Review

The Wireless Solution to Realize Green IoT: Cellular Networks with Energy Efficient and Energy Harvesting Schemes

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Abstract: With the tremendous increase of heterogeneous Internet of Things (IoT) devices and the different service requirements of these IoT applications, machine-type communication (MTC) has attracted considerable attention from both industry and academia. Owing to the prominent advantages of supporting pervasive connectivity and wide area coverage, the cellular network is advocated as the potential wireless solution to realize IoT deployment for MTC, and this creative network paradigm is called the cellular IoT (C-IoT). In this paper, we propose the three-layer structured C-IoT architecture for MTC and review the challenges for deploying green C-IoT. Then, effective strategies for realizing green C-IoT are presented, including the energy efficient and energy harvesting schemes. We put forward several strategies to make the C-IoT run in an energy-saving manner, such as efficient random access and barring mechanisms, self-adapting machine learning predictions, scheduling optimization, resource allocation, fog computing, and group-oriented transmission. As for the energy harvesting schemes, the ambient and dedicated energy harvesting strategies are investigated. Afterwards, we give a detailed case study, which shows the effectiveness of reducing power consumption for the proposed layered C-IoT architecture. Additionally, for real-time and non-real-time applications, the power consumption of different on-off states for MTC devices is discussed.

Keywords: Internet of Things (IoT); energy efficient; energy harvesting; machine-type communication; cellular IoT

1. Introduction

The explosive progress of information technology enables the Internet of Things (IoT) to support billions of devices on a global scale [1], which has built a bridge to connect the virtual cyber world to the real physical world [2]. With tremendous heterogeneous IoT devices and various applications, the world is truly transformed into a global village [3], providing us a platform to enjoy the smart environment and deeply changing the manner in which we live, work, and study [4].

In the traditional IoT deployment, sensor nodes are the main components; however, currently, IoT is also composed of other kinds of IoT devices, such as actuators [5], unmanned aerial vehicles (UAVs) [6,7], robots [8], etc. Furthermore, in the near future, more wearable devices will appear to execute the functionality of health monitoring [9]. Surrounded by various heterogeneous IoT devices, multiple IoT applications are emerging, which advocate diverse latency and energy efficiency (EE) requirements [10,11]. In this context, machine-type communication (MTC) gains momentum and is now a common trend when deploying the large-scale IoT [12].

Compared to the conventional human-to-human (H2H) communications, MTC shows its unique features, which include massive connectivity and transmission, extra low power consumption level,
and high EE and security/privacy requirements [13]. There are several wireless access solutions for realizing MTC in IoT, i.e., ZigBee, WiFi, and Bluetooth [14]. A detailed description of these techniques is given in Table 1. They all work in the 2.4 G spectrum band, and thus, the co-channel interference is severe, bringing a negative effect to the coverage range and transmission distance. Additionally, working in the unlicensed spectrum makes the security issue more challenging to guarantee. As for the wired access solutions, though they are reliable and can provide high data rates, they are not practical in large-scale IoT implementations due to the cost ineffectiveness and lack of scalability and mobility. Therefore, with the trend of massive IoT connectivity, their disadvantages restrict them from going further into practical IoT implementations, and more advanced wireless solutions are advocated [15]. To this end, the cellular network, especially the Fifth-Generation (5G) communication network, exhibits its unique superiority for supporting pervasive connectivity and has been put forward as the most promising wireless solution for massive IoT connectivity [16]. Combining the cellular network with IoT, namely the C-IoT, ubiquitous connectivity and large coverage can be realized [17]. Additionally, the security and quality of service (QoS) requirement can also be guaranteed (Currently, the software-defined network (SDN) is regarded as a crucial technique for IoT deployment. There are two main advantages that can be brought by combining IoT with SDN. Firstly, SDN-based IoT enables the network operator to perform centralized, flexible, and programmable management of numerous IoT devices [18]. Secondly, SDN-based IoT can deal with the challenges arising from heterogeneous access technologies and device infrastructures [19,20]. In this paper, we review the C-IoT architecture, which aims to provide ubiquitous and seamless connectivity to MTC devices. Under the C-IoT architecture, we concentrate on the energy efficient and harvesting designs to implement green C-IoT. The network management and control, however, are not the main focus of this paper, which will be left for our further investigation).

| Details                     | Disadvantages                                      |
|------------------------------|----------------------------------------------------|
| ZigBee                      | 1. Standard low power protocol based on IEEE 802.15.4  |
| 2. Enables low data rate    | 1. Severe interference from a single channel transmission |
| Bluetooth                    | 1. Standard wireless access technology based on IEEE 802.15.1|
| 2. Enables short-range transmission with a data rate of 1 Mbps | 1. Sensitive to fading and interference  |
| 2. The most frequently used wireless access technology | 2. Wide coverage results in a low data rate |
| WiFi                         | 1. Standard wireless access technology based on IEEE 802.11 |
| 2. The most frequently used wireless access technology | 1. Poor mobility  |
|                              | 2. Severe interference                              |
|                              | 3. Lack of security                                 |

Note that the C-IoT is not a major generator of greenhouse emission and global warming, but still has negative effects on environmental conservation owing to the pervasive and ubiquitous connectivity of MTC devices [21]. As for the MTC devices themselves, distributed everywhere and every time to support the functions of sensing, transferring, and communicating, they are typically battery-powered, and it is impossible to recharge them before replacement. In this regard, it is worth considering making the C-IoT operate and work in a more energy efficient manner.

In the literature, there are many research works investigating how to optimally utilize the system power resource and make the C-IoT more energy efficiently. Specifically, Lee et al. in [22] investigated the density clustering-based base station (BS) status control algorithm to reduce total power consumption, where the number of active BSs and their locations could be determined. Similarly, Reference [23] put forward the approach for the BSs to control the on-off states of the IoT devices via downlink signaling. Furthermore, this paper addressed the issues of uplink power control for IoT devices, aiming to improve the uplink coverage performance. Apart from the aforementioned
research towards energy efficient C-IoT, there are also many papers talking about the energy harvesting schemes in the C-IoT. In [24], the authors studied the energy harvesting schemes for uplink and downlink coverage, and the time division-based method was adopted to enable power and information transmission. To realize sustainable communications for massive C-IoT, Qi et al. designed an architecture for channel state information acquisition, signal reconstruction, information decoding, and energy harvesting [25], and the negative effects of channel uncertainty, successive interference cancellation, and non-linear energy harvesting on sustainable communications were also observed. Reference [26] investigated the self-sustainability of the overlay IoT, where the harvested energy was sourced from the downlink cellular networks. The authors in [27] studied the energy and spectrum efficient IoT network, where the spectrum was used for improving spectrum efficiency and energy harvesting. Moreover, the energy transfer was adopted to boost EE in this paper. For non-orthogonal multiple access (NOMA)-based C-IoT, which is equipped with the function of simultaneous wireless information and power transfer (SWIPT), Reference [28] investigated two beamforming designs to maximize the weighted sum rate and minimize the total power consumption, respectively.

In light of the above, in order to solve the ubiquitous and seamless connectivity problem in IoT, we propose a three-plane C-IoT architecture, consisting of the device plane, the access and edge computing plane, and the cloud computing plane. Based on this architecture, we concentrate on the energy efficient and harvesting designs to implement green C-IoT. Specifically, the energy efficient schemes include efficient random access and barring mechanisms, self-adapting machine learning predictions, scheduling optimization, resource allocation, fog computing, and group-oriented transmission. The energy harvesting schemes are classified into two categories, namely ambient energy harvesting and dedicated energy harvesting. More details of these schemes will be presented in the following parts.

The rest of this paper is organized as follows. In Section 2, we propose the layered structure of the C-IoT architecture and present the challenges when deploying the green C-IoT architecture for MTC. The energy efficient and harvesting schemes are depicted in Section 3 and Section 4, respectively. Then, a case study is carried out to validate the superiority of the proposed C-IoT architecture in Section 5. Section 6 concludes this paper and provides future directions for the implementation of the C-IoT.

2. The Green C-IoT for MTC

The IoT is not a fresh concept, but has gained more popularity and momentum recently. It is widely applied in the deployment of smart cities [29,30], such as smart homes [31], smart grids [32], smart monitoring [33], smart transportation [34], eHealth [35], etc., which provides us a platform to improve the work efficiency and bring much convenience to our daily lives. However, everything has its cost. With the IoT devices’ expansion, the network also faces many challenges [36]. Due to the pervasive number of MTC devices, the huge power consumption and carbon dioxide emissions pose great pressure on environmental conservation. This severe situation pushes us to consider the green IoT deployment, which is the general trend of development toward green wireless communications for the future wireless networks’ design [37].

Green IoT aims at reducing power consumption and minimizing operational costs with the aid of energy efficient, sustainable, and environmentally-aware technologies [38,39]. In this regard, green IoT typically implies two meanings. On the one hand, it refers to the schemes adopted by IoT devices bringing a benefit in terms of saving on energy consumption [40]. On the other hand, it means that the IoT architecture, especially the tremendous amount of IoT devices, such as smartphones, notebooks, household electronics, UAVs, etc., is operationally energy-saving. In practical implementations, both aspects are supposed to be considered when realizing the green IoT deployment [41]. By adopting energy efficient and energy-aware schemes, green IoT is able to reduce the greenhouse effect and achieve a sustainable IoT system [42,43].
Owing to the proliferation of IoT devices, MTC will be widely applied to multiple applications, where IoT devices are able to gain the opportunities to communicate with remote automatic devices for monitoring and information exchange without or with minimal manual control [44]. In MTC, the requirements of these applications vary in many aspects [33,45], including the data rate, time latency, coverage area, reliability, security, power consumption, etc. For applications in the residential zone, MTC can be employed in smart homes to provide some intelligent services by automatically controlling the electronic appliances. In farms and factories, MTC is capable of improving the working efficiency of industrial operations. Apart from the aforementioned scenarios, MTC can also be deployed in many other environments, as presented in Figure 1, which has attracted considerable attention from both academia and industry. In particular, some standard work towards the new MTC 3GPP network architecture was published in Release 12 and Release 13 [46], where the overload problem was solved. Moreover, the researchers from the industrial field focus on implementing more practical applications so as to make adequate preparations for smart cities in the coming years (Though the SDN is not specifically studied in this paper, the SDN architecture can be easily extended to the proposed three-tier C-IoT. Specifically, the control plane in the SDN can be implemented in the cloud computing plane with centralized controllers, and the user plane belonging to the SDN corresponds to the device plane and the access and edge computing plane. With this framework, which combines the SDN with the C-IoT, the functions of network management and control can be realized in our future work.).

![Figure 1. The specific application scenarios for MTC.](image-url)
control signaling, the cellular network naturally provides the platform for ubiquitous and seamless connectivity [23]. Different from the traditional wireless sensor network (WSN), the appearance of multiple sensor nodes makes the C-IoT more complicated, and many existing methods cannot be simply extended to the C-IoT deployment [27]. In addition, different from cellular network, such as the LTE-A network, the C-IoT is confronted with a severer situation, which is caused by heterogeneous MTC devices, various delay requirements, wide area coverage, and massive access to the evolved NodeB (eNB). The C-IoT architecture is shown in Figure 2. Additionally, the proposed architecture contains three planes, whose structure is presented in Figure 3. More details are presented as follows.

- **Device plane**: This plane consists of various heterogeneous MTC devices. These devices are capable of accessing the cellular network and can enjoy the ubiquitous connectivities of the C-IoT.
- **Access and edge computing plane**: This plane provides users with a platform for wireless access. Moreover, the fog nodes are equipped with some storage, computation, and processing capabilities. With these nodes, some data traffic for MTC devices can be cached and computed locally, and the traffic burden of the central data center can be alleviated.
- **Cloud computing plane**: In this plane, the cloud server with cloud storage is placed, which are used to execute the centralized computation and processing tasks.

Based on the proposed three-plane architecture, the challenges when deploying green C-IoT are summarized and given as follows.

- **Massive access**: With plentiful heterogeneous MTC devices deployed in the practical scenario, they make diverse attempts to realize access and modify, release, or handover processes [48,49]. Therefore, the random access scheme should be carefully designed so as to provide the high QoS requirement and a high successful access probability, as well as avoid attempt collisions.
- **Load imbalance**: There are many kinds of heterogeneous MTC devices that execute diverse functions and that are distributed in different geographical positions. For some MTC devices providing real-time applications, they often stay in active mode and transmit the sensed data, leading to more power consumption [33]. Moreover, it is obvious that urban areas generally generate more data traffic than rural areas. Therefore, the traffic load is severe in some areas, while in some places, there is light traffic, which will result in the load imbalance problem [50].
- **Coverage holes and interference**: Though the C-IoT has the ability to provide wide area coverage with ubiquitous and seamless connectivity, there still remain some coverage holes due to the improper cell planning and the mobility scheduling of the MTC devices [51]. In addition, the considerable amount co-existing MTC devices brings interference [52], and their interference may be aggravated when the number of devices increases rapidly [53].
- **High EE requirement**: In general, for some sensor nodes, their lifespan of is supposed to be more than 15 years [48]. Though they work at a low power level, it is still necessary and challenging to make them operate in an energy efficient manner [54], since they cannot be re-charged again. Besides, large-scale energy management is a tough task in C-IoT scenario [55].
- **Unavailability of servers**: In some remote and traffic overloaded areas, the sensed data are difficult to transmit to the server, which is power consuming and has negative effects on real-time and delay-sensitive applications [33].

In summary, the deployment of green C-IoT is confronted with huge challenges in terms of the architectural and technical aspects [22]. In the following sections, we intend to handle these severe challenges through energy efficient and energy harvesting schemes.
Figure 2. The cellular IoT (C-IoT) architecture.

Figure 3. The three-plane C-IoT architecture.
3. Energy Efficient Schemes for Green C-IoT

In this section, we propose several energy efficient schemes to deploy green C-IoT to deal with the architectural and technical challenges presented above.

3.1. Efficient Random Access and Barring Mechanisms

In the presence of massive IoT connectivity, the issue of random access is more challenging than in traditional cellular networks. In order to deal with this problem, an efficient random access procedure is strongly demanded [16]. Note that there is a tradeoff between the access attempt and successful access probability. To be more specific, generally, if there are more access attempts for a certain node, the successful access probability of this node will increase. However, more access attempts may lead to more collisions, which will damage the performance of the successful access probability to other nodes and lead to more power consumption. Therefore, the mutually incompatible relationship among them should be considered in the C-IoT deployment.

Additionally, when the network is loaded heavily, the sensed information for time-tolerant applications can be cached in devices [48], in which case the access attempts can be decreased and less power will be spent in the meantime. Then, in light traffic periods, the gathered data will be transmitted and processed. Moreover, if the current network is in a heavily loaded state, the extended access barring (EAB) strategy can also be employed [56]. Under this strategy, eNBs will decline some access requirements of MTC devices, which are assigned with lower priority or looser delay requirements.

3.2. Self-Adapting Machine Learning Predictions

Since the machine learning algorithm, especially the deep learning algorithm, is applicable in large-scale environments [57], it can be adopted as a useful tool to execute the route/position, traffic, and battery predictions in the C-IoT architecture. Through the technical tool of machine learning, the real-world IoT data can be mined and intelligently analyzed [58], after which some features of the IoT applications and the network can be captured and forwarded to users and Internet service providers (ISPs).

When performing predictions, the type of MTC devices should be taken into account. Generally, they can be classified into two categories, i.e., devices generating data frequently (DFD) and devices generating data less frequently (DNFD) [5]. Generally, DFD generates the urgent data, and thus, the predictions of these devices are supposed to be immediately accomplished, which can guarantee the QoS requirement and reliability of these sensitive IoT applications. On the contrary, the prediction requirements of DNFD are not too stringent, and the interval between two successive predictions is allowed to be longer.

Additionally, as for the traffic prediction, it can be performed in both the server’s and devices’ side, through which some useful insights can be yielded from the perspective of load balancing and resource allocation [16]. Specifically, at the server’s side, the accurate traffic predictions enable the server to properly allocate the computation resource and assign different access priorities. Meanwhile, the traffic predictions at the devices’ side make sure that devices can make the decisions to stay awake to transmit sensed data or switch off and enter sleep node.

Last but not the least, the battery levels of some vital sensor nodes, such as the sink nodes, have to be carefully taken into account, in case some emergencies occur and the immediate communications are interrupted. In these cases, what is mentioned above should be jointly considered, so the global decisions can be made to further save power consumption and guarantee reliability [27].

3.3. Scheduling Optimization

With the aim of reducing power consumption and enhancing EE performance, it is a preferable choice to turn the unnecessary nodes into sleeping mode [53]. Thereupon, it is of great necessity to design the optimal scheduling and planning schemes of the MTC devices to decide the on-off states of
these devices. Besides, the duty cycle needs to be carefully designed to make a proper compromise between lifetime and power consumption [59].

When referring to sleeping mode, it can be classified into two categories, namely semi-sleeping mode and total-sleeping mode. Semi-sleeping mode means that the sensors are capable of sensing the ambient environment, and the sensed data are not transmitted immediately. In this case, the sensed data can be locally stored in MTC devices, and the cached data will be transmitted if the value of the sensed data reaches the pre-defined threshold. On the other hand, in total-sleeping mode, the MTC devices are not allowed to sense the surrounding environments. Meanwhile, we note that the transitions between active and sleeping modes are also power-consuming. Therefore, combined with the prediction techniques, it is better to estimate the time of the next data transmission and make the decisions about whether or not to switch off the MTC devices to sleep mode when the current transmission process is almost complete.

As for the wake-up strategies of MTC devices, these can be accomplished in periodical and network-initiate manners. The former strategy is simple, and the devices will be activated in some certain time periods. This method costs little control signaling overhead. The wake-up period needs to be properly decided, and this method fails to deal with the emergent and unexpected scenarios. When confronting these scenarios, the network-initiate strategy can be adopted, where the MTC devices will be woken up if some emergencies happen. However, the latter will result in more control signaling overhead. To this end, there is a tradeoff between these two wake-up strategies, which deserves great consideration in the practical C-IoT deployment [50].

3.4. Resource Allocation

Owing to different priorities, QoS requirements, and residual power levels, the energy efficient resource allocation schemes will play a key role in reducing power consumption and improving EE performance [60]. The resource to be allocated covers many aspects, such as computation, power, frequency, and time resources. There is a myriad of mature scientific research towards resource allocation in cellular networks; however, they cannot be directly applied to the C-IoT scenario, since these works fail to capture the massive connectivity characteristic of the C-IoT. Moreover, the time varying and random traffic arrival properties should also be carefully considered [26].

When designing the resource allocation schemes, ISPs are supposed to pay attention to the QoS-guaranteed and global dynamic resource allocation. The formal scheme is based on the design criterion of the QoS requirement, where the computation, power, frequency, and time resources are allocated to satisfy the minimum QoS requirement of some specific important applications. The latter scheme, from the global view, aims to make sure the overall network is able to run normally and energy efficiently, while capturing the time-varying and mobile features of the observed network. However, the stringent requirements of some applications may be ignored.

3.5. Fog Computing

Following the traditional way, the sensed data will be transmitted to the remote server and then processed in the centralized data center. This may cause much more transmit power consumption and lead to unacceptable time delay in hot spots with severe traffic congestion. Therefore, with a high density of MTC devices, the existing paradigm for cloud computing is not suitable for some remote IoT applications. To shed light on this, the fog computing-based architecture is regarded as a new promising communication model [61].

In the fog computing-based model, fog nodes, distributed at network edges, are equipped with computation and processing capabilities and are able to undertake some computing and caching functions [62]. Then, the transmission and processing tasks can be instantly accomplished by nearby fog nodes, which obviously costs less power consumption and is suitable for time-critical tasks [63]. When considering the dynamic topology of the C-IoT scenario, the mobility of fog nodes should also be considered since the fog nodes should be placed in the hotspots to offload more data traffic.
3.6. Group-Oriented Transmission

In order to reduce the cost caused by extra signaling overheads, multicasting is proposed as an effective manner for signaling distribution [8]. When multicasting transmission is adopted, the MTC devices are firstly grouped, which can provide the same IoT service or serve the same user, and then, identical control signaling can be provided to MTC devices belonging to the same groups.

Compared to the traditional point-to-point unicasting transmission scheme, based on the broadcast nature of the wireless medium, multicasting endows the eNBs with the ability to simultaneously transmit identical signaling information to a group of MTC devices on the same resource block [64]. This transmission design can significantly reduce time latency and power consumption.

4. Energy Harvesting Schemes for Green C-IoT

Different from smart phones and laptops, some MTC devices, such as radio frequency identification device (RFID) tags, require at least a 15 year working life. Owing to the limited battery capacity and non-rechargeable characteristics, effective energy harvesting techniques are strongly demanded to prolong the lifespan of these MTC devices [65,66], which will in turn guarantee the reliability and lengthen the working time of the entire C-IoT.

4.1. Ambient Energy Harvesting

In ambient energy harvesting schemes, the amount of harvested energy depends on many factors, such as the conversion efficiency, distance between the energy source and MTC devices, and their operating environment [67,68]. Among these factors, the operating environment plays the most important role in the energy harvesting process. Taking the wearable device as an example, it is capable of collecting heat from humans. When the skin temperature ranges from 18 °C to 25 °C, the harvested energy is 20–60 µW cm\(^{-2}\) [69], depending on the conversion efficiency of MTC devices. Moreover, when the wearable device moves, the vibrational energy can be collected, and the amount of harvested energy varies from 4 to 800 µW cm\(^{-2}\). As for other MTC devices that gain energy from the Sun, such as those for pollution detection and temperature measurement, the harvested energy can reach 100 µW cm\(^{-2}\) when exposed in strong sunshine.

4.2. Dedicated Energy Harvesting

When concentrating on energy harvesting, the energy arrival rate is a key performance metric, which can guarantee the successive power supply. However, all of the energy sources mentioned in ambient energy harvesting fail to offer a continuous energy arrival rate, and thus, some real-time IoT applications may be interrupted. To solve this issue, the dedicated energy harvesting schemes demonstrate their importance and superiority [25,70]. Dedicated energy harvesting can be realized by simply transmitting radio frequency (RF) signals to energy-hungry MTC devices, since information and energy can both be conveyed by the RF signal [27]. When equipped with multiple antennas in each eNB, the RF signals can be gathered as a beam, after which some beamforming designs can be employed to acquire the directional beams [28].

5. Case Study

We consider the three-tier IoT architecture. In the simulation scenario, there are one eNB and four fog nodes in the access and edge computing plane, and there are 200 MTC devices in the device plane. The eNB is located at the center of the observed area, whose radius is 50 m. The fog nodes and MTC devices are uniformly distributed within this area.

Each MTC device can opt to connect with the eNB or the nearby fog node, which can provide the maximum received signal strength. For an MTC device, if the chosen node reaches the maximum connection number, this device will choose the node that provides the second largest signal strength.
When the connection schemes are determined, the total transmit power consumption arising from the eNB and fog nodes can be accordingly calculated, as shown in Figure 4. To validate the effectiveness of the proposed C-IoT architecture, the traditional access scenario, where devices can only access eNBs, is adopted as the benchmark strategy. Firstly, from Figure 4, it can be concluded that, as the association bias grows, MTC devices are more likely to access fog nodes to accomplish the computation functions, and the total power consumption is reduced. Notably, when the association bias is large enough, though MTC devices have a large probability to access fog nodes, too many access attempts may exceed the maximum connectivity number of these fog nodes. To this end, the fog nodes will reject some access requests, and these devices will access the eNBs. As a consequence, the performance gap between the two access schemes will be steady when the association bias is large enough.

IoT applications can be roughly classified into two categories, i.e., real-time applications and non-real-time applications. The former applications are more likely to be activated. This is because there are more data that need to be exchanged. For these two kinds of applications, there are three states, namely active state, semi-sleeping state, and total-sleeping state. The details of these states are specified as follows.

- In the active state, the MTC devices can transmit the desired data resources straight away, and the power consumption for keeping sensing should be considered.
- In the semi-sleeping state, the MTC devices are periodically activated by the network operator, and then, the sensed data resources can be transmitted. The power consumption for state transition, from sleeping state to active state, is supposed to be taken into account.
- In the total-sleeping state, the MTC devices will be triggered to be active by the data requests, and the power consumption of the state transition also needs consideration in this case.

Taking the three states into account, we present the total power consumption for real-time and non-real-time applications under different scheduling modes in Figure 5. On the one hand, for real-time applications, MTC devices in total-sleeping mode will be frequently activated. Considering the fact that the on-off state transition is much more power-consuming than data transmitting and sensing, the devices in total-sleeping mode cost more power consumption than in the other two modes. On the other hand, for non-real-time applications, MTC devices in total-sleeping mode will be less frequently activated; thus, the devices in total-sleeping mode will cost less power consumption than those in active mode. Moreover, from Figure 5, the consensus is also reached that MTC devices in semi-sleeping mode cost the least power consumption. However, nothing comes without a cost. The MTC devices in
semi-sleeping mode are supposed to be equipped with some storage capacity. Thus, the sensed data can be locally stored and then transmitted if the value of the sensed data reaches the pre-defined threshold.

![Graph showing total power consumption under different scheduling modes.](image)

**Figure 5.** The total power consumption under different scheduling modes.

From the simulation results shown above, we can find that as the association bias grows, MTC devices are more likely to access fog nodes, leading to reduced power consumption. When the association bias is large enough, the performance gap between the two access schemes will be steady. Moreover, it is also found that, for real-time applications, the total-sleeping state costs most power consumption than the other two modes, while the active state will result in the most power consumption for non-real-time applications.

6. Conclusions and Future Directions

The C-IoT shows great potential in supporting pervasive connectivity and providing wide area coverage in the near future. In this paper, we review the C-IoT architecture for MTC and present the challenges when deploying green C-IoT. Based on the unique features and challenges, the energy efficient and energy harvesting schemes are proposed. To validate the effectiveness of the proposed schemes, a practical use case is provided. With the proposed three-tier C-IoT architecture, it is our aim to provide ubiquitous and seamless connectivity to MTC devices, while the network management and control are not taken into account. To address this issue, the SDN can be combined with the C-IoT, where the centralized controller can carry out the functions of flexible and programmable network management and control. This remaining issue will be left for future studies.

In the future, the research directions for implementing the C-IoT are summarized as follows:

- The C-IoT is a fresh and emerging network architecture for supporting massive connectivity, whose market model is not mature in practice [48]. Therefore, the service mode, charging policy, and integration with the traditional service need to be carefully considered. Meanwhile, the inter-inhibitive relationships among subscribers, ISPs, and stakeholders ought to be balanced.
- The fog nodes should not only be limited as the communication relay with computing capabilities, but should also be equipped with more functions, such as resource allocation, scheduling optimization, and some self-adaptive predictions. All these functions mentioned above pose great pressure on fog nodes themselves, both in the hardware and software design, which will be left for further research.
- When IoT devices are employed in the cellular network, the compatibility issue is worth considering. Confronted with different spectrum bands and control signaling, some related
changes and updates may have to be carried out. At the same time, the cost of these changes and updates should be controlled at a lower level.

- The realization of software-defined C-IoT is still a challenging issue. According to different IoT applications and various service requirements, the software design seems tough, and the subsequent changes in hardware should also be considered.

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