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RF SWITCHES IN WIDE-, BROAD-, AND MULTI-BAND RF FRONT-END OF WIRELESS COMMUNICATIONS: AN OVERVIEW

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ABSTRACT

This paper presents an important overview on the RF switches for wide-band, broad-band and multi-band RF front-end of wireless communications. This paper is mainly focused on the discussion of the circuit configuration of RF switches that using Time Division Duplex (TDD) switching in wireless communications such as WiMAX, WiFi and LTE. The previous research works on the RF switches for wide-band, broad-band and multi-band RF front-end are discussed in term of technology used, circuit design, performance and its applications.

Keywords: RF switch, SPDT switch, wide-band, broad-band, multi-band.

INTRODUCTION

In modern wireless communication, there is a requirement of designing a wide-, broad- or multi-band RF front-end. It requires wide-, broad- or multi-band RF subcomponents in the RF front-end to support different band and different standard (e.g. WiFi, WiMAX, LTE, WiBro, HiperLAN and etc.). Therefore, these have created new challenges to circuit and system designers in developing a wide-, broad- or multi-band RF front-end system. Several wide-, broad- or multi-band RF subcomponents can be found in antenna [1], [2], filter [3], [4] and amplifier designs [5], [6].

Take an example in WiMAX system. This system uses Time Division Duplex (TDD) communication at different frequency band such as 2.3, 3.5 and 5.5 GHz bands. These bands are set within 2-6 GHz range for mobile WiMAX and 2-11 GHz range for fixed WiMAX [7]. Hence, it is valuable if the RF front-end is less expensive and/or smaller than simply putting multiple RF components next to each other that has acceptable performance. Moreover, the integration of multiple wireless systems might be required either for different standards (e.g. WiFi and WiMAX) or different spectrum allocations at various locations (e.g. different WiMAX spectrums in different countries as shown in Table-1). To reduce the size, it can be achieved by eliminating or combining RF components as much as possible and reuse building blocks among different frequency bands and standards [8]. Thus, RF switch is one of the solution to reduce the size of wide-, broad- or multi-band RF front-end system.

There are several research work on the RF switch for WiMAX as reported in [9]–[12]. These switches are used broadly in this RF fornt-end system for signal routing from antenna to receive and transmit ports. RF switches can be classified into two main switching elements which are micro-electro-mechanicals (MEMs) and solid state technology (such as PIN diode and field effect transistor (FET)). MEMs switch have not found wide use in RF and microwave applications since the PIN diode was developed and commercialized [13]. However, a new MEMs technology are keep changing over time as reported in [14] and becomes a big competitor to PIN diode and FET technology. Besides, solid state switches show more reliability such as PIN diode due to faster switching time and accomplish a longer lifetime, if compared to MEMs technology. Consequently, when the fast switching time and long lifetime are the key performance requirement in certain applications, the most popular switching element used is either PIN diodes and FETs [14].

Table-1. WiMAX international frequency allocation [15].

No	Name of Country	Frequency Allocation	Possibly
1	Canada	2.3 GHz 2.5 GHz 3.5 GHz	
2	USA	2.5 GHz	
3	Central & South America	2.5 GHz 3.5 GHz	
4	Europe	3.5 GHz 5 GHz	2.5 GHz
5	Middle East & Africa	3.5 GHz 5 GHz	
6	Russia	3.5 GHz	2.3 GHz 2.5 GHz
7	Asia	2.3 GHz 3.3 GHz 3.5 GHz	

RF Switch element and performance

In term of RF switch element, PIN diodes and FET are the most common elements used for RF microwave switches [16]. The PIN diode is a semiconductor device developed for RF and microwave frequencies, with a distinctive feature of varying resistance by changing the current of PIN diode. It is able to control a RF signal with utilizing small amount of voltage and current [14]. Meanwhile, FET is a semiconductor device in which it relies on an electric field (or voltage) to control the shape and the conductivity of a channel in the FET. It has perfect drain-to-source resistance control, hence FET

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switches are more stable an repeatable to PIN diode [14]. Besides, emerging MEMs switch technology attempts to apply the advantages of conventional electro-mechanicals (EMs) switches, but in a small size. MEMS switches employ micro-miniaturized mechanical contacts controlled by electrostatic forces to make RF connections [17].

Generally, the switch performance can be shown by describing its key parameters such as insertion loss, isolation and switching speed [16]. Insertion loss is a power loss ratio of a signal between output and input of RF switch element during the ON state. For instance, as reported in [14] insertion loss is a discriminating detail of a switch in system applications that expect an extra power to recompense for the loss that is not available. Meanwhile, isolation is defined as the ratio of the power level when the switch's path is OFF to the power level when the switch is ON. Perfect isolation keeps stray signals from leaking into the desired state, whether ON or OFF. Switching speed is a time expected to convert the condition of a switch from ON state to OFF state or vice versa. It is usually described in two ways: on/off time and rise/fall time.

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RF Switch configurations

In RF switch configurations in TDD communication, there are three techniques to design the switch for wide-, broad and multi-band applications. An example is taken from WiMAX with three frequency bands, 2.3, 3.5 and 5.5 GHz. As shown in Figure-1, the configuration A uses a single wide, broad- or multi-band single pole double throw (SPDT) switch that connected to transmitter (Tx) and receiver (Rx) chains. Both double throw ports have a triplexer to separate three different frequency bands. Meanwhile, the configuration B in Figure-2 consists of triplexer and three narrow-band SPDT switches operating at three different frequencies (2.3, 3.5 and 5.5 GHz). In this configuration, a single triplexer is used to separate the three different frequency bands. The configuration C in Figure-3 consists of single RF switch which is single pole six throw (SP6T) to switch at different frequency bands at different time. In this configuration, the six throw uses single frequency band [18], [19].

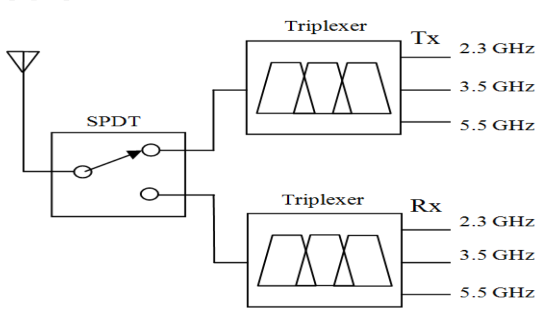

Figure-1. Configuration A: wide-, broad- and multi-band RF switches in RF front-end system.

In applications such as mobile handsets, which need to handle a large number of different signals, and different frequency bands, it needs RF switches with multiple throw such as single pole four throw (SP4T), single pole seven throw (SP7T) or single pole nine throw (SP9T) as reported in [20], [21]. Furthermore, it can simpliying the mobile handsets [22]. In this application, it introduced different implementation of RF front-end: discrete, hybrid and mixed RF front-end designs. As the target application for these designs was smart phones, so the discrete solution of RF front-end was not well-suited.

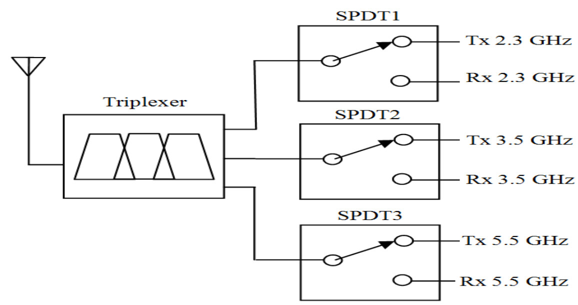

Figure-2. Configuration B: narrow-band RF switches in RF front-end system.

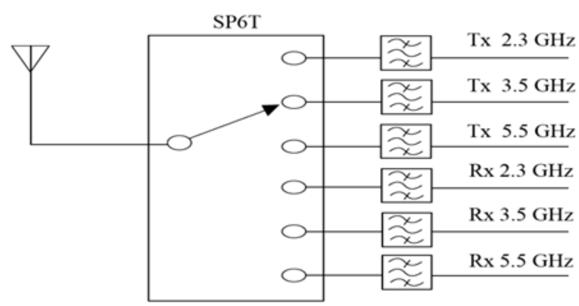

Figure-3. Configuration C: multi-throw narrow-band RF switch in RF front-end system.

Related research works

From literatures, several key designs of RF switches for wide-, broad- and multi-band application are discussed in this section. Most of the research works were focused on the wide- and broad-band RF switches such as in [23]–[26] but there is a few research works on multi-band RF switch such as reported in [27]. Designing wide-, and broad-band RF switches are more challenging compared to narrow-band RF switches. It requires very wide- or broad-band of isolation, insertion loss and return loss. Meanwhile for the multi-band RF switches, it requires to consider the harmonics of each band from distorting the other bands.

Table-2 is the lists of the related and selected research works on the RF switches for wide-, broad- and multi-band application.

An ultrafast wideband low-loss SPDT switch using SiGe bipolar technique was reported in [23]. The authors used HBT transistors as a switch elements in order

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to introduce a configuration of adopting current steering technology. It produced a measured switching time of 75 per second, which recommends a most extreme switching rate of 13 Gb/s in V-band. In this paper, common-emitter topology was offered with the target to minimize the noise figure. As a result, this paper shows less than 1.25 dB insertion loss, about 10 dB return loss and greater than 18 dB isolation from 42 GHz to 70 GHz.

Authors in [24] presented an ultra low-loss 50-70 GHz SPDT switch using 90 nm CMOS technique with FET transistors as switch elements. The circuit consists of λ/4 transmission lines with shunt inductors at the output matching network. To accomplish low insertion loss, this paper used high substrate resistance contacts. As results, it produced less than 2 dB insertion loss, higher than 25 dB isolation and higher than -8 dB return loss from 50 to70 GHz. The layout area is 0.5x0.55 mm2 which, by folding the λ/4 transmission lines. This design shows the lowest insertion loss, if compared with other switches using the same technology.

Table-2. Related and selected research works on the RF switches for wide-, broad- and multi-band application.

No	Year/ Author(s)	Focus of design	Remarks
1	2012/ M. Thiam, et.al [23]	Ultrafast low loss differential SPDT switch in 0.35 m SiGe technology	➢ HBT ➢ 42-70 GHz ➢ > 18 dB Isolation
2	2009/ M. Uzunkol, et.al [24]	Ultra low loss SPDT switchin 90 nm CMOS	➢ FET ➢ 50-70 GHz ➢ > 27 dB Isolation
3	2008/ J. He and Y. P. Zhang [28]	SPST/SPDT switches in 65nm CMOS with 60GHz operation frequency	➢ CMOS ➢ 57-66 GHz ➢ > 25 dB Isolation
4	2011/ N. A. Shairi, et.al [25]	High isolation SPDT switch for broadband	➢ PIN diodes ➢ 0.5–3GHz ➢ > 25 dB Isolation
5	2007/ W. M. L. Kuo, et.al [32]	shunt and series-shunt SPDT switches comparison for X-band Phased array T/R modules	➢ nMOS transistor ➢ 8.5-10.5 GHz ➢ > 20 dB Isolation
6	2007/ Z.-M. Tsai, et.al [34]	Bandpass SPDT using FET filter-integrated	➢ FET ➢ 50 - 70 GHz ➢ >27 dB Isolation
7	2010/ H. Y. Chang, et.al [33]	A low loss high isolation DC-60 GHz SPDT traveling-Wave Switch With a body bias Technique in 90 nm CMOS Process	➢ nMOS Transistor ➢ DC-60 GHz ➢ > 40 dB Isolation
8	2011/ C. Kuo, et.al [26]	A high-isolation switch using CMOS technology with operation frequency of 60GHz	➢ MOS Transistor ➢ 57- 64 GHz ➢ > 25 dB Isolation
9	2006/ S. Tanaka, et.al [27]	Multi-band switches with ladder circuits	➢ PIN diodes ➢ 1.6, 2.5 and 5.8 GHz ➢ > 20 dB

Authors in [28] reported two switches, one is SPST and the other is SPDT. Both switches were proposed that operated from 57 to 66 GHz. In this paper, the circuit was fabricated using 65nm CMOS technology. The SPDT design achieved higher than 21 dB, higher than 10 dB and about 3 dB, for isolation, return loss and insertion loss respectively. Meanwhile, the SPST design produced a good result for isolation and return loss. On the other hand, several CMOS transceiver/receiver switches have been discussed in [29], [30]. However, the performance of RF switch in [30] is not that good for the typical design of shunt-series configuration [28].

In addition, authors in [25] proposed a design of SPDT switch for broadband using PIN diodes. WiMAX, LTE and etc. are the examples of where the proposed design can be applied from 0.5 to 3 GHz. The RF switch was built using PIN diodes of HSMP-389Y. Besides, it is a challenge to achieve good isolation result by using only a single packaged of PIN diode [31], unless circuit design techniques are implimented. As results, isolation higher than 25 dB and insertion loss of 1 dB were achieved.

Moreover, in [32] two different configuration SPDT switches at frequency from 8.5 to 10.5 GHz were reported. The designs were fabricated using 0.13 um SiGe BiCMOS technology with nMOS transistors as switch elements. In this paper, the two designs can be described as follows. One is shunt configuration using λ/4 sections and the other is series-shunt configuration using matching networks. As results, the first design produced 20.5 dB isolation, 1.89 dB insertion loss and 14.5 dB return loss. The second design produced returns loss, insertion loss, and isolation of 22.2 dB, 2.33 dB, and 22.5 dB respectively. It is found that the switches worked as the same as other CMOS switches which are using non-standard processes.

Meanwhile, in [26], SPDT switch using CMOS technology was designed. Authors used switch elements of MOS transistors and body-floating technique in order to increase the linearity and decrease the insertion loss. In addition, to increase isolation, the leakage cancellation technique was used. In measurement results, the switch showed that the isolation is higher than 28 dB and the insertion loss is less than 3.5 dB from 57 to 64 GHz. The proposed design has a good result in terms of return loss, insertion loss and isolation (34 dB) at the center frequency. Also it is observed that the RF switch has a good flatness response of the input 1-dB compression point (IP1dB) of 6.5 to 6.9 dBm at the operation frequency from 57 to 64 GHz. Moreover, the design is useful for the RF front-end integration in 60-GHz CMOS single-chip RF transceiver.

A low loss high isolation broadband single-port double-throw (SPDT) traveling-wave switch using 90 nm CMOS technology was proposed in [33]. In this paper, nMOS transistors was used with body bias technique to improve the circuit performance of the switch, especially for the operation frequency greater than 30 GHz. Moreover, the input P1dB and IMD of the SPDT switch are both enhanced by 2 and 10 dB at 20 GHz, respectively.

Also, the loss and the linearity of the circuit are improved due to the reduction of the capacitance in the cold-mode state. As result, the switch showed an insertion loss of 3 dB and an isolation of higher than 48 dB from DC to 60 GHz. To the best of the authors' knowledge, this work is the widest 3 dB bandwidth among others that uses CMOS SPDT technology.

Adding to that, design in [34] is a bandpass SPDT filter-integrated switches using FET transistors. Authors provided a technique integrating an SPDT switch with a quarter-wavelength bandpass filter. In this paper, two SPDT switches were fabricated to validate the design concept; one is hybrid circuit (at 1 GHz) and the other is monolithic-microwave integrated-circuit (MMIC) (at 60 GHz). Both switches achieved 30% FBW and suitable for wide-band communication system. As a result, the hybrid switch exhibited 20 dB isolation and 1.5 dB insertion loss, at center frequency. Furthermore, the MMIC switch showed that the insertion loss was lower than 2.5 dB and the isolation was higher than 27 dB. In addition, the method used in this paper provides a simple and precise way to obtain the power compression point and the dominant components without generating nonlinear models and nonlinear simulation tools, which is useful to design for the power performance of SPDT switches.

Meanwhile, authors in [27] designed an SPDT switch for multi frequency bands with ladder circuits. This design used PIN diodes to operate with multi-band frequencies in order to be applicable for three wireless applications in 1.6 GHz, 2.5 GH and 5.8 GHz band for global positioning system (GPS), vehicle information and communication system (VICS), and a dedicated short-range communication system/electric toll collection system (DSRC/ETC). On the other hand, this paper introduced a ladder circuit with simple configuration and low cost. Authors fabricated two types of switches; lumped circuit elements and semi-microstrip elements. As result, the variations on the second switch are about 25% of those of the first design. The circuit produced isolation higher than 20 dB and less than 2 dB of insertion loss. The proposed design is a key gadget to bi-directional multi-band automobile communication systems.

CONCLUSIONS

From literatures, there is a demand on the RF switches for wide-, broad- and multi-band RF front-end for wireless communication systems. The purpose is to support different band and different standard (e.g. WiFi, WiMAX, LTE, WiBro, HiperLAN and etc.). Three options of configuration of RF switches for wide-, broad- and multi-band RF front-end were discussed that consist of filter and triplexer. In general, these RF switches for wide-, broad- and multi-band RF front-end are essential to eliminate sub-component and thus reduce the size of RF front-end system.

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