Optimizing contention based access methods for FBMC waveforms

Baher Mawlawi, Jean-Baptiste Doré, Vincent Berg

Optimizing contention based access methods for FBMC waveforms

Baher MAWLAWI, Jean-Baptiste DORÉ, Vincent BERG
CEA-Leti Minatec, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France
{baher.mawlawi, jean-baptiste.dore vincent.berg}@cea.fr

Abstract—**Filter Bank MultiCarrier modulation (FBMC) is a promising waveform technology envisaged for future mobile communication networks. For many transmission scenarios, the combination of multiple non-contiguous spectrum bands is foreseen. Because of coexistence issues, very low Adjacent Channel Leakage is required making FBMC waveforms of particular interest. However the fair frequency localization of FBMC results in a time spreading of the waveform: the filter impulse response introduces transitions which increase the duration of the burst with respect to classical multicarrier schemes such as Orthogonal Frequency Division Multiplexing and may reduce the overall spectral efficiency. In this work, we propose to study the performance of a FBMC waveform considering Carrier Sense Multiple Access with Collision Avoidance. Two mechanisms are employed for packet transmission: a basic access and a reservation scheme (based on RTS/CTS). We study how effective the RTS/CTS handshake is under ideal channel conditions by taking into account the specificities of the FBMC physical layer. Furthermore, we discuss about the RTS threshold value on packet size that maximizes throughput performance by employing one of both possible schemes and the impact of subchannel aggregation strategies on throughput and latency.**

Index Terms—**Cross Layer studies, Carrier sense multiple access/collision avoidance (CSMA/CA), MAC, PHY, multicarrier, FBMC.**

I. INTRODUCTION

The throughput and the efficiency of a wireless network are not only dependent on the physical layer capabilities but also on its medium access control (MAC) protocol. Furthermore, for some applications, coexistence with legacy services is an issue and requirement on Adjacent Channel leakage (ACL) ratio is very strong. In the context of TV White Space, opportunistic communication systems have to coexist with TV broadcast signals and wireless microphones.

The US radio regulator has limited ACL in order to prevent an opportunistic system from interfering with an incumbent operating in another channel, in particular in an adjacent one. In that case the level of ACL ratio is restricted to be at least 55dB [1]. The wireless market evolution has increased the demand for higher user rates. Many scenarios are being studied and the combination of multiple non-contiguous spectrum bands is a promising technique. In multicarrier systems, it is simply achieved by activating a subset of carriers that are within the available frequency slots. One example of such fragmented spectrum usage can be found in the high data rate services to be developed for the Professional Mobile Radio (PMR) [2]. Currently deployed PMR networks support voice and narrowband data services, based on the terrestrial trunked radio (TETRA) standards. It is envisaged to introduce new broadband data services in the same frequency bands, in coexistence with the PMR systems currently in operation[2]. However, here again, the ACL should be low in order to prevent the broadband service from interfering with the existing narrowband network.

Traditional multicarrier modulations such as Orthogonal Frequency Division Multiplexing (OFDM) require additional filtering to meet the out-of-band rejection requirement. If the chosen waveform is not well localized in frequency, dynamic and fragmented spectrum access requires an agile filtering structure. However, such a structure is particularly difficult to design at a reasonable level of complexity [3]. In that case, Filter Bank Multicarrier waveforms have demonstrated their superiority without performance degradation for both simulation and practical implementations [3].

Medium Access Control (MAC) schemes in the context of FBMC multicarrier have not yet been addressed in the literature. It has been assumed that existing MAC sublayers may be transposed to FBMC because of the similarities to classical OFDM waveforms. However, the fair frequency localization of FBMC requires relaxed time localization of the waveform. This imposes some modifications of the MAC to optimize the overall system.

In this work the considered scenario consists in a master-slave and a peer-to-peer (P2P) network that coexist as depicted in Figure 1. Consequently the network has the properties to be distributed and self-organized. This type of scenario is particularly relevant in the context of Device-to-Device (D2D) communication in which efficient and rapidly deployed network is required. Example of applications may include, database checks, geolocation information and broadband data communications.

In the context of these scenarios, contention based protocols are one possibility as this strategy allows many users to use the same radio channel without the need of a pre-coordination. In that case, the risk of collision is deliberately taken and efforts should be made to reduce the probability of collision. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) has been widely used in wireless network as users attempt to avoid collisions by transmitting only when the channel is sensed to be idle. Prior to transmitting, a user senses the channel to determine whether another user is transmitting or not. If the channel is sensed to be idle, data are sent. Otherwise, the user has to wait for a period of time before sensing again for a free channel. Messages of Request to Send (RTS) or Clear to Send (CTS) may optionally be considered to deal with the well-known hidden node issue [4]. Of course performance of such an access method is lower than organized access methods (such as Frequency Division Multiple Access (FDMA) or Time Division Multiple Access (TDMA)) but CSMA/CA offers particular benefits in the context of the proposed scenarios: it is a build-in scalable and self-organized access method.

This work reviews the performance of the CSMA/CA access method combined with the FBMC waveform. We study how effective the RTS/CTS handshake is under ideal channel conditions by taking into account the particular FBMC physical layer. Furthermore, we discuss about the RTS threshold value on packet size that maximizes throughput performance by employing one of the both possible schemes. Finally, the utilization of aggregated frequency subchannel is studied. Two strategies are investigated and compared in terms of latency and throughput: the use of independent subchannels with asynchronous concurrent accesses and subchannel aggregation scheme respectively.

The paper is organized as follows. In section II, the system model is described and a brief review of the FBMC waveform and the CSMA/CA protocol is presented. In section III a cross layer study is described and simulations results are discussed. In section IV, the main features and results are summarized and some perspectives are provided.

II. SYSTEM MODEL

A. PHY layer parameters

For many applications the coexistence with legacy services is an issue. Therefore, very low ACL is required. A modulation scheme is proposed to solve these issues by combining filtering and multicarrier modulation techniques. This technique was introduced in the 60's by Chang [5] and Saltzberg [6]. This approach, also known as filter bank multicarrier (FBMC) allows the control of the frequency response of each carrier by introducing a filter bank which can be used to control adjacent leakage. Because the prototype filter spans across several carriers, the neighboring carriers are no longer orthogonal but orthogonality can be restored by introducing an offset quadrature amplitude modulation. Moreover, successive multicarrier symbols overlap in the time domain.

To meet the coexistence requirement, a pulse shaping function with high rejection is considered. In this work we propose to consider the impulse response of the prototype filter given by [7]. This filter guarantees more than 55dB rejection using an overlapping factor of $K = 4$. LTE-like configuration, i.e a FFT of size $N = 1024$ points and a carrier spacing of 15KHz satisfies the slow and flat fading conditions necessary for multicarrier modulation [8].

A preamble based approach is considered. Synchronization and channel estimation is performed using the training sequence. The preamble has been designed to accurately configure the Automatic Gain Control (AGC) component and

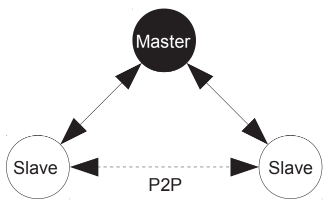

Fig. 1. Illustration of the considered network architecture.

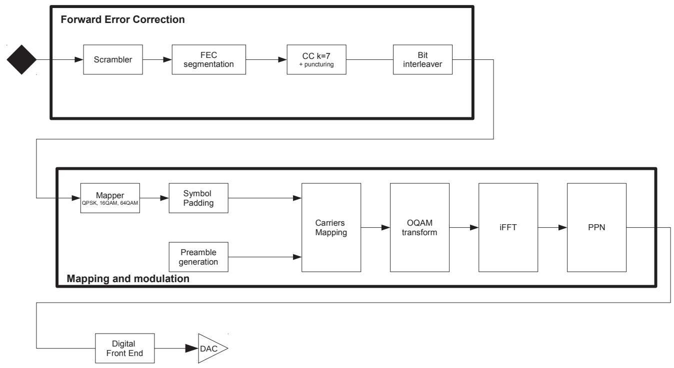

Fig. 2. Architecture of the proposed FBMC transmitter.

to detect the start of the burst. It also gives an estimate of the channel frequency response while preserving the localization properties of the FBMC signal.

The architecture of the proposed transmitter is depicted in Figure 2. The transmitter architecture is composed of two main elements: forward error correction followed by a data mapping and modulation block. Forward error correction (FEC) is implemented using a standard convolutional encoder of constraint length $k = 7$ and rate $1/2$. The code may be punctured to support variable encoding rates $2/3$ and $3/4$. The convolutional code is segmented by blocks of fixed sizes. The trellis is closed at the beginning and the end of each FEC block. The output of the encoder is forwarded to a bit interleaver of size multiple of the output length of the encoder. It should be mentioned that a Cyclic Redundancy Check (CRC) should be added to the bitstream at the input of the FEC module to detect errors in received message.

The second module, called Mapping and Modulation, maps and modulates the encoded bits to the multicarrier modulation. The coded data are mapped to a QPSK, 16QAM or 64QAM modulation. Symbols are then padded to complete the transmitted burst into an integer multiple of multicarrier symbols. A preamble is added to the burst structure. The generated block of data and preamble symbols are mapped to the active carriers and modulated to an Offset-QAM before being inverse transformed into a time domain sequence using an 1024-point IFFT. A polyphase network (PPN) filter structure completes the data stream and shapes the output of the IFFT over the duration of the prototype filter.

A Modulation and Coding Scheme (MCS) index is defined to describe the combination of the modulation and coding schemes that are used when transmitting data. Table I indicates the MCS mapping.

The well-adjusted frequency localization of the prototype filter guarantees low ACL. This justifies the use of FBMC waveforms in the context of dynamic spectrum access as well as fragmented spectrum. It also allows to maximize the spectrum usage as only limited guard band in the frequency domain is necessary to guarantee low leakage. Moreover, as mentioned previously, the FBMC waveform is particularly adapted when the coexistence between two systems is mandatory.

MCS index	Coding rate R_{FEC}	Modulation	Modulation order m
0	1/2	QPSK	2
1	2/3	QPSK	2
2	3/4	QPSK	2
3	1/2	16QAM	4
4	2/3	16QAM	4
5	3/4	16QAM	4
6	1/2	64QAM	6
7	2/3	64QAM	6
8	3/4	64QAM	6

TABLE I
LIST OF MODULATION AND CODING SCHEME (MCS) INDEX VALUES.

B. MAC overview

CSMA/CA access methods have particular benefits in case of un-coordinated and/or D2D communications networks. Each user can access the channel with equal priority through contention at each time instant. Two types of CSMA/CA access method are commonly used, basic and Request to Send/Clear to Send (RTS/CTS) reservation modes. The latter is employed in order to improve performance as it reduces collision duration and addresses the hidden node problem. Due to the four-way handshake mechanism gain is achieved particularly when long data packets are transmitted.

Each nodes with a packet to transmit should first sense the channel. If the channel is sensed to be idle for a time period greater than the distributed inter-frame space (DIFS) time, the node sends its data packet. After the successful reception of a data packet, an acknowledgment (ACK) packet is sent back. If the channel is not sensed idle, the node differs transmission. A random backoff timer is then generated in the interval [0, CW-1] where CW is the contention window. When the channel is sensed idle, the backoff timer is decremented by one. If the channel is sensed busy the backoff timer is frozen. The node sends its data packet when the backoff timer reaches 0. If an acknowledge packet is received, the transmission is declared successful and CW is set to CWmin. In case of unsuccessful transmission, CW is doubled up until it reaches a maximum value, CWmax.

When RTS/CTS mode is activated the node with a packet to transmit sends a RTS packet. If the RTS packet is received without collision, a CTS is sent back to inform all nodes in the cell that the channel is reserved. All nodes defer their transmissions for the duration specified by the RTS: this mechanism is called virtual sensing. After the successful reception of a data packet, an ACK packet is sent back. If the channel is not sensed idle, the backoff procedure is invoked. Under the hypothesis of a perfect transmission, collisions may only occur on RTS packets and transmission of data packets can proceed without interference from other nodes.

III. CROSS LAYER EXPERIMENTATION

A. PHY throughput

Based on the parameters defined in the previous section, it is possible to derive the achievable throughput of the PHY layer in saturation scenario. Saturation condition models the throughput under the assumption that the transmitter has

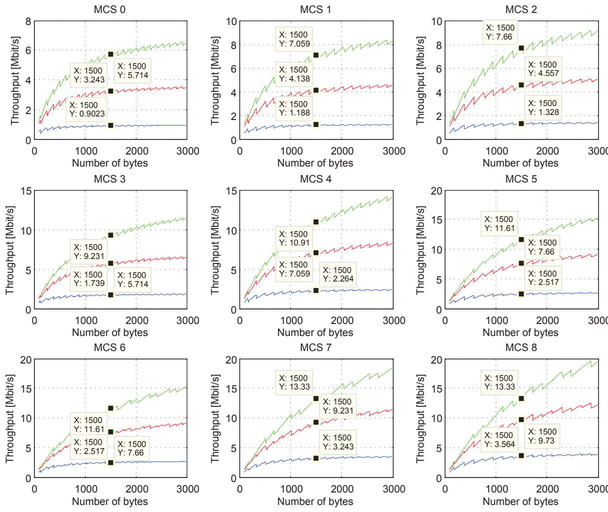

Fig. 3. Achievable throughput in Mbit/s for various size of payload for all the MCS index. Blue lines correspond to 64 active carriers (0.96MHz), red lines to 256 active carriers (3.84MHz) and green lines correspond to 512 active carriers (7.68MHz).

always a packet to send. The throughput of the proposed FBMC PHY layer can be computed as follows:

$$\Gamma_{PHY} = \frac{N_{bit}}{\left(2\left(\left\lceil \frac{M_{FEC}}{mN_a}\right\rceil + L_p\right) - 1\right)0.5 + K} f_c^{MHz} \;\; [Mbit/s] \tag{1}$$

where N_{bit} is the size of the data to be transmitted, f_c^{MHz} is the carrier spacing in MHz, L_p is the number of preamble symbol, N_a is the number of active carrier, m is the modulation order, K is the overlapping factor and M_{FEC} is the number of bit to be transmitted after FEC processing. M_{FEC} is equal to:

$$M_{FEC} = \left\lceil \frac{N_{bit}}{N_{FEC}R_{FEC} - P_{FEC}} \right\rceil N_{FEC} \tag{2}$$

where R_{FEC} is the FEC coding rate, P_{FEC} the number of tail bits and N_{FEC} the size of a coded block.

Figure 3 depicts the physical layer throughput for various size of payload from 100 to 3000 bytes and for three bandwidth configurations, namely 0.96MHz, 3.84MHz and 7.68MHz. For these configurations, the FEC block size N_{FEC} is set to 2048 bits, the number of tail bits $P_{FEC} = 8$, $L_p = 4$, $K = 4$. When the number of data payload bytes to transmit is small, the duration of the preamble combined with the rising and falling time of the prototype filter dominate the duration of the burst, reducing the achievable throughput. This effect is amplified when the spectral efficiency is increased (resp. bandwidth), as less multicarrier symbols are required to transmit the data. For large bandwidth and high spectral efficiency, it should be interesting to consider payload aggregation to maximize the efficiency of the PHY layer.

B. CSMA/CA performance evaluation

Many previous works have been realized to study and optimize the CSMA/CA access method. The theoretical throughput has been derived from the markov chain model by the authors of [9] under the following assumptions [10]:

- No hidden terminal and capture effect.
- Failed transmissions only occur as a consequence of a collision.
- All stations are saturated and always require to send packets.
- For any given user, the probability of collision, is constant and independent of the collision history of the user and all other users.
- The probability of collision does not depend on the backoff stage at which the transmission is made.
- All users have the same data rates and the same amount of time to transmit.

It is then possible to express the saturation throughput as follows [11]:

$$\Gamma_{MAC} = \frac{P_s P_{tr} N_{bit}}{P_s P_{tr} T_s + P_{tr}(1-P_s)T_c + (1-P_{tr})T_{id}} \quad (3)$$

where P_s is the probability of a successful transmission, P_{tr} is the probability that there is at least one transmission in the considered time slot, N_{bit} is the packet payload size, T_s is the time needed to transmit a packet of size N_{bit}, T_{id} is the duration of the idle period (a single time slot); and T_c is the average time spent in the collision procedure. T_c and T_s can be computed for RTS/CTS transmission mode with [11]:

$$T_s = T_{RTS}+3T_{SIFS}+4\sigma+T_{CTS}+T_L+T_{ACK}+T_{DIFS} \quad (4)$$

$$T_c = T_{RTS} + T_{DIFS} + \sigma \quad (5)$$

where, T_{CTS} and T_{RTS} are the transmission times needed to send the CTS and RTS packet. T_{SIFS} is Short Interframe Space, σ is the propagation delay and T_L and T_{ACK} are the transmission times needed to send the packet payload, and the acknowledgment, respectively.

P_s and P_{tr} are calculated by resolving a non linear equation functions [9]. These two probabilities are related to the number of nodes trying to access the channel, and depend on the backoff timer parameters.

C. MAC-PHY throughput evaluation

Based on the results described above, we evaluate the performance of FBMC waveforms with CSMA/CA access method. The efficiency of the CSMA/CA access method is estimated by considering perfect channel conditions for the PHY (no noise, no fading): failed transmissions only occur as a consequence of a collision.

The MAC-PHY saturation throughput evaluated is an upper bound that gives the maximum achievable throughput on a shared channel with a given configuration. The parameters described in Table II are considered for the evaluation of performance. Three bandwidth configurations are studied.

We assume that the MCS configuration for the acknowledge frame is the same as the MCS configuration used for the data payload transmission. Concerning control packets, RTS and CTS, the MCS index 0 is considered. As these messages serve for virtual carrier sensing, they should be decoded by all the nodes within the cell. Consequently a robust configuration is set. Parameter σ, the propagation delay, is related to the network cell radius: 10us corresponds to a cell radius of 3km.

Short Interframe Space (SIFS), is the time interval between a packet and its acknowledgment. This duration corresponds to the time that is required, to decode the packet at each layer and to switch the radio of a node between the reception and transmission modes. The duration of 10us is the amount of time classically considered in WLAN [9]. RTS, CTS and ACK packet size are the ones used in WLAN [9] and include a 32 bit CRC.

We have first evaluated the achievable throughput in the case of a 1500-byte packet for various network load and various bandwidth configurations. The PHY layer is configured to send payload packet with the MCS index 4. The load of the network varies from 1 to 100 nodes trying to access simultaneously the channel. The number of nodes less than 10 corresponds to classical WLAN or small cell scenarios. When the number of nodes is greater than 10, the scenario considers a machine type communication for which numerous nodes transmit at low throughput over the same medium [12]. Results are depicted in Figure 4.

As expected, RTS/CTS mechanism provides better performance for configurations with high collision probability (loaded network) and long packet duration (small bandwidth). For loaded networks, the probability of collision is important, and in that case, more time is spent when a collision occurs

MAC	
Slot duration (us)	8.33
T_{SIFS} **(us)**	10
T_{DIFS} **(us)**	SIFS + 2 × 8.33
σ **(us)**	10
CWmin	15
CWmax	63
ACK payload (bits)	112
CTS payload (bits)	112
RTS payload (bits)	160
PHY	
MCS ACK	MCS DATA
MCS RTS	0
MCS CTS	0

TABLE II
LIST OF PARAMETERS CONSIDERED FOR PERFORMANCE EVALUATION.

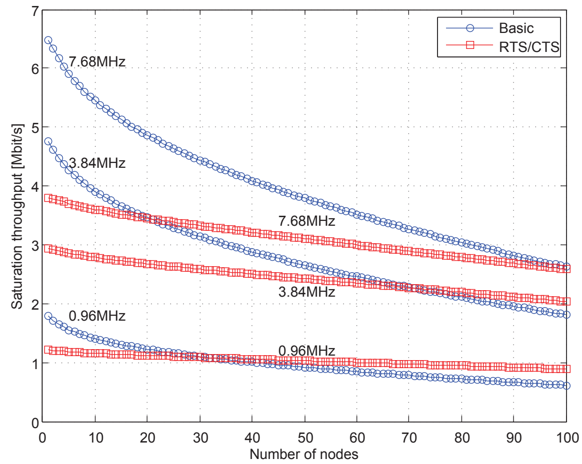

Fig. 4. Achievable throughput in Mbit/s for various bandwidth when a 1500-byte packet is sent using a MCS index 4.

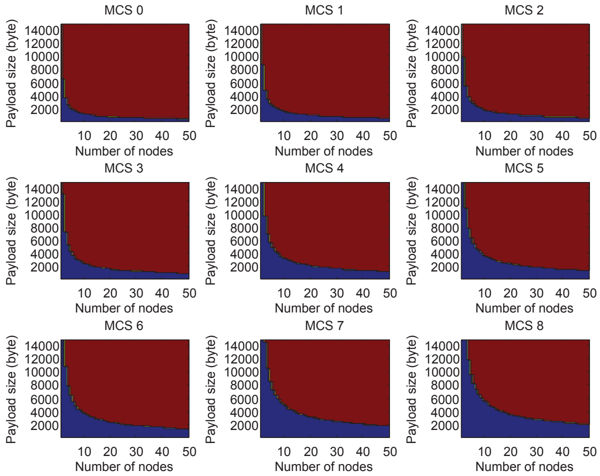

Fig. 5. Set of configurations attractive for basic (resp RTS/CTS) schemes for a 0.96MHz channel bandwidth.

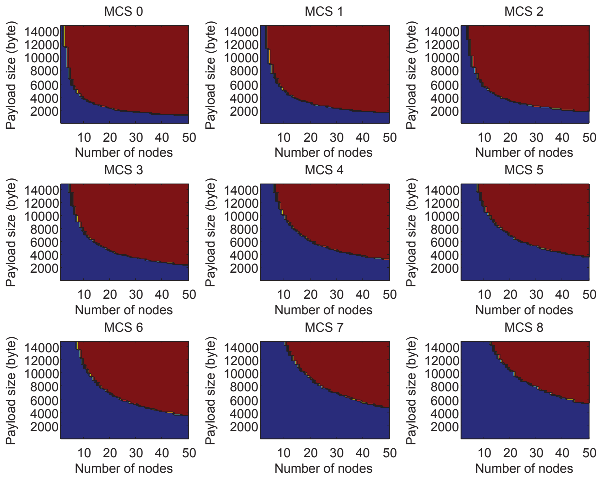

Fig. 6. Set of configurations attractive for basic (resp RTS/CTS) schemes for a 7.68MHz channel bandwidth.

for the basic mode than the RTS/CTS mode. On the other hand, when a short packet is sent, we might not benefit from the RTS/CTS method due the handshaking overhead, but even, consumes extra time, and makes the basic method more efficient. However we have to keep in mind that this extra time is essential to guarantee good ACL ratio and coexistence properties. Moreover, RTS/CTS mechanism provides a solution for the hidden node issue.

RTS/CTS mechanism decreases efficiency as it transmits two additional control packets without any payload. In practice, it should be interesting to specify the RTS threshold , a parameter that indicates the payload size under which the data packets should be sent without RTS/CTS. Figure 5 and 6 plot the area in which RTS/CTS mechanism provides better efficiency versus the network load and the packet size to transmit respectively. Blue areas correspond to configurations in which basic mechanism provides best efficiency.

These results illustrate that the basic mechanism outperforms RTS/CTS when the number of contending nodes is small for all packet size values and all bandwidth configurations. Results confirm that the RTS/CTS scheme is not beneficial for small packet size and low network load due to the low collision probability. It is consistent with state of the art results [13] using OFDM waveforms. When the network load increases, the RTS threshold decreases to lower values. This can be justified since loaded configurations cause more packet collisions. When the available bandwidth increases, the amount of time required to transmit data decreases and therefore the RTS threshold increases. Once again, less time is spent when collision occurs for the basic mechanism.

We point out that only large packet size values and dense network render the RTS/CTS beneficial compared to the basic access scheme for the studied configuration. This suggests the benefits of considering packet aggregation strategies to improve the efficiency of the access method.

The comparison with OFDM PHY layer is not discussed in this work since OFDM does not meet the ACLR requirements even with a large number of guard carrier. However, due to the good frequency localization of FBMC, time is spent by the filtering process. This effect is negligible when the duration of the packet is large and should be compared to the gain offered by the FBMC waveform, i.e the frequency localization and the absence of guard interval, in term of spectral efficiency.

As mentioned previously, the use of FBMC waveforms allows to guarantee low frequency leakage. This makes an efficient use of adjacent channels feasible even in an asynchronous way. Different strategies are considered to access the different frequency channels. First we have investigated a strategy in which aggregated subchannels are used for the transmission; every time the transmitter use all the available bandwidth to transmit by aggregating subchannels.

The second strategy relies on the use of independent subchannels: each subchannel is asynchronously accessed using the CSMA/CA access method.

We have compared these two schemes assuming a granularity of 0.96MHz (the minimal size of a subchannel is fixed to 64 active carriers that corresponds to 0.96MHz). For the case of the use of independent subchannels, when a node has a packet to send, it first makes a random choice on which subchannel (or group of subchannel) the packet will be transmitted. Then, the node accesses the medium using the backoff mechanism described previously.

We depict the estimated saturation throughput in Figure 7 for basic and RTS/CTS scheme respectively. For the two mechanisms, the best performance is achieved when the 8 subchannels are asynchronously addressed in parallel. This can be explained because the probability of collision is reduced. The choice of a subchannel offers a new degree of freedom for nodes. For 10 nodes, the achievable throughput is multiplied by a factor 2.5, if we compare the use of 8 independent 0.96MHz subchannel with a 7.68MHz bandwidth channel.

However, the use of small fragment of bandwidth spreads the duration of the burst and therefore impacts on the system latency. We have measured the impact of the aggregation scheme on the latency of the system. The latency is defined as the time needed for a packet to be sent and decoded. We have analyzed the cumulative distribution function of the latency for the different number of aggregated subchannel. Results are

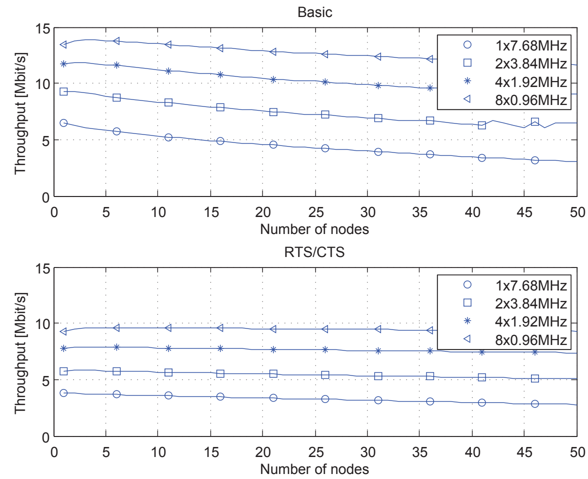

Fig. 7. Achievable saturation throughput for a 1500-bytes packet sent using a MCS index of 4 for various aggregation strategies in case of basic and RTS/CTS scheme respectively.

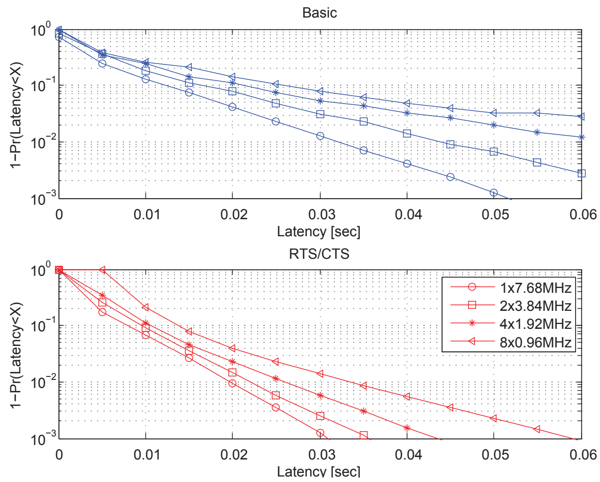

Fig. 8. Latency cumulative distribution function for a 1500-bytes packet sent using a MCS index of 4 for various aggregation strategies in case of basic and RTS/CTS scheme respectively.

illustrated Figure 8 for a 1500-bytes packet, assuming a MCS of 4 and 10 nodes simultaneously accessing the medium.

The results are quite different from that of the saturation throughput. The latency is reduced if the packet is sent over an aggregated channel. The probability that a packet is decoded with a latency less than 0.02s is equal to $1 - 7.10^{-3}$ for an aggregation of 8 subchannels versus $1 - 4.10^{-2}$ if only one subchannel is used.

This suggests that the aggregation strategy should be optimized according to a cost function built from both latency and throughput. If the throughput is maximized, the usage of independent subchannel gives the best results. On the other hand, the use of aggregated subchannel reduces the latency.

IV. Conclusion

In this work, we have performed a series of detailed simulations to evaluate the performance of FBMC waveforms on basic and RTS/CTS CSMA/CA mechanisms. Details about the PHY layer have been provided. The results underline that the packet size and the number of contending node are the main factor that influence the choice of the access mechanism. While the basic access method is well adapted for small packet sizes and low network loads, the RTS/CTS mechanism works better for large packet sizes and dense networks. This fact is amplified by the fact that FBMC is not well localized in time. However these results have to be weighted since RTS/CTS mechanism provides the power to solve the hidden nodes issue. We have determined that the RTS threshold for RTS/CTS mechanism provided better efficiency than the basic one. This suggests the benefits of considering packet aggregation strategies in time domain to improve the efficiency of the access method. Finally we have analyzed the impact of the use of subchannel aggregation in terms of throughput and latency. The use of independent subchannel allows to maximize the throughput while the aggregation scheme reduces the latency. This suggests that the aggregation strategy should be optimized according to a cost function built from both latency and throughput based on the application.

V. Acknowledgment

This work has been carried out in the frame of the PROFIL project, which is funded by the French National Research Agency (ANR) under the contract number ANR-13-INFR-0007-02.

References

[1] "Unlicensed operation in the tv broadcast bands, us federal register," in *FCC final rule, US Federal Register*, Feb 2009.
[2] M. Renfors, F. Bader, L. Baltar, D. Le Ruyet, D. Roviras, P. Mege, M. Haardt, and T. Hidalgo Stitz, "On the use of filter bank based multicarrier modulation for professional mobile radio," in *Vehicular Technology Conference (VTC Spring), 2013 IEEE 77th*, June 2013, pp. 1–5.
[3] V. Berg, J.-B. Dore, and D. Noguet, "A flexible radio transmitter for TVWS based on FBMC," in *Digital System Design (DSD), 2013 Euromicro Conference on*, Sept 2013, pp. 163–167.
[4] F. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part ii–the hidden terminal problem in carrier sense multiple-access and the busy-tone solution," *Communications, IEEE Transactions on*, vol. 23, no. 12, pp. 1417 – 1433, dec 1975.
[5] C. R. W., "Synthesis of band-limited orthogonal signals for multichannel data transmission," *Bell Syst. Tech. J*, dec 1966.
[6] S. B. R., "Performance of an efficient parallel data transmission system," *IEEE Trans. Comm. Tech.*, dec 1967.
[7] M.Bellanger *et al.*, "FBMC physical layer: a primer," 06 2010. [Online]. Available: http://www.ict-phydyas.org
[8] V. Berg, Z. Kollar, R. Datta, P. Horvath, D. Noguet, and G. Fettweis, "Low ACLR communication systems for TVWS operation," in *Future Network Mobile Summit (FutureNetw), 2012*, July 2012, pp. 1–9.
[9] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *Selected Areas in Communications, IEEE Journal on*, vol. 18, no. 3, pp. 535 –547, march 2000.
[10] M. Fang, "Power evaluation and performance enhancement of CSMA/CA based WLANs," in *Masters Thesis, Hamilton Institute*, June 2010.
[11] M. H. Manshaei and J.-P. Hubaux, "Performance analysis of the IEEE 802.11 distributed coordination function: Bianchi model," March 2007.
[12] T. Potsch, S. Khan Marwat, Y. Zaki, and C. Gorg, "Influence of future M2M communication on the LTE system," in *Wireless and Mobile Networking Conference (WMNC), 2013 6th Joint IFIP*, April 2013, pp. 1–4.
[13] P. Chatzimisios, A. Boucouvalas, and V. Vitsas, "Optimisation of RTS/CTS handshake in IEEE 802.11 wireless LANs for maximum performance," in *Global Telecommunications Conference Workshops, 2004. GlobeCom Workshops 2004. IEEE*, Nov 2004, pp. 270–275.