# Multi-Band Filters for Frequency Division Multiplexing Networks in Power Line Communications

Y. Akeboshi, H. Ohashi and S. Saito
Mitsubishi Electric Corp. Information Technology R&D Center
5-1-1 Ofuna, Kamakura-City, Kanagawa 247-8501, Japan
Akeboshi.Yoshihiro@ak.MitsubishiElectric.co.jp

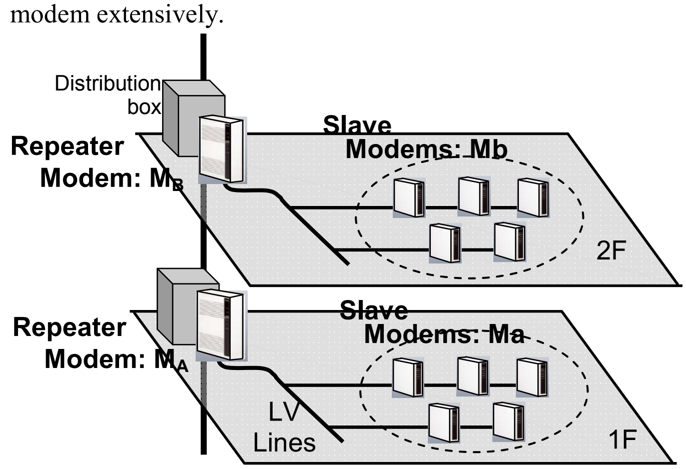
***Abstract*—In order to construct large networks in PLC system, FDM (Frequency Division Multiplexing) or TDM (Time Division Multiplexing) access scheme is often used. In general, the FDM is better solution for the systems which require real-time performance, but interference signals from adjacent sub-networks must be rejected by the analog filters to prevent the receiving sensitivity degradation of the desired signals. In this paper, a novel filter circuit, called "Multi-Band Filters", is proposed to realize analog band-pass filter banks. The design method and the measurement results of the frequency characteristics of the Multi-band Filters are shown in this paper. By rejecting the interference signal with the Multi-band Filters, the equivalent SNR improvement of 10dB is confirmed by data rate measurement.**

***Keywords*— Band-pass filters, Frequency division multi-access, Inter-channel interference, Power line Communications**

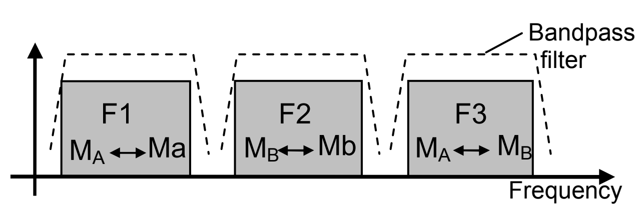
## I. INTRODUCTION

IN PLC systems, FDM(Frequency Division Multiplexing) or TDM(Time Division Multiplexing) access scheme can be used to construct large networks[1,2]. The TDM using timing synchronization scheme is easy and simple way to mitigate ISI and ICI. On the other hand, for the network systems which require real-time performance, the FDM scheme is preferred because each sub-networks in the FDM can operate asynchronously and concurrently, and each FDM frames have less dead-time in time domain. Also the FDM is straightforward way to construct co-existence between different PLC systems. Fig.1 shows an example of the PLC system in FDM scheme of building network application. A repeater modem($M_A$) is located at an electrical distribution box on the 1st flour of the building and communicate with slave modems(Ma) using frequency band "F1". A repeater modem($M_B$) on the 2nd flour communicate with slave modems(Mb) using frequency band "F2". And the repeater modem $M_A$ and $M_B$ communicate each other using frequency band "F3". All three sub-networks of the FDM can operate asynchronously and concurrently by using different frequency bands, thus improve overall throughput of the system.

With this advantage of the FDM scheme, however, there exists a design challenge to overcome with communication systems that has large dynamic range requirement. Although each sub-networks in the FDM uses different frequency range, the amplitude of the interference signal of the adjacent network could be far larger than desired receiving signal. In this case, the receiving sensitivity of the desired signal is severely degraded due to the signal saturation (nonlinear analog circuit characteristics), which is called near/far problem[2] or dynamic range problem [3,4]. In order to solve the dynamic range problem, all repeater modems must have analog bandpass filters to eliminate the interference signals from the adjacent modems. This increases the circuit area and cost of the PLC modem extensively.




(a) An example of FDM network structure




(b) Frequency Division of the network

Fig. 1. An example of FDM network of building application

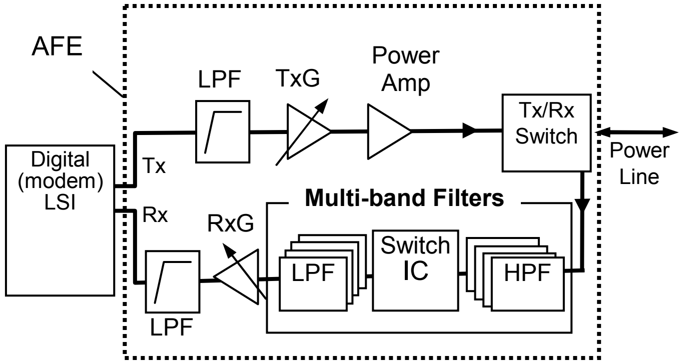



Fig. 2. Block Diagram of PLC modem

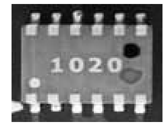
In this paper, a novel circuit filter, called "Multi-band Filters", is proposed to solve the dynamic range problem. The Multi-band Filters are composed of six-HPFs, six-LPFs and a Switch IC. By combining arbitrary HPF and LPF, 22 different type of band-pass filters are available. The components of LPFs, HPFs and Switch IC are newly developed to keep the circuit size of Multi-band Filters as small as possible.

Remainder of this paper is organized as follows. In section II, the design method of Multi-band Filters is indicated. And the measurement results of the Multi-band Filters are also described in section II. Section III presents the rejection effect on the interference signal of the Multi-band Filters in the data rate measurement. And finally, the conclusions of this paper are given in Section IV.

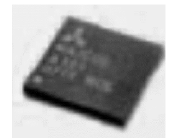
## II. MULTI-BAND FILTERS

In order to solve the dynamic range problem, a novel filter circuit, called "Multi-band Filters", is proposed. A block diagram of a PLC modem and Multi-band Filters is shown in Fig.2. The Multi-band Filters are located at the receiving section of the modem, and composed of six-HPFs, six-LPFs and a Switch IC. The Switch IC in the Multi-band Filters selects one of six-LPFs/HPFs by the F/W control from the digital (modem) LSI. By arbitrarily combining HPF and LPF, 22 different type of bandpass filters are available in the prototype (Note that not all combinations are possible since the cut-off frequency of LPF must be higher than that of HPF). The cut-off frequencies of the LPFs and HPFs are adequately selected to construct the FDM networks for PLC system.

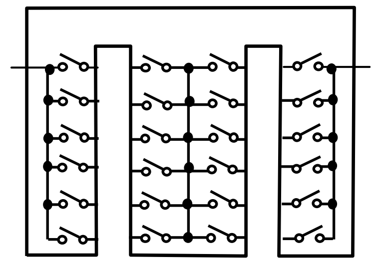
In order to keep the circuit area of the Multi-band Filters as small as possible, each LPF or HPF filter device is newly developed by integrating technology of co-firing the magnetic and the dielectric materials together. The size of the filter device is $3.2\text{mm}\times3.2\text{mm}$, which is very small compare to the ordinary discrete LC filters. The package image of the filter is shown in Fig.3(a)




(a) Filter (HPF/LPF) device : $3.2\text{mm}\times3.2\text{mm}$



(b) Switch IC: $7.0\text{mm}\times7.0\text{mm}$



(c) Block diagram of the Switch IC ($6\times6-\text{crossbar}$)

Fig.3. Components of the Multi-band Filters

$6\times6$ -crossbar switch circuits are integrated in Switch IC using BiCMOS process. The size of Switch IC is $7.0\text{mm}\times7.0\text{mm}$, and the package image of the device is shown in Fig.3(b). Also a block diagram of $6\times6$ crossbar in the Switch IC is shown in Fig.3(c).

Also with this approach, the frequency bands of the Multi-band filters are easily extended to support other bands by replacing the individual filter device shown in Fig.3(a).

### *A. Filter Design*

To achieve sharp response of roll-offs around the cut-off frequency, the elliptic-function filters are selected for both LPFs and HPFs[5-8]. A transfer function H(s) of the elliptic-function filters is expressed in (1),

$$H(s)=\frac{1}{\sqrt{1+\varepsilon^2 Z_n^2(s)}} \tag{1}$$

and an attenuation $A_{dB}$ for the filters is expressed in (2):

$$A_{dB}=10\cdot\log\left[1+\varepsilon^2 Z_n^2(s)\right] \tag{2}$$

where s (=jω) is Laplace variable, ε is determined by pass-band ripple $R_{dB}$ ,

$$\varepsilon=\sqrt{10^{R_{dB}/10}-1} \tag{3}$$

and the nth-order elliptic function $Z_n(s)$ is expressed by (4) if n is odd and n=2m+1 (m is an integer),

$$Z_n(s)=\frac{s\cdot(s^2-a_2^2)\cdot(s^2-a_4^2)\cdots(s^2-a_m^2)}{(a_2^2\cdot s^2-1)\cdot(a_4^2\cdot s^2-1)\cdots(a_m^2\cdot s^2-1)} \tag{4}$$

or by (5) if n is even and n=2m,

$$Z_n(s) = \frac{(s^2 - a_2^2)\cdot(s^2 - a_4^2)\cdots(s^2 - a_m^2)}{(a_2^2\cdot s^2 - 1)\cdot(a_4^2\cdot s^2 - 1)\cdots(a_m^2\cdot s^2 - 1)} \qquad (5)$$

Equation (4)and (5) indicates the zeros of $Z_n$ are $a_2$, $a_4$, …$a_m$, whereas the poles are $1/a_2$, $1/a_4$ …, $1/a_m$. The reciprocal relationship between the poles and the zeros results in equiripple behaviour in both the pass-band and the stop-band [5].

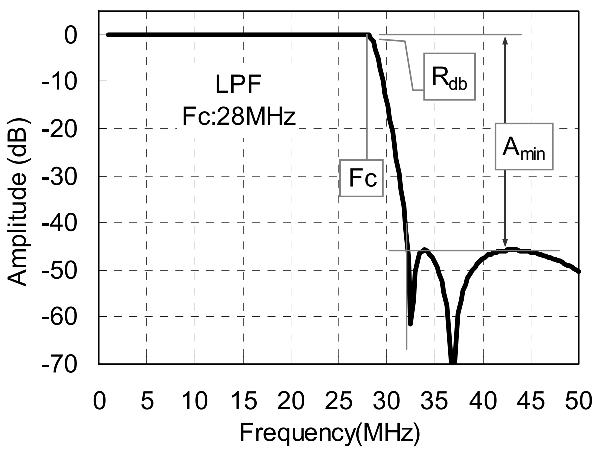
The values of $a_m$ are derived from the elliptic function of Jacobi sn(u, k) indicated in (6):

$$a_m = \sqrt{k}\cdot \mathrm{sn}\left(\frac{2m}{n}K, k\right) \qquad (6)$$

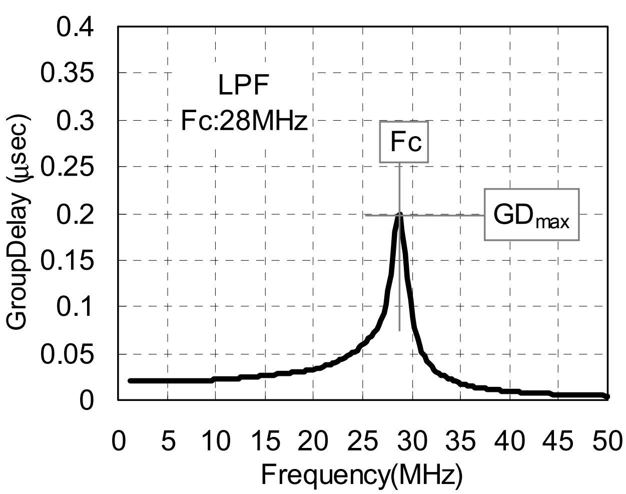
where, k is slope factor of the filter, and K is calculated from complete elliptic integral of the first kind shown in (7)

$$K = \int_0^{\pi/2} \frac{d\phi}{\sqrt{1 - k^2 \sin^2\phi}} \qquad (7)$$

Although numerical evaluation may be difficult, the values for $a_1$ through $a_m$, are extensively tabulated for designing the filters [5-7].




(a) Amplitude characteristics($A_{amp}$)




(b) Group Delay characteristics($T_{gd}$)

Fig.4. Typical characteristics of elliptic-function filter(LPF)

The frequency characteristics of the amplitude $A_{amp}$ and the group delay $T_{gd}$ of the filter are derived from (8) and (9) respectively.

$$A_{amp} = 20\cdot \log_{10}|H(j\omega)| \qquad (8)$$

$$T_{gd} = -\frac{\partial}{\partial\omega}\arg(H(j\omega)) \qquad (9)$$

The numerical calculation (8) and (9) of the elliptic-function filter (LPF:28MHz) is shown in Fig.4.

In order to achieve sufficient interference signal rejection, the attenuation value at stop-band is selected to $A_{min}$: -40dB, and value of pass-band ripple is selected to $R_{dB}$ :0.5dB for all design of LPFs and HPFs in the Multi-band Filters.

### *B. Reduction of Stray Capacitance of Switch IC*

In order to prevent the degradation of the characteristics of Multi-band Filters, it is very important to keep stray capacitance of Switch IC as small as possible.

In general, the stray capacitance of the MOS transistors depends on the gate size of the transistor, and also it shows linear correlation to on-resistance as indicated in Fig.5. In Fig.5, diamond plots are the values from commercial MOS transistors with different gate size, and a black square plot is the value of the Switch IC which is selected for the Multi-band Filter. A line shown in Fig.5 is a result of least square error regression. The designed value of stray capacitance of the Switch IC is 2.3pF, and on-resistance is 3.2Ω.

The simulation results of the pass-band characteristic of the filter with stray capacitance are shown in Fig.6. The value of stray capacitance is varied from 2.3pF to 20pF. As shown in Fig.6, pass-band characteristic is severely degraded in the case of the capacitance over 10pF. In the case of 2.3pF, the average insertion loss of pass-band frequency range is 1.4dB due to the on-resistance, and the pass-band ripple was ±0.4dB which is acceptable value for the Multi-band Filter.

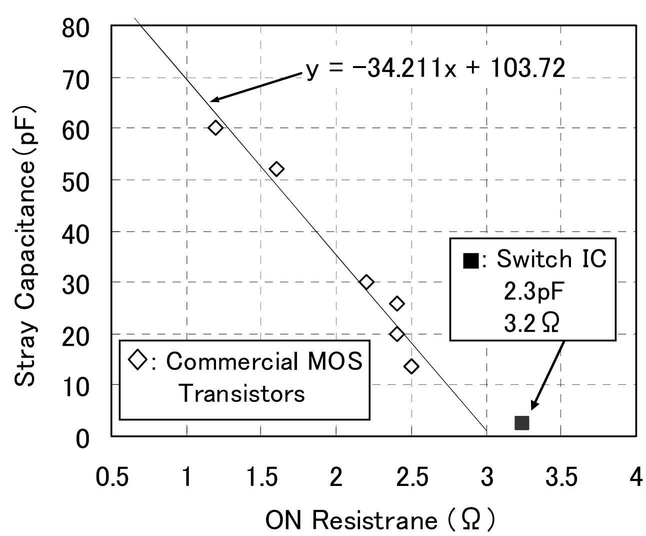
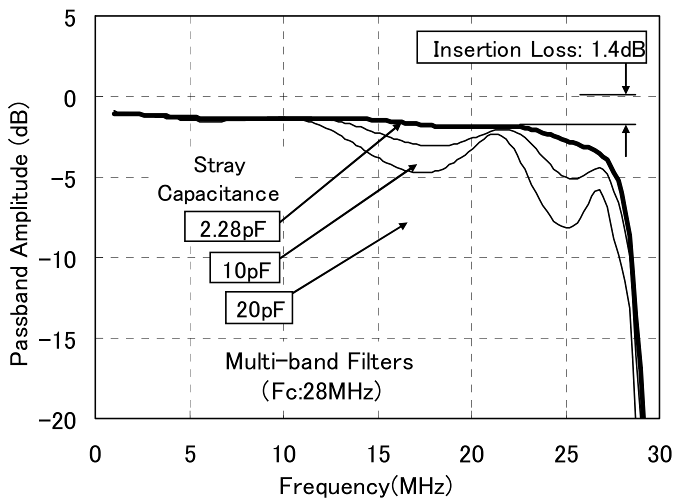
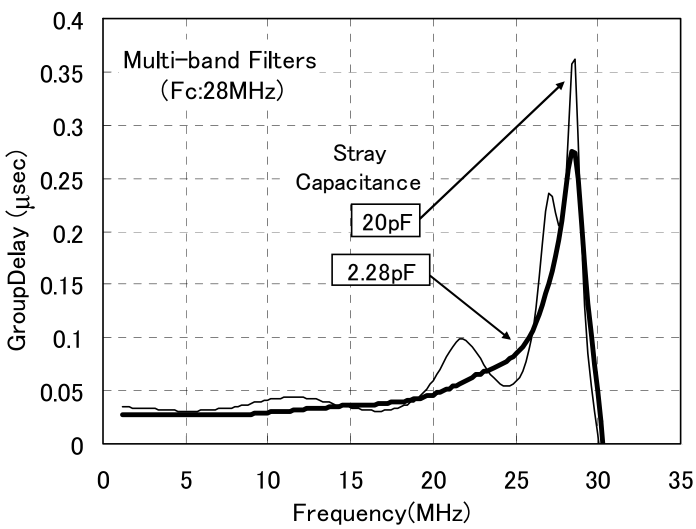



Fig.5. Stray Capacitance of the MOS transistors

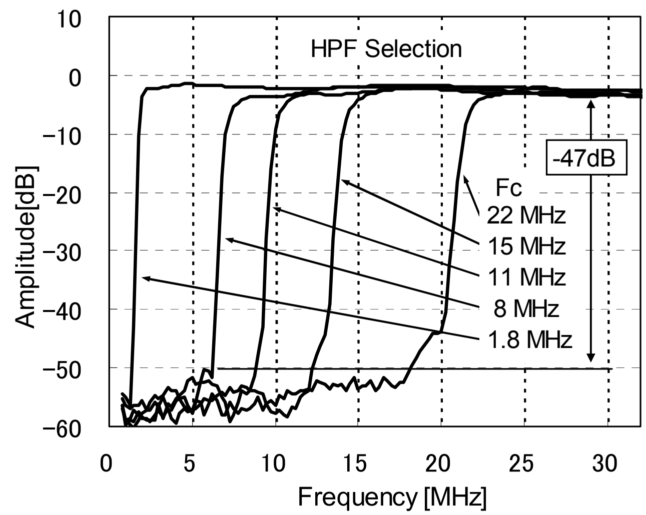



(a) Pass-band Amplitude

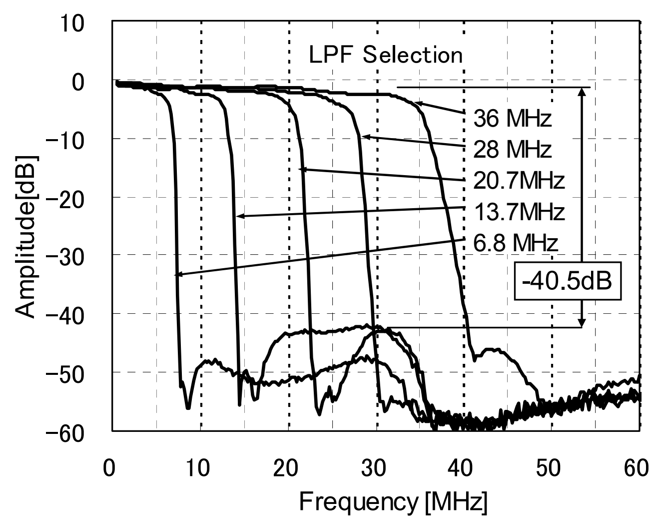



(b) Group Delay characteristics

Fig.6. Simulation Results of Multi-band Filters(LPF)




(a) Frequency characteristics of High Pass Filters




(b) Frequency characteristics of Low Pass Filters

Fig. 7. Measurement results of Multi-band Filters

### *C. Measurement Results of Multi-band Filters*

The measurement results of frequency characteristics of the Multi-band filters are shown in Fig.7. Five different cut-off frequencies(1.8MHz, 8MHz, 11MHz, 15MHz, 22MHz) of the HPFs are shown in Fig.7(a). The stop-band attenuations of every HPFs are bellow -47dB, and all pass-band ripples are within the value of ±1.1dB. The average insertion losses of pass-band frequency for all HPFs are -2.3dB.

Also, five different cut-off frequencies (6.8MHz, 13.7MHz, 20.7MHz, 28MHz, 36MHz) of the LPFs are shown in Fig.7(b). In Fig.7(b), the stop-band attenuations of every LPFs are bellow -40.5dB, and pass-band ripples are within the value of ±0.9dB. The average insertion losses of pass-band frequency for all LPFs are -1.4dB.

## III. Data Rate Estimation

The effect of interference signal rejection by the Multi-band Filter is estimated by measuring the transmission data rate of PLC modem. The measurement setup is shown in Fig.8(a). The frequency range of transmitting OFDM signal between the transmitter modem and the receiver modem is 3 - 13MHz, while the frequency range of interference signal, which is generated by a modem to simulate the noise source, is 17 – 27MHz.

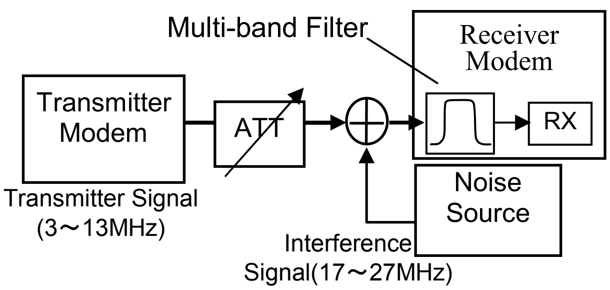
The measurement results of the data rate at the receiver modem with/without Multi-band Filters are shown in Fig.8(b). The vertical axis is average bits per OFDM subcarrier, and the horizontal axis is the value of variable attenuator shown in Fig.8(a). In Fig.8(b), 10 bits per carrier on the vertical axis indicates 1024QAM modulation which is the max transmission rate of the modem. A value of DUR (Desired-to-Undesired signal power Ratio) is defined in (10):

$$\mathrm{DUR} = 10 \cdot \log_{10} \frac{E\left[\left|r_D\right|^2\right]}{E\left[\left|r_U\right|^2\right]} \tag{10}$$

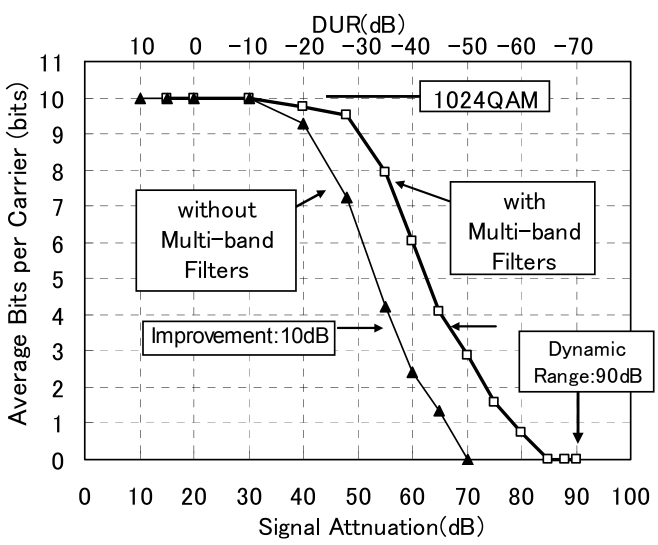
where, $r_D$ and $r_U$ are desired and undesired signals respectively, and the operator $E[\cdot]$ indicates expectation (average).

A curve with triangle plots indicates measurement results without the Multi-band Filter, and a curve with square plots indicates results with the Multi-band Filters. Improvement effect of the Multi-band Filters is about 10dB(equivalent SNR improvement) for wide range of signal strength, and the dynamic range with the filters reaches 90dB (DUR: -70dB).

This measurement results indicates that even though the frequency range of the interference signal differs from that of transmitter signal, the performance of the modem degrades about 10dB due to the signal dynamic range problem, and it is confirmed that the Multi-band Filters are effective to prevent the degradation of modem performance.




(a) measurement setup




(b) Data Rate measurement results

Fig. 8. Data Rate estimation with Multi-band Filters

## IV. CONCLUSION

In order to solve the dynamic range problem, a novel circuit method, called "Multi-band Filters", is proposed. By combining arbitrary HPF and LPF, 22 different type of bandpass filters are available with very small circuit area. To keep the frequency characteristic of the filters, stay capacitance of the Switch IC is reduced to 2.28pF. From the measurement of Multi-band Filters, stop-band attenuation:-40dB, and pass-band ripple: ±0.8dB for all LPFs and HPFs are derived. By rejecting interference signal with the Multi-band Filters, the equivalent SNR improvement of 10dB is confirmed by data rate measurement.

A future work is to confirm the practical effect of the Multi-band Filters in the field trials.

## REFERENCES


[1] J. Bauwelinck, *et.al* , "Analog Front-End ASIC Requirements for a FDM Broadband Powerline System Enabling Co-Existence", *IEEE International Symposium on Power Line Communications and Its Applications 2007*, pp.437 – 440, March 2007

[2] D. Ayyagari and Wai-chung Chan, "Comparison of TDM and OFDMA Access Methods for Powerline OFDM Systems", *IEEE Consumer Communications and Networking Conference, 2005*. pp.364 – 368, Jan. 2005

[3] R.Kimura and S.Shimamoto, "An Orthogonal Frequency Division Duplex (OFDD) System Using an Analog Filter Bank", IEEE WCNC 2007, pp.2275-2280, Mar. 2007

[4] J. Yang, R.W. Brodersen and D. Tse "Addressing the Dynamic Range Problem in Cognitive Radios", IEEE International Conference on Communications 2007, pp. 5183 – 5188, June 2007

[5] A.B. Williams and F.J. Taylor, "Electric Filter Design Handbook", McGraw-Hill Inc., 1981

[6] A.I Zverev, " Handbook of Filter Synthesis", John Wiley & Sons Inc., 1967

[7] K. L. Su, " Handbook of Table for Elliptic-Function Filters", Kluwer Academic., 1990

[8] H.J. Orchard and A.N. Willson, "Elliptic Function Filters for Filter Design", *IEEE Trans. on Circuits and Systems-I*, vol. 44, pp. 273-287, April 1997.