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Virtual Multiple-Input and Multiple-Output Configuration for Massive Data Transmission in the Internet of Things

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This paper presents a virtual multiple-input and multiple-output (MIMO) configuration (abbreviated VMC) approach for massive data transmission in the Internet of Things (IoT), which coordinates distributed gateways (GWs) with a single antenna to implement MIMO capability virtually. The operation of the VMC consists of two steps: 1) multiple distributed GWs (dGWs) logically construct one virtual gateway (vGW) which behaves like a GW equipped with multiple antennas, and 2) using the constructed vGW, the VMC conducts the traffic scheduling and thereby enables virtual MIMO. Through simulation, we verified that the VMC achieves a higher network throughput than the legacy network by at least 16%. Moreover, we evaluated the variations in channel access time of the VMC under various network conditions.

1. Introduction

The main challenge for wireless connectivity in the Internet of Things (IoT) is to provide a sufficient data rate to gather massive data from a plethora of sensors. In this regard, multiple-input and multiple-output (MIMO) capability is being considered as an IoT-enabling connectivity solution due to its outstanding advantages: 1) bonding the multiple channel bands, and 2) avoidance of collision between the adjacent devices by supporting simultaneous transmissions.[1,2]

IoT systems contain numerous sensor devices, and thus they are generally deployed in a hierarchical manner with several gateways (GWs), such as cluster heads, to balance the traffic load. MIMO capability enables simultaneous transmission for multiple spatial streams via multiple antennas. However, an IoT GW is a resource-constrained device, and as such it is equipped with a single antenna. Therefore, it cannot implement MIMO alone.[3]

In this paper, to apply the MIMO capability to an IoT system, we propose a virtual MIMO configuration (VMC) approach for massive data transmission that coordinates distributed GWs

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(dGWs) with a single antenna to implement MIMO capability virtually.[4] The main contributions of this work are summarized as follows: 1) the creation of a virtual GW (vGW) that behaves like a GW equipped with multiple antennas by utilizing the multiple antennas that multiple dGWs have, and 2) traffic scheduling of the VMC to administrate data and backhaul traffic over a wireless domain of virtual GW. In what follows, we describe the design and performance of the VMC in detail.

2. System Model

Figure 1 shows the system architecture for a VMC with three main components, namely, sensor devices, GWs, and the control device, all of which cooperatively support a common task. A number of sensor devices detect any event or phenomena within the target field. GWs gather data from sensor devices and convey it to the control center. The control device is connected with the remote control center via a wired link and is responsible for the administration of sensor devices and resource allocation.

In the MIMO system, the devices with M antennas can pre-code and decode a maximum of M simultaneous spatial streams. For this, a channel matrix $\boldsymbol{H}$ has to be formed with channel state information (CSI) for each spatial stream. Therefore, a CSI-exchanging mechanism has to be defined to use MIMO capabilities. There are generally two types of CSIs: the statistical CSI and the instantaneous one. The former applies the statistical characteristics of the channel (e.g., fading distribution, average channel gain) to define the CSI and performs well in scenarios in which the channel has a large mean component or the network topology is static.[5] An instantaneous CSI means that the current channel state is known. It enables the receiver to decode multiple simultaneous spatial streams using the CSI computed shortly before transmission. Because wireless channels vary over time, the instantaneous CSI has to be estimated repeatedly on a short-term basis. With a VMC, we assume that the network topology has low-level mobility, and thus the control device memorizes the CSI about the sensor devices and the CSI can periodically be updated via GWs.

3. Design of the VMC

The operation of the VMC consists of two steps: 1) the creation of a vGW, and 2) traffic scheduling for every device in VMC.

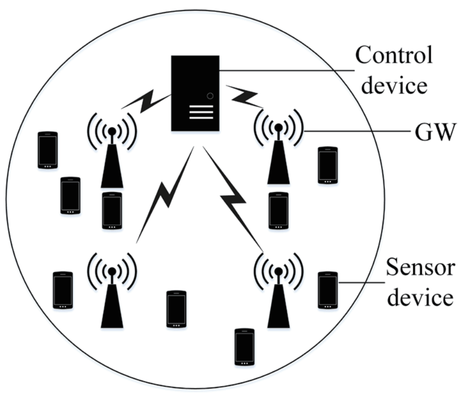

Fig. 1. System architecture for the VMC.

3.1 Creation of vGW

As shown in Fig. 2, a vGW can be built by connecting every GW via a wireless technique such as a wireless mesh network. The control device perceives the service range of each dGW as a sub-cluster and merges all sub-clusters into one large cluster. For this, every dGW has to be tightly synchronized and to operate according to a pre-scheduled superframe.

A control device first makes up a list of all potential dGWs, and then collects information consisting of the following two variables from each dGW: 1) $n_i \in [1, N]$, the number of sensor devices that are already associated with the dGW_i, $i \in [1, M]$; and 2) $k_i \in [1, N]$, the number of sensor devices that exist within the service range of the dGW_i. We assume that N sensor devices and M dGWs are deployed in the system. Using these two variables, the control device redistributes the associated sensor devices to balance the transmission opportunity of each sensor device, considering throughput fairness.

A vGW should behave like a GW equipped with M antennas when M dGWs are deployed in the system. Therefore, the vGW can exploit a maximum of M spatial streams simultaneously over a bi-directional wireless link. A control device composes the channel matrix $\boldsymbol{H}$ for the sensor devices and updates it periodically with the CSI transferred from the dGW.

3.2 Traffic scheduling of the VMC

Figure 3 shows the superframe structure of the VMC, which consists of two sub-periods called the bottom and the upper transfer periods. The former is used for communication between dGWs and their associated sensor devices. During this period, M dGWs, which behave as one vGW equipped with M antennas, transmit and receive M spatial streams simultaneously. The latter, the upper transfer period, accommodates various types of backhaul traffic. The delivery order for the backhaul traffic between dGWs and control devices is shown in Fig. 3. The types of backhaul traffic are defined as follows.

- Uplink (UL) user #i, $i \in [1, M]$: the information about a UL user for uplink data transmission (i.e., address and CSI value). This is reported from the dGW_i to the control device. Every dGW selects one sensor device within its sub-cluster as a UL user. Using the information from the dGWs, the control device forms uplink channel matrix $\boldsymbol{H}_{ul}$.

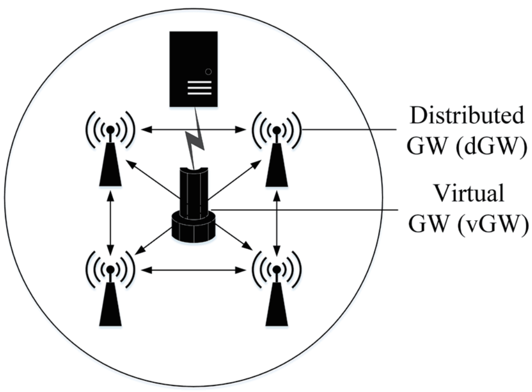

Fig. 2. Virtual GW of the VMC.

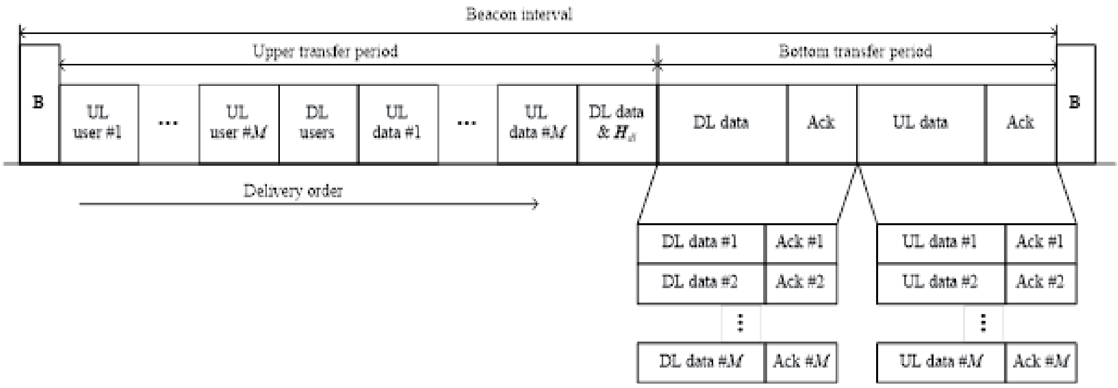

Fig. 3. Superframe structure of the VMC.

- Downlink (DL) users: the list of sensor devices for downlink traffic, which is broadcast by the control device to the dGWs. This list consists of M sensor devices that are individually selected from M sub-clusters.
- UL data #i, $i \in [1, M]$: the data transmitted from a sensor device to its cluster head (dGW_i) in the previous superframe. These data are delivered from the dGW_i to the control device in the current superframe. Multiple UL data from dGWs are merged and decoded by the control device with the channel matrix $\boldsymbol{H}_{ul}$ that was formed in an upper transfer period of the previous superframe.
- DL data: the aggregated traffic of M data frames for downlink, which is broadcast by the control devices to the dGWs. The DL data is pre-coded with the channel matrix for DL spatial stream ($\boldsymbol{H}_{dl}$) at the control device. Every dGW detaches its own data frame from the aggregated traffic and transmits the data frame to DL users at an upcoming bottom transfer period.

4. Performance Evaluation

In this section, the performance of the VMC is compared with that of the legacy network (i.e., IEEE 802.11), which operates by a contention-free medium access protocol under saturated conditions. The system parameters used in the simulation are listed in Table 1. For convenience, we assume that the sensor devices are uniformly distributed and that each dGW maintains the same number of associated sensor devices to construct the sub-cluster.

Figure 4 shows the network throughput of the VMC and legacy network for varying network sizes. The throughput of the VMC is almost constant regardless of the network size, because the quantity of manageable traffic and control overhead (including the inter-frame space) is fixed during the beacon period (i.e., superframe). The network throughput of the VMC increases with any increment in the number of dGWs (M). The more dGWs the system has, the more simultaneous spatial streams can be supported in the VMC.

We compare the VMC with legacy network when M is 8 and observe that the throughput of the VMC is higher than that of legacy network by at least 16% when the legacy network has the maximum network throughput (when the network size is 40). Simultaneous transmissions in the VMC prevent inter-cluster collisions, which enables the merging of available channel resources.

Table 1
Simulation parameters.

Parameter	Value
SIFS	16 µs
DIFS	34 µs
PHY overhead	20 µs
Channel bandwidth	20 MHz
MAC service data unit (MSDU)	1500 B

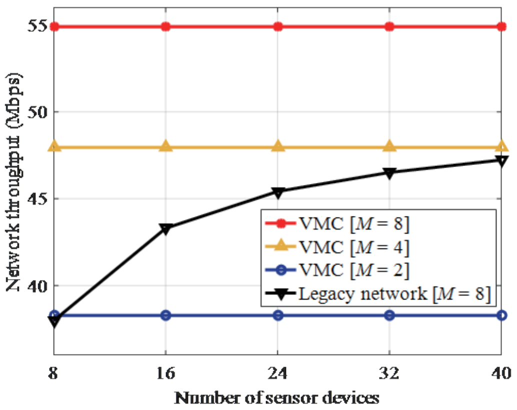

Fig. 4. (Color online) Network throughput.

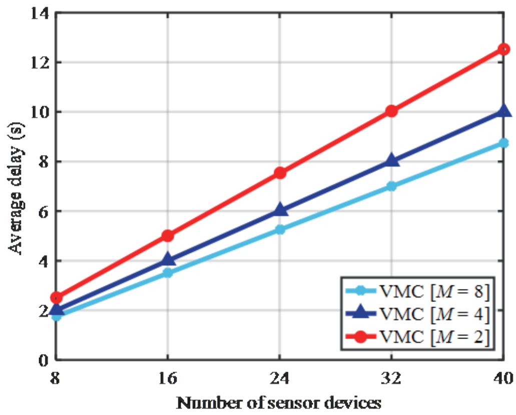

Fig. 5. (Color online) Average channel access time.

As a result, the data rate of the VMC is improved. Figure 5 shows the average channel access time for a sensor device in the VMC. The channel access time means the waiting time to transmit data from any sensor device. The channel access time includes the transmission time of both the control and the data frame for others. As more sensor devices join the system, the devices have to yield more time to traffic for other devices. However, if there are more dGWs in the system, more devices can transmit data at a time, and thus the average channel access time for any sensor device is reduced.

5. Conclusions

In this paper, a VMC is proposed, having a new virtual MIMO configuration approach for massive data transmission in the IoT. The VMC supports simultaneous multiple spatial streams using multiple legacy GWs that each have but a single antenna. The operation of the VMC includes the construction of a virtual GW and the scheduling of traffic. The VMC outperforms the legacy network by at least 16% with regard to network throughput due to multiplexing gain. The multiplexing gain is increased when more GWs are implemented in the system. Therefore, the network throughput of a VMC increases as the number of GWs increases.

Acknowledgments

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