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Hardware Complexity Reduction in Universal Filtered Multicarrier Transmitter Implementation

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ABSTRACT The inclusion of machine-type communication in the 5G technology has motivated the research community to explore new derivative waveforms of orthogonal frequency division multiplexing. Filter bank multicarrier, universal filtered multicarrier (UFMC), and generalized frequency division multiplexing techniques are under evaluation with respect to their suitability to 5G requirements. In addition to acceptable spectral performance, investigation on computational complexity reduction while addressing flexibility can help in the selection of suitable waveform among multiple options available for 5G. In this regard, based on analysis of computation involved in UFMC waveform construction, few reduced complexity solution for UFMC transmitter implementations are recently proposed. However, hardware-implementation-related issues have not been discussed in detail. In this paper, we have proposed reduced complexity hardware solutions for all three constituent blocks, i.e., inverse discrete Fourier transform (IDFT), finite impulse response (FIR) filter, and spectrum shifting blocks of a UFMC transmitter. For IDFT part, a reduced complexity IFFT solution using Radix-2 decimation in a time technique is presented, where more than 42% computations can be avoided. It is also shown that how five times less number of multipliers can be used in an FIR filter to simplify filter architecture. Finally, a highly efficient method is presented to compute spectrum shifting coefficients through small sized lookup table.

INDEX TERMS 5G, UFMC, reduced complexity, IFFT, FIR filtering, spectrum shifting.

I. INTRODUCTION

Future 5G mobile telecommunication technology needs to support new use-case scenarios and applications. Three main directions: Extreme Mobile Broadband, Massive MTC, and Ultra-reliable MTC are envisioned for 5G [1], [2]. It is therefore, the key design principles for 5G systems are flexibility, versatility, scalability and efficiency to serve diverse use-cases and scenarios [1], [2]. The support for MTC is a challenging aspect of 5G technology as there is a forecast that around 50 billion devices will be connected by year 2020 [3]. Hence, in order to accommodate these huge number of machines, there is a need of efficient use of available spectrum. Hence, for 5G, new waveforms better than CP-OFDM are under discussion [4], [5]. The candidates having better spectral properties than CP-OFDM include, Filter-Bank Multi-Carrier (FBMC) [6], Generalized Frequency Division Multiplexing (GFDM) [7] and Universal Filtered Multicarrier (UFMC) [8]. In order to contribute towards the evaluation of a waveform, providing optimal enabling technology, certain performance metric are required to be established. In this regard packet size flexibility, spectral efficiency, power spectral density, peak to average power ratio (PAPR), multi-user interference, implementation complexity and backward compatibility (needing minimal changes to upgrade existing to future system or vice versa) are the salient metrics upon which a waveform can be evaluated.

In literature UFMC has been evaluated for above-mentioned metrics. Schaich *et al.* in [9] and Robin *et al.* in [10], showed that the UFMC is better than FBMC in case of very short packets while performing similar for long sequences. While looking at out of band power spectral density and complementary cumulative distribution function (CCDF) of the PAPR, they are very close as evaluated in [10]. Similarly if we see the implementation complexity and backward compatibility, UFMC is less complex than FBMC and it is easy to change a CP-OFDM to UFMC as compared to FBMC. As far as multi-user multi-service scenario is concerned, recently an investigation is made in [11] on a framework for different use case scenarios of 5G e.g. MTC, V2V etc. In this work, generalized synchronous (GS) multi-service (MS) sub band filtered multi-carrier (SFMC) (where SFMC can be considered as generalized name for UFMC) systems have been proposed. Low-complexity ISBI cancelation and equalization algorithms are proposed in this paper which can significantly improve the system performance in comparison with the existing algorithms.

Keeping aforementioned salient features of UFMC in view, we have focused on computational complexity reduction of

UFMC while keeping flexibility into consideration. In case of MTC this factor is very critical in order to meet extreme low area, power and cost budget of a machine connected in Internet of Things (IoT) framework.

For UFMC, in [12], a reduced complexity architecture has been proposed which targets both IFFT and filtering portions of UFMC transmitter. They proposed a 64-point IFFT to each physical resource block (PRB) in place of 1024-point IFFT and applying filtering in frequency domain. This is what they call as frequency domain generation method for UF-OFDM. Finally, before transmission, the filtered data is converted back into time domain data by taking IFFT. With this strategy, they claim that if the classical scheme of UFMC transmitter [6] has complexity of 150 times that of CP-OFDM then applying frequency domain solution the complexity reduces to 120 times that of CP-OFDM. Raymond *et al.*, in [13], presented a different scheme than classical scheme where the reduction in complexity is achieved firstly through reducing the size of IFFT again to 64-point and the result is then up sampled by performing zero padding between samples. In filtering part, on one side only single set of filtering coefficients are required and on the other side, due to zeros in up-sampled data, a large number of computations can further be avoided. However, in last part i.e. spectrum shifting part, large number of complex coefficients are required for spectrum shifting. On the bases of computations involved the calculated complexity is 25 times CP-OFDM.

In this work, we have taken the most simplified UFMC transmitter scheme to date [13] as the baseline and proposed simplified methods to perform computations involved in all three building blocks of UFMC transmitter while keeping the flexibility requirements into the consideration in terms of IFFT size, filter length and parameters associated to spectrum shifting. Hence, first of all, a simplified IFFT computation mechanism is proposed which avoids redundant radix-2 DIT butterflies. Secondly, a reduced complexity hardware architecture for filtering scheme is proposed to avoid large number of multipliers involved in the hardware architecture. Finally, a mechanism is proposed for the generation of large number of complex coefficient required for spectrum shifting. This mechanism uses only 82 memory locations along with one multiplier and an adder for 10MHz LTE channelization specification.

The rest of the paper is organized as follows. The next section presents two different UFMC transmitter structures while Section III details proposed hardware complexity reductions in UFMC transmitter. Finally Section IV concludes the paper.

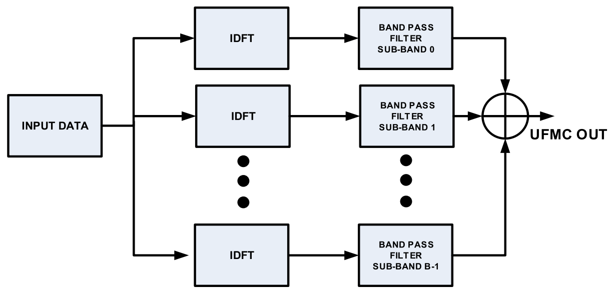

FIGURE 1. **Block diagram of classical UFMC scheme.**

II. UFMC TRANSMITTER STRUCTURES

In [5], the concept of UFMC was proposed. The concept is shown in Fig. 1 where to achieve UFMC waveform each frequency block i carrying m subcarriers may be converted from frequency-domain to time-domain by a frequency block specific IDFT module, after which filtering is performed to eliminate out of band emissions. At the end filtered time-domain data in each frequency block is added to form a UFMC waveform. Hence, in contrast to OFDM where a single joint IDFT is performed by combining all frequency block, separate IDFTs operations are required to be performed on each frequency block. Moreover, there are few non-zero inputs m to IDFT block which are placed at different locations in total N number of inputs of N- point IDFT block whereas rest of $N - m$ data entries are filled with zeros. Mathematically speaking the input to the UFMC waveform generator block is a set of constellation mapped symbols X which are considered as frequency response of available carriers. The symbols X are divided into frequency blocks $\mathbf{X}$ where each frequency block is made up of m sub carriers. If B are number of frequency blocks then $\boldsymbol{X} = [\boldsymbol{X}_0, \ldots, \boldsymbol{X}_{B-1}] = \left[X_0, \ldots, X_{m(B-1)}\right]$. Inside UFMC transmitter each frequency block is zero padded for carriers which are not related to that frequency block to make a block of N symbols. Each zero padded symbol stream passes through an $N-$ point IDFT block to generate x_i which is then filtered by a Dolph-Chebyshev FIR filter with side lobe level attenuation of 60 dB, tuned to properly sub-band with impulsive response h_i. After filtering, all processed frequency blocks z_i are added together to form UFMC waveform z expressed as:

$$z\left(u\right) = \sum_{i=0}^{B-1} \sum_{k=0}^{N-1} x_i\left(k\right) h_i(u-k) \tag{1}$$

where $u = 0, \ldots, N + L - 1$.

In the work presented in [13], a simplified scheme of UFMC modulation is provided which is shown in Fig. 2. This scheme, provides low complexity solution for UFMC

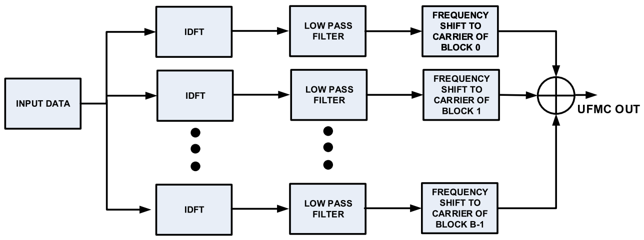

FIGURE 2. Block diagram of simplified UFMC scheme.

transmitter where the key features include smaller size of IDFT operation represented as N_0, taking IDFT of all frequency block on first m sub-carriers, up sampling the data, use the same filter and changing the spectrum of each frequency block after filtering.

In IFFT part, first reduction for LTE 10 MHz bandwidth scenario, is the use of smaller size IDFT with $N_0 = 64$ in place of $N = 1024$. This provides required out of band suppression while saving a lot of mathematical computations involved in performing IFFT to achieve IDFT. Secondly, it is proposed to take the IFFT of each frequency block comprised of 12 sub-carriers (i.e. $m = 12$ complex numbers) appended with 52 zeros at the end. This strategy has significant impact on simplifying the filtering part as explained below.

Before sending the result to the filtering part, each output of IFFT block containing 64 complex numbers is up sampled by a factor of 16 through placing 15 zeros between each sample to get a block length of 1024. Since, here all frequency blocks have the same frequency spectrum i.e. on first m-subcarreires, same filtering coefficients having real component only, are required to suppress out of band emissions. Now, if we compare the filtering portion of both types of implementations. The filtering is simpler in scheme of Fig. 2 as filtering coefficients are real, hence, we save 2 real multiplications, 1 addition and 1 subtraction when one multiplication of one incoming data with one filter coefficient is performed. Similarly, we only need to store one set of filtering coefficients each has only real part. Finally, multiplication of zeros in incoming data to filter does not need any actual multiplication.

In order to bring each frequency block to its actual spectrum location, each processed frequency block is then multiplied with $e^{-j2\pi(m\times i)n/N}$ where $m = 12, i = 0, 1, 2, .., B-1$ and $n = 0, 1, \ldots, N+L-1$. Although the overall scheme provides the simplest approach towards UFMC transmitter implementation, to perform spectrum shifting we need as many coefficients as there are samples in the processed frequency block. Furthermore, separate set of coefficients are required for each frequency block. No mechanisms of generating or storing these coefficients is described in [13] though it has a significant effect on hardware timing and resource utilization to either generate or store these coefficients.

Finally, all spectrum shifted streams and added to form final UFMC waveform.

III. PROPOSED SIMPLIFICATIONS

As mentioned before, complexity of work in [12] is 120 times as that of CP-OFDM waveform for 10 MHz channelization. On the other hand, for same channel specifications and acceptable performance of 60 dB side lobe level attenuation, the complexity associated with work in [12] is almost 25 times as that of CP-OFDM. In this section, efficient implementation solutions are discussed which further reduces computations in IDFT block and provide reduced complexity solution for filtering and spectrum shift block of scheme presented in [13].

A. IFFT COMPLEXITY REDUCTION

In this work, IFFT through radix-2 DIT is selected to implement IDFT operation as many computations can be avoided with low complexity solution. Consider the butterfly hardware architecture presented in Fig. 3. Here, two complex number a and b are the input to the butterfly. The b input is multiplied with another complex number w called as twiddle factor. Finally, this product is added in input a to produce first output $O1$ and is subtracted from a to form second output $O2$. Here, it can be noticed that if b is zero than a will appear on both outputs of the butterfly, hence no arithmetic operations are required within the butterfly.

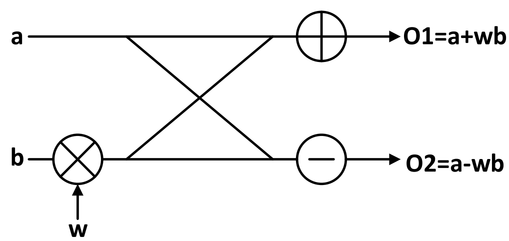

FIGURE 3. Radix-2 Butterfly implementation using complex adders and multipliers.

Now consider butterfly architecture of Radix-2 Decimation in Time IFFT with bit reversed order inputs for $m = 12$ and $N = 2^l = 64$ in Fig. 4. This architecture has $l = 6$ stages where each stage has N/2 butterflies (only first three stages are shown in Fig. 4). Here, due to only 12 non-zero input data, all butterflies in first stage have zero on their second input. Whereas, there are 12 butterflies which have non-zero first input. These 12 non-zero inputs will be transferred on 24 locations of inputs of stage two butterflies. Here, again all second inputs are zero resulting in copying of 24 inputs to the 48 locations to the input of third stage without performing any computation. In third stage, there are 16 butterflies that have both non-zero inputs whereas rest of 16 butterflies have second input as 0. In this stage only 16 butterflies are computed and for reset of butterflies, their input data will be copied on 32 locations of input of stage-4. From stage-4 onwards all butterflies in each stage will be computed. With this analysis, it is shown that out of 192, only 112 butterflies are actually computed.

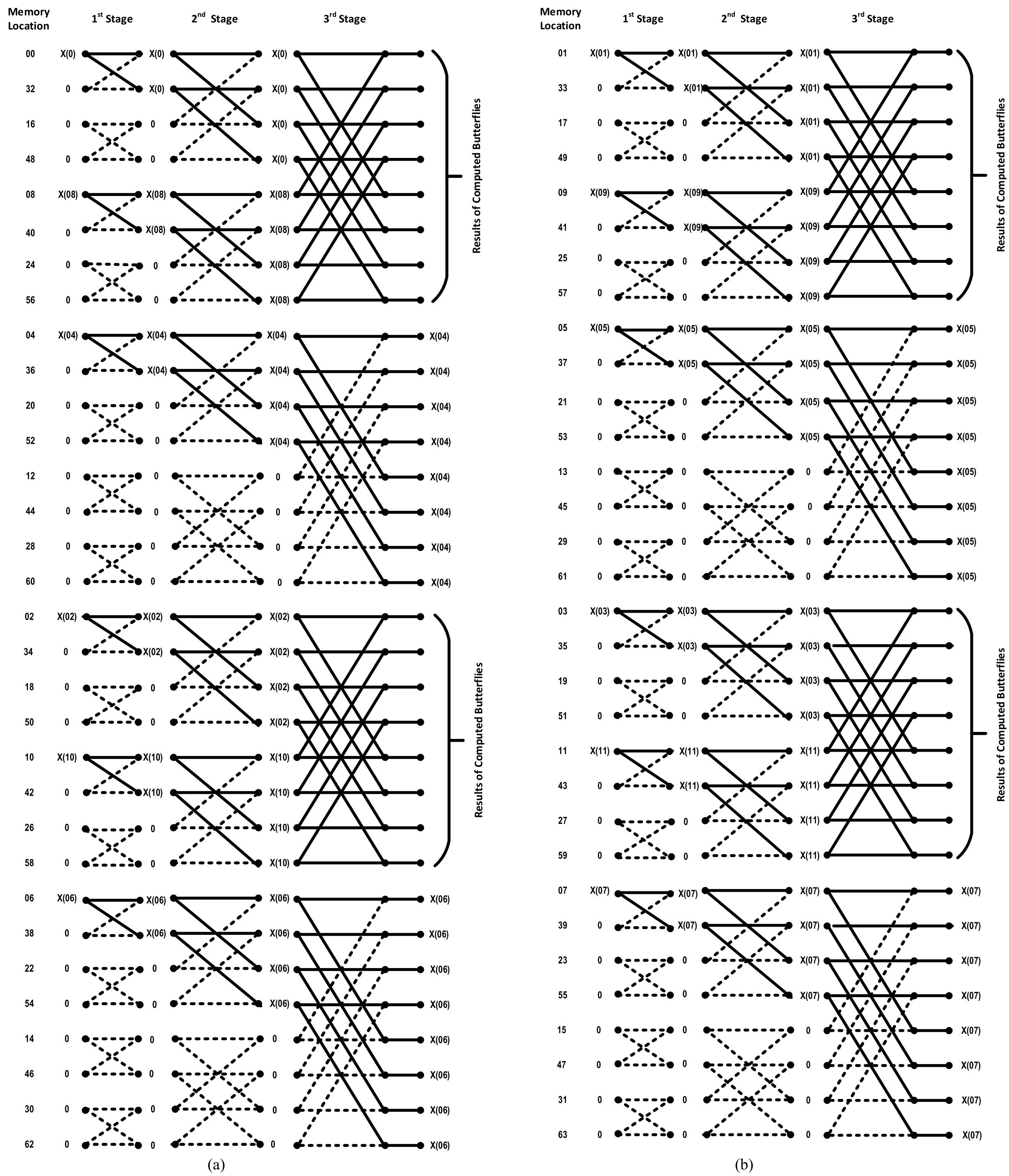

FIGURE 4. Redundant Butterflies in first 3 stages of 64 point Radix-2 DIT IFFT Computation. (a) First 16-Butterflies each of 3 Stages (b) Last 16-Butterflies each of 3 Stages.

Hence, 42% reduction in computations is achieved which will have significant effects on simplifying the hardware architecture. The same is applicable for higher values of N e.g. in case of $N = 1024$. i.e. $l = 10$, 256 butterflies out 512 are computed in seventh stage and all in next three stages. Hence, computation of 512 butterflies in each of first 6 stages and half of the butterflies in seventh stage are redundant. This results in computation of 1792 butterflies out of 5120 total butterflies i.e. only 35%.

In order to estimate the useful butterflies in this kind of application, either one need to draw the data path or write a software program. In order to facilitate the designers to quickly asses the number of useful butterflies in N-point IFFT/FFT with m consecutive non-zero inputs, following

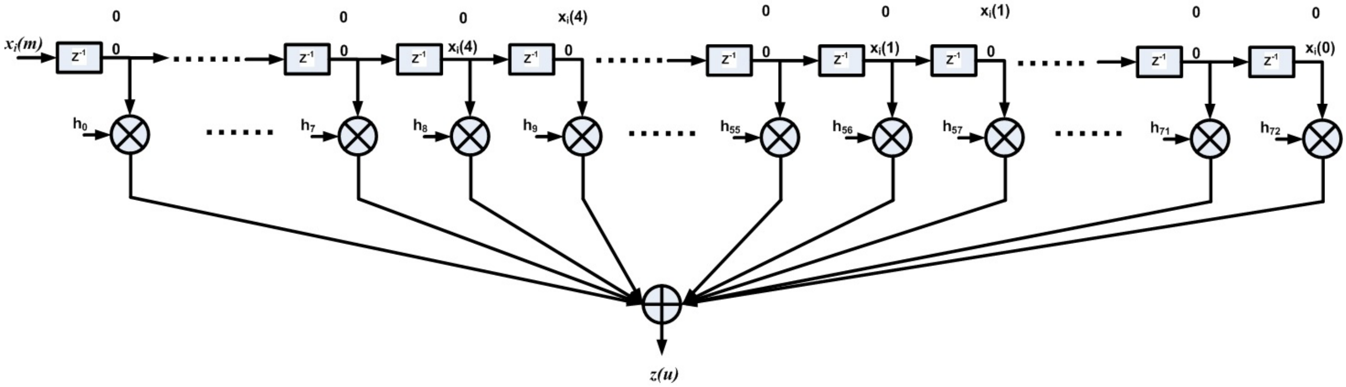

FIGURE 5. FIR Filter of classical UFMC.

expression is derived.

$$\text{No. of Butterflies} = \lfloor log_2^m \rfloor \times \frac{N}{2} + (m\%(2^{\lfloor log_2^m \rfloor})) \times \frac{N}{2^{\lceil log_2^m \rceil}} \quad (2)$$

where m starts from 1 and can range up to N.

This simplification can significantly reduce the hardware architecture of IFFT in terms of use of memory, operators and latency which is a critical factor in 5G. Using the generic expression in (2), one can calculate the number of butterflies required to be computed for any value of N and m and hence the techniques is flexible for different use case scenario having different number of carriers in a frequency block. Hence, in order to exploit this simplification, one need to copy the data related to m subcarrier of a frequency block from main memory (carrying data related to multiple frequency blocks) to the memory block used in IFFT processing unit at specific locations as shown in example of Fig. 4. Secondly, only required number of butterflies should be computed which can be easily achieved in hardware. The possibility of using this reduction is limited to the scheme in [13] and can not be used in scheme presented in [12] as the non-zeros are not starting from first carrier in all frequency blocks except the first one.

B. FIR FILTERING COMPLEXITY REDUCTION

Consider the case where total carriers are N and the IDFT applied on each frequency block has N_0- points. In [13], for 10MHz channelization, they proposed $N_0 = 64$ for $N = 1024$.

Hence, in this case an up sampling by a factor of $\alpha = N/N_0$ is required which is achieved by placing 15 zeros after each sample of IDFT output.

For a 73 tap FIR filter, one possible scenario is shown in Fig. 5. Here $x_i(0)$ is multiplied with h_{72}, $x_i(1)$ is multiplied with h_{56} and so on. Once, next filter output is required, the samples are shifted to right by one position and now $x_i(1)$ is multiplied with h_{57} and so on as shown in the top of Fig. 5. Here, multiplication of only non-zero samples with filter coefficients are useful which can reduce the number of used multipliers in the architecture.

The circuit diagram shown in Fig. 6 implements this idea [14]. In Fig. 6, once a sample $x_i(m)$ enters the filter and shift of memory elements is performed, then in next 16 cycles the filter coefficients are multiplexed one by one to generate 16 outputs of the filter. Hence, on one side only 64 samples from IFFT operations will be required i.e. no actual zero padding and secondly only 5 multipliers, 4 shift registers, 4 adders and 5 16-to-1 multiplexers will be used in place of 73 multipliers and 72 adders and shift registers.

In order to satisfy the scalability and flexibility requirement, the architecture presented in Fig. 6 can be scaled for higher processing speed requirements by replicating the presented architecture. Moreover, flexibility can be achieved by storing different filter coefficients in a separate memory and using them according to the requirement.

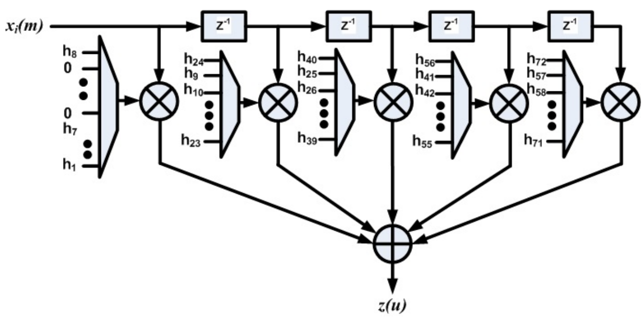

FIGURE 6. Proposed Reduced Complexity FIR Filter.

C. SIMPLIFIED SPECTRUM SHIFTING COEFFICIENTS GENERATION

In frequency shifting process each filtered data sample is multiplied with:calc

$$e^{\frac{-j2\pi(m\times i)n}{N}} = \cos(\frac{2\pi(m\times i)n}{N}) - jsin(\frac{2\pi(m\times i)n}{N}) \quad (3)$$

where: n = sample number of filtered data coming as input data for spectrum shifting and ranging from 0 to $N+L-1$. As N = total number of available subcarrier in the order of power of 2 taken as 2^l. In (3), the first step is to reduce $\frac{m}{N}$ by eliminating common factor to $\frac{m'}{N'}$ such that $N' = 2^{l'}$. Hence expression in (3) becomes:

$$e^{-j\frac{2\pi}{N'}\times m'\times(i\times n)} = \cos(\frac{2\pi}{N'} \times m' \times (i \times n)) - j\sin(\frac{2\pi}{N'} \times m' \times (i \times n)) \quad (4)$$

In (4), it can be seen that complete circle of 2π radian is divided into equal N' steps of $\frac{2\pi}{N'}$ where N' ranges from 0 to $N' - 1$. Hence, we can store the table of corresponding sine and cosine values of N' angles in a LUT of N' locations. The next step is to access this table based on the product of $(m' \times i \times n)$.

Since LUT values are repeated after every 2π radian i.e. N' locations, we can access any table location corresponding to $\left(m' \times i \times n\right)$ by computing $\left(m' \times i \times n\right) modN'$. Moreover, as $N' = 2^{l'}$, the l' number of Least Significant Bits (LSBs) of $\left(m' \times i \times n\right)$ in binary format will give $\left(m' \times i \times n\right) modN'$. Hence, a memory storing N' precomputed values of sine and cosine values with a step size of $\frac{2\pi}{N'}$, addressed by l' number of Least Significant Bits (LSBs) of $\left(m' \times i \times n\right)$ in binary provides solution for the expression given in (3) and (4).

Considering the example where simplifying the $N = 1024$ and $m = 12$ ratio, $N' = 2^{l'}$ becomes 256 while $m' = 3$. Hence, we need 256 location ROM addressed by $l' = 8$ address lines. Each location contains cosine and sine values as shown in Fig. 7 whereas 8 bit address of ROM is generated through the 8 LSBs of the result of the product of i, n and 3. The whole idea for 10 MHz channelization of LTE with $N = 1024$ and one PRB of 12 subcarrier i.e. $m = 12$ is shown in Fig. 7.

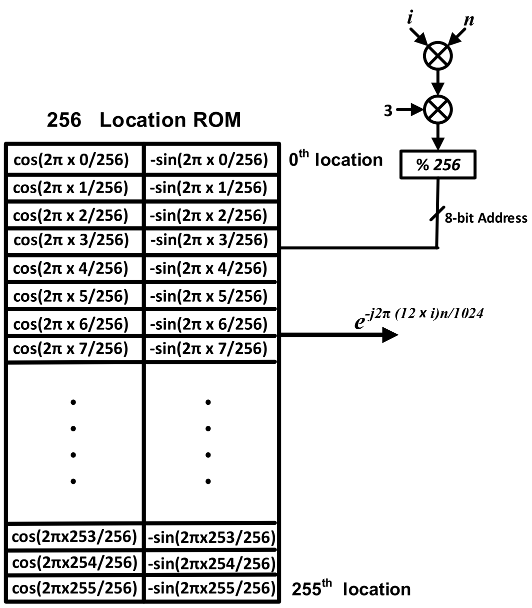

FIGURE 7. LUT based solution for storing frequency shifting coefficients in 256-Location ROM for LTE 10 MHz channelization specifications.

A further complexity of memory reduction can be achieved due to the fact that in Fig. 7 each third location is of interest. Hence, if dedicated Read Only Memory (ROM) is designed for frequency shift. As given in (4), m' is multiplied with $\frac{2\pi}{N'}$ step, the step size increases and the location required to store the sine and cosine values within 2π radian are reduced to $\left\lceil \frac{N'}{m'} \right\rceil$. Hence, we need $\left\lceil \frac{N'}{m'} \right\rceil$ storage spaces and a multiplexer attached to it. The multiplexer will have $\left\lceil \frac{N'}{m'} \right\rceil$ inputs attached to storage location, one output and l' select lines.

The whole idea is shown in Fig. 8 for $N = 1024$ and $m = 12$. We can simplify their ratio to get $N' = 256 = 2^8 (l' = 8)$ and $m' = 3$. Hence, $\left\lceil \frac{N'}{m'} \right\rceil = 86$ i.e. 86 locations required to store all possible coefficients. These 86 values are connected to a multiplexer with 86 inputs and one output. The 8 select lines of multiplexer are connected to the 8 LSB of the result of product of $(k_i \times n)$ with 3. With this solution, 1096×50 coefficient, that were required for frequency shifting to form UFMC waveform for 10 MHz bandwidth of LTE (containing 50 PRBs), are generated with very low complexity solution.

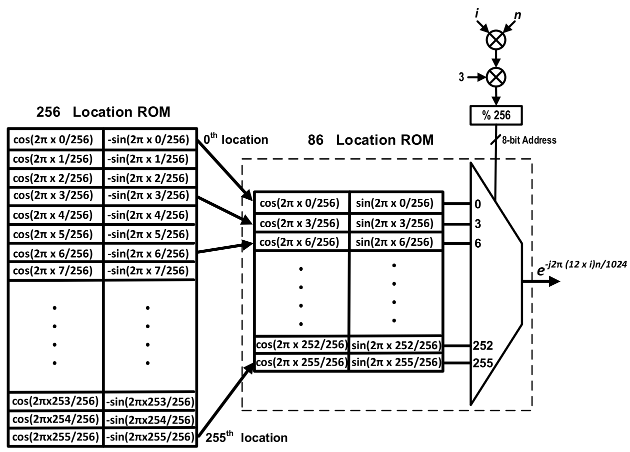

FIGURE 8. LUT based solution for storing frequency shifting coefficients in 86-Location ROM for LTE 10 MHz channelization specifications.

The above example is taken for illustration purposes with specific values of N, m and n. In order to provide flexibility for other multiple use cases having different values of N, m and n, the same idea can be used. In that case, a memory having locations equal to highest value of N' i.e. N'_{max} with l'_{max} address lines, similar to Fig. 7, shall be required. This memory will hold all possible filtering coefficient in all possible use case scenarios. In order to get right coefficient, the result of multiplication of i, n and m' is shifted right by a factor of N'_{max}/N' (which will always be an integer) prior sending l'_{max} least significant bits of product on address lines of memory. Hence, the solution proposed here provides flexibility in addition to its simplicity for hardware implementation.

IV. CONCLUSION

New waveforms are under evaluation to achieve MTC in order to further enable IoT under 5G wireless communications framework. UFMC is a promising waveform which provides required waveform properties both in case of single service and multiple services. However, a part from performance, hardware implementation cost along with flexibility is a key factor for the deployment of the concept of IoT. In this paper, we have proposed further simplifications in all functional building blocks of the most simplified UFMC transmitter scheme to date while addressing flexibility. In this work we have identified the redundant computations in IFFT process and provided a mathematical relation to identify only the required computations based on number of IFFT point and number of subcarriers in a frequency block. By exploiting the proposed scheme 42% computations can be avoided while performing 64-point IFFT on one frequency block of LTE which is comprised of 12 subcarriers each whereas for IFFT size of 1024 the reduction is 65%. In filtering part, a scheme is proposed which can be used to avoid redundant multiplications involved in FIR filter. Hence, only 5 pair of multipliers and adders are required in place of 73 pairs. Finally, in the spectrum shifting part a mechanism is proposed which uses a very small memory, a multiplier and an adder to generate large number of coefficient required for spectrum shifting. Hence, up to best of our knowledge our proposed solution provides most simplest solution for UFMC in terms of computations involved as well as hardware guidelines to achieve simplest implementations.

REFERENCES

[1] G. Mange *et al.*, "Initial report on horizontal topics, first results and 5G system concept," METIS, Tech. Rep. ICT-317669-METIS/D6.2, Apr. 2014. [Online]. Available: https//:www.metis2020.com/

[2] H. Tullberg *et al.*, "METIS research and standardization: A path towards a 5G system," in *Proc. IEEE Workshop-Telecommun. Standards-From Res. Standards Globecom*, Dec. 2014, pp. 577–582.

[3] "More than 50 billion connected devices," Ericsson, Stockholm, Sweden, White Paper 284 23-3149, Feb. 2011. [Online]. Available: http://www.ericsson.com/res/docs/whitepapers/wp-50-billions.pdf

[4] G. Wunder *et al.*, "5GNOW: Non-orthogonal, asynchronous waveforms for future mobile applications," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 97–105, Feb. 2014.

[5] F. Schaich and T. Wild, "Waveform contenders for 5G-OFDM vs. FBMC vs. UFMC," in *Proc. 6th Int. Symp. Commun., Control Signal Process. (ISCCSP)*, Athens, Greece, 2014, pp. 457–460, doi: 10.1109/ISCCSP.2014.6877912.

[6] B. Farhang-Boroujeny, "OFDM versus filter bank multicarrier," *IEEE Signal Process. Mag.*, vol. 28, no. 3, pp. 92–112, May 2011.

[7] G. Fettweis, M. Krondorf, and S. Bittner, "GFDM—Generalized frequency division multiplexing," in *Proc. IEEE 69th Veh. Technol. Conf. VTC Spring*, Apr. 2009, pp. 1–4.

[8] V. Vakilian, T. Wild, F. Schaich, S. Ten Brink, and J. F. Frigon, "Universal-filtered multi-carrier technique for wireless systems beyond LTE," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2013, pp. 223–228.

[9] F. Schaich, T. Wild, and Y. Chen, "Waveform contenders for 5G suitability for short packet and low latency transmissions," in *Proc. IEEE 79th Veh. Technol. Conf. VTC Spring*, Seoul, South Korea, May 2014. pp. 1–5. [Online]. Available: http://dx.doi.org/10.1109/VTCSpring.2014.7023145

[10] R. Gerzaguet, "The 5G candidate waveform race: A comparison of complexity and performance," *EURASIP J. Wireless Commun. Netw.*, vol. 2017, no. 1, p. 13, Dec. 2017, doi: 10.1186/s13638-016-0792-0

[11] L. Zhang, A. Ijaz, P. Xiao, A. Quddus, and R. Tafazolli, "Subband filtered multi-carrier systems for multi-service wireless communications," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1893–1907, Mar. 2017, doi: 10.1109/TWC.2017.2656904.

[12] T. Wild and F. Schaich, "A reduced complexity transmitter for UF-OFDM," in *Proc. IEEE 81st Veh. Technol. Conf. (VTC Spring)*, May 2015, pp. 1–6.

[13] R. Knopp, F. Kaltenberger, C. Vitiello, and M. Luise, "Universal filtered multicarrier for machine type communications in 5G," in *Proc. Eur. Conf. Netw. Commun. (EUCNC)*, Athens, Greece, Jun. 2016. [Online]. Available: http://www.eurecom.fr/publication/4910

[14] G. R. Lyon, *Understanding Digital Signal Processing*, 3rd ed. Englewood Cliffs, NJ, USA: Prentice-Hall, 2011.

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