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Survey on Multiband RF Energy Harvesting

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Abstract: Modern life style depending on wireless technologies has made the surrounding environment full of free wireless energy. RF energy harvester exploits this free energy and converts it to DC power which is used as power sources for many low power applications as wireless sensor network (WSN) and internet of things (IOT). RF harvester circuit contains antenna, matching network, rectifier/voltage multiplier, power storage element and finally load represented in targeted application. Each part has many challenges in its design to improve the coveted performance. Antenna aims to collect most accessible power from the ambient, matching network aims to deliver the collected power to rectifier with minimum reflection, rectifier/voltage multiplier aims to use a topology that achieve high output dc power with suitable sensitivity. Overall Performance of RF harvester can be progressed by increasing the collected power from the ambient; it depends on availability of wireless energy in the surroundings or ability of harvester design to capture more power from available ambient wireless energy. From this view point many researchers propose many designs to capture more power by receiving from multiple frequency bands at the same time using multiband RF harvester. So, this paper presents an outline of some recent achieved work in multiband RF harvesters and the achieved results.

Keywords: RF energy harvester, multiband, rectifier

الملخص العربى:

نمط الحياة المعاصرة تعتمد بشكل كبير على التقنيات اللاسلكية مما جعل البيئة المحيطة مليئة بالطاقة اللاسلكية المجانية ولذلك من المغري جدا إستغلاها من خلال تقنية اكتساب الطاقة من ترددات الراديو وتحويلاها لطاقة مفيدة لتشغيل التطبيقات قليلة الطاقة كمصدر بديل للبطاريات مثل شبكة أجهزة الإستشعار اللاسلكية. تحتوي تقنية اكتساب الطاقة من ترددات الراديوعلي هوائي لتجميع أكبر قدر من الطاقة اللاسلكية المحيطة، ودائرة مطابقة لتضمن وصول الطاقة المجمعة بأقل نسبة فقد للدائرة التي تليها وهي دائرة الموحد ومضاعف الجهد لتحقيق القيمة التي يتطلبها التطبيق المستهدف تشغيله. تحسين كفاءة هذه التقنية تعتمد علي عدة عوامل و منها تحسين القدرة علي تجميع أكبر قدر من الطاقة اللاسلكية المتاحة في البيئة المحيطة ولذلك قدم الكثير من الباحثين تصميمات تعتمد علي إستخدام اكتساب الطاقة من ترددات الراديو من أكثر من حيز ترددي في نفس الوقت لتجميع قدر أكبر من الطاقة اللاسلكية. هذا البحث يعرض بعض الأبحاث التي قدمت مؤخرا وحققت تحسينات في كفاءة تقنية اكتساب الطاقة من خلال حيزات الراديو المتعددة في نفس الوقت.

1. Introduction

Energy extraction from nature and reuse it to energize or replace the ordinary power sources is called Energy Harvesting (EH). Energy harvesting techniques utilize energy from ambient environment as (vibration, heat, wind, solar, electromagnetic waves, etc).

Energy harvesting plays a vital role for replacing batteries or expanding their lifetime, due to batteries limited lifetime they need frequent replacements. With the aids of applying power harvesting techniques, devices can become power independent to energize itself, thereby obtaining an unlimited operating lifetime. Thus, the need for power maintenance will become immaterial [1].

Radio frequency harvesting (RFH) is a promising harvesting technology because wireless technologies became vital to our modern lifestyle.

RF energy is available in extensive range of frequency band as (mobile bands, Wi-Fi bands, radio and TV bands). So, why these numerous free energy isn't recycled by harvesting and coverting it to DC power to be alternative energy sources for many low power applications as wireless sensor network (WSN) and internet of things (IOT).

RF harvesting fundamental block diagram shown in Fig.1 contains rectenna which include (antenna, matching network and rectifier/voltage multiplier), power management and finally load represented in targeted application. Each part has a specific task, antenna collects most of the accessible ambient RF power and its performance associated with Gain, resonance frequency and bandwidth. Impedance matching network is to let power transfer from antenna to rectifier/voltage multiplier done with minimal reflections and its performance related to S parameter S11, quality factor, resonance frequency and bandwidth. Rectifier and multistage DC voltage multiplier responsible to rectify and amplify the low harvested power to a specified level required for targeted application and performance related to sensitivity, number of voltage multiplier stages, rectifier configuration and RF-DC power conversion efficiency (PCE). Power management provides a topology for storing and distribution of the amplified dc power (rectifier/multiplier output) and its performance related to energy storage element, output power and output voltage.

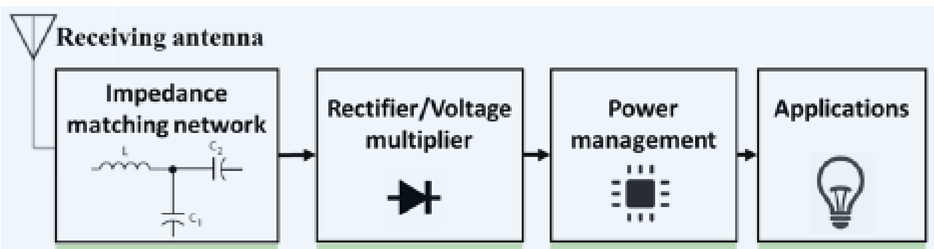


Figure 1: RF harvesting fundamental block diagram

Overall Performance of RF harvester measured by many parameters as power conversion efficiency, sensitivity, operation distance and output power [1]. So designing RF harvester faces many challenges to realize an optimum value of each mentioned parameter. Among these challenges increase power conversion efficiency (PCE) which measure ratio between harvester output power which measured on load terminals and that harvested by the antenna. If RF harvesters design able to accumulate more from the ambient power, PCE will increase.

Collecting more power depend on availability of wireless energy in the surrounding environment or ability of harvester design to capture more power from available ambient wireless energy.

From this view point many researchers propose many designs to capture more power by receiving from multiple frequency bands at the same time using multiband RF harvester.

So we talk about the contrast between using multiband, broadband and tunable harvester and how multiband harvester can achieve an enhancement PCE in next section.

First, paper presents brief to show the contrast between multiband, broadband and tunable harvester and their effect on the harvester performance (in section 2). Then, we introduce an outline of some achieved work in multiband RF harvesters and the achieved result (in section 3).

2. Tunable band, broadband and multiband RF harvester

As mentioned the ability of harvester to capture more power from the ambient will increase the overall performance of harvester, so decision to use tunable band harvester or broadband harvester or multiband harvester is critical due to different ability of each to capture power from the ambient. Brief discussion on each is illustrated in following subsections.

2.1. Tunable band RF harvester

Tunable harvesting uses a designed antenna which is tuned to capture a specific band. All used components in harvester system are designed to deal with the tuned band only. So it will discard energy outside the band to which they are tuned [2]. So improving harvester performance and increasing output power restricted with the captured power from tunable single band.

2.2. Broadband RF harvester

Energy can be captured across large bandwidth from available spectrum using broadband harvester [2]. But matching circuit between antenna and rectifier required to be matched along this wide frequency range, this impractical mission provide very low efficiency at any particular source frequency as the quality of the impedance matching circuit is reduced as the bandwidth increase. Another challenge in design broadband harvester is to keep up high power conversion efficiency over a broad frequency band [3].

2.3. Multiband RF harvester

The main idea of multiband harvester is using single wide band antenna or multiple narrow band antennas to capture and transfer the maximum power from the ambient wireless energy; multiband harvester is able to harvest power in efficient performance from multiple bands at once. In case of using multiple antennas, each one is tuned to a specific band and each connecting to independent rectifiers or single rectifier through a tuned matching circuit or multiple matching circuits due to aimed performance of the suggested design. Output dc incase of using multiple rectifiers may serially combined to output a voltage sum as harvester output. This concept also can be achieved using broadband antenna using a specific technique which is electrically split the broadband into multiple bands then each band connected to independent rectifier as in [2],[4] and will be mentioned later.

3. Some achieved work on multiband RF harvester

Rectennas with high power conversion efficiency, wide frequency bandwidth and a consistent performance in different operating range is the target of researchers. Too many researches proposed their designs trying to achieve one or more of these goals. This section introduces some of these research that done on multiband RF harvester.

In [5] presents the possible configurations of multiband RF harvesters based on parallel array as shown in Fig.2. Switching between aimed frequency bands and summing the harvested power can be configured by many topologies. It may be configured electromagnetically at single antenna or at the output from various antennas, or output of multiple rectifiers or output of multiple power management modules (PMM) which is used to make power point tracking (MPPT) reach to optimum value.

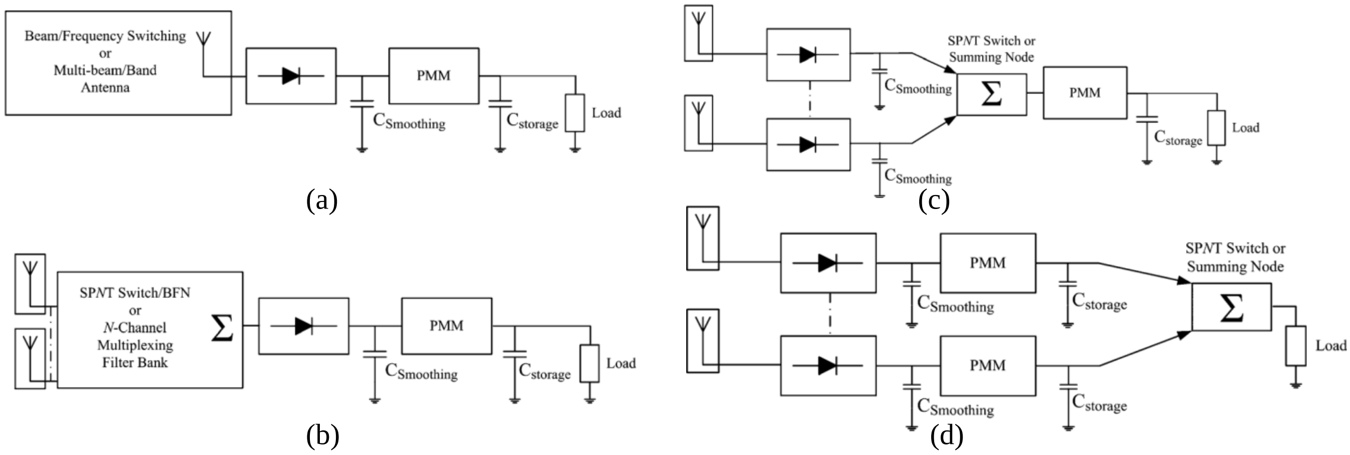


Figure 2 Multiband RF harvester with parallel array architectures with switching at the (a) antenna (b) output of multiple antennas (c) output of multiples rectifiers (d) output of multiple PMMs.

They introduced a study in two different configurations; four frequency bands suggested to be covered (DTV, GSM 900, GSM 1800 and 3G). First using multiple rectifiers with single PMM and achieved 15% efficiency with a combined input RF power of 12 dBm, but it achieves low efficiency if compared to a single-band harvester; they referred it to the imbalance of rectifier outputs. Second one using multiple rectifiers with multiple PMMs connected with each rectifier, the efficiency using more than one PMM is barely decrease at 13% at same combined input power. They referred this low efficiency because useful dc output power from the cold starting harvester is being provided to the other harvesters for hot-starting, even though number of them might not surely be sharing any of their own harvested power.

In [6], propose triple band antenna to cover frequency bands (900MHZ, 1800MHZ and 2.45 GHZ). Fig.3 shows the proposed layout. They combine the dc output voltage of three single frequency RF harvesters and efficiency is extended through 15 % as compared to efficiency of every sub-system. As at -15dBm, system efficiency reaches 45% at 900 MHZ, 46% at 1800 MHZ and 25% at 2.45 GHZ. The components of each designed rectifier in this system are varied in each sub-system due to relation between multiplier impedance, frequency and number of multiplier stages or frequency increase. So they use different number of voltage multiplication stages for each operating frequency to reach the maximum output voltage.

In [2], the suggested design shown in Fig.4 introduces a more realistic multiband harvester using single wideband antenna instead of using multiple antennas. Absence of multiple antennas compensated by using a trunk node which is electrically split wide frequency bands into independent branches by orthogonally tuned bandpass filters. Impedance matching network is connected to an independent rectifier which uses Dickson charge pump method, and the rectifier outputs are summed at the DC output using a network of diodes.

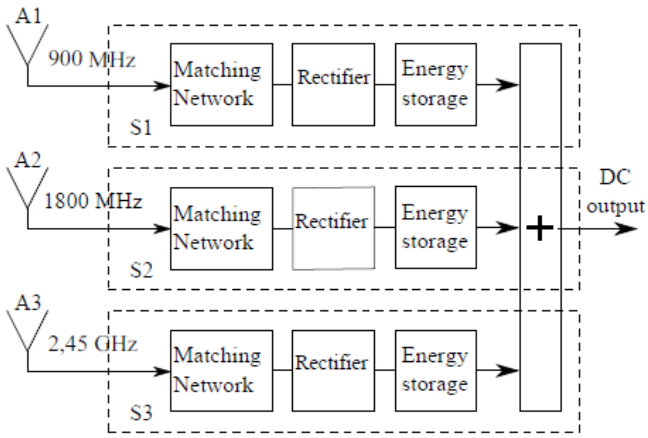


Figure 3: Triple band RF energy harvester

They introduce dc summation network depends on using diodes “shortcut diodes” which is characterized by low threshold and low leakage to skip the bands that have negligible power, so this summation method permitting an automatic configuration to be accomplished in summing the voltages produced by every band rectifier.

Proposed harvester is aimed to cover N adjacent frequency bands and the geometric spacing between them is calculated by frequency ratio R= (f_n/f_n-1).

Two-band and five-band harvester prototypes are implemented. Three stages Dickson charge pumps are selected for each band; diode network summation topology is applied. Frequencies (539 MHz and 915 MHz) are selected for two band harvester. Frequencies for five band harvester were chosen by applying a fixed ratio of 1.5 between adjacent frequency bands (267 MHz, 400 MHz, 600 MHz, 900 MHz, and 1.35 GHz).

The two-band and five-band prototypes were first tested using a single-tone with power level of -10 dBm (100 μW). Two-band harvester showed better results than five-band harvester. They supposed that was due to interaction between adjacent bands in the system, as the quality factor of the isolating bandpass filters was not satisfied.

In [4] the proposed configuration shown in Fig.5 adds power coming from limitless number of sub frequency bands which increase output voltages ratios due to increasing number of RF bands. Prototype is done using four RF band rectennas to cover four bands (GSM 900, GSM 1800, UMTS and Wi-Fi bands). Rectenna contains RF band pass filter to match each parallel rectifier, Greinacher rectifier and low pass filter for each sub frequency band. 84% is provided as RF to DC power conversion efficiency measured at 0-dBm input power set on each of the four branches.

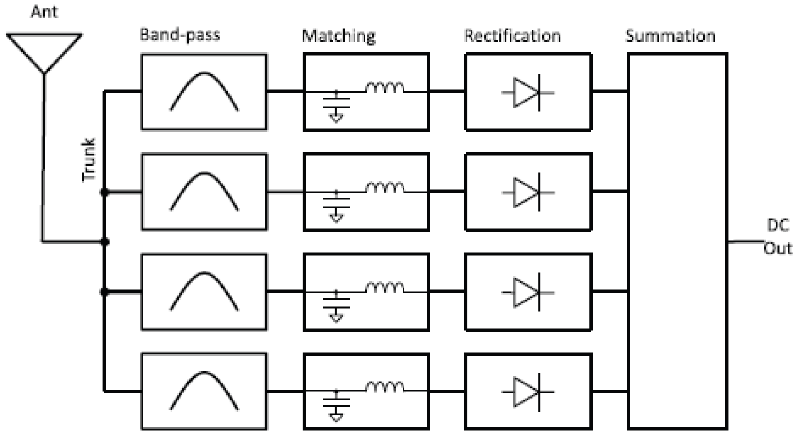


Figure 4: Multiband harvester using single wideband antenna

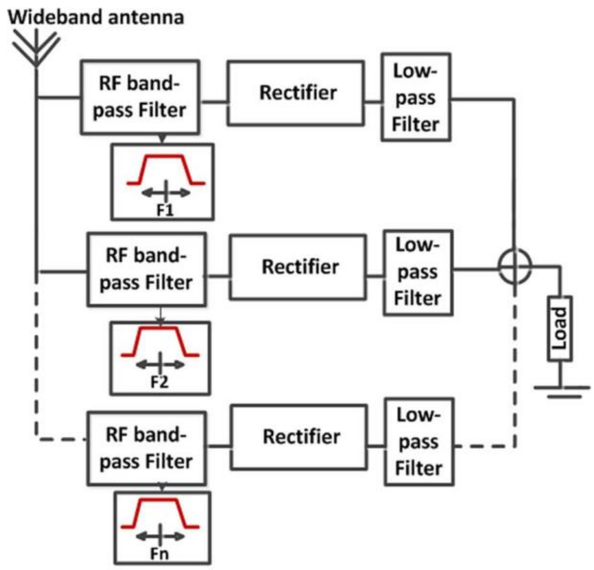


Figure 5: Multiband band stacked RF energy harvester

In [7] presents six-band dual circular polarization (CP) rectenna convenient to be used in RF energy harvesting, they proposed different impedance matching technique for multiband rectennas. The distinctive part of this research is adding a special section formed by microstrip lines to the matching network. This modification in matching circuit targets to improve the matching performance against a varying load. The complete matching network was divided in three branches. Same topology of dual-band matching network but with unequal components values is applied for different frequency bands. Six different frequency bands (from 550 to 2450 MHz) are covered by the rectifier. 80% is provided as maxiumum conversion efficiency. A compact ultra-wideband dual circular polarization (CP) receiving antenna is selected for this layout with a frequency bandwidth from 500 MHz to 2.5 GHz. The complete rectenna provide about 96 μW dc harvested power at input power level -15 dBm. The bright achievement in this research is ability of rectenna to have a constant performance at variant operating conditions such as multiple frequency bands, different input power levels and several values of load impedance.

In [8], they propose a multiband rectifier to cover four frequency bands (1.3, 1.7, 2.4 and 3.6 GHz) using a simpler matching technique than traditional ones. The proposed matching technique is shown in Fig.6.circuit depends on using capacitors and transmission lines as an approximation on inductance in traditional LC matching circuit. Designed transmission lines and capacitor values depend on the operating frequency of each network. The design network can be expanded to more than four bands as mentioned in research. 1V output voltage at -11 dBm input power is successfully achieved for each of the four mentioned bands.

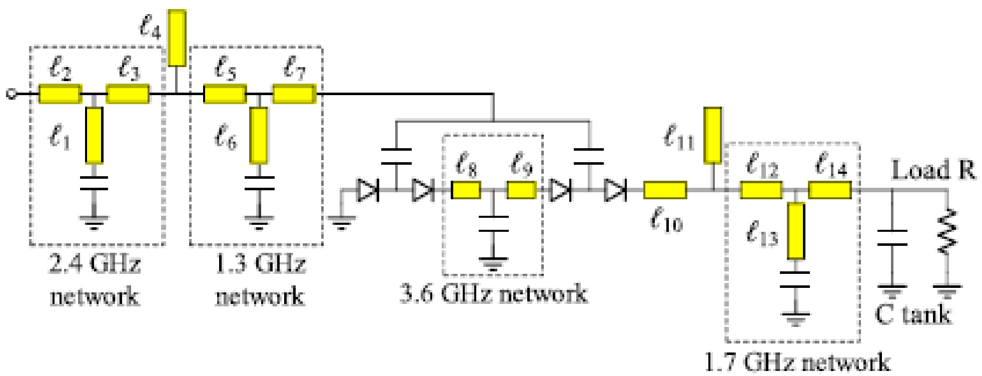


Figure 6: Matching network proposed for four bands rectifier

In [9], GSM-1800, UMTS-2100 and Wi-Fi bands are the aimed frequency bands for this research using multiband rectifier. As shown in Fig.7 one input port and three output ports hybrid junction is exploited in this design to work as one to three band pass filter which connected to three branches. They used Villard voltage doubler technique in each branch with matching circuit and low pass filter, the output of three branches collected to increase the output voltage. At measured 9 dBm input power, this configuration achieved 61.7% as peak efficiency.

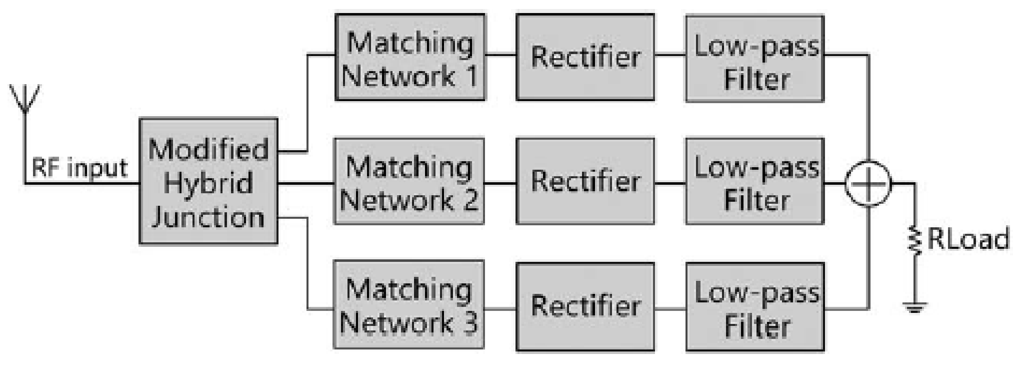
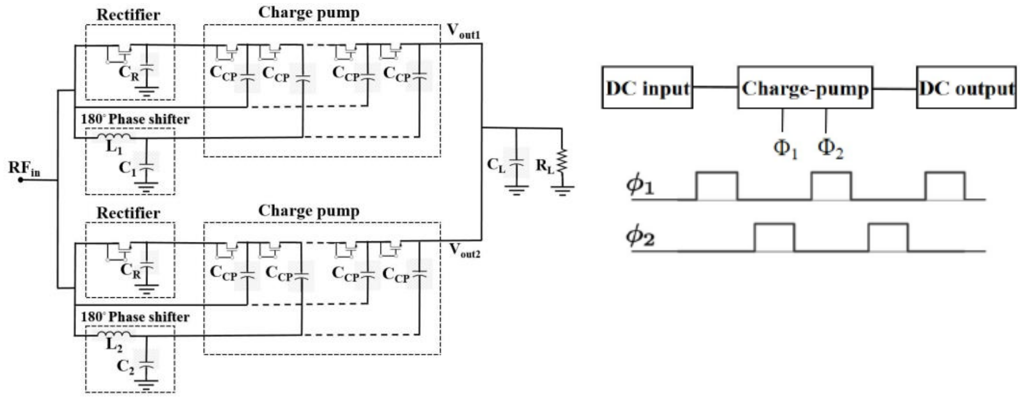


Figure 7: Multiband harvester with 3 output port hybrid junction

In [10], recent configuration is proposed using diode- connected Mosfet as an alternative to schottkey diode which is used in pervious mentioned researches as a component in rectifier and doubler circuits. As shown in circuit diagram in Fig.8 (a) multiband harvester is designed to harvest from two frequency bands (900 and 1800 MHz). They modify conventional Dickson charge pump circuit in Fig.8 (b) by replacing two antiphase clock pulses and dc input by 180^{o} phase shifter. At -11.8 dBm input power, 1.41 V is obtained using 70kΩ load and 21.39% as achieved as power conversion efficiency.



(a) **(b)**

Figure 8: Multiband Harvester

4. Conclusion

RF multiband harvester circuit contains single antenna or multiple antennas, single matching network or multiples ones, rectifier/voltage multiplier or also multiple ones, power storage element and finally load represented in targeted application. using single wideband antenna with aid of multiple rectifiers and multiple matching circuits is more realistic than multiple antennas and provide 84% DC power conversion efficiency at 0 dBm input power using four frequency bands [4]. Similar approach is introduced but with modified DC power summing network using diode network but it showed better result at two frequency bands and may needs improvements for more two frequency bands [2]. Constant performance at variant operating conditions are obtained with aid of adding microstrip lines to the matching circuit which provide 96 µw DC harvested power at -15 dBm input power using six dual circular polarization rectenna [7]. Simple approach uses simple matching circuit is designed with capacitor and transmission lines and provide 1v output at -11 dBm input power using four frequency band rectifier [8]. Adding one input port and three output ports hybrid junction to three bands rectifier achieve 61.7% as peak efficiency [9]. Traditional Dickson charge pump multiplier circuit also modified using diode connected Mosfet as an alternative to Schottky diode and 21.39% is achieved as power conversion efficiency at -11.8 dBm input power using two bands harvester [10]. Among previous configurations, some needs improvements to meet the targeted application requirements, some others already made an enhancement in the traditional designs.

Acknowledgements

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