# HAPs Special OFDMA Technique for Fast Mobile Radio Systems

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**Abstract—** In this paper we investigate the performances of the Orthogonal Frequency Division Multiple Access (OFDMA) and Frequency Bank Signal (FBS) methods over High Altitude Platforms ( HAPs) systems with different Doppler scales.

FBS is an enhanced OFDMA technique, which is capable to eliminate the negative effects of Doppler shifts even in extreme cases, such as non-uniform Doppler shifts across the OFDMA subcarriers. Our simulations show that HAP- OFDMA systems can work if frequency shift due to Doppler Effects is smaller than 2% of carrier frequencies separation. These conditions correspond to the frequency band of 2GHz and train velocity 120 km/h. FBS method allows increasing the permissible Doppler shift up to 6 - 8 %, hence enabling higher carrier frequency bands and higher speed vehicles.

***Keywords***— HAPs, OFDMA, Doppler shift, Pilot signals, FBS, Mobile communications.

## I. INTRODUCTION

Terrestrial mobile radio Communication systems are expanding fast but suffer limitations in the quality and operation range, which, to a certain extent, can be related to lack of Line of Sight (LOS) conditions. The operation ranges can be extended significantly using Geostationary (GEO) satellites at an altitude around 36000 km [1,2]. A new emerging technique for efficient mobile radio communication systems is the High Altitude Platforms (HAPs) in the stratosphere at an altitude in the order of 17 to 24 km, where wind velocity is minimal [3,4]. The recent technological advances allow stabilizing the position of these HAPs stations, relative to the ground, as Stratospheric Quasi Stationary Platforms (SQ-SP) [5,6]. The performances of HAPs radio systems are in several aspects superior over both the GEO/ LEO satellites and terrestrial radio systems [1].

One important future HAPs application is radio communication with very high speed trains or aircrafts. In these cases HAPs are significantly better than terrestrial radio due to the improved LOS propagation conditions, less Doppler frequency shift effects and less often hand over events as depicted in the scenario of Fig.1. The reduction in Doppler frequency shifts is due to the relatively low transmission angles because of the HAPs high altitude [7, 8]. HAPs are also better than GEO satellites due to the significantly less dispersion losses and shorter time delays involved. However, the effect of Doppler shift is important even in the HAPs radio communication systems operating at 1.8 to 2.2 GHz frequency bands and even more in the next allocated band of 5.85 to 7.05 GHz with high-speed vehicles such as rapid trains traveling at high speeds up to 300 km/h or aircrafts which are more vulnerable to the Doppler effects [1,7].

The Frequency Bank signal (FBS) is an improved OFDMA technique that eliminates the need for pilot signals, and yet efficiently combats the Doppler Effect. FBS combines the OFDMA technique without Pilot signals [11] with the phase shift compensation method used in the PAL. The FBS method can be implemented also in HAPs using various modulation techniques.

In [12] the impact of the Doppler effects on frequency-selective linear channels has been examined. To combat the Doppler effects the authors presented a novel space-frequency-Doppler coded OFDM, which is based on converting the non-linear time-varying Doppler fading channel to a virtual frequency selective linear channel [12].

## II. THE EFFECT OF DOPPLER SHIFT ON THE OFDM SIGNALS

In a multi-path channel the duration of a received symbol is subject to changes due to the variations in the length of the signal propagation path. However, since the frequency changes by the same factor $k_d$ the number of carrier cycles in each symbol does not change, regardless of how fast the Transmitters (Tx) or Receivers ( Rx) move. So in case of Doppler Shift, the frequency f and symbol time T are varied by a factor of $k_d$ [2]

$$k_d = 1 + \frac{V}{c}\cos\varphi, \qquad (1)$$

Where V is the moving object velocity, c is the light velocity and φ is the angle between the directions of signal propagation and the moving objects .Note that under these circumstances, the orthogonal condition prevails:

$$[(f_{i+1}-f_i)\cdot k_d]\cdot[T/k_d]=1$$

Furthers influences include ICI (Inter-carrier interferences) due to partial loss of the orthogonal, changes of the pilot signals parameters, and a time delay (or forestalling) between adjacent symbols due to incompatibility between of the received symbol duration and Rx clock synchronization system [1, 2].

A typical HAP system using the OFDMA technology system [5,10] with symbol duration 0.1ms, frequency difference between carriers (ΔF) 10kHz, central frequency in the 2GHz L band range and from 5.85 to 7.o75 GHz allocated by the ITU for the future HAPS. These higher frequency bands are required especially for broadband mobile radio, vehicles at speed of up to 300 km/h, and even more for aircrafts . The,angle shift change as function of the distancebetween the HAP and the vehicle.

Using Equation. (1) the Doppler shift is estimated as ±2.8 kHz or 30% of ΔF. It should be noted that also the reflected signals undergo a Doppler shift.

We now proceed with the mathematical description of the OFDMA signal variations due to Doppler shift. The discrete Fourier transform (DFT) of $\{x_j\}_{j=0}^{N-1}$ is given by :

$$X_k=\sum_{j=0}^{N-1}x_j e^{-i\frac{2\pi}{N}kj}, \quad k=0,...,N-1 \qquad (2)$$

And the inverse discrete Fourier transform:

$$x_j=\frac{1}{N}\sum_{k=0}^{N-1}X_k e^{i\frac{2\pi}{N}kj}, j=0,...,N-1 \, (3).$$

Here $x_j$, $j=0,...,N-1$ are $N$ samples in time domain, and $X_k$, $k=0,...,N-1$ are $N$ spectral components. Defining: $t_j=\frac{T}{N}j$, $\omega_k=\frac{2\pi}{T}k$, Eq.s (2) and (3) can be rewritten as

$$X_k=X(\omega_k)=\sum_{j=0}^{N-1}x(t_j)e^{-i\omega_k t_j}, \quad k=0,\dots,N-1 \qquad (4)$$

$$x_j=x(t_j)=\frac{1}{N}\sum_{k=0}^{N-1}X(\omega_k)e^{i\omega_k t_j}, \quad j=0,\dots,N-1 \qquad (5).$$

In general, $X_k$ is a complex number whose absolute value $|X_k|$ and angle $\angle X_k$ are the amplitude and phase of the k[th] frequency component. Since $\{x_j\}_{j=0}^{N-1}$ is a real signal, its DFT is symmetric, i.e. $X_{N-k}=X_k^*$ (where $X_k^*$ denotes the complex conjugate of $X_k$ ).

As stated above, the Doppler shift leads to spectrum variations [9,11],.

Due to the Doppler frequency shifts, the frequency of each component is shifted to s $\tilde{\omega}_k=\omega_k+\Delta\omega_k$, where $\Delta\omega_k=\frac{2\pi}{T}\delta_k$ and $\delta_k$ denotes the relative shift of the k[th] component. In the time domain the new signal

$$\begin{aligned}\tilde{x}_j&=\tilde{x}(t_j)=\frac{1}{N}\sum_{k=0}^{N-1}X(\omega_k)e^{i\tilde{\omega}_k t_j}\\&=\frac{1}{N}\sum_{k=0}^{N-1}X(\omega_k)e^{i(\omega_k+\Delta\omega_k)t_j}\\&=\frac{1}{N}\sum_{k=0}^{N-1}X_k e^{i\frac{2\pi}{N}(k+\delta_k)j}\\&=\frac{1}{N}\sum_{m=0}^{N-1}X_m e^{i\frac{2\pi}{N}(m+\delta_m)j}\end{aligned} \qquad (6)$$

since $\{\tilde{x}_j\}_{j=0}^{N-1}$ is a real signal , $\Delta\omega_{N-k}=-\Delta\omega_k$, i.e. $\delta_{N-k}=-\delta_k$.

The spectrum of the new signal is

$$\begin{aligned}\tilde{X}_k&=\sum_{j=0}^{N-1}\tilde{x}_j e^{-\frac{2\pi i}{N}kj}\\&=\sum_{j=0}^{N-1}\left(\frac{1}{N}\sum_{m=0}^{N-1}X_m e^{i\frac{2\pi}{N}(m+\delta_m)j}\right)e^{-\frac{2\pi i}{N}kj}\\&=\sum_{m=0}^{N-1}X_m\sum_{j=0}^{N-1}\frac{1}{N}e^{i\frac{2\pi}{N}(m+\delta_m)j}e^{-\frac{2\pi i}{N}kn}\\&=\sum_{m=0}^{N-1}X_m\frac{1}{N}\sum_{j=0}^{N-1}e^{i\frac{2\pi}{N}(m+\delta_m-k)j}\end{aligned}$$

Therefore

$$\tilde{X}_k=\sum_{m=0}^{N-1}a_{km}(\delta_m)X_m \qquad (7)$$

Where

$$a_{km}(\delta_m)=\frac{1}{N}\sum_{j=0}^{N-1}e^{i\frac{2\pi}{N}(m+\delta_m-k)j} \qquad (8)$$

In other words, we can obtain the new spectrum vector $\tilde{X}$ of length $N$ by multiplying the $N\times N$ matrix $a$ by the original spectrum vector $X$ of length N. Matrix element $a_{km}(\delta_m)$ shows how the original m[th] spectral component affects the new $k^{th}$ spectral component. The matrix elements can be computed using Eq. (8).

If $\delta_m = 0$, then

$$a_{km}(0) = \begin{cases} 1, & k = m \\ 0, & k \neq m \end{cases} \quad (9.1).$$

For small $\delta_m \neq 0$ ($0 < |\delta_m| < 1$), using

$$\sum_{j=0}^{N-1} q^j = \frac{1-q^N}{1-q}, \qquad q \neq 1,$$

for $q = e^{i\frac{2\pi}{N}(m+\delta_m-k)}$, we obtain

$$a_{k,m}(\delta_m) = \frac{1}{N}\sum_{j=0}^{N-1} e^{i\frac{2\pi}{N}(m+\delta_m-k)j}$$

$$= \frac{1}{N}\cdot\frac{1-e^{i2\pi(m+\delta_m-k)}}{1-e^{i\frac{2\pi}{N}(m+\delta_m-k)}} \qquad (9.2)$$

$$= \frac{1}{N}\cdot\frac{1-e^{i2\pi\delta_m}}{1-e^{i\frac{2\pi}{N}(m+\delta_m-k)}}$$

$$= \frac{1}{N}\cdot\frac{1-e^{i2\pi(m+\delta_m-k)}}{1-e^{i\frac{2\pi}{N}(m+\delta_m-k)}}$$

$$= \frac{1}{N}\cdot\frac{1-e^{i2\pi\delta_m}}{1-e^{i\frac{2\pi}{N}(m+\delta_m-k)}}$$

$\left\{a_{k,m}(\delta_j)\right\}_{k,m=0}^{N-1}$ is a N x N matrix whose entries are complex numbers depending on $\left\{\delta_m\right\}_{m=0}^{N-1}$. If $\delta_m = 0$ for all $m = 0,\ldots,N-1$, then (9.1) implies that $\left\{a_{k,m}(\delta_m)\right\}_{k,m=0}^{N-1}$ is the identity N x N matrix and in this case $\widetilde{X}_k = X_k$ for all $k = 0,\ldots,N-1$. In other words, if there are no frequency shifts, then the spectrum is not changed, as expected [8].

The relation $\delta_{N-k} = -\delta_k$ implies $a_{N-k,N-m}(\delta_{N-m}) = \left(a_{k,m}(\delta_m)\right)^*$.

Note that the spectral components affected by the Doppler effect can be computed by Eq.s (7), (8) . Remarkably, these numerical simulation and calculations do not require FFT size increasing. We believe that this can be a significant contribution to simulation design.

## III. FBS

FBS combines the OFDMA principles with the phase shift compensation techniques used in the PAL-TV systems, and spread spectrum concept using Walsh functions based on the Walsh-Hadamard matrix.

For transmitting N signals on N carriers, the FBS signals are:

$$s_{(kl),FBS-1} = E_l \sum_{k=0}^{N-1} e^{j[2\pi f_k t + (-1)^{W_{kl}}(\theta_l + \beta_l)]} \qquad (10)$$

where $E_l$ is the magnitude of component l, l = 0,…, N -1 corresponds to rows of the Walsh-Hadamard matrix, $\theta_l$ is the initial phase chosen for a certain signal, $\beta_l$ is the information symbol of the $l^{th}$ FBS signal (BPSK or QPSK), $f_k = f_0 + k\Delta f$ - are FBS carrier frequencies, k = 0,…, N -1 for Walsh-Hadamard matrix columns and $W_{kl}$ are sequence of phases of the $l^{th}$ FBS carrier pattern.

In case of a (mirror) symmetrical Walsh function(e.g, 0 1 1 0 0 1 1 0) the Doppler shift and delay have no influence on FBS-1 performance. This can be seen in Fig.3 where the phase shift due to the delay is proportional to frequency. For non-symmetrical Walsh functions such as 0 0 1 1 0 0 1 1, there will be an additional phase shift, which is independent of the phase information and can be cancelled out. Details of the encoding and decoding algorithms for of FBS-I are given in [13].

During the phase compensation process of the FBS-1 method, there is usually a certain level of data loss in the amplitude. FBS-1 is applicable only to phase modulations such as MPSK. FBS-2 overcomes this limitation [11], allowing for other modulation methods such as MQAM. For transmitting N/2 sub-signals in the FBS-2 system we use N orthogonal sub-carriers f1, f2, fm and a Walsh-Hadamard matrix of order N. For each symbol of each sub-signal, $x(t) = A\sin(\omega t + \varphi)$, we present I and Q components $I = A\sin\varphi$ *and* $Q = A\cos\varphi$ *and*

The I and Q values are transmitted separately for N sub-carriers corresponding to one pair of Walsh functions selected from a N×N Walsh-Hadamard matrix. For example, in the case of N = 8, using the pair:

0 1 1 0 1 0 0 1
0 1 0 1 0 1 0 1

The following I and Q values are transmitted: I –I –I I –I I I –I ; Q –Q Q –Q Q –Q Q –Q

When receiving a transmitted sub-signal, it is necessary to implement the opposite process with the help of the same pair of Walsh functions. The sum of all values in the first line is 8I and the sum of all values in the second line is 8Q. By knowing the values for I and Q, we can find A and φ.

The I and Q sums of the other signals will be equal to zero.

## IV. The FBS-1 Method

FBS combines the OFDMA principles with the phase shift compensation used in the PAL-TV systems, and spread spectrum concept using Walsh functions based on the Walsh-Hadamard matrix.[?]

In PAL –TV systems, prior to transmitting a color signal, the system's phase sign is changed every second line. In decoders, the phase sign is returned and summed together with phases of neighboring lines. As a result, phase deviations in the channel φ are compensated for [9].

In the first version of the FBS method (FBS-1) [ 9,10], an OFDMA system with eight single-carrier MPSK modulation signals is transformed to an FBS-1 system with the same eight signals on the same eight carriers (see Fig. 1). In this method, each signal phase is transmitted eight times with a varying phase sign corresponding to one of the eight Walsh-Hadamard matrix rows.

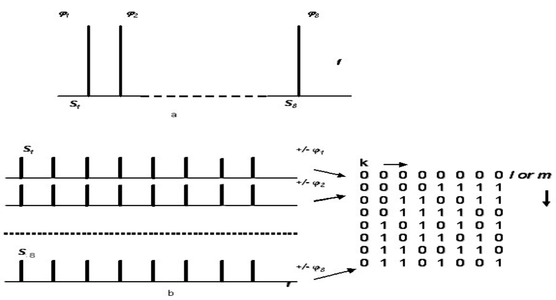

Figure 1. Transition from OFDMA (a) to FBS-1 (b)

For transmitting N signals on N carriers, the FBS signals are:

$$s_{(kl),FBS-1} = E_l \sum_{k=0}^{N-1} e^{j[2\pi f_k t + (-1)^{W_{kl}}(\theta_l + \beta_l)]}, \qquad (10)$$

where

$E_l$ - component magnitude, l = 0,…, N -1 or Walsh-Hadamard matrix lines

$\theta_l$ - initial phase, chosen for a certain signal. For example, it is either $45^0$ or other

$\beta_l$ - information symbol of the $l^{th}$ FBS signal (BPSK or QPSK representation),

$f_k = f_0 + k\Delta f$ - FBS carrier frequencies, k = 0,…, N -1 or Walsh-Hadamard matrix columns

$W_{kl}$ - sequence of phases of the $l^{th}$ FBS carrier pattern.

We calculate arithmetical (not vector) sum $\varphi_k$ of all signals on each carrier and use amplitude corresponding to:

$$A_m, \quad 2\pi m \le \varphi_k < 2\pi(m+1)$$

The advantage of using the FBS-1 method is phase shift compe3nsation.

In the case of symmetrical Walsh functions, for example, 0 1 1 0 0 1 1 0, the Doppler Shift and Delay have no influence on FBS-1 reception. One can see that in Fig. 3 when phase shift due to delay is proportional to frequency. If the Walsh function is nonsymmetrical, (for example 0 0 1 1 0 0 1 1), there will be an additional phase shift, which is independent of the phase information and can be compensated for.

## V. The FBS-2 METHOD

During the phase compensation process of the FBS-1 method, there is usually a certain level of data loss in the amplitude. Therefore, it is possible to implement only phase modulations e.g. MPSK [9,10]. To overcome these difficulties we present the FBS-2 system [ 11,12]. In this upgraded version, one can implement other modulation methods, such as MQAM. For transmitting N/2 sub-signals in the FBS-2 system we use N orthogonal sub-carriers f1, f2,.., fm and Walsh-Hadamard matrix of order N. For each symbol of each sub-signal:

$$x(t) = A\sin(\omega t + \varphi)$$

we present I and Q components

$$I = A\sin\varphi \quad and \quad Q = A\cos\varphi \quad and$$

$$A = \sqrt{I^2 + Q^2}; \qquad \varphi = arctg\frac{I}{Q}$$

The I and Q values are transmitted separately on N sub-carriers correspond to one of the pairs of Walsh functions selected from an N×N Walsh-Hadamard matrix. For example, in the case of N = 8, using the pair:

0 1 1 0 1 0 0 1
0 1 0 1 0 1 0 1

the following I and Q values are transmitted:

I –I –I I –I I I –I
Q –Q Q –Q Q –Q Q –Q

When receiving a transmitted sub-signal, it is necessary to implement the opposite process with the help of the same pair of Walsh functions. The sum of all values in the first line is 8I and the sum of all values in the second line is 8Q. By knowing the values for I and Q, we can find A and φ.

The I and Q sums of the other signals will be equal to zero. Each selected pair of Walsh functions may be added to make a symmetric form. One of the FBS-2 signals with *row* l for I and *row* m of the Walsh-Hadamard matrix for Q, can be presented as follows [12] For comparison purposes, we shall use a typical FBS-2 system, that uses N carriers for transmitting N signals. Since FBS-2 utilizes only the I and Q carriers, N/2 signals may be transmitted on the same allocated channels. Nevertheless, the QAM modulation technique (used in FBS-2) allows transmitting twice as much data as the PSK modulation technique (used in FBS-1), for the same allocated channels.

## VI. SIMULATION RESULTS

A typical mobile communication system consisting of a HAP and various cellular combinations, was implemented in order to make a comparative study between OFDMA and the FBS systems [11,12]. We consider a system with four receivers and symbol duration of $T = 100\ \mu s$, such that, the frequency difference between sub carriers will be $\Delta F = 1/T = 10\ kHz$. We assume the Doppler shift is 3% of ΔF, and the phase shift per each symbol time due to delay $3.9^0$. Four signals are transmitted. In case of OFDMA, each symbol is transmitted on two sub-carriers using QPSK, and in case of FBS-2 on eight sub-carriers using 16QAM. Simulation results in Fig. 3 (FBS-2). Acceptable BERs ($5\cdot10^{-3}$) are obtained only by increasing the pilot ratio up to 1:2. Taking into account the 3 dB higher powers of the pilots, the resulting redundancy is more then 100%.

The simulation results show for the case of the FBS-2. It is seen that in this case the BER is not affected by phase distortions due to the Doppler Effect. The relatively higher values of the forth signal are attributed to the fact that for this signal the all zero Walsh function W0 was applied.

Two main restrictions exist equally for both FBS and FDMA system design: $T > \tau_{max}$ and $\Delta F \times N < B_c$.

Where Bc is the coherence bandwidth [1].

***A future HAP broadband mobile radio system based on the FBS method is presented for high speed vehicles., and compared to OFDMA based HAP systems..***

***It is shown in this paper that the FBS-HAP system allows transmission of the same quantity of information on the same frequency band and with the same power, as the OFDMA-HAP system.***

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