Spectrum and Energy Efficient D2DWRAN

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Abstract

IEEE 802.22 is the first world-wide standard for wireless regional area networks (WRANs) using cognitive radio technologies. Some of the drawbacks of WRAN are limited network capacity and low energy efficiency. One potential solution for these drawbacks is Device-to-Device (D2D) communication, and thus D2DWRAN is proposed in this article. It features direct intra-cell communication, reuse of channels, and use of multiple operating channels. In this article, we mainly discuss energy efficient spectrum sharing in D2DWRAN. We explicate a mechanism to increase energy efficiency for long distance links using relaying. Along with energy, channel utilization and fairness are also considered while choosing relays. Thus, significant improvement in both network capacity and energy efficiency can be achieved. The schemes discussed here can also be used in other D2D communication settings.

Index Terms

D2DWRAN, IEEE 802.22, WRAN, cognitive radio, channel allocation, energy efficiency, green networks.

I. Introduction

Spectrum is a scarce resource however, many measurement studies suggest that the licensed radio frequencies are not being utilized efficiently. Cognitive radio (CR) was proposed to address this issue by identifying unused spectrum and using them efficiently [1]. With CR, unlicensed users can use the licensed frequency bands if no interference is caused to the licensed users. The standardization of IEEE 802.22 wireless regional area network (WRAN) is a milestone in the domain of CR. WRANs make use of the unused TV bands in order to offer broadband services in rural areas. WRANs cover up to 100 km, which is one of its unique features [2]. Cellular topology is adopted in WRAN to simplify the network management, where a base station (BS) serves multiple customer premises equipment (CPE) in a cell. This cellular topology leads to two crucial constraints for IEEE 802.22 networks: (a) limited network capacity and (b) low energy efficiency.

The network capacity is limited due to many reasons, such as:

(i) Only one pair of transceiver can communicate simultaneously on one channel, not exploiting the possibility of spatial reuse of channels. (iii) Single operating channel is used in a WRAN cell. Multiple adjacent TV channels can be used as a bundled channel, but non-adjacent vacant TV channels still cannot be used at the same time in a cell. Thus, vacant channels are wasted while wireless frequencies are scarce. Multi-input multi-output (MIMO) is potential solution, but it is not supported currently due to the size of antennas at lower frequencies [2], [3], though there are some discussions recently in the IEEE 802.22 working group [2].

Since WRANs are designed to provide broadband access to rural areas, CPEs may not be energy rich. CPEs that are far away from BS require higher power due to long distance transmissions, which further increase energy requirements. Additionally, for CPEs that are far from the BS, the energy requirements vary hugely from the CPEs that are closer to the BS. In this work, we are interested in increasing the energy efficiency of the CPEs and overall network capacity of WRANs using device-to-device (D2D) communication.

Device-to-device (D2D) communication can enhance the throughput and resource utilization in cellular networks [4]. However, because of the unique features of IEEE 802.22 networks, the current D2D proposals in the literature are not suitable for WRAN. For example, the physical layer protocols and cognitive radio features are not considered in [4]. A distributed spectrum sharing mechanism with D2D communication is demonstrated in [5], but it is for ad hoc networks and not for cognitive radio cellular networks. A cognitive radio based D2D resource allocation approach is presented in [6] by modeling the behavior of the secondary users, but the physical layer is different from that of D2DWRAN. To address some of these issues, device-to-device WRAN (D2DWRAN) was proposed in [7].

The main ideas in D2DWRAN are to support CPE-CPE communication, reuse of slots, multiple operating channels and energy efficient spectrum sharing. D2DWRAN can increase network capacity significantly as compared to IEEE 802.22 networks [7]. Based on our previous work, in this article, we briefly introduce and explain energy efficiency, multiple access with multiple operating channels, some use cases, and some challenges in implementing D2DWRAN. Note that, the IEEE 802.22 working group has also recently established a new task group, called IEEE 802.22*b*, to enhance the network capacity by D2D communication and MIMO [2]. Our proposal can be a solution for IEEE 802.22*b*.

The rest of this article is organized as follows. The main ideas, use cases, characteristics and requirements of D2DWRAN are described in Section II. Based on the overview, we modify the orthogonal frequency-division multiple access (OFDMA) of WRAN to enable D2D communication in Section III. Then, a fair and energy efficient spectrum sharing mechanism is discussed and validated. Finally, we conclude this article in Section IV.

II. An Overview of D2DWRAN

D2DWRAN is an enhancement of WRAN with four main modifications. They are - CPE-CPE communication, channel reuse, use of multiple operating channels, and energy efficient spectrum sharing. We describe the first three in this section and energy efficient spectrum sharing is discussed in Section III. Except these four modifications, other issues in D2DWRAN for example synchronization, re-transmissions, neighbor discovery, and channel estimation in a cell are centrally managed by the BS in the same ways as that of WRAN. More details of these issues can be found in [2].

In WRANs, the channel access is achieved through both time and frequency division multiplexing. A frame is divided into downstream (DS) and upstream (US) subframes in time domain. In the DS-subframe, spectrum sharing information and data to CPEs are broadcasted by the BS. In the US-subframe, mainly the data is sent from CPEs to BS. In the frequency domain, OFDMA is employed for communication among the BS and the CPEs in a cell. Before detailed discussion, we first list the important terminology used in the rest of this article.

TABLE I
TERMINOLOGY.

Terms	Description	IEEE 802.22 Specifications
Subchannel	A group of subcarriers and the smallest allocation unit in the frequency domain of the OFDMA system.	One subchannel contains 28 subcarriers.
Channel	A TV channel that contains multiple subchannels.	TV channels with a bandwidth of 6, 7, or 8 MHz. One channel consists 60 subchannels.
Symbol	The smallest allocation unit in the time domain of the OFDMA system.	There are 26 to 42 symbols in a frame.
Slot	One symbol on a subchannel. The smallest allocation unit in the OFDMA system.	60×26 to 60×42 slots in a frame.
CPE request	The required number of OFDMA slots from a CPE for either CPE to BS or CPE to CPE communication.	CPEs send their requests to the BS, and there are only CPE to BS requests in WRANs.
Link	A transceiver pair between a CPE and the BS (CPE-BS or BS-CPE) or two CPEs (CPE-CPE). It is used interchangeably with *transceiver pair*.	CPE-BS links and BS-CPE links in a cell. Direct CPE-CPE links are not supported.
Slot (re)use	When a slot is allocated to a link, this slot is (re)used. It is interchangeably used with the term *channel (re)use* here.	

A. Direct CPE-CPE communication

In order to protect the licensed users and maintain compatibility with IEEE 802.22 WRANs, the spectrum in a D2DWRAN cell is still managed by the BS in a centralized manner. That means if a CPE wants to start a communication with another CPE in the same cell, it needs to send the request to the BS and wait until the BS makes the allocation of available spectrum.

Direct CPE-CPE communication in a cell can avoid unnecessary routing through BS. Several other benefits can also be obtained. First, end-to-end delay can be decreased if the source CPE directly sends packets to the destination CPE. Second, some traffic through the BS can be off-loaded. In IEEE 802.22 networks BS accesses incumbent database[1] for channel information, senses all TV channels frequently, and collects sensing results from CPEs. The BS also makes spectrum sharing decisions every frame and negotiates spectrum sharing with the neighboring cells. Hence, off-loading some tasks from BS by way of CPE-CPE communication is useful.

Compared to WRAN, D2DWRAN may have some long distance CPE-CPE links that may be out of reach of the source CPE. It can be solved by using the BS. That is, if a CPE cannot directly reach the destination CPE via direct

[1]Incumbent database is maintained by the authorities and provide TV channel usage information in local areas.

D2D links, then it can still ask the BS to be a router. Another option is to use another CPE to relay. Some works on *cognitive relay networks* in the literature can be adopted in this case, e.g., the cooperative relay mechanism by Zhang *et* al. [8].

B. Channel Reuse

We define the interference area for a transceiver pair (or called link, e.g., CPE-BS, BS-CPE, or CPE-CPE) on a channel as the area in which another link would be interfered if both links are used simultaneously. It is nothing but the field of signal coverage of the transmitter. The size of an interference area is mainly decided by the transmission power, path loss and small scale fading of the signals. Note that two links used simultaneously, do not interfere with each other if neither of the receivers is in the interference areas of the other transmitter. Power control strategies assign minimal transmission power required for a successful transmission. With transmission power control, the same channel can be reused by multiple links in a cell. In this way, the size of the interfering areas of CPE-CPE links are reduced, and thus the chances of reusing channels increase and also the energy efficiency. With reuse of channels spectrum utilization is increased.

C. Multiple Operating Channels

To increase the network capacity, channel bonding is supported in WRAN, in which up to three channels are combined as one channel with wider bands [2]. But each cell can only work on a single channel if the vacant channels are scattered or non-adjacent i.e., two non-adjacent but unused TV channels cannot be used simultaneously. In this case, resources are wasted. Therefore, we adopt channel aggregation to use multiple non-adjacent channels. In the downstream, the BS can broadcast on all multiple channels. To limit the transmission power of CPEs, one CPE can only operate on one channel at an instance. Regarding non-adjacent multiple channels, similar studies such as *dispersed spectrum cognitive radio systems* offer significant improvement in network performance [9].

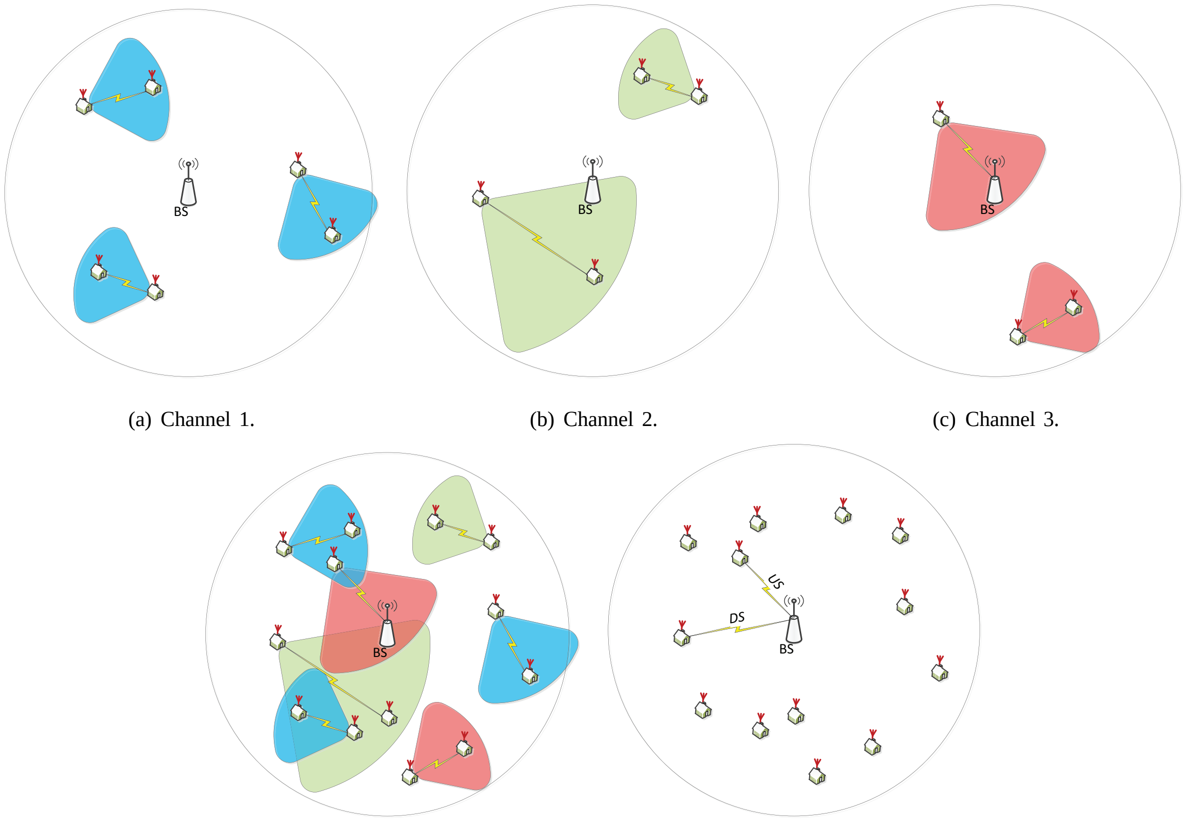
An example of spectrum sharing in D2DWRAN and WRAN is shown in Fig. 1. The enhancement of the network capacity in D2DWRAN is evident from the figures.

D. Use Cases

According to recent Internet traffic study, peer to peer (P2P) applications are widely being used [10]. D2DWRAN supports P2P applications by enabling direct CPE-CPE communication thereby some traffic on the BSs is offloaded. Some applications are presented below to show the necessity of D2DWRAN.

Many P2P applications can be found for direct CPE-CPE communication because of the large coverage area of a single cell, for example,

- **Video streaming**: Video content has become the major Internet traffic and it is predicted by Cisco that 80 to 90 % of the Internet traffic will be videos by 2017 [10]. P2P video streaming is an efficient way to offload the centralized servers. The basic idea of P2P video streaming is that all users share their video resources with others directly. During important national/local events multiple video streams are transported through the same



(a) Channel 1. (b) Channel 2. (c) Channel 3.

(d) The US-subframe of a D2DWRAN cell. (e) DS and US of a WRAN cell.

Fig. 1. An example of a D2DWRAN cell in US-subframe that uses three TV channels at the same time with direct CPE-CPE communication and channel reuse, and the comparison of D2DWRAN and WRAN. The US-subframe of D2DWRAN uses three different channels and each channel is reused multiple times by different links. In contrast, only one channel and one communication can happen in the US-subframe of a WRAN cell.

BS because many people in an area are watching the same video via Internet. There is a high possibility of existence of many P2P video streams in a WRAN because of its large coverage area. In these cases D2DWRAN can achieve much better performance than WRAN. That is because D2DWRAN can avoid the repeated traffic going through BSs.

- **File sharing**: According to [10], file sharing also takes a large portion of the Internet traffic. One popular example is cloud computing/storage. As in the case of video streaming, if a group of people/devices in a WRAN are involved in frequent file sharing activities, then these devices may employ D2D intra-cell communication. D2DWRAN can offload the BSs and backbone networks in the synchronization of cloud storage.
- **Other real time applications** such as, video conferences and video chats between the CPEs in the same cell can also be included since there is a high possibility of local interactions in rural areas.

E. Application Scenarios

There are many discussions on how to increase the network performance in the IEEE 802.22b task group [2]. We take two scenarios that have been discussed in the IEEE 802.22b task group to explain the architecture and applications of D2DWRAN.

In an archipelago area, it is almost impossible to provide Internet to each island using cables or cellular networks because of physical constraints or limited coverage. However, D2DWRAN could manage communication between all the islands and ships together and, provide the Internet services because of its large coverage. The BS is connected to the backbone network in the mainland either through cables or other wireless technologies. The incumbent database can be accessed from the BS to query channel information. A CPE could be in a hotel, school, a ship or even a single house that provides network access to the users. At the same time, CPEs can communicate with each other directly via multiple vacant channels under the supervision of the BS. By this CPE-CPE communication, not only the network capacity can be increased, but also the coverage of the cell can also be stretched with CPEs that act like relays.

Another application can be the emergency network after natural disasters like earthquake, tsunami and forest fire. These disasters can cause connection outages in large areas for long periods because of breakdown of infrastructure. However, just after the disaster, the data and traffic requests in these areas would increase dramatically. For example, the rescuers need instructions from their officers, families want to check safety of their relatives and friends, in the emergency hospital the doctors and nurses need the medical data of patients to be analyzed and, so on. A D2DWRAN based emergency network can provide temporary broadband services for these needs. The large coverage provided by a single BS is the main advantage for this type of networks. Portable CPEs access the BS and provide connection to instructors, rescuers, doctors, citizens, the police, fire-fighters and other users. CPEs can also relay for other CPEs thereby increasing network coverage.

F. Requirements

Implementation of D2DWRAN requires some moderate changes to CPEs, which differs from the IEEE 802.22 standard. These changes to the CPEs are necessary to increase the network capacity. CPEs should have the ability to communicate with other CPEs on any possible vacant channels. This requires either omni-directional antennas or directional antennas in which the azimuth can be adjusted in real-time. The CPEs should be capable of switching channels faster so that if the BS allocates different channels in every frame, they need to hop onto the newly allocated channel. Transmission power control is required to achieve multiple reuse of channels without causing interference to the other CPEs. An analysis based on different fading and path loss models can provide quick guidance regarding transmission power selection, but the accuracy is a major concern. Experiments based estimations, e.g., by ranging, can provide accurate power information, but takes longer time. Therefore a combination of theoretical and experimental methods should be considered in the power control strategies. Because of channel reuse and multiple operating channels, sophisticated spectrum sharing mechanisms should be adopted. We address the spectrum sharing issue in the subsequent sections.

III. Energy Efficient Spectrum Sharing in D2DWRAN

We modify this OFDMA system and enable D2D communication based on it in this section. We first analyze spectrum sharing problem in D2DWRAN. Later, we describe an energy efficient spectrum sharing algorithm.

A. Modified OFDMA System in D2DWRAN

In recent 3GPP release (Release 12), similar OFMDA-based D2D communication is considered for the Long Term Evolution (LTE) devices [11]. However, it is not suitable for D2DWRAN, because single-carrier in the upstream is adopted in LTE devices and it is different from the multiple-carrier OFDMA in IEEE 802.22 upstream. Thus, we cannot adopt the LTE OFDMA-based D2D communication in WRAN. In this section, we develop a D2D OFDMA based on IEEE 802.22 for D2DWRAN.

The OFDMA system of IEEE 802.22 standard cannot be used as is in D2DWRAN because of channel reuse and CPE-CPE communication, necessitating changes. We keep these changes to a minimum. The superframe structure is the same and also the DS-subframe in case of single operating channel. The DS-subframe is used for broadcast from the BS to CPEs, and contains spectrum sharing information in the DS-MAP and US-MAP. The US-subframe is for CPE-BS and CPE-CPE communication. Using transmission power control, an OFDMA slot can be reused by different links simultaneously as long as no interference is caused. While using multiple operating channels both the DS- and US-Subframes need to be modified. Note that the self-coexistence window in the OFDMA system is used for neighboring cells to communicate with each other to share vacant TV channels [3]. Since it is the same in D2DWRAN as in WRAN, we mainly describe the modifications to DS- and US-subframes.

1) DS-subframe: In the DS-subframe, multiple operating channels are divided into main operating channel (MOC) and data channels (DCs). A MOC contains the spectrum sharing information (US-MAP and DS-MAP), US and DS channel descriptors (UCD and DCD), and the frame control header (FCH) to manage the data transmission. In this way, all control information of this frame is received by the CPEs via MOC. Data units are also transmitted in the MOC similar to IEEE 802.22 standard. However, the DCs only carry the data units (BS-CPE broadcast). The DS capacity can be increased almost linearly with number of operating channels.

2) US-Subframe: To reduce the transmission power, CPEs are divided into logical groups and each group only operates on one vacant TV channel in a frame. The first two subchannels of every TV channel are reserved for ranging, bandwidth requests or urgent coexistence situation (UCS), which is similar to the OFDMA system in IEEE 802.22 standard. The rest of the subchannels are used for data units. The spectrum sharing of data units can either be CPE-CPE or CPE-BS. Because of using multiple operating channels and higher channel reuse in the US-subframe, network capacity can be increased significantly as shown in Fig. 3. To guarantee the performance of CPEs, first the CPE-BS link requests (“Reuse 1” in Fig. 3) and then the CPE-CPE link requests (“Reuse 2” and “Reuse 3” in Fig. 3) are allocated.

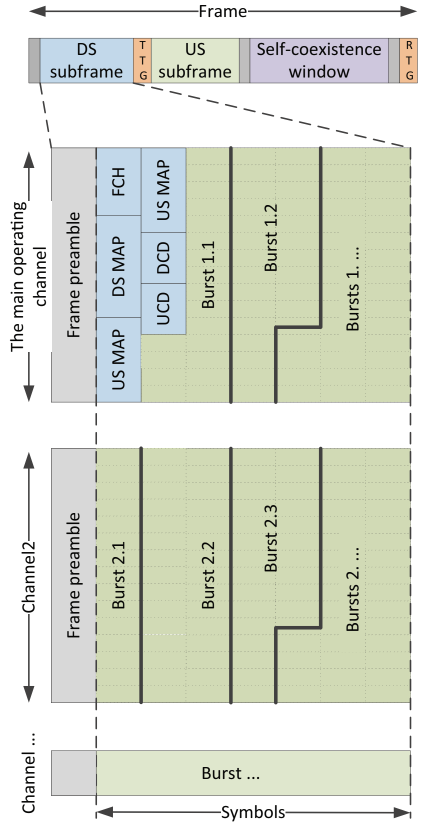


Fig. 2. The OFDMA structure of the DS-subframe with multiple operating channels in D2DWRAN

B. *Spectrum Sharing*

The spectrum allocation in the DS-subframe of D2DWRAN is similar to that of IEEE 802.22 standard, which is not a computationally hard problem. On the contrary, the spectrum sharing in the US-subframe is much more complicated in D2DWRAN than that of IEEE 802.22 standard due to the reuse of slots and multiple operating channels. The main differences are: (a) to avoid the harmful interference between links (CPE-CPE or CPE-BS) in US-subframe, an interference map is needed to supply information about possible interference; (b) the US-subframe spectrum sharing problem is computationally hard in D2DWRAN, and it can be reduced to a vertex coloring problem; (c) minimizing the number of empty slots while sharing spectrum is not crucial in D2DWRAN because of channel reuse. The main goal in D2DWRAN is to maximize reuse of slots.

With this description, we now discuss some constraints for spectrum sharing in D2DWRAN. Since allocation decisions are to be made in real time for the whole cell, algorithms should be simple and implementable. Further, the BS needs to make an allocation decision in every frame (i.e., 10 ms). A link request can only be allocated once in a US-Subframe. A subchannel allocated to a link should contain at least 7 symbols, which requires allocation algorithms to adapt to the length (in time domain) of the US-subframe. The allocated links should not interfere with each other. Since many use cases of IEEE 802.22 deal with rural and remote areas, *energy efficiency* and fairness

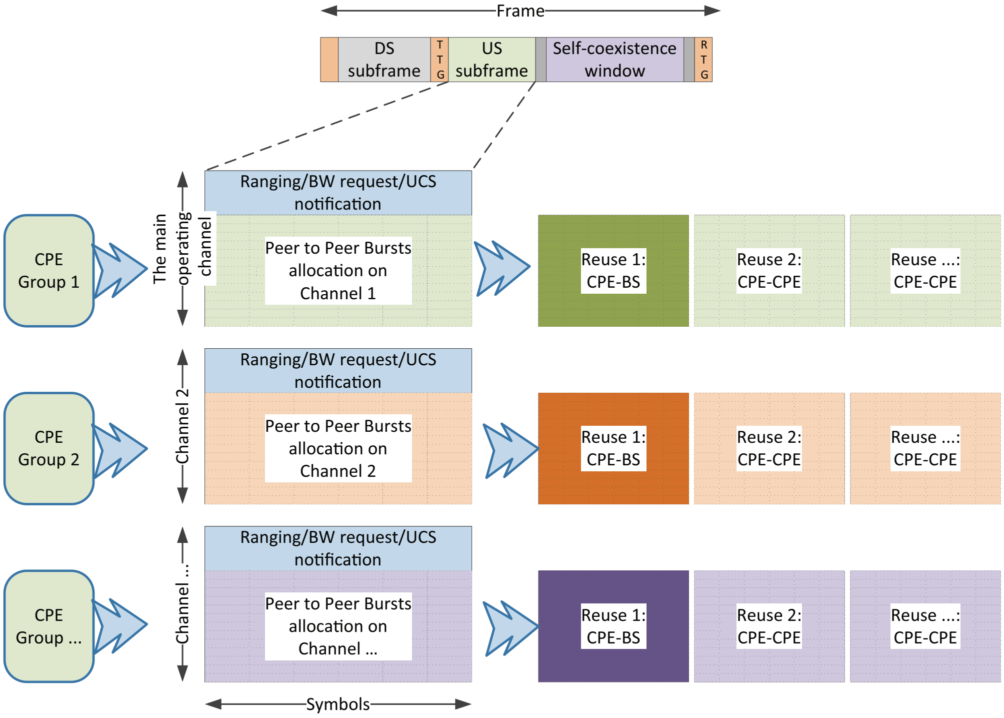


Fig. 3. The OFDMA structure in the US-subframe with multiple operating channels in D2DWRAN.

are important aspects, and should be considered in spectrum allocation. The objective is not only efficient spectrum sharing but also the energy efficiency of CPEs. Moreover, CPEs need to be fair when CPEs switch packets for other CPEs. Therefore, we need to consider joint energy efficiency and spectrum utilization.

Energy efficiency e_i of a CPE-i can be defined as $e_i = \frac{D_i}{T\overline{P_i}}$, where $\overline{P_i}$ is the average transmission power of i over a period of T s, and D_i is the total transmitted data generated by the CPE-i. D_i/T is the throughput of CPE-i. Note that $\overline{P_i}$ includes power consumed for both transmitting its own data and relaying packets for others whereas, D_i excludes the routing data belonging to other CPEs. Therefore, e_i is the ratio between its own throughput and the average transmission power. In IEEE 802.22 standard, CPEs only communicate with the BS and BS knows the distances to each CPE. The energy efficiency of CPEs in the periphery of a cell is much lower than that of the CPEs closer to the BS. However, it is possible to balance the energy efficiency of CPEs in D2DWRAN because CPEs can communicate with the BS and other CPEs with varying transmission power and also relay the packets for other CPEs. That means by controlling $\overline{P_i}$, one can balance e_i in D2DWRAN. With power control over links, D2DWRAN can also increase the energy efficiency of CPEs and possibly the whole network. With the above objective and constraints, we describe briefly an energy efficient spectrum sharing algorithm in the following section.

C. Energy Efficient Spectrum Sharing

Spectrum allocation algorithms in the US-subframes should maximize network capacity and fairness while at the same time balance energy efficiency amongst CPEs. Greedy algorithms are widely used as heuristics for computationally hard problems such as vertex coloring problems. For most of the cases, greedy strategies can achieve acceptable results with low complexity. Therefore, we describe a fair and energy efficient allocation algorithm based on greedy approach. A brief outline of the algorithm is given in Algorithm 1.

Algorithm 1 The fair and energy efficient spectrum sharing algorithm.

1: **Greediness:** Every link interferes with zero or more links. Create a vector of links that is sorted in ascending order of the number of interfering links.

2: For every link repeat steps 3-6.

3: **No interference:** If a link causes interference to the already allocated links, ignore this link. Otherwise, execute steps 4-6.

4: **Fairness in allocation:** If a link has been treated fairly enough with Eq. (1), ignore this link. Otherwise execute steps 5-6.

5: **Energy Efficiency:** If the source CPE has lower energy efficiency than average (satisfying Eq. (2)), and the allocation of the link would decrease the energy efficacy, then a relay is found; Otherwise, the link is allocated directly.

6: All possible positions in the US-subframe should be checked for each link.

The main idea of Algorithm 1 is that the request by a link which interfere with least with other links is considered first. For each request, every possible position in the US-subframe is evaluated. If the source CPE has been already allocated more than the average number of channels, it would not be considered further. The fairness in allocation is thus guaranteed. Otherwise, current and expected energy efficiency of the source CPE is examined. If the source CPE has higher current energy efficiency than others, then the request is allocated directly because energy efficiency is not an issue for the source CPE. If the source CPE has lower current energy efficiency but the expected energy efficiency would be increase by the request allocation, then this request is also allocated directly. Otherwise, a relay would be found that can increase the energy efficiency of the source CPE.

In Algorithm 1, we adopt K_a and K_e ($0 \leqslant K_a \leqslant 1$ and $0 \leqslant K_e \leqslant 1$) as the relaxation factors for fairness and energy efficiency, respectively. With the adjustment of K_a and K_e, the fairness and energy efficiency can be jointly controlled. During the resource allocation for frame t, both the fairness in spectrum sharing and energy efficiency in the previous frame $t-1$ are examined. The two criteria in Algorithm 1 are,

$$f_a(i,t-1) - \overline{f_a(t-1)} \leqslant K_a \max_j \{|f_a(j,t-1) - \overline{f_a(t-1)}|\}, \tag{1}$$

and,

$$f_{ee}(i,t-1) - \overline{f_{ee}(t-1)} \leqslant K_e \max_j \{|f_{ee}(j,t-1) - \overline{f_{ee}(t-1)}|\}. \tag{2}$$

$f_a(i, t-1)$ is the fairness in spectrum allocation of the CPE-i in frame $t-1$, and $\overline{f_a(t-1)}$ is the average fairness in spectrum sharing in frame $t-1$. Similarly, $f_{ee}(i, t-1)$ is the fairness in energy efficiency of CPE-i at frame $t-1$, and $\overline{f_{ee}(t-1)}$ is the average fairness in energy efficiency at frame $t-1$. Allocation fairness index $f_a(i, t-1)$ reflects whether CPEs share channels fairly and all have reasonable channel access opportunities. Energy efficiency fairness index $f_{ee}(i, t-1)$ measures whether CPEs can achieve similar energy efficiency. The definitions of both $f_a(i, t-1)$ and $f_{ee}(i, t-1)$ may vary according to user and system requirements in different scenarios. Further, in this article, we adopt the indices as described in [12].

When $K_a = 0$, fairness is tightly constrained, and if $K_a = 1$ then fairness is not considered. In contrast, when $K_e = 1$ the energy efficiency of CPEs is strictly balanced, and if $K_e = 0$, the energy efficiency is not considered. Thus, a BS can adapt the algorithm depending on the situation: if energy is not limited at the CPEs, fairness should be the first consideration in spectrum sharing along with network capacity. In the other extreme case, the BS can ignore fairness and give importance to energy efficiency along with network capacity.

D. Simulations and Results

We evaluated the schemes described in the previous sections through simulation of D2DWRAN system in Matlab. CPEs are randomly positioned in a cell with uniform distribution. The interference maps are generated according to the geo-location of CPEs. The traffic of the network is generated in a saturated manner. With the saturated traffic, every CPE generates a request with random destination. As soon as the request of a CPE is allocated, another request is generated. With this the maximum achievable network capacity can explored. Other parameters used in our simulation can be seen in Table. II.

TABLE II
SIMULATION PARAMETERS

Parameters	Values
Radius of cells	40 km
CPEs per cell	20
Channel bandwidth	6 MHz
MCS	64-QAM
Length of US-Subframe	18 symbols
US subchannels	58
Frame duration	0.01 s
BS antennas	Omni-directional
CPE antennas	Directional (angle: $\frac{\pi}{4}$)
Traffic generation	Saturated

The results of slot reuse times (slot utilization), energy efficiency, fairness of allocation and fairness of energy efficiency are shown in Table III[2]. Slot reuse times indicate the network throughput in the OFDMA system. Fairness

[2]We use the fairness index given in [12] to measure fairness.

of allocation and fairness of energy efficiency measure the fairness in channel access opportunities and energy consumption amongst CPEs. In general, D2DWRAN offers much better performance than WRAN, e.g., higher slot utilization and higher energy efficiency. With our algorithm in D2DWRAN, when K_a increases, the channel allocation fairness decreases. At the same time, slot utilization increases because the algorithm gets close to greedy algorithm. The energy efficiency increases too when K_a increases. This is because, when K_a increases, the impact of K_e on allocation becomes significant. When K_e decreases, links are broken into multihop through a relay and more links can be allocated. Hence, higher slot utilization can be seen with smaller K_e. With short links, the transmission power is lowered and high energy efficiency is achieved. We can also see that fairness over energy efficiency increases when K_e decreases. That is because energy efficiency is guaranteed by K_e.

TABLE III
SIMULATION RESULTS

Alg.	K_a	K_e	Slot utilization	Energy Eff. (10^5 bit/J)	Fairness (Alloc.)	Fairness (Energy Eff.)
802.22			0.9828	0.0098	0.9737	0.0004
D2DWRAN	0	0	3.7566	0.5589	0.9775	0.0561
		0.2	3.7026	0.3622	0.9792	0.0573
		0.5	2.5184	1.4297	0.9758	0.0846
		1	1.9631	0.9297	0.9693	0.0678
	0.2	0	4.1055	0.4677	0.9785	0.0634
		0.2	4.2284	1.192	0.977	0.0699
		0.5	2.3759	0.4181	0.9746	0.1141
		1	1.9484	5.8674	0.9746	0.1409
	0.5	0	4.8131	1.0121	0.9723	0.0914
		0.2	4.5183	0.6605	0.9738	0.0993
		0.5	2.4103	0.2379	0.9724	0.1841
		1	1.9975	0.7346	0.9743	0.1533
	1	0	4.8522	0.115	0.9672	0.1045
		0.2	4.1692	0.7113	0.966	0.1539
		0.5	2.3267	0.6166	0.9651	0.5279
		1	1.9877	1.736	0.9735	0.2368

E. Open Issues

This work is one of the foremost studies on D2DWRAN. We provided a detailed study of energy efficiency in D2DWRAN. Further extensions and improvements of D2DWRAN is possible, especially energy efficiency. We enlist some of them here:

Physical Layer: Characteristics of the physical layer should be considered while targeting the energy efficiency. For example, the instantaneous transmission power is still an open issue in OFDM systems [13], especially for long distance links. The maximization of energy efficiency on the physical layer based on the constraints of transmission power budget, interference threshold of the licensed users, and the traffic demands of the CPEs are considered in

[13]. Therefore, spectrum sharing strategies at MAC layer should jointly consider physical layer characteristics to achieve higher energy efficiency.

Relay and routing: We considered one relay to keep the delay at the minimum, while reducing the transmission power of long distance links. However, sophisticated multi-hop routing protocols can increase the energy efficiency further for applications where delay is not critical. This needs joint network layer and MAC layer investigations.

Standardization: D2D communication can increase the network capacity and energy efficiency greatly. There is a requirement for standardizing these proposals within IEEE 802.22 standards. Further other similar standardization efforts such as Dynamic Spectrum Access Networks (DySPAN) [14] [15] may also be targeted.

IV. Conclusions

IEEE 802.22 networks suffer from limited network capacity and low energy efficiency because of long distance communication. Thus WRAN is extended with D2D communication by proposing D2DWRAN. To increase the network capacity and channel utilization in D2DWRAN, direct CPE-CPE communication, channel reuse and multiple operating channels are incorporated. To enhance the energy efficiency, a greedy energy efficient spectrum sharing algorithm is described for the OFDMA system of D2DWRAN. The simulation results show that the network capacity can be increased significantly in D2DWRAN. At the same time, energy efficiency can be guaranteed too. D2DWRAN is a promising solution for IEEE 802.22*b*. To enhance the energy efficiency further, cross-layer design is required.

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