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Uplink Capacity Enhancement in IEEE 802.22 Using Modified Duplex Approach

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Abstract Efficient usage of spectrum is highly needed for wireless communication application. Cognitive radio (CR) is capable of using unused spectrum at any time/location by without causing any interference to neighbour. IEEE 802.22 wireless regional area network (WRAN) standard operation principles are based on CR technology and it follows time division duplex/Orthogonal frequency division multiplex as a multiple access scheme. Main problem with these access schemes are large turnaround time or idle time exist in the network. Due to the presence of large turnaround time in a network, severe cross time slot interferences and throughput inefficiency are observed in WRAN network. To combat this effect, modified duplex schemes are developed in this article. From the simulation results, it is observed that proposed technique considerably reduces idle time of the network, and additional data are transmitted through available elapsed time. Hence overall system throughputs are improved in the proposed system.

Keywords Customer premise equipments (CPE) · Wireless regional area network (WRAN) · Up link (UL) · Down link (DL)

1 Introduction

The wireless sector has seen unprecedented growth in the recent years finding use in mobile communication, Wi-Fi, TV broadcasting and many such applications. This shows that the society has become more dependent on radio spectrum than in the industrial and agricultural era [1]. Radio spectrum is soon becoming a valuable and scarce resource of the modern era. To preserve this resource, Federal Communications Commission (FCC)

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through its Spectrum Policy Task Force (SPTF) tried to analyse the current usage of the spectrum and recommendations to improve the usage of the spectrum [2, 3]. Measurements carried out in the United States gave several crucial results. It can be inferred that the spectrum usage efficiency is about 30 % of the total spectrum allocated. It has also been observed that there are significant fluctuations in the radio spectrum usage that is unlicensed bands (e.g., ISM) experience heavy utilisation whereas the licensed bands (e.g., TV, Cellular) experience low or medium utilization [4].

This led to significant changes in the spectrum management by the FCC. This wastage of spectrum coupled with scarcity was considered as a hindrance for the development of many applications, mainly in providing broadband in the rural areas. Cognitive radio (CR) is considered as a solution to the problem of providing broadband services by exploiting the low usage of the radio spectrum [5]. CR is basically a transceiver that detects the wireless channels in a particular spectrum. Based on that detection, the transmission/ reception parameters of the system are altered. It has the ability of utilizing the unused spectrum in such a way that it does not interfere with the other licensed bands in the region [6].

IEEE 802.22 is the standard for WRAN that makes use of CR for providing broadband services, especially in rural areas. The IEEE 802.22 system takes advantage of the unused spectrum of the TV band in the range of 42–862 MHz [7]. This unused spectrum, popularly called as TV white space has an enormous potential to provide internet services without allocating a separate spectrum. To ensure that no interference is caused to the primary television system, cognitive technology is used by this system, which ensures that the television bands currently being used are not incorporated into the WRAN system [8].

IEEE 802.22 employs time division duplex (TDD) and Orthogonal Frequency Division Multiple Access (OFDMA) as the access scheme. The efficient range of this technique varies from 33 to 100 km making it useful in the rural areas. The advantage of using TDD includes asymmetric traffic demand between uplink (UL) and downlink (DL), channel reciprocity and higher trunk efficiency [9]. But such a system suffers from disadvantages like long guard time intervals with increasing cell size. Moreover if the frames of the TDD scheme are not synchronized with the adjacent cell, severe interference is observed between the Base Stations (BS) and Mobile Stations (MS). This interference, called as cross time slot (CTS) interference [10] is one of the major issues in employing TDD on a large scale.

The rest of this study is organized as follows. Various methods to solve idle time in WRAN systems are discussed in Sect. 2. We discuss the basic preliminaries of IEEE 802.22 in Sect. 3. Turnaround time problem of IEEE 802.22 system and frame structure of OFDMA system employing TDD are introduced in Sect. 4. Further, operational details of Modified duplex approach and its performance characteristics are simulated. Finally, concluding remarks and suggested future work is provided in Sect. 5.

2 Related Works

In Westerveld et al. [11] proposed a telecommunication system for rural India using a fixed cellular radio system making use of the capacity of an existing mobile cellular network of which the investment cost could be spread over a large amount of subscribers with a higher financial capacity than the average village dweller. Through the design of the village station with a double radio transceiver, the availability of an outside connection is improved substantially and also the access from a central maintenance center is better guaranteed.

In Cordeiro et al. [12] provided a detailed overview of the 802.22 architecture, its requirements, applications, and coexistence considerations. The standard operates in the TV bands, makes use of techniques such as spectrum sensing, incumbent detection and avoidance, and spectrum management to achieve effective coexistence and radio resource sharing with existing licensed services. According to them, CRs are seen as the solution to the current low usage of the radio spectrum and it is the key technology that will enable flexible, efficient and reliable spectrum use by adapting the radio's operating characteristics to the real-time conditions of the environment. The paper concluded that the future of CR-based wireless communication holds great promise.

Sengupta et al. [13] studied the limitations of the IEEE 802.22 MAC in mesh establishment and proposed a coordinated distributed scheme for IEEE 802.22 enabled devices to establish a mesh network with reduced latency and control signaling. The coordination in the proposed scheme is initiated by the base station and is followed by the gradual joining of the IEEE 802.22 consumer premise equipments (CPE) to the mesh network in a repeated, distributed manner. Through extensive simulation experiments, it was demonstrated how the proposed mesh creation algorithm helped minimize mesh initialization latency, reduce control signaling, reduce start-up delay, reduce collisions during network initialization and increase spectrum utilization among IEEE 802.22 devices.

Yagunuma et al. [14] proposed a guard band aggregation scheme, which aggregates the multiple guard bands between digital TV signals and uses them for a control channel and/or a communication channel. They showed the performance evaluation results of the digital TV signals when the guard band is used by the proposed scheme. Furthermore, they discussed the permissible transmitting power and occupied bandwidth to avoid the performance degradation of the digital TV signals. Evaluation results revealed that the guard band of integrated service digital broadcasting-terrestrial (ISDB-T) signals can be used with the bandwidth of $192/\mathrm{T}_0 = 190$ kHz (where T_0 is subcarrier spacing) and 20 dB higher power density at the TV receiver. Thus the proposed technique shows a good improvement in terms of signal received.

In Leem et al. [15] investigated the spectral efficiency of IEEE 802.22 WRAN spectrum overlay when it is used in TV white space. The WRAN system makes use of TV white space in the frequency ranges from 42 to 862 MHz in an opportunistic way but depends on the radio regulations of the country for the WRAN service. Thus, WRAN spectrum overlay is very important for the efficient use of a limited radio spectrum. They analyzed the spectral efficiency of WRAN spectrum overlay as a function of the power of WRAN BSs. The simulation results showed that spectral efficiency decreases as the power of WRAN BSs and guard distances increase. Moreover, the lower the power of a WRAN BS is, the higher the spectral efficiency. Comparison showed that the spectral efficiency of a WRAN BS with 4 W effective isotropic radiated power (EIRP) is five times higher than it is with 100 W EIRP.

Leem et al. [16] discussed the spectral efficiency and coverage efficiency of WRAN system in TV bands which are under standardization at the IEEE 802.22 working group (WG). Instead of spectrum underlay technologies which have been used conventionally, spectrum overlay technology model was subjected to analysis and simulations. Their research results revealed that the increase of spectral reuse distance (guard distance) negatively affects the spectral and coverage efficiency. In WRAN system that uses spectrum overlay technologies and where the transmission power of TV stations and WRAN BSs are constant, decrease in both of the spectral efficiency and the coverage efficiency were observed in counter-proportion to the increasing guard distance at the size of given area (about 400–800 km). This shows that there is a trade-off between the spectral efficiency and the phenomenon that interference between cells reduces as the guard distance increases. The coverage efficiency of the radio resource is also improved over several 1000 times with the use of WRAN.

Chan et al. [17] discussed the features, the design and implementation challenges of frequency division duplex (FDD) and TDD systems for 4G wireless systems. They presented a number of advantages and flexibilities of a TDD system over a FDD system and identified the major challenges, including cross-slot interference, in applying TDD in practice. CTS interference in a TDD system is a major challenge because BS-to-BS interference may have a lower path loss exponent than BS-to-MS interference. This poses a serious challenge in the system engineering of TDD 4G networks. They have quantitatively analyzed the impact of cross-slot interference for TDD systems with respect to the co-channel and adjacent channel interfering cells. From the results, they found that the employment of sectored antennas and time slot grouping are very effective to alleviate cross-slot interference.

In Ni et al. [18] characterized the capacity of an adaptive modulation assisted, beam-steering aided TDD/code division multiple access (CDMA) system. In TDD/CDMA the mobiles suffer from interference inflicted by the other MSs both in the reference cell the MS is roaming in (intracell interference) as well as due to those in the neighboring cells (intercell interference). Furthermore, in contrast to FDD/CDMA, where the BSs transmit in an orthogonal frequency band, in TDD/CDMA there is additional interference imposed by other BSs of the adjacent cells, since all times-slots can be used in both the uplink and downlink. In return for this disadvantage, TDD/CDMA guarantees the flexible utilization of all the available bandwidth, which meets the demand for the support of asymmetric uplink and downlink services, such as high data rate download in mobile Internet services, etc. The work studied the achievable network performance by simulation and compared it to that of the FDD/UTRA system. The employment of adaptive arrays in conjunction with AQAM limited the detrimental effects of co-channel interference and resulted in performance improvements both in terms of the achievable call quality and the system's capacity.

Haas et al. [19] varied the separation distance of the TDD and FDD base station and the load in each system and considered a symmetrical speech service in both with non-ideal power control assumed. They found that for an FDD cell radius of 1000 m, a TDD cell radius of 50 m and 10 % maximal tolerable outage, the effects of Adjacent Channel Interference (ACI) on capacity can be compensated by dynamically increasing the required power at each BS, without affecting the coverage. They found that the interference from the TDD system to the FDD system in universal mobile telecommunication system (UMTS) is decreased by increasing the BS separation distance. Also, they found that the FDD uplink is very sensitive to ACI for a BS separation distance of less than 100 m, i.e. if co-location was considered, a significantly increased adjacent channel interference power ratio (ACIR) was necessary. Further, they detected that dynamic power control could compensate for increased interference in order to maintain the capacity, provided that system instability was prevented. Finally, they also found that the global mobility of FDD MS can cause severe ACI at the TDD BS.

Yun et al. [20] proposed a new duplex scheme, called hybrid division duplex (HDD) that is suitable for fourth-generation mobile communication systems. The proposed mobile communication system was much more flexible and efficient in providing asymmetric data service and managing intercell interference by exploiting the advantages of both TDD and

FDD schemes. The HDD scheme had a pair of frequency bands such as the FDD, performing a TDD operation using one of the bands in such a manner that allows for simultaneous FDD and TDD operations. Considering the properties of the HDD system architecture, frequency hopping orthogonal frequency division multiple access (OFDM) access was adopted in one band for the TDD operation and CDMA in the other band for the FDD uplink operation. The important advantage of the HDD scheme was the robustness against cross time slot interference that is inherent to the TDD system, which is caused by the asynchronous downlink/uplink switching boundaries among all neighbor cells. From the simulation results, their proposed system was shown to achieve approximately 7 and 30 % improvement with regard to the downlink and uplink throughput, respectively, as compared to the conventional TDD system under cell-independent downlink/uplink traffic asymmetries. They thus demonstrated that the HDD scheme was a viable solution for future communication systems that are projected to have a cell-independent asymmetric-traffic-supported hierarchical cell structure.

Sang et al. [21] proposed an overlaid HDD concept in cellular systems which divides a cell into inner and outer regions and utilizes the merits of both TDD and FDD. The proposed system took advantage of both TDD and FDD without handover between two duplex schemes. It was shown that the overlaid HDD system could exploit the power gain of FDD with the DL/UL asymmetry of TDD. Moreover, their proposed system could also solve the synchronization issue in multi-hop for OFDMA systems. Hence they considered the overlaid HDD as a promising duplexing scheme for future cellular communication systems.

Yun et al. [22] proposed a novel hybrid duplex (HD) scheme that combines features of TDD and FDD schemes that aimed at providing advantages of both schemes for future mobile communications system. They also proposed a scheduling algorithm for the HD scheme. They demonstrated that the HD system can provide flexibility of varying uplink/downlink transmission ratio in a multi-cell environment. They anticipate that other good features of the HD scheme can be demonstrated in the future by developing various algorithms. They believe a new air interface can be designed based on the HD scheme for future mobile communications system.

Shi et al. [23] proposed an analytical approach to determine the permissible transmit power for short-range secondary users under aggregate adjacent channel interference constraint in TV white space. Their approach employed statistical interference modeling which considered random deployment of secondary users, antenna gain pattern, shadow fading, and the cumulative effect of interference from multiple adjacent channels. They proposed a statistical approach to determine the permissible secondary transmit power under aggregate ACI constraint, exploiting the specific features of TV white space, such as the random deployment of SUs, TV receiver antenna directivity, and the cumulative effect of ACI. Numerical results showed that their proposed scheme permitted significantly higher transmit power than the existing deterministic methods, while at the same time, keeping the required level of TV protection. They showed that their approach could be easily applied to the real-world scenarios by conducting a sample analysis for Stockholm area which indicated considerable potential for short-range secondary access in TV white space. Thus, with their approach, they expected considerable potential for the short-range secondary access to TV white space.

In Choi et al. [24] analyzed an effect co-existence between digital TV (DTV) and 802.22 WRAN based systems. They set DTV as an interfering system and 802.22 WRAN as the victim system. When they shared the same spectrum, they calculated the minimum separation distance. They calculated the minimum coupling loss (MCL). Then, they compared transmission loss (TL) with the calculated MCL at a separation distance of 195 m and interpreted that there was potential interference when the TL was not greater than the calculated MCL. They added that when spectrum is managed, the results of their paper could be applied for determining the minimum separation distance not only between DTV device and 802.22 WRAN but also among several radio systems. The minimum separation distance was determined when the TL is larger than the MCL. In such a case, the DTV system did not have any harmful effect on 802.22 WRAN. To the best of our understanding, no studies in the literature focus on eliminating idle time in WRAN system. This is the motivating force for eliminating idle time in regional area networks.

3 An Overview of IEEE 802.22

The IEEE 802.22 system specifies a fixed point-to-multipoint (P-MP) wireless air interface whereby a base station (BS) manages its own cell and all associated CPEs, as depicted in Fig. 1. The BS (a professionally installed entity) controls the medium access in its cell and transmits in the downstream direction to the various CPEs, which respond back to the BS in the upstream direction. In addition to the traditional role of a BS, it also manages a unique feature of distributed sensing.

This is needed to ensure proper incumbent protection and is managed by the BS, which instructs the various CPEs to perform distributed measurement of different TV channels. Based on the feedback received, the BS decides which steps, if any, are to be taken.

3.1 Service Capacity and Coverage

The 802.22 system specifies spectral efficiencies in the range of 0.5 bit/(s/Hz) up to 5 bit/(s/Hz). If we consider an average of 3 bits/s/Hz, this would correspond to a total PHY data rate of 18 Mbps in 6 MHz TV channel. In order to obtain the minimum data rate per CPE,

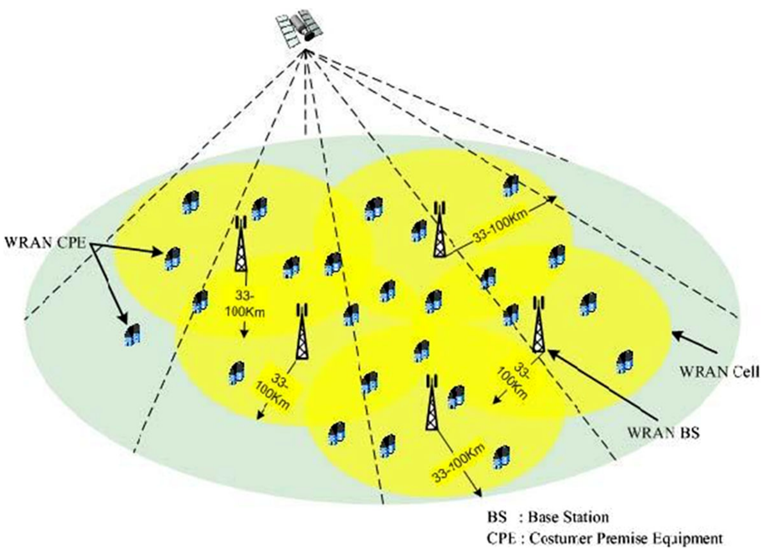

Fig. 1 Topology of IEEE 802.22

Table 1 IEEE 802.22 characteristics

Parameter	Values
Capability	Close to ADSL or cable modem (1.25–60 people/km$^{2)}$
Service range	30 km in General (100 km maximum)
User terminal characteristic	Fixed
Service type	Point to multi-point (P-MP)
Frequency range	42–862 MHz (VHF/UHF TV band)

a total of 12 simultaneous users have been considered which leads to a required minimum peak throughput rate at edge of coverage of 1.5 Mbps per CPE in the downstream direction. In the upstream direction, a peak throughput of 384 kbps is specified, which is comparable to DSL services [12]. Various characteristics of IEEE 802.22 are listed in Table 1. Another distinctive feature of 802.22 WRAN as compared to existing IEEE 802 standards is the BS coverage range, which can go up to 100 km if power is not an issue (current specified coverage range is 33 km at 4 Watts CPE EIRP). WRANs have a much larger coverage range than today's networks, which is primarily due to its higher power and the favorable propagation characteristics of TV frequency bands [4].

3.2 Physical Layer

In the specific case of the PHY, it needs to offer high performance while keeping the complexity low. In addition, it needs to exploit the available frequency in an efficient manner to provide adequate performance, coverage and data rate requirements of the service. WRAN applications require flexibility on the downstream with support for variable number of users with possibly variable throughput. WRANs also need to support multiple access on the upstream. Multi-carrier modulation is very flexible in this regard, as it enables to control the signal in both time and frequency domains. This provides an opportunity to define two-dimensional (time and frequency) slots and to map the services to be transmitted in both directions onto a subset of these slots. The 802.22 PHY has also to provide high flexibility in terms of modulation and coding. Preliminary link budget analysis has shown that it would be difficult to meet the 802.22 requirements (about 19 Mbps at 30 km) by using just 1 TV channel for transmission. The use of channel bonding by aggregating contiguous channels allows this requirement to be met. There are two channel bonding schemes.

- Contiguous bonding
- Non-contiguous bonding

Figure 2 shows the simplified diagram of the contiguous channel bonding scheme. In principle, bonding as many TV channels as possible is desirable. However, practical implementation limitations impose constraint on how many channels can be bonded. For implementation purposes, it is desirable to limit the bandwidth of the RF front-end part of the communication system. The current US grade-A TV allocation restricts adjacent allocated TV channels to have at least 2 empty channels between them. This is done so to reduce interference from one high-power TV channel to the other. Thus, the minimum vacant TV channel spacing needed for the WRAN device to operate is 3 TV channels.

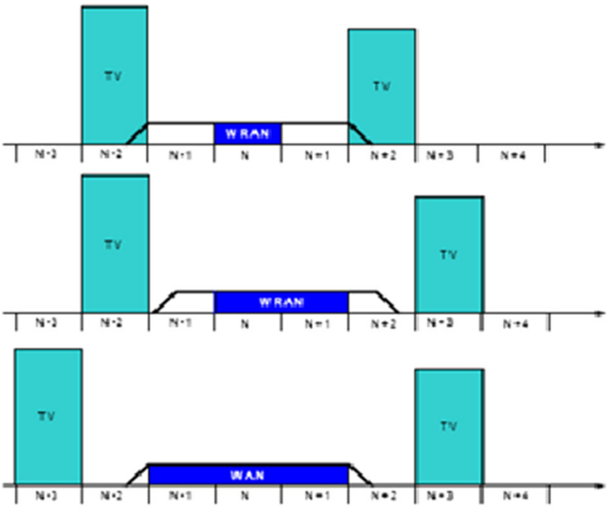

Fig. 2 Channel bonding scheme illustrating one (*top*), two (*middle*), and three TV channels (*bottom*)

Based on this, RF bandwidth is limited to 3 contiguous channels only. For 6 MHz TV channels, this implies in a RF bandwidth of 18 MHz.

3.3 MAC Layer

The CR-based MAC needs to be highly dynamic in order to respond quickly to changes in the operating environment. Besides providing traditional MAC services, the 802.22 MAC is required to perform an entirely new set of functions for effective operation in the shared TV bands.

3.3.1 Super Frame Structure

The current 802.22 draft MAC employs the super frame structure depicted in Fig. 3. At the beginning of every super frame, the BS sends special preamble and SCH (super frame control header) through each and every TV channel (up to three contiguous) that can be used for communication and that is guaranteed to meet the incumbent protection requirements. CPEs tuned to any of these channels and who synchronizes and receives the SCH, are able to obtain all the information it needs to associate with the BS. During the lifetime of a super frame, multiple MAC frames are transmitted which may span multiple channels and hence can provide better

- System capacity
- Range
- Data rate
- Multipath diversity

However, that for flexibility purposes the MAC supports CPEs which are capable of operating on a single or multiple channels. During each MAC frame the BS has the responsibility to manage the upstream and downstream direction, which may include ordinary data communication, measurement activities and coexistence procedures.

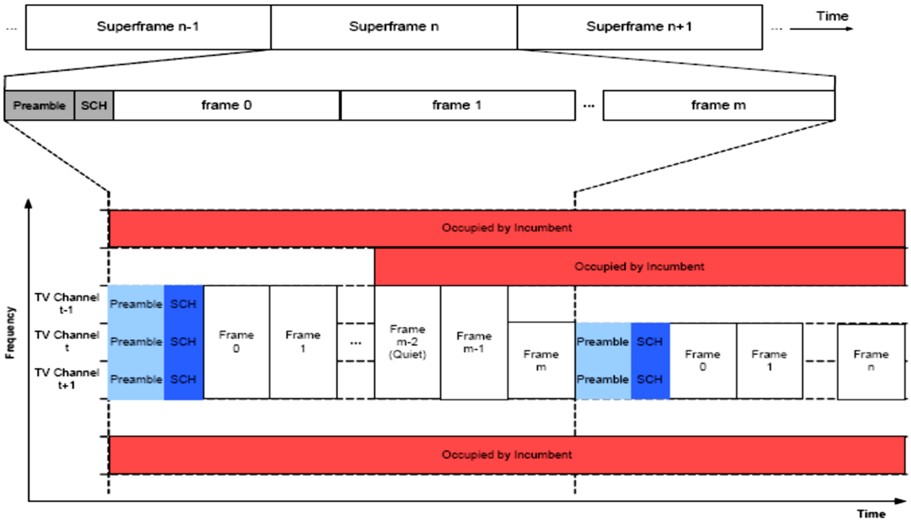

Fig. 3 Super frame structures

In the 802.22 draft MAC, whenever a CPE starts up its first scans (perhaps all) the TV channels and builds a spectrum occupancy map that identifies for each channel whether incumbents have been detected or not. This information may be later conveyed to a BS and is also used by the CPE to determine which channels are vacant and hence use them to look for BSs. In those vacant channels, the CPE must then scan for SCH transmissions from a BS. The duration a CPE stays in a channel is at least equal to the super frame duration. Once the CPE receives the SCH, it acquires channel and network information that is used to proceed with network entry and initialization. The MAC frame structure is shown in Fig. 4. A frame is comprised of two parts: a downstream (DS) sub frame and an upstream (US) sub-frame. The boundary between these two segments is adaptive, and so the control of the downstream and upstream capacity can be easily done. The downstream sub frame consists of only one downstream PHY PDU with possible contention intervals for coexistence purposes. An upstream sub-frame consists of contention intervals scheduled for initialization (e.g., initial ranging), bandwidth request, Urgent Coexistence Situation (UCS) notification, and possibly coexistence purposes and one or multiple upstream PHY PDUs, each transmitted from different CPEs.

3.4 Sensing in IEEE 802.22

One of the key elements of the 802.22 standard is the fact that it can coexist with other users of the radio spectrum, causing no undue interference. As any 802.22 system is likely to be given access to any spectrum on a secondary basis where no undue interference is caused to the primary user, it is essential that the system is effectively able to adapt itself around the primary users. To achieve this, a cognitive radio networking is required to provide the spectrum sensing and adaptation.

Each station in an 802.22 network is required to perform spectrum sensing. The 802.22 network consists of a BS and a number of client stations, referred to as CPEs. The BS controls when sensing is performed and the results of all spectrum sensing are reported to the BS. The final decision as to the availability of a television channel is made by the base

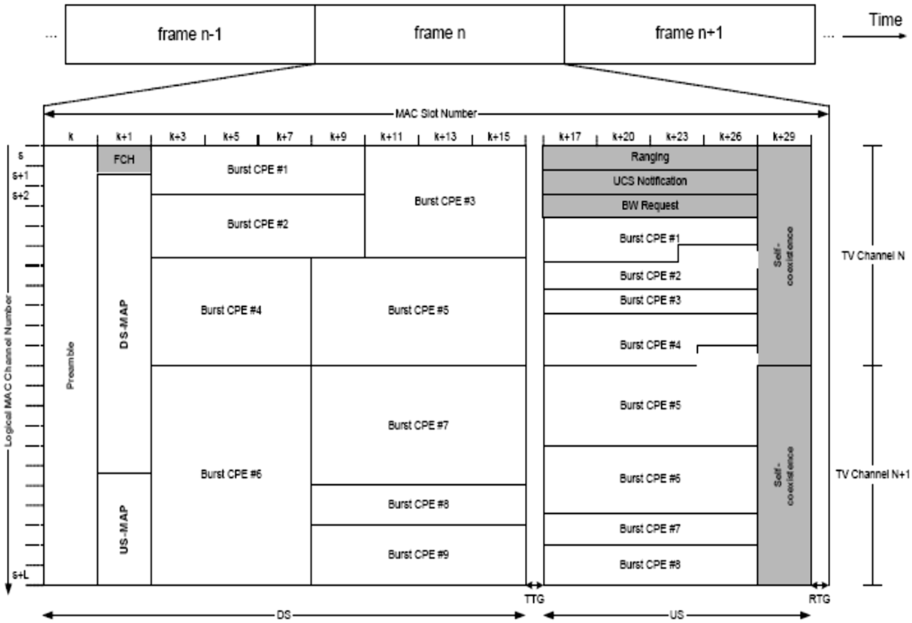

Fig. 4 Time/frequency structure of a MAC frame

station. The base station can rely on spectrum sensing results, geo-location information and auxiliary information provided by the network manager, to make its final decision about channel availability. Since all sensing results are reported to the base station one can think of spectrum sensing as a signal processing and reporting function. The draft standard does not mandate use of a specific signal processing technique; instead it mandates specific sensing performance and a standardized reporting structure.

4 Proposed Modified Duplex Approach

4.1 Conventional Technique

The conventional technique used for data transmission in IEEE 802.22 is TDD. This method involves sending data to CPEs in a queue by allocating different time slots. Each CPE receives the data only during its turn. This method works well with wireless networks that consider only short range applications like Wi-Fi and cellular networks. But when it comes to long range networks like WRAN, the turnaround time becomes a major problem. The 802.22 rural networks should target large service areas, for example, up to 100 km in a coverage radius. This means that the difference in the round-trip propagation delay between nearby and edge CPE can be significant.

4.2 Turnaround Time Problem

Due to the difference in propagation delay from BS to the CPE, different CPE finish the downlink reception at different time instances. Specifically, a nearby CPE can finish its DL

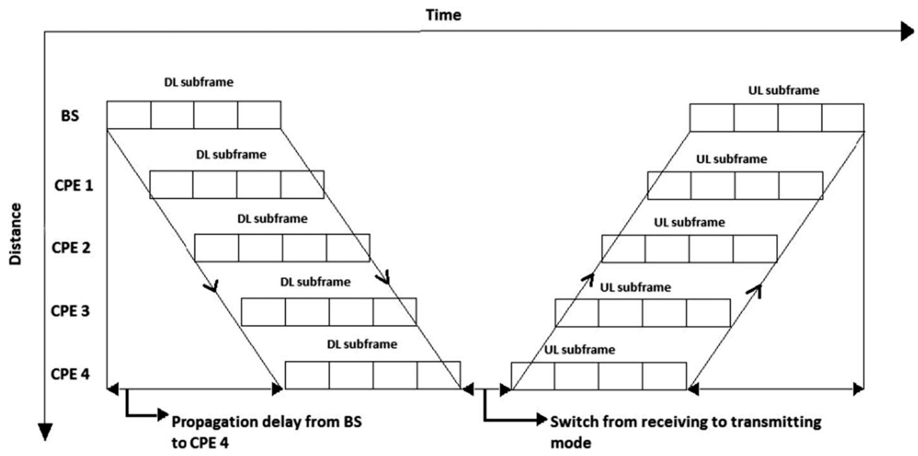

Fig. 5 Data transmission by conventional TDD

reception long before a faraway CPE does. This also means that a nearby CPE is ready to start uplink transmission before a faraway CPE is. However, to guarantee reliable reception at the BS, the UL transmissions from different CPE must be scheduled in a way such that the OFDMA symbol boundaries are aligned at the BS. This makes TDD method to have the drawback of long turnaround time. Turnaround time is the time taken by the BS to send data to CPEs and receive acknowledgements back from them which indicates that the data had been successfully received by all CPEs.

The data transmission by conventional TDD technique is shown in Fig. 5 and it is clear that the UL transmission of CPE 1 has to wait until CPE 4 completes its UL transmission. It shows that the CPE which receives the DL sub frame first will send its UL sub frame at last. This reverse order between DL and UL is the reason for the alignment of OFDMA symbol boundaries at the BS. The nearer CPEs are the most affected by this process of TDD transmission that its turnaround time is long even if they are close to the BS.

4.3 Modified Duplex Technique

The Modified duplex technique involves the following specifications:

- The data transmission to CPEs in the range 1 (nearer to base station) is done by TDD method.
- The data transmission to CPEs in the range 2 (farer to base station) is done by FDD method. Due to this, the time taken for data transmission in both the ranges is almost equal. Also the overall turnaround time taken is reduced than compared to the conventional TDD method.

Figure 6 shows the data transmission by modified duplex Technique. Here, TDD technique is used for CPEs 1 and 2 which are nearer to BS and FDD technique for CPEs 3 and 4 which are farer from the BS. In FDD, each CPE is allocated with a unique channel that the data transmission of one CPE doesn’t need to wait for other CPEs to complete.

Frame duration and idle time: No matter what the frame duration is, due to the fact that only an integer number of OFDMA symbols can be transmitted during each frame, there will be always some extra idle time available during each frame.

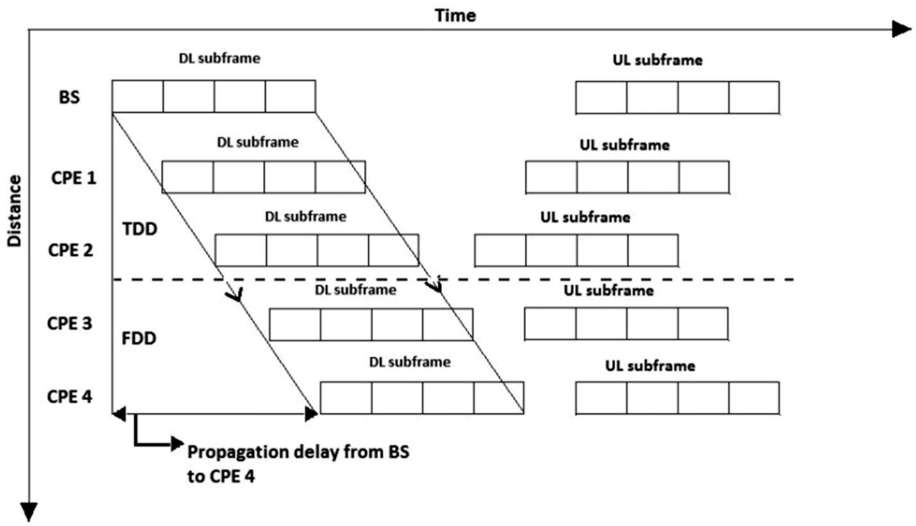

Fig. 6 Data transmission by modify duplex technique

The above argument is illustrated in Fig. 7. Consider a MAC frame of duration T_{FRAME}. This frame is divided into DL and UL sub frames for transmitting downlink and uplink data respectively. A CPE at the edge of the cell will finish DL reception after a propagation delay time $T_{PD\text{-}edge}$ plus the multipath delay spread $T_{DS\text{-}edge}$. It then needs to switch from receiving to transmitting mode. This switching time is denoted by T_{SSRTG}. After that, the CPE can start transmitting its UL data to BS and the BS will receive this UL transmission after a delay of $T_{PD\text{-}edge}$. For the BS, after finishing all UL reception, it needs to switch from receiving to transmitting mode before starting the next frame. The switching time at BS is denoted by T_{BSRTG}. Given all these delay and switching times, we can calculate the maximum number of OFDMA symbols transmitted during each frame as:

$$N_{OFDMA} = \left\lfloor \frac{T_{FRAME} - 2T_{PD\_edge} - T_{DS\_edge} - T_{SSRTG} - T_{BSRTG}}{T_{OFDMA}} \right\rfloor \quad (1)$$

where, T_{OFDMA} is the OFDMA symbol duration (including cyclic prefix). Then, for nearby CPEs, the idle time during each frame can be calculated by:

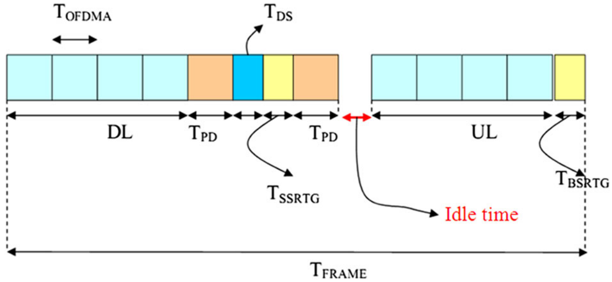

Fig. 7 Components of an OFDMA frame

Table 2 Calculation of number of OFDMA symbols and idle time-30 km cell radius

	Parameter set I	Parameter set II
T_{FRAME}	20 ms	20 ms
T_{OFDMA}	373.33 µs (2048 FFT, 1/4 CP)	336 µs (2048 FFT, 1/4 CP) CP—cyclic prefix
$T_{DS\text{-}edge}$	50 µs	50 µs
$T_{DS\text{-}edge}$	100 µs (cell radius 30 km)	100 µs (cell radius 30 km)
$T_{DS\text{-}nearby}$	8.33 µs (within 5 km radius)	8.33 µs (within 5 km radius)
$T_{PD\text{-}nearby}$	16.67 µs (within 5 km radius)	16.67 µs (within 5 km radius)
T_{SSRT}	50 µs	50 µs
T_{BSRTG}	50 µs	50 µs
N_{OFDMA}	52	58
T_{IDLE}	445 µs	370 µs

$$T_{IDLE} = T_{FRAME} - N_{OFDMA}T_{OFDMA} - T_{DS\_nearby} - 2T_{PD\_nearby} - T_{SSRTG} - T_{BSRTG} \quad (2)$$

Here, T_{PD_nearby} and T_{DS_nearby} are the propagation delay and multipath delay spread of nearby CPEs respectively. Let us illustrate the above calculation by plugging in some typical values for the parameters as shown in Table 2.

There are two important conclusions that can be drawn from the calculation in Table 2:

- Firstly, as only an integer number of OFDMA symbols can be supported in each frame, the idle period exist in network and it is greater than one OFDMA symbol.

Secondly, even when the round-trip propagation delay, i.e., $2xT_{PD}$, is less than the OFDMA symbol duration, i.e., T_{OFDMA}, the actual idle time, T_{IDLE}, can be longer than T_{OFDMA}.

Table 3 summarizes the simulation parameters. The free space path loss model is considered for simulation. Also an assumption of 40 users per cell is taken considering the fact that this service is provided in the sparsely populated rural areas. The final assumption made considers the interference to have a larger value compared to the noise in the system, neglecting the noise.

4.4 Simulation Results

4.4.1 Representation of the Cells

For this simulation, specific coordinates are set for the base stations (centre of each cell). Using these coordinates, circles are drawn around the base station representing the TDD and the FDD zones. The users are randomly distributed by randomly generating coordinates in the x and y direction. Those users whose coordinates are outside of the circle are given new coordinates till they do not lie inside the circle. Figure 8 is a representation of three cells with forty users in each cell. These forty users are randomly distributed in the cell so that some users are in the inner region (TDD) and some are in the outer region (FDD).

4.4.2 Performance of the Modified Duplex System

In Fig. 9, the performance of the TDD is compared with the proposed modified duplex system for the same transmit powers. The performance is obtained by computing the Cumulative distribution function (CDF) for various SIR trails.

Table 3 Simulation parameters

Parameter	Specifications
Number of users in the desired cell	40
Number of users in the adjacent cell	80
Number of desired BSs	1
Number of adjacent BSs	2
Multicarrier multiplexing	OFDM
Path loss model	Free space path loss model
Path loss exponent	4
User equipment transmit power	1 W (30 dBm)
BS transmit power	16 W (42 dBm)
Radius of the cell	17.5 km

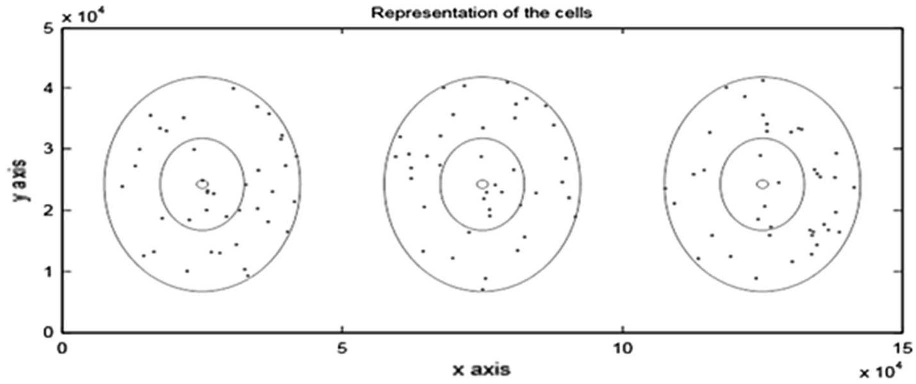

Fig. 8 Representation of the cells

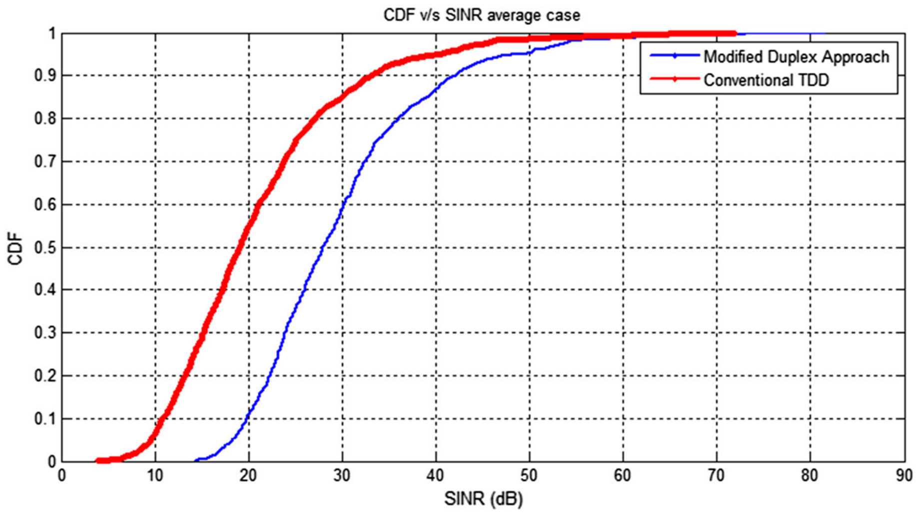

Fig. 9 Performance of modified duplex and TDD systems

Table 4 SIR values of TDD and Modified duplex system

SIR of TDD system (dB)	SIR of Modified Duplex system (dB)
9.4968	18.2096
14.7601	21.7156
23.6467	34.0601
9.4689	17.6122
20.0039	27.7638
25.1401	32.8527
25.9875	35.1888
15.1854	25.7885
13.6543	22.7423
16.7411	25.3445

The results are obtained for a traditional TDD system and a modified duplex system with an inner radius of 7.5 km. It can be inferred from Fig. 9 and Table 4 that there is a performance improvement of 9 dB or 39 dBm in the HDD system when compared to the TDD system. Table 4 summarizes the results obtained in successive iterations. 1000 Iterations are performed in which 10 are shown. From Table 4, it can be observed that the best SIR performance of 34.0601 dB was obtained for the proposed modified duplex system whereas it was only 25.9875 dB for the TDD system. Also, the worst case performance observed for the modified duplex system had a value of 18.2096 dB which is better when compared to the worst value of the traditional TDD system, which was obtained as 9.4689 dB. This reiterates our previous result that there is a 9 dB performance improvement.

4.4.3 Variation in the Number of Users

The increase in number of users increases the interference in the system. In this article, we change the number of users to 20, 40 and 100 and compare the two systems. Figure 10 describes the system in reference. We consider 20 users in each cell for one case and 100 in the other. The number of users was varied for both the TDD as well as modified duplex system. Then the CDF is plotted for both these cases.

From Fig. 11, it can be inferred that the performance of the modified duplex system is better than that of the TDD system, showing an 8 dB improvement in the 20 users per cell case and 7 dB in the 100 users per cell case. Furthermore, the performance of the proposed system in the 100 users per cell case is even better than the performance of the TDD system in the 20 users per cell case, concluding that modified duplex is a better scheme for the WRAN system. Moreover, increasing the number of users to 100 users from the standard 40 users per cell case resulted in a performance degradation of only 2 dB. Thus, the modified duplex system is not hugely affected by the increase in the number of users.

Turnaround time reduction analysis: The reduction of turnaround time by modified duplex technique can be witnessed using simulation results. The simulation result shows the turnaround time difference between conventional technique and modified technique. The variations are shown by the availability of free channels. This result depends on the result of spectrum sensing which is carried out every 2 μs. From Fig. 12, it is clearly shown that the turnaround time due to modified duplex technique is considerably lesser than that of conventional method.

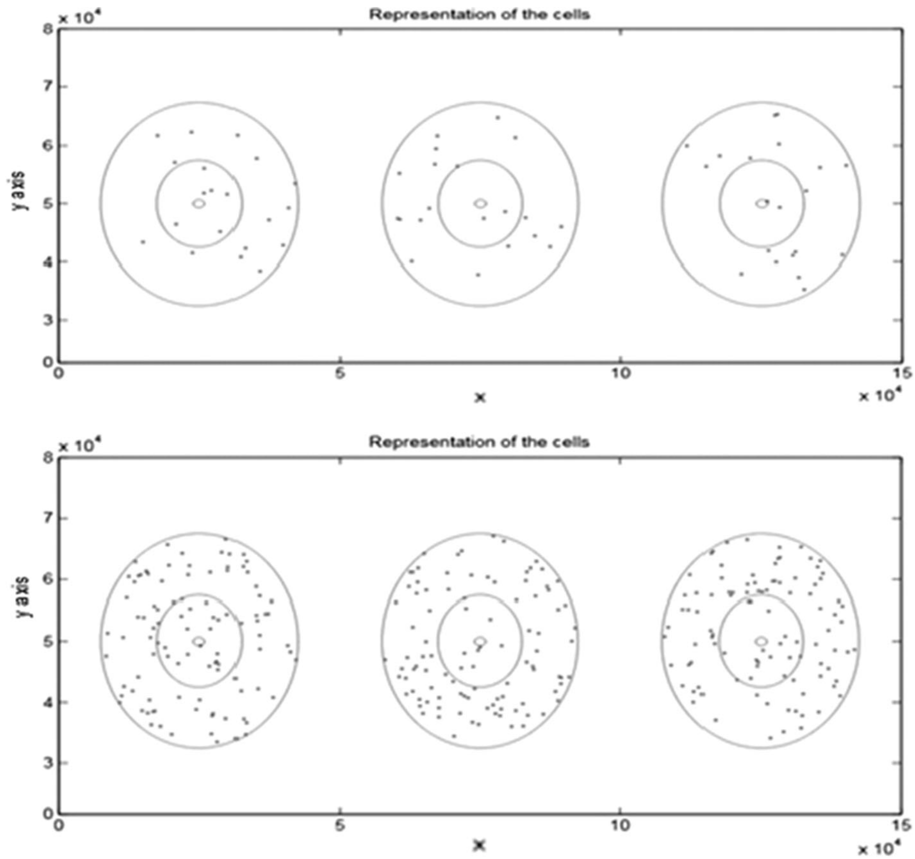

Fig. 10 Representation of 20 and 100 users

In this case it is considered that the sensing result declares 25 % of the TV channels to be free.

From Fig. 13, it is clearly shown that even in the worst case of all 512 users lying in range 2, the overall turnaround time by modified duplex technique is considerably lesser. Also if the 512 users are equally distributed in range 1 and range 2 the turnaround time reduces further due to modified duplex technique. In this case we consider that the result of sensing shows that 50 % of channels are free. It is clearly shown that if the available free channel increases then the turnaround time decreases further. Amount of reduction of turnaround time is proportional to number of free channels available in region 2 (Table 5).

$$TAT_{TDD} = \left(2^{*} WRAN\, cell\, size/3 \times 10^{8}\right) \tag{3}$$

$$\begin{aligned} TAT_{MOD} = {} & \left(2^{*} WRAN\, region\, 1\, dis\tan ca/3 \times 10^{8}\right) \\ & + free\, channel\, seneing\, time\, and\, propagation\, time\, of\, user\, in\, regoin\, 2 \end{aligned} \tag{4}$$

Throughput improvement of modified duplex scheme: The performance gain of Modified duplex scheme, relative to the existing solution, depends on the following factors:

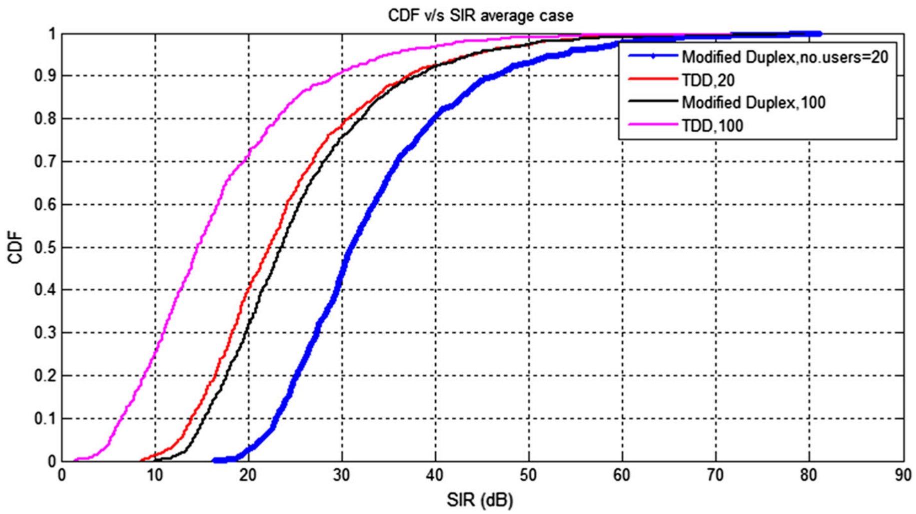

Fig. 11 CDF v/s SIR for a variable number of users

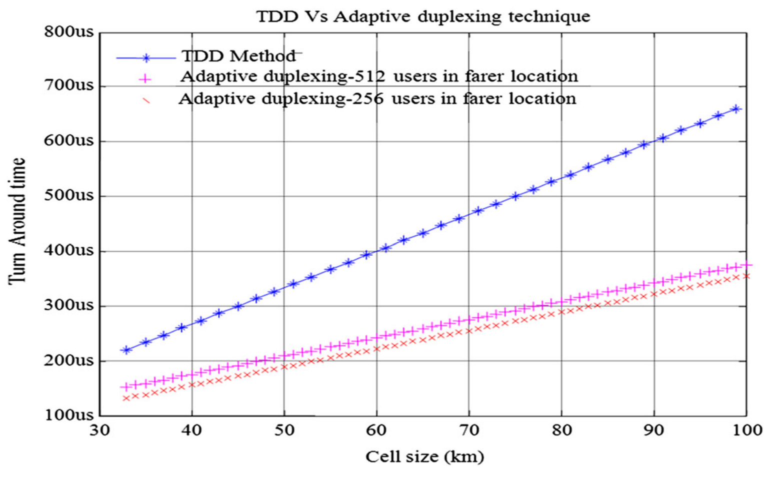

Fig. 12 Reduction of turnaround time (when 25 % free channels)

- The coverage radius of BS: Here, we assume the cell radius is 30 km. All CPEs located inside a 5 km inner disk from BS are regarded as nearby CPEs. All CPEs located outside this inner disk are regarded as faraway CPEs. We assume that delay spread at cell edge = 50 μs and delay spread at 5 km radius = 8.33 μs.
- The OFDMA symbol duration: Here, we assume FFT size = 2048, CP length = 1/4 and 1/8. With the chosen parameters, a CPE located inside the inner disk (of radius 5 km) can transmit UL data by TDD-OFDMA scheme. A CPE located outside the inner disk can transmit by FDD-OFDMA.
- The percentage of CPEs located inside the inner disk: We may vary this number from 10 to 60 %. When this percentage is 10 %, it represents the case of near uniform CPE

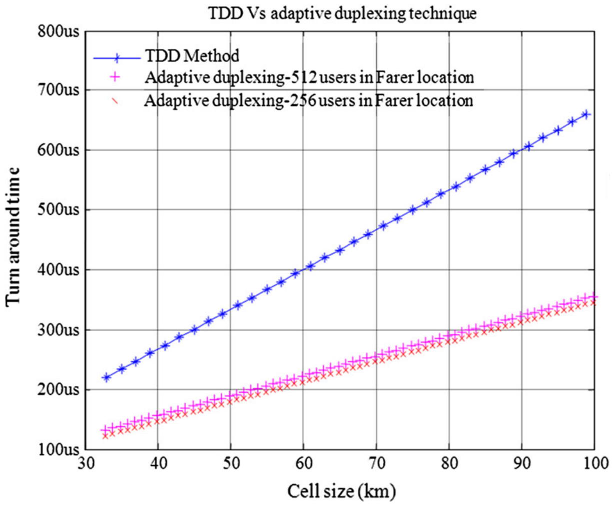

Fig. 13 Reduction of turnaround time (when 50 % channels free channels)

Table 5 Total number of frame transmission and uplink capacity of modified duplex technique

	Parameter set I	Parameter set II
T_{FRAME}	20 ms	20 ms
T_{OFDMA}	373.33 µs (2048 FFT, 1/4 CP)	336 µs (2048 FFT, 1/4 CP) CP—cyclic prefix
$T_{DS\text{-}nearby}$	8.33 µs (within 5 km radius)	8.33 µs (within 5 km radius)
$T_{PD\text{-}nearby}$	16.67 µs (within 5 km radius)	16.67 µs (within 5 km radius)
T_{SSRT}	40 µs	40 µs
T_{BSRT}	50 µs	50 µs
First part of equation i.e., Eqs. (1) and (2)	53	59
Free channels in region 2 (assume 25 %)	15	15
N_{OFDMA}	68	74
UL-efficiency improvement	30.07 %	25.45 %

distribution within the cell. When the percentage is equal 60 %, it represents the case of localized distribution of CPEs.

- The transmission rates of nearby and faraway CPEs: Nearby CPEs usually experience good channel condition, they can transmit at high rates. On the other hand, faraway CPEs usually transmit at relatively lower rates due to less favorable channel condition.
- The frame size: When the number of extra OFDMA symbol gained is fixed, the percentage gain in uplink capacity depends on the frame size. The shorter the frame size, the higher the percentage gain in uplink capacity. Typical values for the frame size are 5, 10, 20 and 40 ms.
- The downlink and uplink traffic ratio: When the downlink and uplink traffics are symmetric, roughly half of the frame is assigned for uplink transmission. On the other

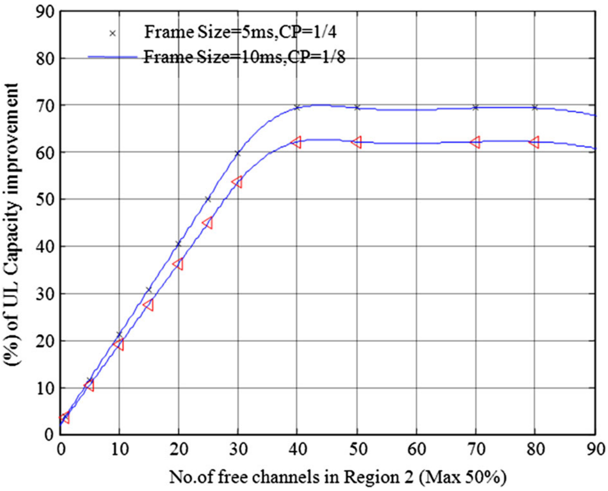

Fig. 14 UL capacity improvement by using modified duplex scheme

hand, if there is more downlink traffic than uplink traffic (which is usually the case for broadband communications), then the uplink sub frame will be considerably smaller than the downlink sub frame.

In Fig. 14 we plot the performance gain of Modified duplex scheme, with respect to the case when normal TDD is employed. The gain here is in terms of the percentage increase in the average uplink throughput. As can be seen, the gain in average uplink capacity while employing the Modified duplex scheme is very significant. The gain increases when the frame size decreases. The gain decreases when the number of free channels decreases in region 2.

5 Conclusion

The spectrum scarcity problem that is being faced now can be solved only using effective spectrum utilization. Cognitive radio is an effective tool that helps for this purpose. IEEE 802.22 standard is being developed for the purpose of using the unused analog TV bands and provide broadband access to rural areas. The proposed duplexing technique for this standard is TDD. But it has the problem of long turnaround time as WRAN deals with large distance applications. This drawback of long turnaround time in conventional TDD method has been reduced considerably using Adaptive Duplexing technique. In WRAN, the splitting of range for TDD and FDD while implementing Adaptive technique is flexible. It depends on the range of base station which varies from 33 to 100 km and also the number of users within the range covered by base station. The simulation results show that the turnaround time is further reduced by the factor that the availability of free channels increases. This clearly depicts that in future when the analog TV spectrum becomes completely free due to usage of digital DTH services; the Adaptive technique improves the data transmission with high throughput by reducing the turnaround time to greater extent.

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