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Intermittent DCF: a MAC protocol for Cognitive Radios in Overlay Access Networks

Athanasios V. Adamis and Prof. Philip Constantinou
*National Technical University of Athens
Greece*

1. Introduction

Cognitive Radios have recently appeared as a solution to the RF spectrum underutilization problem, which results from the sparse use of wireless networks services at certain time periods and the static spectrum allocation policies. A plethora of measurement campaigns have pointed out that there is a lot of unused spectrum, referred to as “white space”, even in the commercial broadcast and mobile networks frequency bands, which are considered to be crowded. Cognitive Radios - CR, that inherently can sense and adapt to their environment, can form Dynamic Spectrum Access - DSA networks by utilizing the white spaces and thus improve spectrum utilization. In Overlay Access - OA, the DSA network operates on spectrum bands currently licensed to and used by conventional radio systems that are called Primary systems. The DSA network, which is called the Secondary system, is allowed to access spectrum portions that currently remain unused by the Primary system, provided that it will respect the interference criteria of the licensees. New functions and capabilities, not needed by conventional networks, must be developed at DSA networks. A few of these are spectrum sensing methods, spectrum sharing algorithms and spectrum access techniques. Our work lies in the spectrum sharing function and more specifically at the MAC sublayer.

This chapter presents a modified version of the Distributed Coordination Function-DCF, originally found in the IEEE 802.11 (IEEE Standards, 1999), as the MAC protocol for OA networks. The overlay environment poses certain challenges to the MAC design. In order for the DSA network to be up to date with spectrum availability, it must perform periodic spectrum scan procedures. During scan procedures the MAC must be interrupted and hold its state. Moreover, it must synchronize the scan procedures across the DSA network terminals, in order for them to simultaneously cease transmission attempts and perform the sensing task. After the scan procedures, it must adapt to the new PHY layer provided transmission rate. Frequent scan procedures result in frequent interruptions. Fast changes in spectrum availability, caused by fluctuating Primary network traffic, necessitates frequent scan procedures and results in sharp changes in the transmission rate. All these form the demanding overlay environment, that an overlay MAC protocol must deal with. The

proposed modified DCF, called the Intermittent DCF - iDCF, is stable and robust in this demanding environment and moreover in low achievable transmission rates. DCF has been also proposed as the MAC protocol for OA in many DSA research works. Nevertheless, no modifications have been described on it. Moreover it is proposed mostly for accessing a dedicated control channel, or data channels in a multichannel environment of multi-transceiver terminals. We show that in the demanding overlay environment, an unmodified DCF can lead to heavy channel saturation, unfairness and pure performance. The proposed iDCF maintain fairness and performance.

Moreover, this chapter presents an analytical iDCF throughput and packet delay calculation method in the overlay environment. The analysis is based on existing Markov chains models and extends them in order to include the characteristics of the intermittent operation (Adamis et al., 2009). The predictions of the model are validated against simulations and are found to accurately capture many interesting features of the iDCF. The analytical model can be used by researchers for feasibility studies in various overlay scenarios and in admission control algorithms at QoS enabled future overlay networks. Using the model, we present a numerical example for the effect of the transmission rate, the scan interruptions frequency and the packet payload length on the iDCF performance.

2. The Distributed Overlay Access Environment

Many different coexistence scenarios between Secondary and Primary systems can be found in the literature. Worldwide research on overlay access technologies is still at the beginning and at this point it is not clear which scenarios are the most realistic and practical. We study the case in which the Primary system utilizes some kind of TDMA/FDMA combination access scheme (Berthold et al., 2007 b), and thus spectrum holes are created at idle Primary system channels.

The Secondary System is a distributed network of CR terminals and its main objective is to operate in the same spectral band with the Primary system. This spectrum coexistence of two radio systems, a Primary and a Secondary, poses certain rules and priorities in spectrum access. The ultimate goals of a Secondary System are (a) to access the spectrum respecting the interference tolerance metrics imposed by the Primary system, that is causing no harmful interference to it, and (b) to accomplish goal (a) without requiring neither any modification to the Primary system nor control information exchange with it. A lot of DSA research studies propose centralized architectures for Secondary systems and also engage information exchange mechanism between the coexisting systems. Nevertheless the road through distributed approaches and complete independence from the Primary system can lead to the implementation of autonomous, fast deployed, low cost CR networks for a variety of applications such as broadband internet access through self organizing mesh networks, rural access with reduced delay and cost and pervasive content access at home (Stirling, 2008). In the following subsections some important MAC design issues for the OA Environment are presented.

2.1 The Scan Period T

In order to identify the spectrum portions left unused by the Primary system and catch up with this knowledge, the CR terminals must perform spectrum scan procedures. These scan procedures are performed periodically with a *scan period* T . Communications services are

stopped during the scan and the PHY layer performs the spectrum sensing task. The *scan period* is a Secondary system parameter that directly affects its performance as it designates how frequently the communications services must be interrupted.

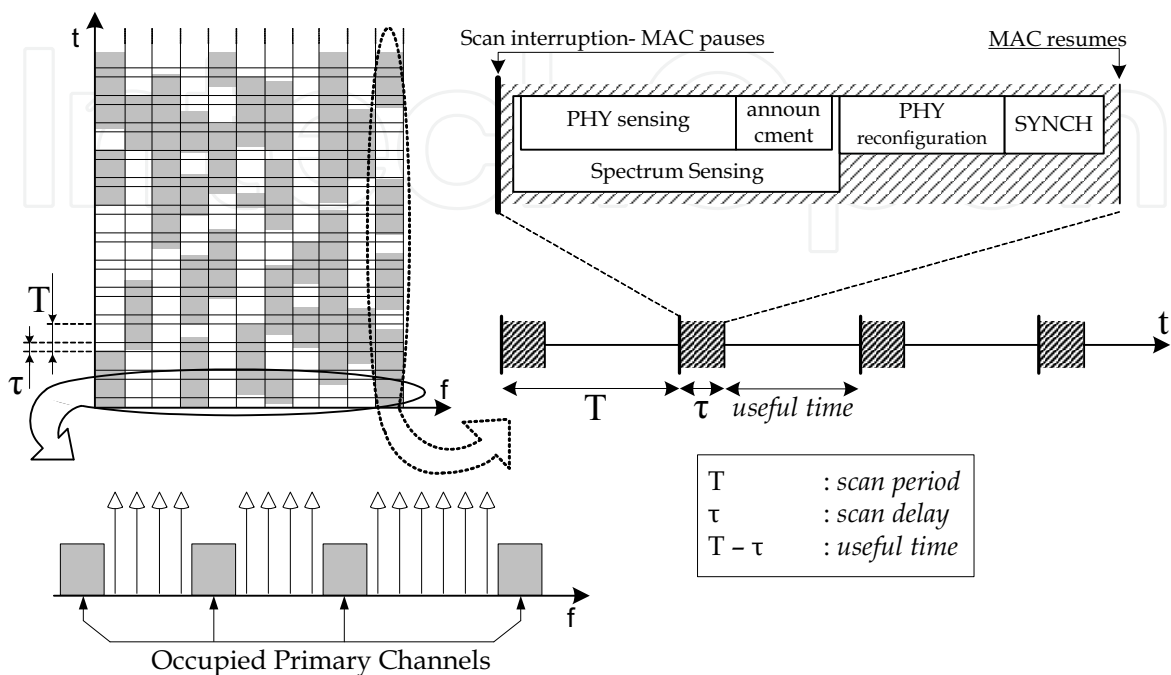


Fig. 1. Spectrum Pooling for Overlay Access Networks

The figure above presents in the time axes, the intermittent operation of Secondary networks having to perform spectrum scan procedures periodically. The scan procedures should be frequent enough, depending on the underlying Primary system, in such a way that the DSA network meets its design targets (Berthold & Jondral, 2007b) and respects the interference criteria of the Primary system. T may vary considerably. In the presently developing IEEE 802.22 standard (Cordeiro et al., 2005) and other approaches (Yuan et al., 2007) a maximum value is set to 30 min. for operation over TV spectrum, while for operation over a GSM Primary system (Papadimitratos, et al, 2005) it is set to 577 μ s. Certain approaches (Ghasemi & Sousa, 2008) propose that the *scan period* should be set for each licensed band by the spectrum regulator. In (Willkomm et al., 2008) the advantages of using dynamic selection of the *scan period*, as the secondary system roams over different Primary systems and operates on different times of a day and different days of a week, are depicted, using real world spectrum usage measurements. It is clear that an overlay MAC protocol should be robust and capable of operating at a wide *scan period* range.

2.2 The Scan Delay τ

The intermission, within which the sensing task takes place, has a total duration of τ as shown in Fig. 1. At the beginning of the interval τ the PHY layer performs spectrum sensing. The spectrum sensing duration may include a measurements announcement procedure between CR terminals in case of a cooperative sensing scheme. At the end of the sensing task the identified white spaces are treated as a single channel, common for all participating

terminals. PHY layer reconfigures to meet the new parameters and a communication channel is established. It is very crucial that the scan procedure is performed simultaneously by all participating CR terminals. This will ensure that all terminals will stop transmitting during the scan. Otherwise the sensing algorithm may not be able to distinguish between Primary and Secondary system transmissions. This crucial time synchronization is a task to be performed by the MAC layer, which is responsible to pause its operation and initiate the scan procedure. In our scenario we assume that the synchronization task is performed within the time interval τ and specifically at the end of it (Fig. 1): after a common channel has been established between terminals, some synchronization messages exchange mechanism similar to the one proposed in (Berthold et al., 2007 a) can be applied. For simplicity τ is called *scan delay* and the included functions scan procedure.

The mechanisms for spectrum sensing, measurements announcement, PHY layer reconfiguration and synchronization affect the total τ duration. Scan delay may also vary depending on the total scanned bandwidth, the sensing algorithm and the number of samples needed to achieve the required sensing performance. In other words different Primary systems, having different interference tolerance behaviour, demand different sensing algorithm performance in the Secondary network, which is obtained by different sensing times. An overlay MAC protocol should be robust and capable of operating at a wide *scan delay* range, too.

2.3 The PHY layer provided Transmission Rate

After the finish of the scan procedure, for a time interval equal to $T-\tau$, till the next scan procedure, the identified spectrum holes are treated as a single channel, common for all participating CR terminals and the MAC performs the communications functions. This time interval between successive spectrum scans is called *useful time* in our study, as shown in Fig. 1. OFDM based spectrum pooling (Weiss & Jondral, 2004) is a transmission technology that can accommodate the adaptive and smooth filling of the spectrum white spaces. This kind of accessing the spectrum by transmitting on idle Primary system channels, shown in Fig. 1, is called Overlay Access and gives its name to the Overlay Access Networks.

The number of the available data subcarriers, and thus the transmission rate, depend on the primary channels current usage. After every scan procedure, the transmission rate may be different. Small *scan periods*, imposed by rapidly changing Primary system traffic characteristics, may result in rapid changes in the transmission rate. This type of the continuously adapting PHY layer provided transmission rate must be handled efficiently by the MAC layer.

A Secondary system MAC protocol, designed for such an OA mode, must be able to operate in a wide range of the varying *scan period*, *scan delay* and transmission rate. Next, we modify the DCF in order to be robust in the demanding environment described above.

3. The DCF in Overlay Access Research

Many OA studies propose the DCF as the MAC scheme to be used. In the majority, it is proposed as the scheme for accessing the Common Control Channel (CCC) (Hang & Xi, 2008); (Motamedi & Bahai, 2007). The CCC is a separate dedicated channel, which is continuously available to the CR terminals, as no Primary system operates on it. In these approaches the CCC is accessed using the DCF or a p-persistent CSMA scheme. The access

on CCC is not intermittent and thus no modifications on the DCF are required. In our proposed scenario the DCF is used for accessing the unique available common channel in the intermittent overlay mode. Moreover, the former approaches utilize at least two RF Front Ends, i.e. transceivers, one of which is always tuned to the CCC. Increase of the number of transceivers increases the reliability of the system and reduces certain delays, however it also increases the total cost. Our approach utilizes a single transceiver and all terminals use a single channel. This can be seen either as a single channel environment, or as a multi channel one with the focus given on the coexistence of multiple terminals in each channel with the use of DCF.

Other approaches with a single transceiver also use schemes similar to the DCF during the contention period (Juncheng et al., 2008). The difference from our approach is that they use it exclusively on the CCC. Moreover, to the best of our knowledge, no modifications on the DCF have been proposed that can handle its operation in the demanding overlay mode. In (Papadimitratos et al., 2005) the DCF protocol is used in an intermittent way over a GSM network with scan procedures at the beginning of each GSM-slot. This implementation is a modification of DCF, but only for overlay access on the GSM band and is applicable only to this Primary system. For example, the NAV counter for the virtual carrier sensing mechanism is set in number of GSM-slots needed for the data transmission. The backoff interval in this approach, is generated after every scan procedure, which can lead to heavy congestion in the CCC and unfairness. In our work though, the DCF is modified in a way that it can be robust in a variety of overlay scenarios.

4. The Intermittent DCF - iDCF implementation

The intermittent DCF performs data transmission functions between successive spectrum scan procedures, during the *useful time* shown in Fig. 1. The basic communications operation of the protocol, as in the standard protocol (IEEE Standards, 1999), is by successive Frame Exchange Sequences - FES which always take the form *rts-cts-data-ack*. The three way handshake mechanism is mandatory in the OA environment because of the substantially lower levels of interference it causes to the Primary system as compared to the direct *data-ack* FES form (Adamis et al., 2008). Each station contends for gaining access by having to sense the medium idle for a DCF interframe space - DIFS period and then by performing a backoff procedure for a random number of protocol slots. Upon backoff expiration it initiates a FES by sending the *rts* message. In case of a successful transmission it receives the *cts* message by the receiver and the FES continues with the data transmission.

Except from the basic access scheme functions, which are identical for both the iDCF and the standard DCF, some functions had to be added or modified because of the intermittent operation mode in the OA environment, described earlier. We present these modifications in detail in the following sections.

4.1 Control and Data Packet Transmission

As described in Section 2.2 it is very important that all CR terminals cease transmissions when the scan procedure takes place. The iDCF is always aware of the remaining *useful time* until the upcoming scan procedure and it does not initiate a transmission if it will exceed the *useful time* boundary. There is a distinction in this iDCF behaviour between control packets and data packets. Control packets *cts* and *ack* cannot be fragmented. Upon a control packet

transmission, in case the remaining *useful time* is not adequate, the packet is sent after the end of the scan procedure in the beginning of the next *useful time* period. This way the remaining time until the scan procedure is wasted. The *rts* control packet is not examined here because the backoff modification described later in Section 4.2 guarantees that on backoff expiration, there will always be enough remaining *useful time* for an *rts* message transmission.

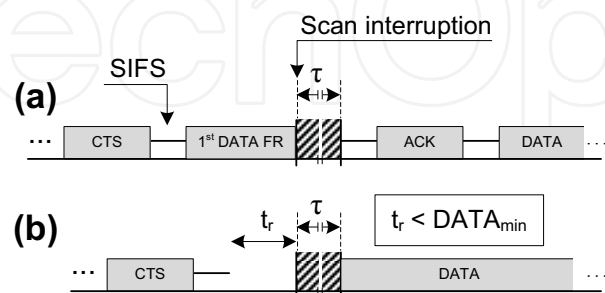


Fig. 2. Data Packet Transmission at Scan Procedure Interruption

When a data packet is ready to be sent and there is not enough remaining time for the entire packet, then it is fragmented and the first data fragment fills the remaining time, as shown in Fig. 2a. This fragmentation is performed only if the fragment to be transmitted contains more than L_{min} data bits. Fig. 2b presents the case in which the remaining time t_r is shorter than the one required to accommodate a data fragment containing L_{min} data bits', denoted as $DATA_{min}$. L_{min} is a parameter that shows the least amount of data bits that can be sent in a single fragment. As in the standard protocol, each data fragment is followed by an *ack* message. The rest of the data bits are sent at subsequent fragments.

4.2 Backoff Freezing

The intermissions imposed by the scan procedures necessitate a modification in the way that the backoff counter freezes, when the scan procedure approaches, in order for the protocol fairness and priorities to be preserved. The backoff down counter must freeze when the last *rts* transmit opportunity t_{ITxOp} time point is crossed. The t_{ITxOp} is defined as the time point in which if an *rts* message is transmitted, it will fit exactly in the remaining *useful time* before the interruption and can be seen in the figure below. A maximum anticipated propagation delay δ is also considered in the above definition.

Fig. 3 presents the back off counter values of two terminals that contend for the medium. As soon as a terminal's backoff counter expires the terminal wins the contention and transmits the *rts* message. In Fig. 3a the backoff procedure is presented without modifications. Here, the expiration of both terminals backoff counters when the t_{ITxOp} and before the scan interruption resulted in a collision, because both terminals transmitted at the beginning of the next *useful time*. This type of collisions occurs frequently in the intermittent operation mode, especially for low transmission rates (i.e. long $RTS+\delta$ duration) and small scan periods. Fig. 3b presents the modified backoff procedure with the counter freeze after the t_{ITxOp} is crossed. Using the proposed modification the priorities are preserved and the terminal with the lower backoff value wins the contention.

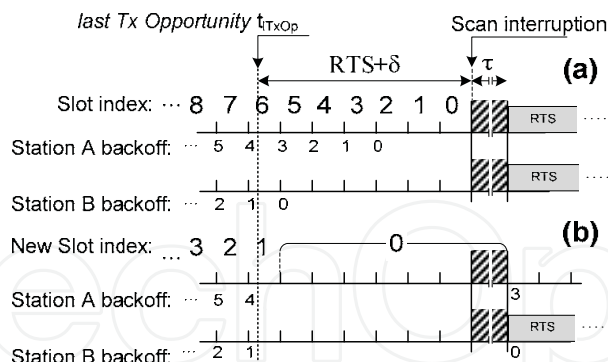


Fig. 3. Backoff freeze when a scan procedure interruption approaches.

The problem of the backoff expiration at time points that the transceiver is not able or allowed to carry out the transmission has been also identified in (Shu et al., 2007) for multi-mode terminals. There, by the name of the disruptive CSMA, it is encountered by a credit payback mechanism. The fact that in the iDCF the disruptions occur concurrently at all CR terminals, due to the scan procedure, leads to the previous simple and effective solution of freezing the backoff counter at an earlier point.

4.3 The Interframe Spaces - IFS

The inter frame spaces are time periods lying in between packet transmissions, during which the medium must be sensed idle. They exist for (a) leaving time to PHY and MAC layer to perform packet processing tasks, (b) anticipating a certain amount of propagation delay and (c) last but not least, priority setting among terminals through the IFS length differentiation, e.g. a terminal that adopts a shorter IFS before attempting transmissions has a larger probability of accessing the medium than one that adopts a longer IFS.

An IFS may be interrupted by an upcoming scan procedure before it is completed. When this occurs, the IFS is expanded to include the scan procedure and it is completed within the next *useful time*. Fig. 4 presents the different tasks performed within the IFS. Whether the IFS is extended by the *scan delay* duration τ , or more, depends on which task the interruption occurs at. Thus, if the interruption occurs at either a PHY or MAC layer processing task (D1, M1), the task is suspended, the scan procedure begins and the task is resumed after the scan procedure end. However, the transceiver switching task from receiving to transmitting mode (Rx>Tx), the anticipated air propagation delay task (AAPT) and the clear channel assessment procedure (CCA) are tasks that cannot be suspended and resumed. These are tasks that must be performed uninterrupted within a single *useful time* either before the scan procedure, or after it. If the interruption occurs at either of these IFS parts, these tasks are performed entirely in the upcoming *useful time*. Fig. 5 and Fig. 6 depict examples of a SIFS being interrupted at the PHY layer processing delay and a DIFS at the CCA task of the second slot.

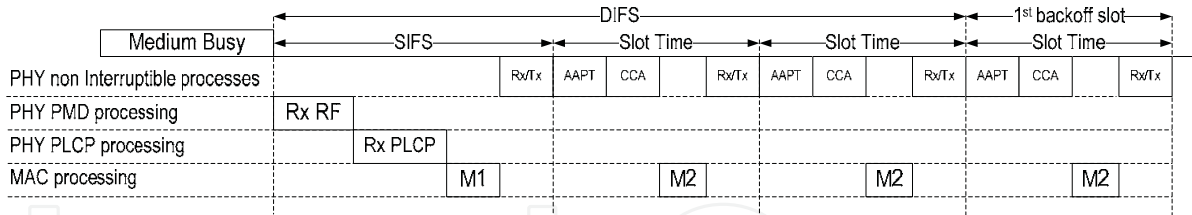


Fig. 4. IFS and Protocol Slot performed tasks

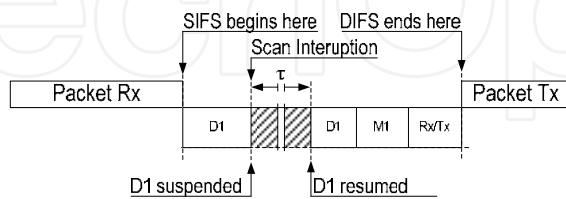


Fig. 5. SIFS interrupted at PHY layer processing task

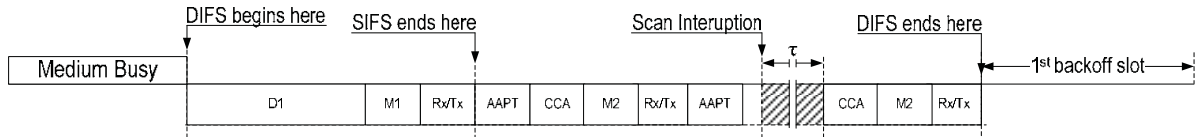


Fig. 6. DIFS interrupted at CCA task.

4.4 Dynamic Virtual Carrier Sensing

The virtual carrier sensing mechanism is implemented as a decreasing time counter called NAV (Network Allocation Vector), which holds a prognosis for how much longer the medium is expected to be busy due to the current FES. In the standard protocol, the NAV counter is set to the most recently received value, found in the DurationID packet field of the MAC header. This is calculated and set by the transmitting terminal. In the iDCF, a FES may take over more than one successive *useful times*. Moreover, the transmission rate after each scan procedure is unknown. Thus, the duration of an ongoing FES cannot always be calculated and inserted in the DurationID packet field and a different virtual carrier sensing mechanism must be implemented in the intermittent OA environment.

In iDCF the DurationID packet field instead of carrying direct information on the time needed until the end of the ongoing FES, it holds the data payload size L_P that the FES is going to transmit. In case of multiple MPDUs, either because the data payload size exceeds the maximum MPDU size, or because scan procedure interruptions force data fragmentation, DurationID holds the remaining payload size L_{PR} that has not been transmitted yet. DurationID is set to the values given in Table 1 for each case. Except from the FES transmitter and receiver, each terminal sets its NAV counter according to (a) the type of the received packet, which designates what is going to be transmitted next, (b) the received data payload size, (c) the current transmission rate and (d) the remaining *useful time*. Based on the above information the NAV counter is set accordingly to include the transmission of the next expected packet and the two idle SIFS periods before and after this packet. When the next expected packet cannot fit in the remaining *useful time* the NAV counter is not set until the transmission rate is updated in the beginning of the next *useful time*. Fig. 7 shows some examples of the NAV counter setting. The virtual carrier sensing

mechanism has to operate this way in iDCF, because it is not known how many scan procedures will take place before the FES completion and what will be the value of the transmission rate after each scan procedure.

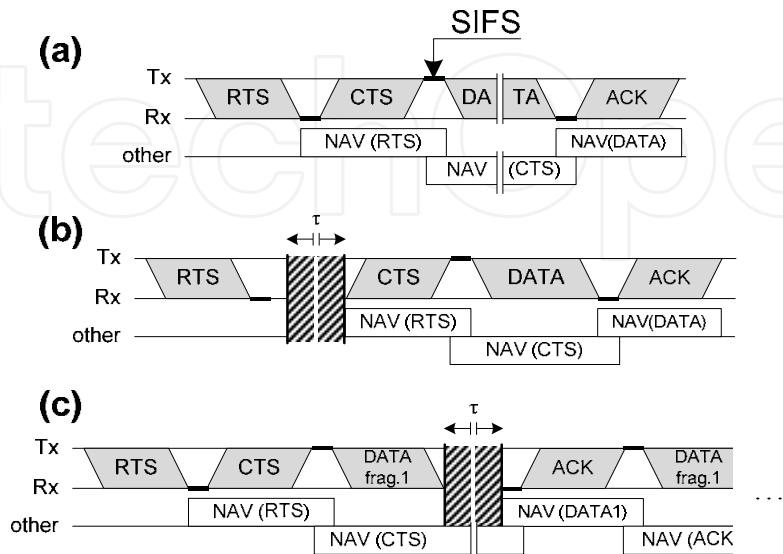


Fig. 7. Three examples of the Virtual Carrier Sensing Mechanism in the iDCF. (a) No scan procedure Interruption. (b) Interruption at *cts* packet transmission. (c) Interruption at *data* transmission forcing data fragmentation.

Packet Type	Multiple MPDU case		Single MPDU case	
	More Fragment	DurationID	More Fragment	Duration ID
rts	-	L_P	-	L_P
cts	-	L_P	-	L_P
data	1	L_{PR}	0	0
ack	-	L_{PR}	-	0

Table 1. Duration ID setting for each packet type and multiple MPDU case.

5. iDCF Analytical Model

A plethora of Markov chain models for the DCF performance analysis can be found in the literature since the first one was proposed in (Bianchi, 2000). Markovian models capture DCF features with good accuracy, which is proved by extensive simulations. The diversity of these models comes from different assumptions regarding the source traffic models, the wireless channel modelling and the levels of DCF details integrated into the Markov Chain. For example different models have been implemented using various fading channel models and ideal channel conditions, varying hidden terminal assumptions, saturated traffic conditions and various non saturation traffic models, finite and infinite number of packet retransmission attempts. Moreover a lot of Markovian models explore the DCF behaviour under different back-off algorithms and concern the optimal selection of the algorithm.

The common thing among these models analysis is that embedded points of the Markov chains are epochs where the backoff counter decrements. Between backoff counter decrements either a successful transmission, or a colliding transmission, or an idle protocol slot may take place. The Markov chain is used for calculation of certain probabilities such as the probability of successful transmission, colliding transmission and idleness in a randomly chosen slot. Then, using these probabilities and the slot durations, as calculated from the utilized DCF access scheme, throughput, packet delay and other system metrics equations are derived.

In the standard DCF analysis the idle slot, successful slot and collision slot durations are deterministic values σ , T_S and T_C respectively. In the iDCF, on the contrary, they are random variables t_{idle} , t_S and t_C , depending on the position of these slots in time relatively to the scan procedure interruptions and may include several scan procedures. Our analytical model (Adamis et al., 2009) concerns the slots duration expectations calculation. It is used to extend the existing Markovian models in order to obtain performance metrics for the iDCF operation in the intermittent overlay access mode.

5.1 Successful and Collision Slot Duration

In the following equations a packet transmission time is denoted by capital letters. In order to calculate the expected duration of a successful FES, first we calculate the duration expectations of each FES part. Then:

$$E[t_S] = RTS + \delta + 3 \cdot E[t_{SIFS}] + 2 \cdot E[t_{RSP}] + E[t_{DATA}] + E[t_{DIFS}] \quad (1)$$

The rts packet transmission time is used directly without an expectation operator. The modification of the backoff procedure described earlier in Sect. 4.2 ensures that whenever an rts packet is to be transmitted there will always be enough time left before the upcoming scan interruption. Similarly the collision slot duration expectation is computed as:

$$E[t_C] = RTS + \delta + E[t_{DIFS}] \quad (2)$$

Our general key assumption in the following calculations is that every FES part is interrupted by scan procedures at any point with probability proportional to its length. This assumption leads to very accurate results. The IFS durations remain unchanged when the IFS is not interrupted by a scan procedure. When they are interrupted they expand to include the scan procedure as presented in Sect. 4.3. Since an IFS duration is mostly occupied by MAC and PHY processing times, which are suspended during a scan procedure, our model uses the following approximation:

$$E[t_{IFS}] = \frac{T_{IFS}}{T - \tau} (T_{IFS} + \tau) + \left(1 - \frac{T_{IFS}}{T - \tau}\right) T_{IFS} , \quad (3)$$

where the IFS is either SIFS or DIFS. As shown by the simulations this approximation has a minor effect to the analytical results.

The rsp packets - response packets cts and ack - expected duration can be found similarly by noting that when the upcoming scan interruption does not leave enough *useful time* for the

rsp transmission, the packet is sent directly after the end of the scan. In this case the remaining time till the beginning of the scan procedure is wasted. The wasted time is uniformly distributed in $(0, RSP+\delta)$. This yields:

$$E[t_{RSP}] = \frac{RSP + \delta}{T - \tau} \left(\frac{RSP + \delta}{2} + \tau + RSP + \delta \right) + \left(1 - \frac{RSP + \delta}{T - \tau} \right) (RSP + \delta) \quad (4)$$

The current analysis on the data packet expected transmission duration $E[t_{DATA}]$ is performed for a constant data payload size L_P . As presented in Sect. 4.1, when the data packet transmission is ready to start, either the whole packet is sent if there is enough remaining time, or fragmentation takes place if the fragment to be transmitted contains at least L_{min} payload bits. Each fragment is followed by a positive ack as the standard protocol dictates. The total sequence of data fragments and their associated ack packets, excluding the last ack or the unique one (in case a unique data packet is sent), is referred to as Data Fragment Sequence - DFS. The DFS may take different forms in time, depending on the *useful time* length relatively to the length of certain FES parts. Let x be the number of data bits sent at the first fragment of the transmission. $x \in [L_{min}, L_{ut}]$ where:

$$L_{ut} = \min \left(L_P, \left\lfloor (T - \tau - \delta - t_{oh}) \cdot R \right\rfloor - L_H \right) \quad (5)$$

is the number of data bits that can fit in a fragment, which occupies the entire *useful time*. In (5), if R is the transmission rate, an L bit packet transmission time is calculated as $t_{oh} + L/R$, where t_{oh} is the PHY layer time overhead, e.g. OFDM preamble. The bit overhead that comes from PHY and MAC layer headers is denoted as L_H . The DFS duration, denoted as $t_{DFS}(x)$ is a function of x and thus of the data transmission start position in time, relatively to the scan procedure. Moreover $t_{DFS}(x)$ depends on the *useful time* length relatively to the SIFS and ack transmission durations. Fig. 8 shows the possible DFS formulation cases and subcases in time.

We make the following observations/assumptions in these cases:

- All data fragments, except the last one, occupy the entire remaining *useful time*
- Which case, I, II or III, specifies the DFS form, depends on the SIFS and RSP duration. Which subcase, a or b, specifies the DFS form, depends on the transmission time of the minimum data fragment, $DATA_{min}$, which is controlled by the L_{min} parameter
- Decrease of the *useful time*, causes the transition of the DFS formulation from case I to III. Increase of L_{min} within a certain case, causes the transition of the DFS formulation from subcases a to b.

The inequalities that designate which form the DFS takes appear in Table 2. Except the first fragment, the entire data packet takes up $n_F(x)$ more successive fragments, containing L_{PF} data bits each. We denote as t_{av} the time within the useful time which is available for every data fragment, except the first one. Excluding the PHY time overhead and the anticipated propagation delay we obtain:

$$t_{av} = T - \tau - \delta - t_{oh} - \lambda \quad (6)$$

$$L_{PF} = \lfloor t_{av} \cdot R \rfloor - L_H \tag{7}$$

$$n_F(x) = \left\lfloor \frac{L_P - x}{L_{PF}} \right\rfloor \tag{8}$$

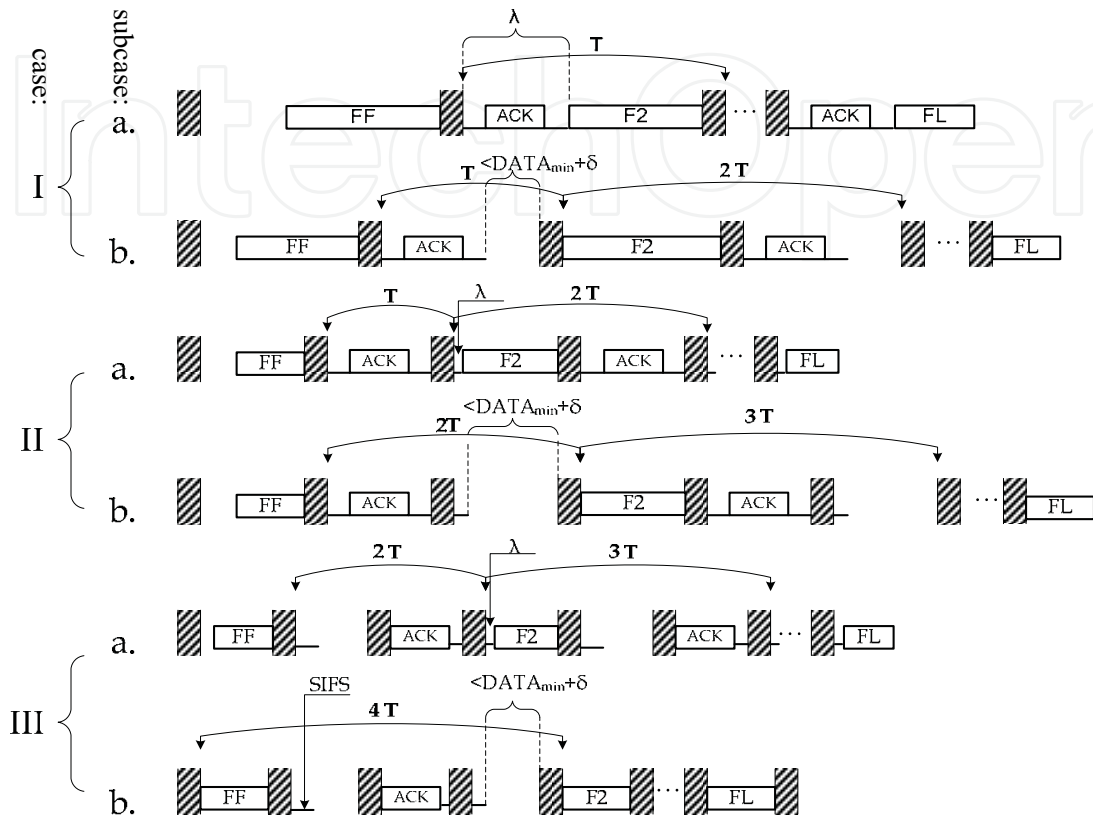


Fig. 8. DFS formulation in time. FF: first data fragment, Fn: nth data fragment, FL: last data fragment

Where λ is the part of the useful time before the fragment transmission occupied by an ack and/or SIFS and its value is given in Table 2 for every case/subcase. The DFS duration resulted from Fig. 8 is given by:

$$t_{DFS}(x) = \begin{cases} DATA_{FF}(x) + (n_T - 1)T + n_T T [n_F(x) - 1] + \tau + \lambda + DATA_{FL}(x), & x < L_{FF} \\ DATA + \delta, & x = L_P \end{cases} \tag{9}$$

n_T is the number of scan periods T needed for the transmission of one data fragment with the corresponding ack for cases Ib to IIIb. For case Ia, n_T is the number of scan periods needed for the transmission of a single data fragment and the ack of the previous fragment. The n_T value for every case is also given in Table 2. Note that the ack packet of the last (or the unique) data fragment is not included in (9) because it is considered separately in (1) as an $E[t_{RSP}]$, which is given by (4). $DATA_{FF}(x)$, $DATA_{FL}(x)$ are the transmission times for the first and last fragment containing $L_{FF}(x)$ and $L_{FL}(x)$ bits respectively, that are given by (10) and (11).

Table 2. Case/Subcase inequalities, λ and n_T values.

case	Inequality Satisfied	subcase	Inequality Satisfied	n_T	λ	Con
I	$T-\tau \geq RSP+\delta+2SIFS$	A	$T-\tau \geq RSP+DATA_{min}+2\delta+2SIFS$	1	$RSP+\delta+2SIFS$	The ack and the subsequent transmission can fit in the
		b	$T-\tau < RSP+DATA_{min}+2\delta+2SIFS$	2	0	There is not enough remaining time for the transmission and the SIFS transmission. It takes place following useful time
I I I	$RSP+\delta+SIFS \leq T-\tau < RSP+\delta+2SIFS$	a	$2(T-\tau) \geq SP+DATA_{min}+2\delta+2SIFS$	2	$SIFS - (T-\tau-RSP - \delta-SIFS)$	The SIFS that comes after is completed within the following time, adequate for fragment transmission
		b	$2(T-\tau) < RSP+DATA_{min}+2\delta+2SIFS$	3	0	After the completion of the ACK, there is not enough time for the data fragment. The transmission begins at the beginning of the following
I I I	$RSP+\delta \leq T-\tau < RSP+\delta+SIFS$	a	$2(T-\tau) \geq RSP+DATA_{min}+2\delta+SIFS$	3	$SIFS - (T-\tau-RSP - \delta)$	The SIFS, which comes after the transmission, does not leave time for the ack, which is transmitted after the completion time. The next data fragment is transmitted after the one of the completion
		b	$2(T-\tau) < RSP+DATA_{min}+2\delta+SIFS$	4	0	The ack is transmitted after the data fragment. The SIFS that follows the ack is not transmitted, remaining for the data fragment. The ack is transmitted two useful times

$$L_{FL}(x) = L_H + x \quad (10)$$

$$L_{FL}(x) - L_H + L_P - x - [n_F(x) - 1]L_{PF} \quad (11)$$

The probabilities that a data packet will be interrupted a) at a point where no fragment can be sent P_{DIDm} b) at a later point where fragmentation can take place P_{DIDr} and c) nowhere P_{DNI} , are:

$$P_{DIDm} = \frac{(DATA_{min} + \delta)}{T - \tau} \quad (12)$$

$$P_{DIDr} = \frac{\min(T - \tau, DATA + \delta) - (DATA_{min} + \delta)}{T - \tau} \quad (13)$$

$$P_{DNI} = \frac{\max(T - \tau, DATA + \delta) - (DATA + \delta)}{T - \tau} \quad (14)$$

respectively. $DATA_{min}$ is the transmission time of the minimum permissible data fragment. When $DATA + \delta > T - \tau$ the last probability is zero and the rest two probabilities become complementary. Using (9), (12), (13) and (14) the expectation $E[t_{DATA}]$ can be expressed as:

$$E[t_{DATA}] = P_{DNI} \cdot (DATA + \delta) + P_{DIDr} \cdot E[t_{DFS}(x)] + P_{DIDm} \cdot \left[\frac{DATA_{min} + \delta}{2} + \delta + t_{DFS}(x = L_{ut}) \right] \quad (15)$$

From the general key assumption made earlier, x follows the uniform distribution. $E[t_{DFS}(x)]$ can be easily found by first arithmetically computing $E[n_F(x)]$ as:

$$E[n_F(x)] = \frac{1}{L_{ut} - L_{min} + 1} \sum_{x=L_{min}}^{L_{ut}} \left[\frac{L_P - x}{L_{PF}} \right] \quad (16)$$

The successful slot duration expectation can now be calculated from (1).

5.2 Idle Slot Duration

The expected duration of an idle slot $E[t_{idle}]$ can be found by observing Fig. 3b. It depends on its position in time as related to the scan procedures interruptions, similar to the previous analysis for the FES parts. For example the slots having index 1, 2, 3, ... have duration σ while the index 0 has duration $\nu_\sigma \sigma + \tau$. ν_σ is the number of protocol slots that lay entirely after the t_{TxOp} time point. Idle slots begin after DIFS periods and subsequently their duration depends on the relative DIFS positions. Let I be the total number of idle slots after a certain DIFS period, before a transmission starts. If W_N is the maximum contention window size then $I \in [1, W_N - 1]$. By calculating the integral over all possible DIFS positions y , $y \in [0, T - \tau]$, the expected idle slot duration given a certain I can be obtained as:

$$E[t_{idle} | I = i] = \frac{1}{T - \tau} \int_0^{T - \tau} \frac{1}{i} \sum_{k=1}^i [T_{k^{th} slot}] dy \quad (17)$$

Where $T_{k^{th}slot}$ is the duration of the k^{th} protocol idle slot after the DIFS period and the integrated quantity is the expected idle slot duration for a unique y DIFS position. The sum quantity within the integrated quantity in (17) is a function $F(y,i)$ of both the discrete variable i and the continuous variable y . In the standard DCF it would be a function of just the variable i as $F(i)=i\sigma$. By observing the duration of the idle slots for different DIFS positions we obtain the multi-branch function:

$$\sum_{k=1}^i [T_{k^{th}slot}] = F(y,i) = \begin{cases} i\sigma & \begin{cases} 0 < y \leq T - \tau - (RTS + \delta) - (DIFS + i\sigma) \\ \text{or } T - \tau - DIFS < y \leq T - \tau \end{cases} \\ (i-1)\sigma + (v_\sigma\sigma + \tau) & \begin{cases} y \leq T - \tau - (RTS + \delta) - DIFS \\ \text{and } y > T - \tau - (RTS + \delta) - (DIFS + i\sigma) \end{cases} \\ (i-1)\sigma + T - (y + DIFS) & \begin{cases} y \leq T - \tau - DIFS \\ \text{and } y > T - \tau - (RTS + \delta) - DIFS \end{cases} \end{cases} \quad (18)$$

By breaking the integral into each branch and calculating the summations we finally obtain:

$$E[t_{idle} | I = i] = \sigma + \sigma \frac{\tau + (v_\sigma - 1)\sigma}{T - \tau} + \frac{(RTS + \delta) \left[\tau - \sigma + \frac{1}{2}(RTS + \delta) \right]}{i(T - \tau)} \quad (19)$$

For large *useful times* the above quantity tends to σ , the value that is valid for the standard DCF, too. Finally, using the I pdf $P[I = i] = P_{idle}^i (1 - P_{idle})$, the idle slot duration expectation can be calculated by (20):

$$E[t_{idle}] = \sum_{i=1}^{W_N-1} P[I = i] \cdot E[t_{idle} | I = i] \quad (20)$$

P_{idle} is the probability that a randomly chosen slot is idle and is calculated using the Markov chain extracted probabilities.

5.3 An example of application to a specific Markov Model

The analytical model for the calculation of the slots duration expectations is applied to an existing DCF Markovian model in order to obtain performance metrics for the iDCF. The existing Markovian model used was presented in (Kim et al., 2008). This model includes in great detail the DCF functionalities described in the 802.11 standard. Its main difference from other models is that it incorporates the immediate transmission of a packet, with no backoff procedure, when the packet arrives at an empty-queue station and the medium is detected idle for a DIFS period. The non-saturation traffic model, it uses, is described by packet flows with geometrical distribution of the number of packets in a flow, with mean $1/(1-\phi)$. Idle period durations between flows are exponentially distributed with mean $1/\lambda_f$. The assumption of an ideal channel, which is also used in most of the proposed Markov models, is useful to isolate and study the effect of the intermittent operation on the iDCF performance.

In the Markov model (Kim et al., 2008) equations the slot durations T_s , T_C and T_{Idle} are replaced by the expectations $E[t_s]$, $E[t_C]$ and $E[t_{idle}]$ respectively, calculated in the previous Sections. For example the probabilities P_a and P_b of new flow arrivals at a station, which has no packet to transmit - empty station, during an idle slot and a busy slot, respectively, are replaced by:

$$P_a = P_0 \cdot \left(1 - e^{-\lambda_i \cdot E[t_{idle}]}\right) \quad (21)$$

$$P_b = P_1 \cdot \left(1 - e^{-\lambda_i \cdot E[t_s]}\right) + P^* \cdot \left(1 - e^{-\lambda_i \cdot E[t_C]}\right) \quad (22)$$

where P_0 , P_1 and P^* are the probabilities of a randomly chosen slot to include idleness, successful transmission and collision, as seen by an empty station and are given in (Kim et al., 2008). In this way the probabilities P_s of a successful transmission, P_C of a collision and P_{idle} of an idle slot occurrence are calculated according to the common method described in the DCF Markov Chain Models. Only that, in this context, their values depend not only on the engaged back-off algorithm, the number of contending terminals and the traffic model used. They also depend on the overlay intermittent mode parameters such as T and τ , which are silently incorporated in the Markov chain through the $E[T_s]$, $E[T_C]$ and $E[T_{idle}]$ quantities. Throughput and mean ordinary packet delay can now be derived as:

$$S = \frac{P_s L_p}{P_{idle} E[t_{idle}] + P_s E[t_s] + P_C E[t_C]} \quad (23)$$

$$E[Y] = \sum_{i=0}^N p^i (1-p) \left(\sum_{m=0}^i E[Y_m] + iE[t_C] + E[t_s] \right) + \sum_{i=N+1}^M p^i (1-p) \left(\sum_{m=0}^N E[Y_m] + (i-N)E[Y_N] + iE[t_C] + E[t_s] \right) + \left(1 - \sum_{i=0}^M p^i (1-p) \right) \left(\sum_{m=0}^N E[Y_m] + (M-N)E[Y_N] + (M+1)E[t_C] \right) \quad (24)$$

In (24) p is the conditional collision probability, N is the maximum back-off stage, M is the packet retransmission limit and Y_m is the delay of staying in the m^{th} back-off stage. If W is the initial contention window size, $(2^m W - 1)$ is the contention window size at the m^{th} back-off stage and $E[Y_m]$ is given by:

$$E[Y_m] = \frac{2^m W - 1}{2} (P_{idle} E[t_{idle}] + P_s E[t_s] + P_C E[t_C]) \quad (25)$$

Other performance metrics such as packet delay for the first packet of a flow, expected time to complete the transmission of a flow and packet loss probability presented in (Kim et al., 2008) can be derived accordingly.

5.4 Evaluation and Numerical Examples.

Numerical results obtained by the application of our model to the Kim et al. Markov chain, as described earlier, were validated with simulations. An OPNET discrete event network simulator was built, which models in detail all the DCF functional details and incorporates the iDCF modifications described in section 4. The numerical values used in both the analytical and the simulation models are presented in Table 3. PHY transmission rate, bit overhead, time overhead and guard interval correspond to 802.11a PHY parameters, for subcarrier spacing equal to 100 kHz and QPSK modulation per subcarrier. The required transmission rate in the simulator is controlled by the number of data subcarriers.

	Parameter	Value
MAC layer parameters	(N, M, W)	(6, 11, 16)
	$(\text{SIFS}, \text{DIFS}, \sigma, \delta)$	(16, 34, 9, 1/3) μs
	(rsp, rts, data header)	(112, 160, 272) bit
PHY	t_{oh}	62.5 μs
	PHY bit overhead	22 bit
	R	var
Overlay Scan Procedure	T, τ	var, 200 μs
Source Traffic	$n, \varphi, \lambda, L_p, L_{min}$	30, 0.95, 2, var, var

Table 3. Analytical & Simulation Model parameter set up. var: varying parameter.

In the following figures the analytical results, represented by the continuous line plots, closely follow the simulated results represented by discrete plots. By keeping the scan period T constant and having the scan delay τ varying a linear relationship between the *scan delay* and the saturation throughput is obtained which results from the linear relationship between τ and the *useful time*. The relation, though, between the throughput and the *scan period* is non-linear, if the *scan delay* is kept constant. The more frequent the scan procedures are performed, the stronger the effects of the intermittent operation.

In the following figures τ is set to 200 μs and is kept constant. This choice of τ leaves enough *useful time* for packet transmissions in the entire examined T range. Fig. 9 presents the throughput versus the *scan period* for three different constant packet sizes. It is shown that the throughput of the iDCF strongly depends on the *scan period* that the system operates with. It heavily deteriorates for very frequent scan procedures, while as T gets larger values the throughput is approaching its upper bound specified by the standard DCF operation. For large values of the scan period, the effect of the intermittent operational mode on iDCF performance is negligible. Because of the DFS formulation, presented in Fig. 8, while T grows and the DFS switch over the cases III to I, the throughput regresses before it takes the final course towards higher values. This shows that in certain cases it is preferable not to transmit a data fragment before the upcoming *scan procedure*, but to transmit a longer fragment after the scan procedure. This decision is controlled via the L_{min} parameter.

Fig. 10 presents the obtained throughput as a function of the transmission rate R for various T values and for the standard DCF. Normal DCF's weakness in exploiting high transmission rates is depicted as the throughput decreases for higher values of R . This effect tends to disappear for extremely frequent scan interruptions in the iDCF. The obtained throughput versus the payload size L_p of the data packet is presented in Fig. 11. This figure shows that

although in the standard DCF the throughput increases for larger packet sizes, in iDCF this increase is not very notable as the *scan period* is getting shorter.

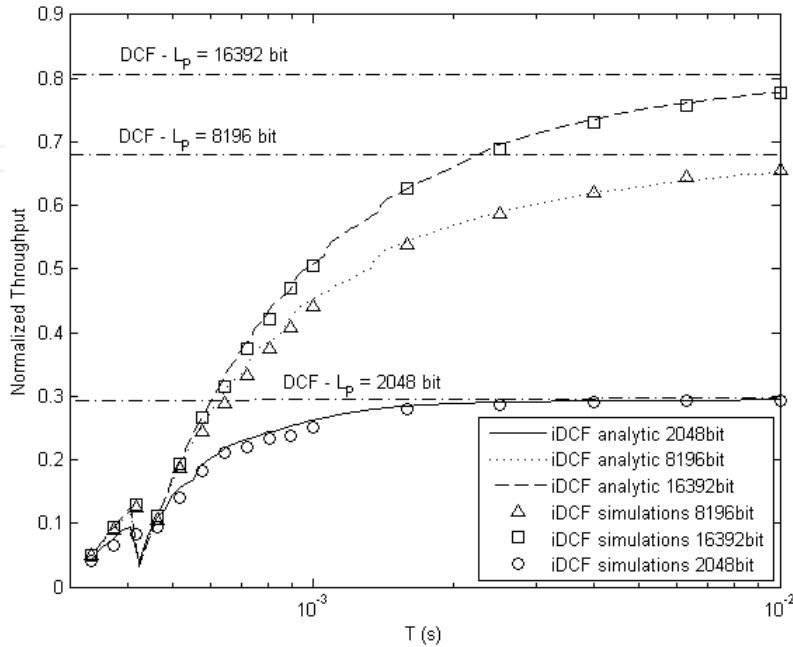


Fig. 9. Throughput versus scan period. $R=8\text{Mbps}$, various L_p .

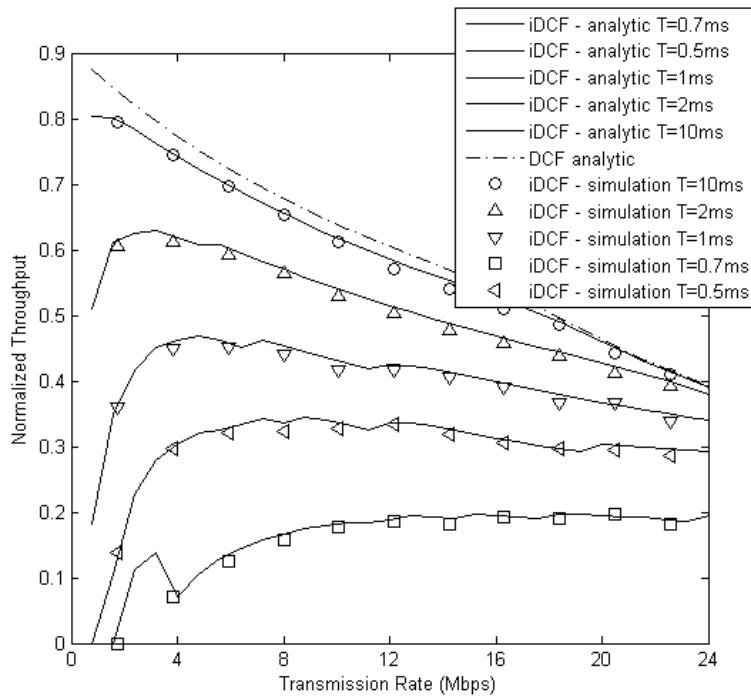


Fig. 10. Throughput versus transmission rate. $R=8\text{Mbps}$, various T

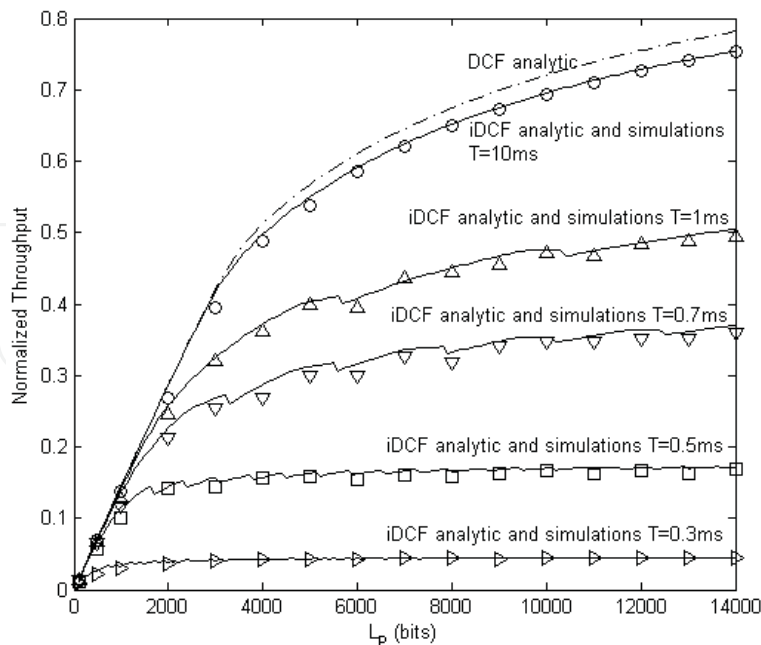


Fig. 11. Throughput versus data Packet payload. $R=8\text{Mbps}$, various T

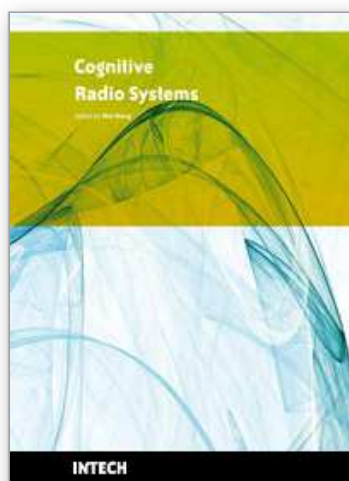
6. Conclusions and Further Work

In this chapter we presented the intermittent DCF as the MAC protocol for OA Networks. Furthermore an analytical method for calculating the expected performance metrics of iDCF was introduced. This model can be used in feasibility studies of realistic OA environments to provide realistic wireless access solutions and in Admission Control Algorithms of QoS enabled OA networks.

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Cognitive radio is a hot research area for future wireless communications in the recent years. In order to increase the spectrum utilization, cognitive radio makes it possible for unlicensed users to access the spectrum unoccupied by licensed users. Cognitive radio let the equipments more intelligent to communicate with each other in a spectrum-aware manner and provide a new approach for the co-existence of multiple wireless systems. The goal of this book is to provide highlights of the current research topics in the field of cognitive radio systems. The book consists of 17 chapters, addressing various problems in cognitive radio systems.

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University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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InTech China

Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
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