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Design and Optimization of a Miniaturized Stub-Based Branch-Line Coupler at 900 MHz for GSM Applications

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ABSTRACT
The branch-line coupler (BLC) is a four-port passive component widely used in wireless and microwave systems to divide or combine power equally with a 90° phase difference between its output ports. Because each branch of a conventional BLC is a quarter-wavelength long, the circuit becomes bulky at low frequencies such as the 900 MHz GSM band. This study presents the design and optimization of a miniaturised stub-based BLC operating at 900 MHz. We first designed a conventional coupler with 50 Ω ports on a Rogers RT5880 substrate (εr = 2.2, h = 0.78 mm) and simulated it in CST Studio Suite. Each quarter-wavelength branch was then replaced by an equivalent compact section loaded with stubs, and the stub dimensions were optimized by a parametric sweep to recover bandwidth. The conventional coupler gave a return loss (S_{11}) and isolation (S_{41}) of about -32 dB at 0.92 GHz, through and coupled transmission (S_{21}, S_{31}) of about -3.1 dB at 900 MHz and a -10 dB bandwidth of 379 MHz. The stub-loaded coupler reduced the circuit area by 50.2% (from 9109.9 mm² to 4536.6 mm²), with S11 and S41 reaching about -48.6 dB, S21 and S31 of about -2.9 dB and -3.4 dB at 900 MHz (0.5 dB amplitude imbalance) and a bandwidth of 307 MHz. After optimization, the bandwidth increased to 420 MHz (0.715-1.135 GHz) with S11 and S41 better than −18 dB at 900 MHz, but the amplitude imbalance between S21 and S31 rose to about 3.1 dB. These simulation results show that stub loading halves the coupler area while maintaining good matching and isolation; fabrication and measurement are required to confirm the performance.

Keywords: Branch Line Coupler, Coupler, Defected Ground Structure (DGS), Global System for Mobile (GSM), Miniaturized

INTRODUCTION

Most microwave devices require power monitoring so that the input or output power can be combined or divided. A microwave device that splits or combines power with a 90° phase difference between the output ports is called a branch-line coupler (BLC). These components are widely used in communications, especially in the microwave range (Letavin, 2018; Niu et al., 2019; Sun, 2019). A power divider splits a power signal into two or more lower-power signals, and a power combiner combines two or more power signals into one (Idris et al., 2026).

Hybrid junctions have a 90° or 180° phase difference between the output ports. It's also known as a branch-line hybrid. With all ports matched, a branch-line coupler divides the power into two equal parts, setting the power at port 2 equal to the power at port 3 and the phase shift between the two ports to 90°, with no power delivered to port 4 (isolated port) (Du et al., 2018).

A major challenge in designing a BLC is its relatively large size and limited bandwidth. Because each series and shunt branch is a quarter-wavelength long, the coupler dimensions are proportional to the guided wavelength and become large at low frequencies such as the 900 MHz GSM band (Chaudhary et al., 2023; Idris et al., 2026). Compact, low-cost couplers are therefore needed for mobile and other space-constrained systems (K. V. P. Kumar & Alazemi, 2021). Reported miniaturization techniques include defected ground structures, meandered lines, lumped elements, stepped-impedance and other resonators, slow-wave lines and stubs (Jutru & Vijay, 2020; Naderi & Abbasi, 2017; Roshani, Yahya, Roshani, & Rostami, 2022; Sardi et al., 2018; Selga et al., 2019). Related designs have used T-shaped lines (M. Kumar et al., 2018), coupled lines (W. Wang et al., 2019), patch-type couplers (Bekasiewicz & Koziel, 2018) and compact ring and rat-race topologies (Kulkarni et al., 2019; Lalbakhsh et al., 2021; Tayebi & Zarifi, 2020; Y. Wang et al., 2018). Defected ground structures, which are slots etched in the ground plane beneath a microstrip line, change the effective inductance and capacitance of the line, but like lumped-element and filter-based approaches they add fabrication steps (Chaudhary et al., 2023). Stub loading, used in this work, is attractive because it is realized entirely on the top conductor without vias, lumped components or ground-plane etching.

The branch line coupler (BLC) has four (4) ports and may ideally function without loss. Three-port networks typically resemble a T-junction, while four-port networks are generally directional couplers and hybrids, as illustrated in Figure 1,

which shows a conventional four-port network (Idris et al., 2026). Port 1 is the input port, port 2 is the through port, port 3 is the coupled port and port 4 is the isolated port, which ideally receives no power (Jutru & Vijay, 2020).

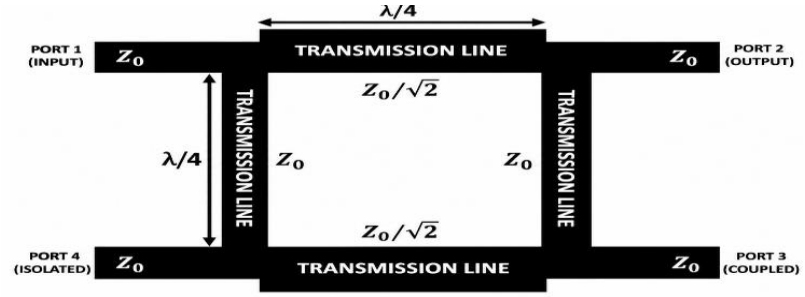


Figure 1: Configuration of the conventional 3-dB branch-line coupler

Contribution

The primary contributions of this research include:

i. The development of a 900 MHz branch line coupler tailored for GSM applications,
ii. The application of a stub-based method to achieve miniaturization in place of standard quarter-wave transmission lines,
iii. A 50.2% reduction in circuit area obtained by stub loading,
iv. A −10 dB bandwidth of 420 MHz achieved by parametric optimization of the stub dimensions, and
v. A quantitative evaluation of return loss, transmission, isolation and amplitude balance for the conventional, miniaturized and optimized couplers, which identifies the trade-off between bandwidth and amplitude balance.

Aim of the Study

The aim of this study is to design and optimize a compact stub-based branch-line coupler operating at 900 MHz for GSM applications while maintaining acceptable coupling, isolation, return loss, phase balance and bandwidth. To achieve this aim, a conventional BLC is first designed and simulated, its quarter-wavelength branches are then replaced by stub-loaded sections to reduce size, and the stub dimensions are finally optimized parametrically to recover bandwidth.

MATERIALS AND METHODS

This section presents a mathematical model based on step-by-step procedures for miniaturizing a coupler using a stub. It also briefly describes the simulation software and the design equations. Throughout this paper, "proposed BLC" refers to the conventional quarter-wavelength coupler, "improved BLC" to the stub-loaded miniaturized coupler, and "optimized BLC" to the improved coupler after parametric optimization of the stubs. The main advantage of using Rogers RT5880 (lossy) is that the dielectric constant and loss tangent are stable over a wide frequency range. The design specification for this work is given in Table 1.

Table 1: Coupler Design Specifications

Description	Specification
Design Frequency (GHz)	0.9
Substrate	Rogers RT5880 (lossy)
Dielectric Constant (ε_r)	2.2
Height (h) in mm	0.78
Thickness (t) in mm	0.035

The conventional 90° hybrid design is shown in Figure 2.

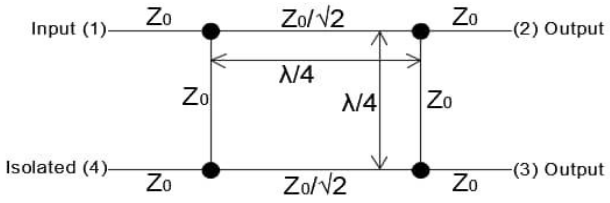


Figure 2: Conventional 90° hybrid

Design Analysis of the Proposed Branch Line Coupler

The branch line coupler has four ports, each at $Z_0 = 50\Omega$, and four quarter-wavelength branches, of which the two vertical (shunt) branches are at $Z_0 = 50\ \Omega$ impedance, while the horizontal two are at $\frac{Z_0}{\sqrt{2}}$ impedance, which is 35.35Ω. The dimensions of the proposed BLC were calculated using Equations (1)–(5).

Equations (1) to (5) are the microstrip transmission-line design equations (Idris & Fakandu, 2023).

$$Z_0 = \frac{87}{\sqrt{\varepsilon r + 1}} \ln\left[\frac{5.98h}{0.8Pw}\right] \quad (1)$$

Where;

Z_0 is the characteristic impedance of the line (Ω)

εr Is the relative permittivity (dielectric constant) of the substrate

h is the substrate height (mm)

Pw is the width of the microstrip line (port width) (mm).

$$AL = \frac{\lambda g}{4} \quad (2)$$

Where;

AL is the physical length of the quarter-wavelength line section (mm)
λg is the guided wavelength in the microstrip line (mm)

$$\lambda g = \frac{\lambda}{\sqrt{\varepsilon reff}} \quad (3)$$

Where;
λ is the free-space wavelength (mm)
$\varepsilon reff$ is the effective relative permittivity, given by Equation (5)

$$\lambda = \frac{V0}{fr} \quad (4)$$

Where;
V_0 is the speed of light in free space (3×10^8 m/s)
f_r is the design frequency (0.9 GHz)
Also,

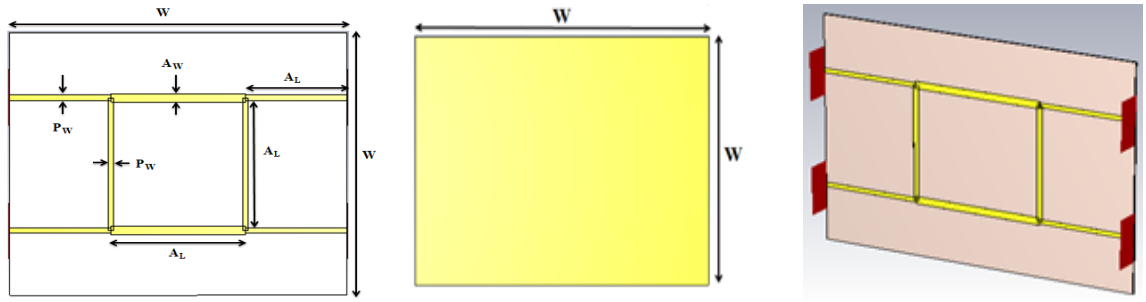
$$\varepsilon reff = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left[1 + \frac{12h}{Wp}\right]^{-\frac{1}{2}} \quad (5)$$

Where;
W_p is the width of the line being designed (Pw for the 50 Ω lines and Aw for the 35.35 Ω lines).

Table 2: Dimensions of the Proposed BLC at 900 MHz

Parameters Name	Numerical Values (mm)
Width of the substrate (W)	149
Thickness of the substrate (h)	0.78
Port Length (A_L)	59.84
Port Width (P_W)	2.08570
Shunt Width (A_W)	2.81845
Series Width (P_W)	2.08570

Figure 3 shows the design of the proposed branch line coupler (BLC). The coupler has four ports: port one is the input, port two is the output, port three is the coupled port, and port four is the isolated port. The coupler substrate is designed using Rogers RT5880 with a dielectric constant of 2.2, a loss tangent of 0.0009, and a thickness of 0.78 mm. The ports and the ground plane of this coupler are designed using annealed copper. Figure 3(a), (b), and (c) show the front, back, and perspective views of the proposed BLC, respectively.



(a) (b) (c)

Figure 3: Proposed BLC: (a) Front view, (b) Back view, (c) Perspective view

Improved (Stub-Loaded) Branch Line Coupler

The stub technique helps reduce the size of the simulated proposed coupler. With this method, we replace each part of the transmission line in the proposed BLC, which has an electrical length of 90°, with shorter transmission-line sections connected end to end, as shown in Figure 4.



Figure 4: λ/4 transmission line and its equivalent stepped impedance structure circuit

Figure 5 shows the schematic diagram of the improved branch line coupler after inserting the stubs for size reduction $Z_1\Theta$ and $Z_2\Theta$.

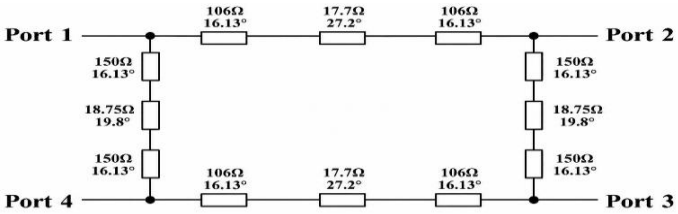


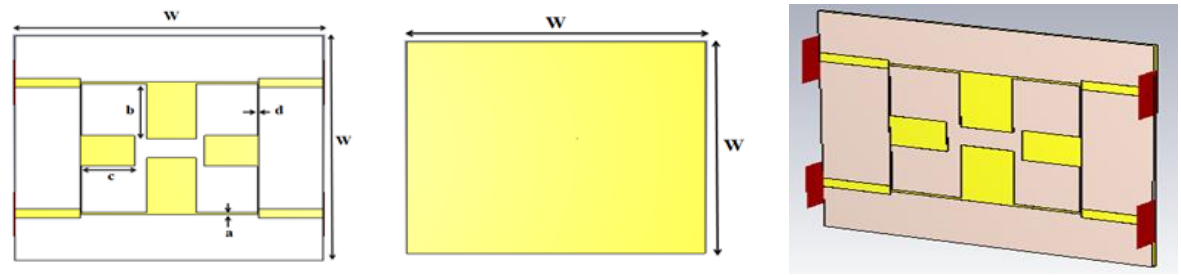
Figure 5: Quadrature coupler based on the stub circuit

From Figures 4 and 5, we calculated the impedance values as 106 ohms, 17.7 ohms, 18.75 ohms, and 150 ohms, while the transmission lines stayed at 50 ohms, using Equations (1)–(5). At Z0 = 150 ohms, the stub width was 0.2668 millimeters. Table 3 lists the parameters along with their calculated values from the equations.

Table 3: Dimensions of Stubs of the Improved BLC

Parameters	Numerical Values (mm)
Substrate width W	75
Stub width 1 (a)	1.5168
Stub width 2 (b)	4.0516
Stub width 3 (c)	3.9651
Stub width 4 (d)	0.2668

Figure 6 shows the improved branch-line coupler with stubs used to reduce the coupler size. The coupler is designed on a Rogers RT5880 substrate with a dielectric constant of 2.2, a loss tangent of 0.0009 and a thickness of 0.78 mm. All stubs, ports, and the ground plane are made of annealed copper. The coupler is totally grounded. The stubs reduce the coupler size while maintaining the same resonant frequency.



(a) (b) (c)

Figure 6: Design of an Improved Branch Line Coupler (BLC) with Stubs: (a) Front view, (b) Back view, (c) Perspective view

Simulation Setup and Optimization Procedure

All full-wave simulations were performed in CST Studio Suite (version 2022) using the time-domain (transient) solver, which was also used for the parameter sweep shown in Figure 12. The substrate and ground plane were modelled with their finite dimensions and a copper conductor thickness of 0.035 mm, and open (add space) boundary conditions were applied on all faces of the computational domain to include radiation and surface-wave effects.

Four 50 Ω waveguide ports were assigned to the feed lines: port 1 as the input, port 2 as the through port, port 3 as the coupled port, and port 4 as the isolated port. All S-parameters were normalized to 50 Ω and are plotted in dB. We used a hexahedral mesh, and ran each simulation until the energy remaining in the computational domain decayed below the solver accuracy of −40 dB, which we used as the convergence criterion.

Optimization was carried out in three stages. First, the proposed BLC was designed from Equations (1)–(5) and simulated. Second, we replaced each quarter-wavelength branch with the stub-loaded section in Figures 4 and 5, using the dimensions in Table 3, to obtain the improved BLC. Third, we performed a parametric study with the CST Parameter Sweep tool, varying the stub dimensions b and c in linear steps while keeping all other dimensions fixed. The combination that gave the widest −10 dB bandwidth of S_{11} and S_{41} around 900 MHz (b = 16 mm and c = 9 mm) was selected as the optimized BLC.

RESULTS AND DISCUSSION

This section presents the simulated results of the proposed, improved and optimized couplers obtained with the set-up described in Section 2.3. For each design, the return loss (S_{11}), transmission to the through and coupled ports (S_{21}, S_{31}), isolation (S_{41}) and −10 dB bandwidth is reported, and the results are summarized quantitatively in Tables 4 and 5. All results are from simulation and have not yet been validated experimentally.

Proposed Branch Line Coupler (BLC)

Figure 3 shows the structure of the proposed branch line coupler (BLC). The coupler was designed on a Rogers RT5880 substrate, and the ground plane and transmission lines are made of annealed copper.

Figure 7 shows the simulated S-parameters of the proposed BLC. Because the four-port coupler is symmetrical and reciprocal, the sixteen S-parameters (S_{11}–S_{44}) collapse onto a small number of curves. The reflection coefficients (S_{11}, S_{22}, S_{33}, S_{44}) and isolation (S_{41}, S_{14}, S_{23}, S_{32}) reach a minimum of about −32 dB at 0.92 GHz and are about −24 dB to −26 dB at 900 MHz. The through and coupled transmission coefficients (S_{21} and S_{31}) are both about −3.1 dB at 900 MHz, within 0.1 dB of the ideal −3 dB equal-power split.

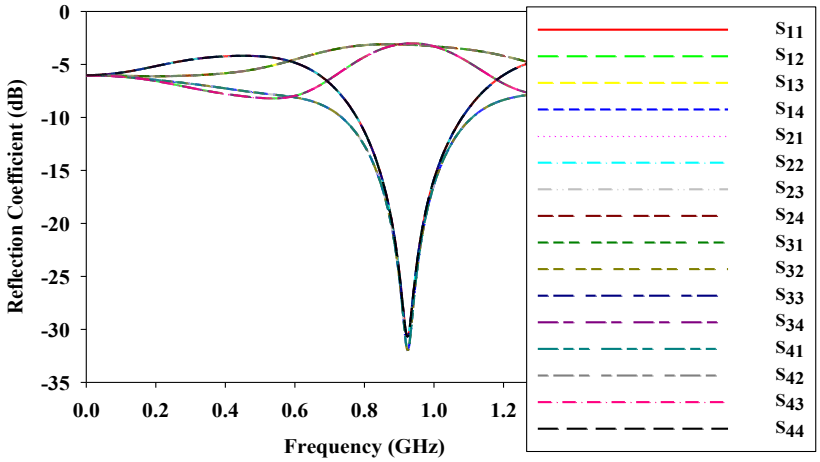


Figure 7: S-Parameter of the Proposed Branch Line Coupler (BLC)

Figure 8 shows the −10 dB bandwidth of the proposed BLC. The reflection and isolation coefficients remain below −10 dB from about 0.735 GHz to 1.114 GHz, giving a bandwidth of 379 MHz (42.1% fractional bandwidth relative to 900 MHz). The bandwidth is obtained by subtracting the lower −10 dB frequency from the upper −10 dB frequency.

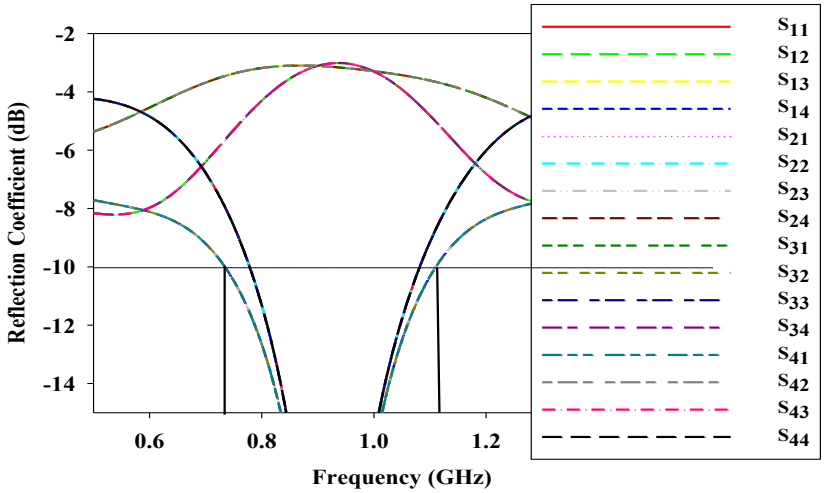


Figure 8: Bandwidth of the Proposed Branch Line Coupler (BLC)

Improved (Miniaturized) Branch Line Coupler (BLC)

Figure 9 illustrates the geometry of the improved branch line coupler (BLC). The improved coupler is more compact than the proposed (conventional) coupler, reducing its circuit area by 50.2%. The coupler is designed on a Rogers RT5880 substrate, while the ports and stubs are made of annealed copper. The stubs reduce the coupler's overall size while keeping its operating frequency close to 900 MHz. The percentage size reduction is obtained from Equation (6).

$$\%\ Size\ Reduction = \frac{Area\ of\ conventional\ coupler - Area\ of\ improved\ coupler}{Area\ of\ conventional\ coupler} \times 100\% \quad (6)$$

Length of the conventional coupler = 149.861mm
Width of the conventional coupler = 60.789mm

Therefore, the area of a conventional coupler is;
Area = length x width = 149.861 x 60.789 = 9109.900 mm^2
While,
Length of the improved coupler = 84.871mm
Width of the improved coupler = 53.453mm
Therefore, the area of the improved coupler is;
Area = length x width = 84.871 x 53.453 = 4536.610 mm^2

$$\%\ Size\ Reduction = \frac{Area\ of\ conventional\ coupler - Area\ of\ improved\ coupler}{Area\ of\ conventional\ coupler} \times 100\%$$

$$\%\ Size\ Reductio = \frac{9092.112 - 4536.609}{9092.112} \times 100\%$$

$$\%\ Size\ Reduction = \frac{4555.503}{9092.112} \times 100\%$$

$$\%\ Size\ Reduction = 0.5020 \times 100\% = 50.2\%$$

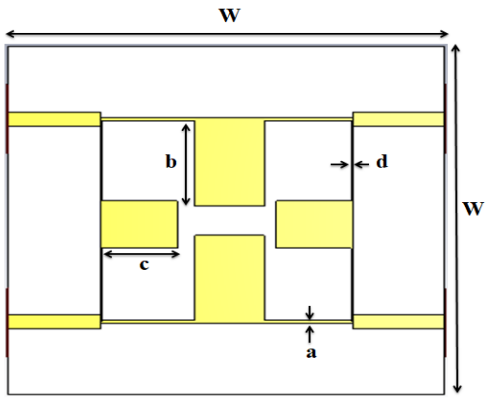


Figure 9: Geometry of an Improved Branch Line Coupler (BLC)

Figure 10 presents the simulated S-parameters of the improved BLC. Although the stubs halve the circuit area, the coupler still operates around 900 MHz: S_{11} and S_{41} reach a minimum of about −48.6 dB at 0.92 GHz and are about −24 dB to −27 dB at 900 MHz, while the two output ports receive about −2.9 dB and −3.4 dB, corresponding to an amplitude imbalance of about 0.5 dB. The improved coupler can therefore be used for the same applications as the proposed coupler.

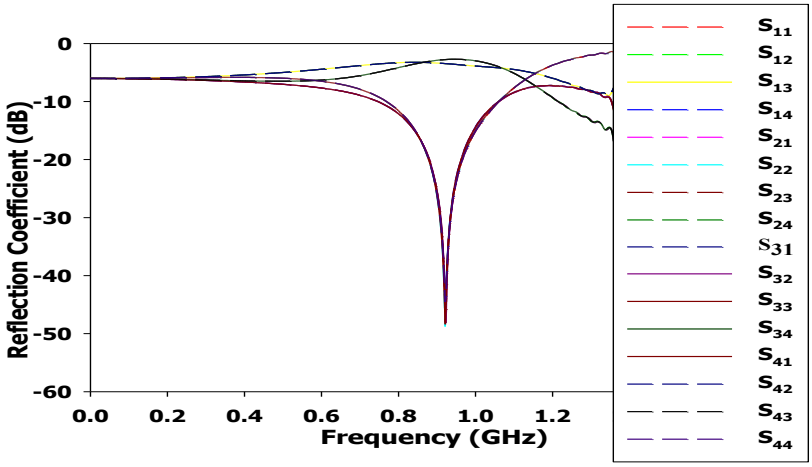


Figure 10: S-parameter result of an Improved Branch Line Coupler (BLC)

The bandwidth of the improved BLC is shown in Figure 11. The −10 dB band extends from about 0.761 GHz to 1.068 GHz, giving 307 MHz (34.1% fractional bandwidth), which is 72 MHz narrower than that of the proposed coupler. This reduction is a consequence of miniaturization, as explained in Section 3.3.

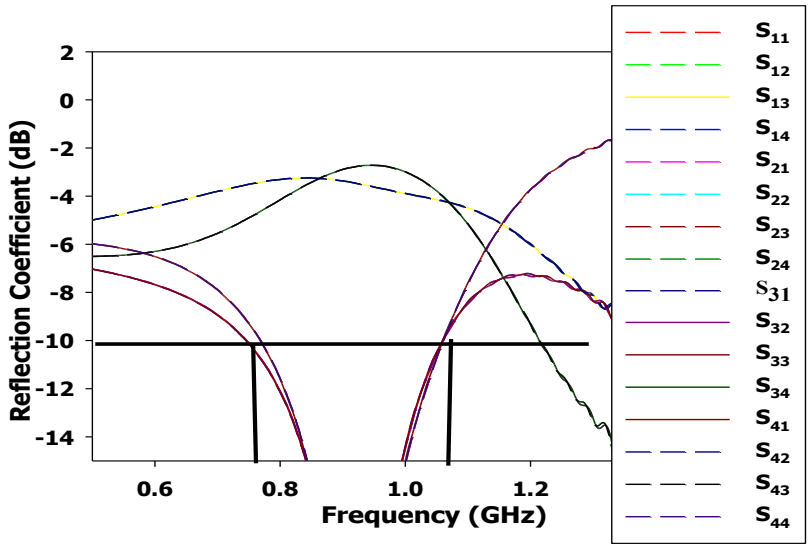


Figure 11: Bandwidth of an Improved Branch Line Coupler (BLC)

Bandwidth Enhancement by Parametric Optimization (Optimized BLC)

The reduction in bandwidth from 379 MHz in the conventional branch-line coupler to 307 MHz after miniaturization is an expected consequence of replacing the uniform quarter-wavelength transmission lines with compact stepped-impedance sections loaded with stubs. Although the stubs provide the required 90° electrical length within a shorter physical dimension, their frequency-dependent reactance varies more rapidly than that of a conventional transmission line, causing the equivalent quarter-wavelength behavior to occur over a narrower frequency range. Therefore, the improved stub-loaded coupler achieves a significant 50.2% reduction in circuit area while maintaining acceptable matching, isolation, and power division characteristics, but with a reduced impedance bandwidth. To compensate for this bandwidth reduction, a parametric study was performed by varying the stub dimensions b and c, as presented in Figure 12. The optimized dimensions redistributed the reactive loading of the stubs, extending the −10 dB bandwidth from 307 MHz to 420 MHz. However, this bandwidth enhancement introduced a trade-off by increasing the amplitude imbalance between the output ports from approximately 0.5 dB in the miniaturized design to approximately 3.1 dB in the optimized design. Therefore, the optimization improves matching and isolation bandwidth at the expense of ideal equal power division, demonstrating the inherent compromise between bandwidth enhancement and quadrature coupler balance. The simulated results indicate that the proposed stub-loading approach provides effective miniaturization, while experimental fabrication and measurement remain necessary to validate the practical performance of the coupler.

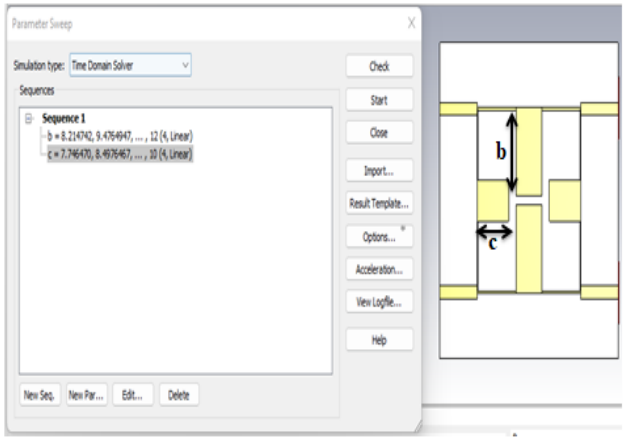


Figure 12: Parameter sweep set-up and stub dimensions b and c used in the parametric study

The S-parameters obtained from the parametric study are shown in Figure 13. Among the simulated combinations, b = 16 mm and c = 9 mm gave the widest −10 dB bandwidth. With these dimensions, the reflection and isolation minima become shallower and shift slightly downwards in frequency (about −22.8 dB at 0.886 GHz), and at 900 MHz S_{11} and S_{41} lie between about −18 dB and −23 dB.

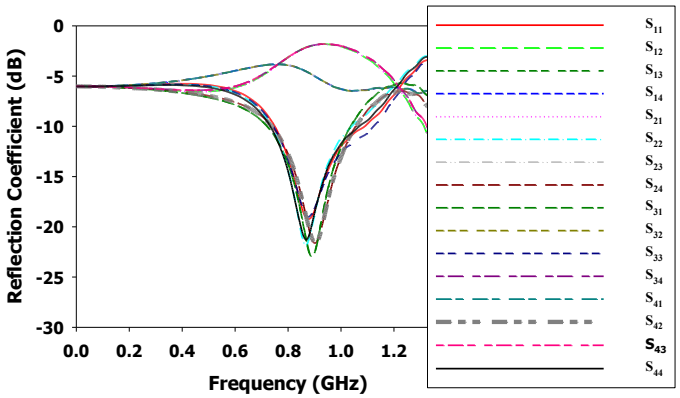


Figure 13: S-parameters of the optimized BLC (b = 16 mm, c = 9 mm)

The bandwidth of the optimized BLC is shown in Figure 14. The −10 dB band extends from about 0.715 GHz to 1.135 GHz, giving 420 MHz (46.7% fractional bandwidth), which is wider than that of both the proposed (379 MHz) and improved (307 MHz) couplers. This improvement involves a trade-off. At 900 MHz the two output ports receive about −1.9 dB and −5.0 dB, so the amplitude imbalance increases to about 3.1 dB, compared with about 0.5 dB for the improved coupler. Adjusting b and c spreads the reflection and isolation zeros over a wider band, which widens the matching bandwidth but disturbs the equal power split. The 420 MHz value therefore describes the matching and isolation bandwidth; the band over which the outputs remain close to an equal split is narrower. The optimized dimensions are best suited to applications where wide matching matters more than precise power balance, whereas the improved (unoptimized) dimensions are preferable when equal power division is required.

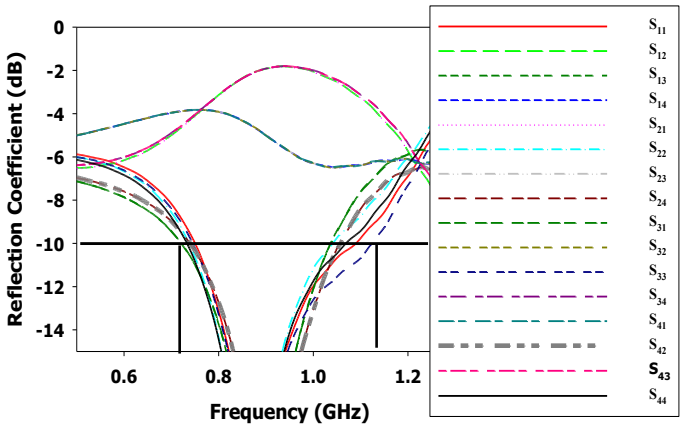


Figure 14: Bandwidth of the optimized BLC (b = 16 mm, c = 9 mm)

Table 4 shows the summary of the results obtained in the design of the proposed branch line coupler (BLC), the improved branch line coupler (BLC) and the optimized improved branch line coupler.

Table 4: Results Summary of the Branch Line Coupler (BLC)

S/N	Description	Bandwidth (MHz)	Circuit size (mm × mm)	Percentage reduction (%)
1	Proposed branch line coupler (BLC)	379	149.86 × 60.79	-
2	Improved branch line coupler (BLC)	307	84.87 × 53.45	50.2
3	Optimized improved branch line coupler (BLC)	420	84.87 × 53.45	50.2

Table 5 summarizes the principal simulated S-parameters of the three couplers, read from Figures 7, 8, 10, 11, 13 and 14. Miniaturization halves the circuit area while keeping return loss, isolation and power split close to those of the proposed coupler, whereas the parametric optimization trades amplitude balance for bandwidth.

Table 5: Simulated S-Parameter Performance of the Proposed, Improved and Optimized Blcs

Parameter	Proposed BLC	Improved BLC	Optimized BLC
Frequency of S_{11}/S_{41} minimum (GHz)	0.92	0.92	0.886
S_{11}, S_{41} at minimum (dB)	≈ −32	≈ −48.6	≈ −22.8
S_{11}, S_{41} at 900 MHz (dB)	−24 to −26	−24 to −27	−18 to −23
S_{21}, S_{31} at 900 MHz (dB)	−3.1, −3.1	−2.9, −3.4	−1.9, −5.0
Amplitude imbalance at 900 MHz (dB)	≈ 0.0	≈ 0.5	≈ 3.1
−10 dB band (GHz)	0.735–1.114	0.761–1.068	0.715–1.135
Bandwidth (MHz) / FBW (%)	379 / 42.1	307 / 34.1	420 / 46.7
Area reduction (%)	–	50.2	50.2

Values are read from the simulated curves and are approximate (about ±0.2 dB). FBW is the fractional bandwidth relative to 900 MHz. The two transmission values correspond to the through and coupled ports.

Table 6 compares the present work with previously reported compact BLCs. The reported designs achieve larger size reductions by using resonators, lumped LCL filters or combinations of several resonator types, and they have been validated by fabrication and measurement. The present design gives a moderate size reduction of 50.2% but uses only planar stubs on the top conductor, with no vias, lumped components or ground-plane etching, and it has the widest −10 dB bandwidth (420 MHz) among the compared designs. Unlike the compared works, the present results are from simulation only.

Table 6: Comparison of the Present Work with Previously Reported Compact Branch-Line Couplers

Reference	Technique	Size reduction (%)	BW (MHz)
Jutru, M. S., & Vijay. (2020)	Two types of compact resonators	38	260
Roshani, Yahya, Roshani, Farahmand, et al. (2022)	T-shaped and cross-shaped resonators, open and radial stubs	50	200
Chaudhary et al. (2023)	LCL filters and meandered stubs	48.5	300
This work	Stub-loaded branches with parametric optimization	50.2	420

The improved BLC is 50.2% smaller in area than the proposed BLC and operates at the same frequency, with S_{11} and S_{41} below about −24 dB and an amplitude imbalance of about 0.5 dB at 900 MHz. Miniaturization reduced the −10 dB bandwidth from 379 MHz to 307 MHz. A parametric study of the stub dimensions increased the bandwidth to 420 MHz, wider than both earlier designs, at the cost of an amplitude imbalance of about 3.1 dB at 900 MHz. All results are simulated and require experimental validation.

CONCLUSION

This study designed and optimized a miniaturized stub-based branch-line coupler for the 900 MHz GSM band on a 0.78 mm Rogers RT5880 substrate using CST Studio Suite. Replacing the conventional coupler's quarter-wavelength branches with stub-loaded sections reduced the circuit area by 50.2%. The miniaturized coupler retained good performance, with S_{11} and S_{41} of about −48.6 dB at 0.92 GHz, S_{21} and S_{31} of about −2.9 dB and −3.4 dB at 900 MHz and a −10 dB bandwidth of 307 MHz, compared with 379 MHz for the conventional coupler. Parametric optimization of the stub dimensions (b = 16 mm, c = 9 mm) increased the bandwidth to 420 MHz (0.715–1.135 GHz, 46.7% fractional bandwidth) with S_{11} and S_{41} better than −18 dB at 900 MHz, at the cost of an output amplitude imbalance of about 3.1 dB. The principal limitation of this work is that all results are from full-wave simulation; no prototype has been fabricated or measured. Future work should fabricate the optimized coupler and measure its S-parameters and output phase difference with a vector network analyser to validate the simulated results, and should refine the stub dimensions to restore amplitude balance while keeping the wider bandwidth.

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