a) is the average summation of the transmission delay and propagation delay to successfully perform a BRF transmission. The transmission delay, D_f means the time required to transmit the DATA frame from the source node to the destination on the channel, which is computed as:

$$D_f = T_{Pre} + T_{LRTS} + T_{LSTS} + \frac{H}{R_b} + \frac{M}{R^{mcst}} + T_{LACK} \tag{5}$$

where T_{Pre} is the preamble time for synchronization, T_{LRTS} is the duration for the LRTS frame set, T_{LCTS} is the duration for the LCTS frame set, T_{LSTS} is the duration of LSTS frame set, H is the header of the FRM payload, R_b is the basic rate of the LoRa system, M is the FRM payload size, R^{mcst} is the transmission rates of SR transmission and RD transmission of a BRF transmission through MCST scheme, which is calculated as in [26] and T_{LACK} is the duration of the LACK frame set. By following the concept of bi-directional transmission in the LoRa network, this paper considers only one receiving slot for ANS transmission and zero receive delay between uplink/downlink transmission and receiving slot for theoretical study purposes. As a result, the transmission time for ANS in receiving slot is similar to the uplink/downlink transmission. The propagation delay, D_{prop} means the time required to propagate the DATA frame across the channel, is computed as:

$$D_{prop} = \frac{M}{c} \tag{6}$$

where c is the speed of light equal to 3×10^8 [m/s] and is constant for all transmissions of every protocol. Then, L_a is computed as:

$$L_a = \frac{1}{F} \sum_{f=1}^{F} L_f \tag{7}$$

where $L_f = D_f + D_{prop}$ is the transmission latency, L of fth BRF transmission.

The achievable BRF throughput (S_a) is the number of bits that can be transmitted from the source node to the destination node of a BRF transmission in one second and is computed as:

$$S_a = \frac{1}{F} \sum_{f=1}^{F} \frac{M}{L_f} \tag{8}$$

Meanwhile, the achievable energy consumption (E_a) is the average of the total energy consumed for transmitting both the control messages and DATA packets from the source node to the destination node and is computed as:

$$E_a = \frac{1}{F} \sum_{f=1}^{F} P \times L_f \tag{9}$$

where P is the transmit power of a transmitting node.

6.2. Simulation Results and Discussion

Firstly, Table 2 describes the performance comparison between CSMA/LoRa, the proposed MCST/LoRa and mMCST/LoRa in terms of achievable BRF throughput, transmission latency and energy consumption for a single BRF transmission in the network with a fixed FRM payload size of 250 bytes. As we can observe that MCST can bring a higher achievable BRF throughput over CSMA in the LoRa network. Besides, MCST also shows its superiority in reducing the achievable transmission latency and energy consumption to CSMA-based LoRaWAN MAC. This is because MCST optimizes the transmission capacity by controlling the time fraction, which results in better throughput, lower latency and lower energy consumption.

Table 2. Performance comparison between CSMA, MCST, and mMCST over the LoRa network with single BRF transmission and a fixed frame payload size of 250 bytes.

	Achievable BRF Throughput [kbps]	Achievable Transmission Latency [s]	Achievable Energy Consumption [mJ]
CSMA/LoRa	4.79	0.418	8.36
MCST/LoRa	4.89	0.409	8.17
mMCST/LoRa	4.92	0.407	8.13

Figure 9 shows the performance comparison of three LoRaWAN MAC in terms of achievable BRF throughput and latency by varying FRM payload size in the 30-node random topology with the fixed basic rate of 200 kbps. We can observe that BRF throughput and transmission latency increase as the FRM payload size increases in the 30-node random topology. However, the simulation reveals that MCST/LoRa gives a higher achievable BRF throughput than CSMA/LoRa. Furthermore, the simulation results show that mMCST/LoRa provides much higher BRF throughput compared to MCST/LoRa. Quantitatively, when the size of FRM payload is 250 bytes in a 30-node random topology scenario, MCST/LoRa and mMCST/LoRa provide 4.75 Mbps and 4.85 Mbps of achievable BRF throughput, respectively, while CSMA/LoRa gives 4.41 Mbps. It means that MCST and mMCST can give 7.71% and 9.98% BRF throughput improvement than CSMA. The reason is MCST optimizes the transmission capacity which results in higher BRF throughput and lower transmission latency. In addition, reducing the control frame transmission time via mMCST gives benefits not only in improving BRF throughput but also in reducing transmission latency.

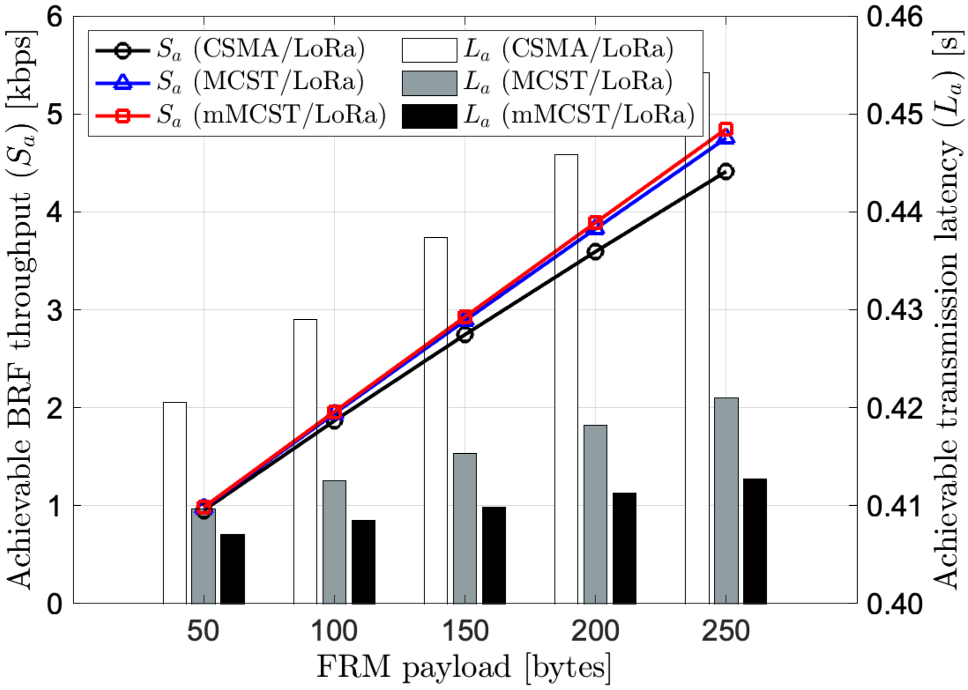

Figure 9. Performance of achievable BRF throughput and latency versus FRM payload for 30-node random topology.

Table 3 describes the performance comparison in terms of energy consumption for the three LoRaWAN MAC. The result shows that MCST/LoRa can provide a better energy-efficient MAC than CSMA-based LoRaWAN MAC in the LoRa network 30-node random topology. This is because MCST/LoRa reduces the latency with the optimized transmission capacity through the MCST scheme and results in less energy consumption. However, the proposed mMCST/LoRa is the best energy-efficient MAC among the three MAC in this paper. Quantitatively, mMCST/LoRa can give up to 9.24% and 2.02% achievable energy consumption reduction compared to CSMA/LoRa and MCST/LoRa, respectively, when the FRM payload size is 250 bytes. The reason is mMCST/LoRa reduces the transmission latency by mitigating the control frame transmission time than MCST/LoRa.

Table 3. Performance comparison between CSMA/LoRa, MCST/LoRa and mMCST/LoRa in energy consumption versus FRM payload for 30-node random topology scenario.

	FRM Payload [Bytes]				
	50	**100**	**150**	**200**	**250**
CSMA/LoRa	8.41	8.58	8.75	8.92	9.09
MCST/LoRa	8.19	8.25	8.31	8.36	8.42
mMCST/LoRa	8.14	8.17	8.20	8.23	8.25

Notes: All the values are in the unit of mJ.

Figure 10 illustrates the comparison of achievable BRF throughput and latency when the number of nodes varies in the network with the fixed FRM payload size of 250 bytes. The results show that MCST can accomplish a higher BRF throughput regardless of the number of nodes compared to CSMA-approached LoRaWAN MAC. The BRF throughput decreases as the number of nodes increases because of the interference in the dense network. However, the optimal transmission capacity provided by the MCST scheme results in a better BRF throughput. Besides, the MCST scheme also outperforms in reducing the transmission latency, especially when the number of nodes is 240 in the network.

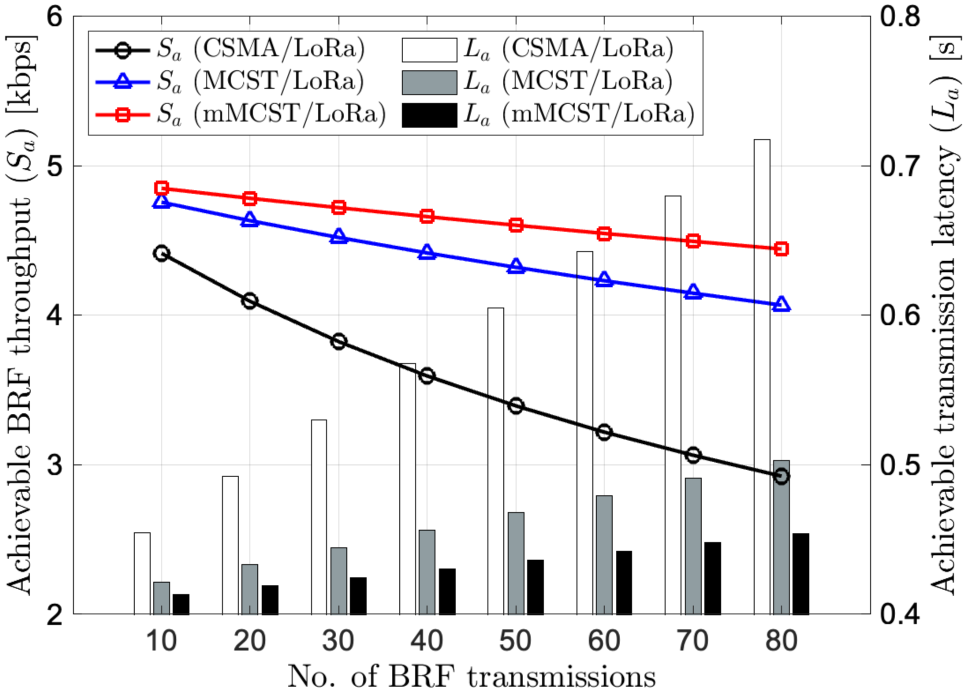

Figure 10. Performance of BRF throughput and latency versus the number of nodes in the network.

Table 4 depicts the performance comparison in terms of energy consumption when the number of nodes increases in the network with the fixed FRM payload size of 250 bytes. As we can observe, MCST/LoRa can save energy up to 29.97% compared to CSMA/LoRa when the number of nodes is 240 in the network. This is because MCST enables DATA transmission at a higher rate and results in a shorter time for successful transmission, leading to less energy consumption than the other MAC.

Table 4. Performance comparison between CSMA/LoRa, MCST/LoRa and mMCST/LoRa in energy consumption versus the number of BRF transmissions.

	No. of BRF Transmissions							
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**
CSMA/LoRa	9.09	9.84	10.59	11.35	12.10	12.85	13.59	14.35
MCST/LoRa	8.42	8.66	8.89	9.12	9.35	9.59	9.81	10.05
mMCST/LoRa	8.25	8.37	8.49	8.61	8.72	8.84	8.95	9.07

Notes: All the values are in the unit of mJ.

Regardless of the number of nodes in the network and FRM payload size, the simulation results show that MCST/LoRa is superior in BRF throughput, latency, and energy consumption compared to CSMA/LoRa. Moreover, by reducing the control frame transmission, the achievable BRF throughput can be optimized, and the transmission latency and consumed energy can be minimized through the proposed mMCST/LoRa. For example, as illustrated in Figure 10 and Table 4, in the 240-node random topology, mMCST/LoRa can achieve 4.44 kbps BRF throughput, 0.45 s of transmission latency, and 9.07 mJ transmission energy consumption when MCST/LoRa gives 4.07 kbps, 0.50 s and 10.05 mJ, respectively, when FRM payload size is 250 bytes. In summary, applying the MCST scheme is beneficial as a contribution to the advantage in terms of achievable BRF throughput, transmission latency and energy consumption of the transmission scheme regardless of the FRM payload size and number of BRF transmissions in the LoRa network.

7. Conclusions

In this paper, we performed the network capacity improvement study of the MCST scheme over the LoRa networks. Besides, we proposed the mMCST/LoRa protocol by suppressing the control frames transmission to operate the MCST scheme. For performance evaluation, we performed two simulation scenarios of variance of frame payload size and the number of nodes in the network. Our simulation studies reveal that applying the MCST scheme in the LoRa network is possible. Furthermore, MCST/LoRa can give superiority up to 52% BRF throughput, 38% of latency, and 37% of energy consumption compared to existing LoRaWAN MAC, i.e., CSMA/LoRa. In addition, the proposed mMCST/LoRa protocol can achieve its superiority over the MCST/LoRa scheme and CSMA/LoRa, regardless of the frame size and the number of nodes in the network. The research works have contributed to the advantages of the transmission scheme, i.e., MCST and mMCST, in the LoRa network. Both schemes are designed to optimize the network capacity through the mixture of concurrent and sequential transmission in the network. If the implementation in the real network scenario is considered, the complexity of designing the mMCST scheme could be higher than the MCST scheme. As a preliminary network capacity study of the MCST scheme over the LoRa network, we simply consider the UAV systems as the application case study and concurrent transmission can be performed on the drone-to-drone communication. In this paper, the proposed MCST scheme contributes to reducing transmission latency that benefits the round trip time, which influences the TCP transmission throughput performance and quality of service of applications. However, this paper remains to consider the other parameters, i.e., the maximum size of an IP packet and packet loss rate, for fully considering the throughput performance of TCP connections, which can be considered as further future research works. Then, the consideration of hardware specification, medium access time, and collision management regarding the implementation in the real network scenario should be considered for a complete capacity improvement study. Besides that, future research should be extended with the performance investigation of the proposed protocol by considering the packet collision using the Markov Chain model and the network node mobility model.

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Abbreviations

The following abbreviations are used in this manuscript:

ACK	Acknowledgement
AI	Artificial Intelligence
ANS	Answer frame transmission
BRF	Basic relaying flow transmission
CSMA	Carrier sense multiple access
CSMA/LoRa	Carrier sense multiple access over LoRa network
CT	Concurrent transmission scheme
CTS	Clear-to-send
DCF	Distributed coordination function

FD	Full-duplex
FD-MCST	FD MAC protocol with MCST scheme
FRM	frame
HD	Half-duplex
IoT	Internet of Things
IUI	Inter-user interference
LACK	LoRaWAN acknowledgement
LCTS	LoRaWAN clear-to-send
LoRa	Long-range low-power wireless communications
LoRaWAN	LoRa wide area network
LPWAN	Low-power wide-area network
LRTS	LoRaWAN request-to-send
LSTS	LoRaWAN set-to-send
MAC	Medium access control protocol
MCST	Mixture of concurrent and sequential transmission scheme
MCST/LoRa	Mixture of concurrent and sequential transmission scheme over LoRa network
mMCST/LoRa	Modified MCST scheme over LoRa network
RTS	Request-to-send
RTS/CTS	Request-to-send/clear-to-send mechanism
SI	Self-interference
SIC	Self-interference cancellation
SINR	Signal-to-interference-plus-noise ratio
SNR	Signal-to-noise ratio
STS	Set-to-send
TDMA	Time-division multiple access
UAV	Unmanned aerial vehicle

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