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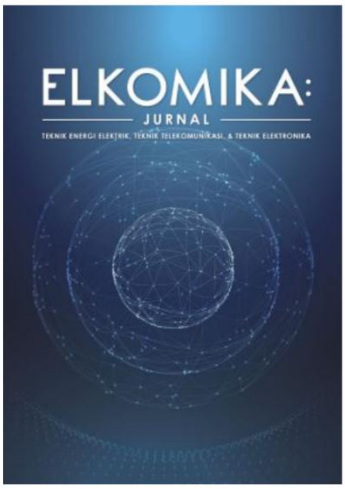

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Antena Mikrostrip MIMO dengan Teknik *Planar Series Array* 4x2 elemen untuk Sistem Komunikasi 5G

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ABSTRAK

Makalah ini mengusulkan antena mikrostrip dengan dengan performansi tinggi yang beroperasi pada frekuensi resonansi 3,5 GHz untuk sistem komunikasi 5G. Antena dikembangkan dalam dengan teknik array planar seri 4x2 elemen yang dikonfigurasi MIMO. Berdasarkan hasil pengukuran, antena yang dirancang memiliki koefisien refleksi ≤ -10 dB, koefisien isolasi ≤ -40 dB dengan rentang frekuensi 3.1 GHz – 3,7 GHz dan gain maksimum sebesar 12,52 dB pada frekuensi resonansi 3,5 GHz. Bandwidth dan penguatan antena masing-masing meningkat sebesar 172.72% dan 160.83 %. Penelitian ini dapat direkomendasikan untuk digunakan sebagai antena penerima sistem komunikasi 5G.

***Kata kunci**: antena, array, mikrostrip, MIMO, planar, 5G*

ABSTRACT

This article suggests a microstrip antenna with high performance, designed to operate at the resonant frequency of 3.5 GHz in 5G communication systems. The antenna is developed in a MIMO-configured 4x2 element series planar array technique. Based on measurement results, the proposed antenna exhibits a reflection coefficient of ≤ -10 dB, an isolation coefficient of ≤ -40 dB, within the frequency range 3.1 – 3.7 GHz and maximum gain of 12.52 dB at the resonant frequency of 3.5 GHz. The antenna's bandwidth and gain enhanced until 172.72% and 160.83%, respectively. This study suggests the potential use of the developed antenna as a reception device in 5G communication systems.

***Keywords**: antenna, array, microstrip, MIMO, planar, 5G*

1. PENDAHULUAN

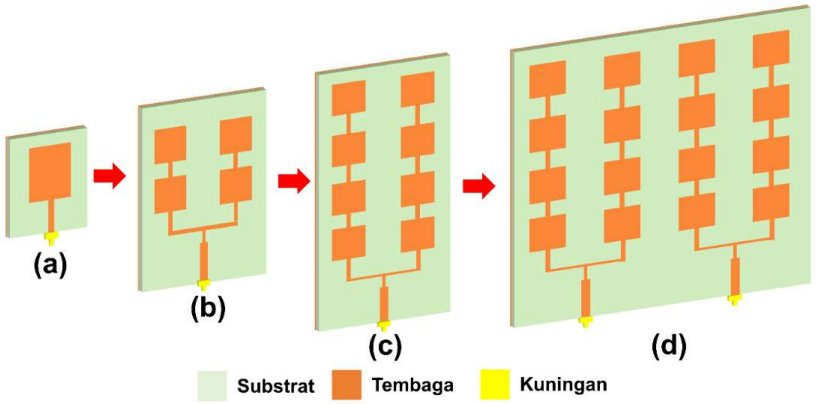
Pada tahun 2018, diperkenalkan *5G communication system* yang menawarkan keunggulan, termasuk *high transfer data rate* dan pita frekuensi yang lebar **(Hobbs, 2018)**. Dalam aturan yang telah ditetapkan oleh **(Admaja, 2018)** pada tahun 2018, frekuensi kerja yang digunakan dalam sistem komunikasi generasi kelima (5G) dibagi menjadi beberapa pita salah satunya adalah 3,5 GHz. Kondisi wilayah di Indonesia yang padat dan memiliki kontur tanah yang beragam membutuhkan frekuensi kerja yang rendah sehingga jangkauan dari sinyal yang dipancarkan menjadi lebih jauh. Untuk itu frekuensi 3.5 GHz dapat menjadi opsi untuk frekuensi kerja dari 5G khususnya di wilayah yang padat khususnya perkotaan di wilayah Indonesia **(Hikmaturokhman, dkk, 2018)**. Selain itu, komunikasi 5G juga membutuhkan sistem multi masukan dan multi keluaran untuk dapat melayani pengguna dalam jumlah yang banyak **(Cai, dkk., 2019)**. Keuntungan dari penggunaan MIMO adalah komunikasi antar pengirim dan penerima dapat berjalan lebih stabil dan optimal khususnya untuk system komunikasi 5G yang bersifat masif dengan menggunakan beberapa antena yang berfungsi untuk mengirim dan menerima sinyal **(Murugan, 2021)**. Antena memegang peranan penting dalam sistem komunikasi nirkabel yang berfungsi sebagai pemancar dan penerima sinyal **(Alam et al., 2022)**. Hal ini menjadi kebutuhan mendasar khususnya untuk sistem komunikasi bergerak yang membutuhkan kehandalan yang tinggi. Kajian dan penemuan terkait antena MIMO telah dipaparkan sebelumnya **(An, dkk, 2018) (SANDI, dkk, 2020) Zhang, dkk, 2018)**. Penelitian yang diusulkan oleh **(Biswas & Gupta, 2020)** telah berhasil merancang antena microstrip MIMO bentuk L pada frekuensi 3,5 GHz dengan nilai koefisien refleksi ≤ -10 dB, koefisien isolasi -18 dB dan gain 2 dBi , selanjutnya pada penelitian yang diusulkan oleh **(Abdullah, dkk, 2017)** antena mikrostrip MIMO 4 port dikembangkan pada frekuensi 3.5 GHz dengan nilai koefisien refleksi ≤ -10 dB dan gain sebesar 5,1 dBi. Namun, *gain* dan keterarahan yang rendah menjadi limitasi dan celah penelitian yang perlu dikaji lebih lanjut. Beberapa metode optimasi untuk meningkatkan keterarahan telah dipaparkan pada penelitian sebelumnya antara lain *array* **(Alam, dkk, 2021) (Cai, dkk, 2019)**, dan parasitik **(Pratiwi, dkk, 2020)**. Temuan lain yang diusulkan oleh **(Parchin, dkk, 2019)** metode plannar *array* MIMO digunakan untuk meningkatkan keterarahan dan menghasilkan penigkatan gain sebesar 8 dBi sedangkan pekerjaan yang dilakukan oleh **(Hussain, dkk, 2017)** menghasilkan *gain* 12,07 dB dengan menggunakan metode 6 sektor *array*. Selain itu, antena array dengan tiga notched telah dikembangkan oleh **(Alam, dkk, 2022),** namun antena yang diusulkan belum mendukung untuk komunikasi MIMO dan memiliki penguatan yang rendah. Penelitian ini mengusulkan pengembangan antena *array* 4x2 elemen dengan konfigurasi MIMO 2 port untuk meningkatkan penguatatan dari antena. Penggunaan metode *array* bertujuan meningkatkan *gain* dari antenna sehingga sudut berkas pancar menjadi lebih sempit dan jarak penerimaan menjadi lebih baik. Kebaruan dan *state of the art* dari pekerjaan ini adalah mengusulkan disain antena mikrostrip dengan mengkombinasikan metode *array* dan MIMO sehingga antena yang dirancang menghasilkan *bandwidth* yang lebar, *gain* yang tinggi dan pola pancar yang memiliki keragaman *(beamforming)* sehingga dapat direkomendasikan untuk system komunikasi 5G.

2. PERANCANGAN ANTENA

2.1 Pengembangan Model Antena

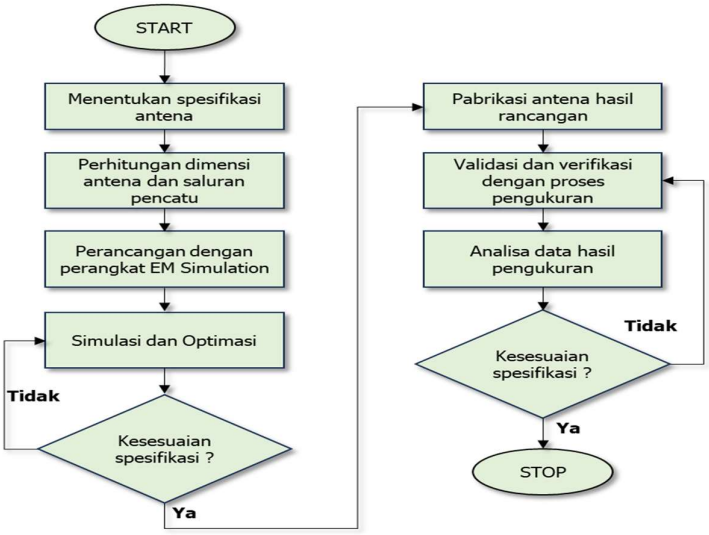
Dalam makalah ini, antena microstrip dirancang dan dikembangkan melalui beberapa tahapan antara lain antena elemen tunggal *(single element)*, antena *array planar* 2x2 elemen, antena *array planar* 4x2 elemen dan antena MIMO *array planar array* 4x2 elemen. Substrat yang digunakan adalah FR-4 epoxy dengan konstanta dielektrik (ε_r) 4,3, *loss tan* (tan δ) 0,0225 dan

ketebalan (h) 1,6 mm. Antena dirancang untuk beroperasi pada frekuensi resonansi (f_r) 3,5 GHz untuk diaplikasikan sebagai antena penerima pada sistem komunikasi 5G. Gambar 1 menampilkan pengembangan model antena pada makalah ini.



Gambar 1. Pengembangan Model Antena; (a) Elemen Tunggal, (b) *Array Planar* 2x2 Elemen, (a) *Array Planar* Seri 4x2 Elemen, (d) MIMO *Array Planar Seri* 4x2 Elemen

Tahapan awal dari pengembangan model antena adalah dengan merancang antena bentuk persegi panjang yang beroperasi pada f_r=3,5 GHz seperti yang ditunjukkan pada Gambar 1 (a). Selanjutnya, untuk meningkatkan *bandwidth* dan *gain*, antena dikembangkan menggunakan teknik *array planar* seri 2x2 elemen dan *array planar* seri 4x2 elemen yang masing-masing ditunjukkan pada Gambar 1 (b) dan Gambar 1 (c) dimana masing-masing elemen tersusun secara seri dan terkoneksi dengan saluran microstrip. Tahap akhir adalah merancang antena MIMO dengan 2 *port* yang masing-masing terdiri dari antena *array planar* seri 4x2 elemen dan dipisahkan oleh jarak tertentu seperti yang ditunjukkan pada Gambar 1 (d). Elemen peradiasi dari antena terbuat dari tembaga yang berada pada bagian atas dari substrat sedangkan bagian bawahnya berfungsi sebagai *groundplane*. Antena terkoneksi secara langsung dengan konektor yang terbuat dari kuningan dengan impedansi 50 Ω menggunakan saluran mikrostrip. Selanjutnya diagram alir dari pekerjaan makalah ini ditunjukkan pada Gambar 2.



Gambar 2. Diagram Alir Perancangan Antena

Gambar 2 menunjukkan bahwa tahapan awal dalam perancangan antena adalah menentukan spesifikasi parameter antena. Spesifikasi antena yang diusulkan dalam makalah ini ditunjukkan pada Tabel 1.

Tabel 1. Spesifikasi Antena Rancangan

Parameter	Nilai
Frekuensi resonansi (f_r)	3,5 GHz
Bandwidth	200 MHz
Koefisien refleksi (S_{11})	≤ -9,54 dB
Koefisien isolasi (S_{11})	≤ -20 dB
Gain	≤ 10 dB

Selanjutnya, dimensi dari antena dan saluran pencatu ditentukan menggunakan rumus dasar dalam perancangan antena mikrostrip yang ditunjukkan pada Persamaan (1) sampai dengan Persamaan (5)**(Fang, 2017)**. Dalam makalah ini bentuk elemen peradiasi yang digunakan adalah persegi panjang.

$$W = \frac{c}{2f_o\sqrt{\frac{\varepsilon_r}{2}}} \tag{1}$$

$$L = L_{eff} - \Delta_L \tag{2}$$

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}} \tag{3}$$

$$\varepsilon_{eff} = \frac{\varepsilon r+}{2} + \frac{\varepsilon r-1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{4}$$

$$\Delta_L = 0.412\frac{(\varepsilon_{reff} + 0{,}3)\,(\frac{W}{h} + 0{,}264)}{(\varepsilon_{reff} - 0{,}258)\,(\frac{W}{h} + 0{,}8)} \tag{5}$$

dimana *W* dan *L* mewakili panjang dan lebar patch, fo mewakili frekuensi resonansi, εr mewakili permitivitas substrat, ε_{eff} mewakili permitivitas efektif substrat pada frekuensi resonansi tertentu, *h* mewakili ketebalan substrat sedangkan Δ_L mewakili efek tepi bidang permukaan dari antena. Selanjutnya, saluran mikrostrip diusulkan untuk mengontrol impedansi dan koefisien refleksi antena. Dimensi saluran mikrostrip sangat dipengaruhi oleh impedansi masukan dan frekuensi resonansi yang digunakan. Pada makalah ini, impedansi masukan yang digunakan adalah 50 Ω. Dimensi garis mikrostrip dapat ditentukan dengan menggunakan Persamaan (6) dan Persamaan (7) berikut ini **(Fang, 2017)**:

$$W_z = \frac{2h}{\pi}\left\{B - 1 - \ln(2B-1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left[\ln(B-1) + 0{,}39 - \frac{0{,}61}{\varepsilon_r}\right]\right\} \tag{6}$$

$$B = \frac{60\pi^2}{Z_0\sqrt{\varepsilon_{eff}}} \tag{7}$$

dimana W_z adalah lebar garis mikrostrip, Z_o adalah impedansi antena dan *B* adalah konstanta impedansi. Impedansi antena sebesar 50 Ω sesuai dengan impedansi konektor yang digunakan. Selanjutnya panjang saluran mikrostrip (L_z) adalah ¼ lambda (λ_g) yang ditentukan dengan Persaman (8) dan Persamaan (9) berikut **(Fang, 2017)**:

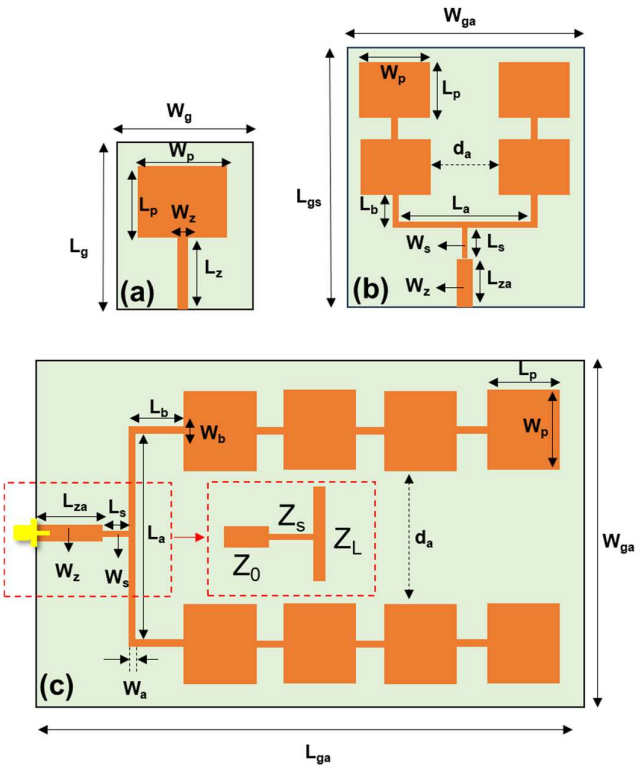
$$L_z = {}^1/_4 \lambda_g \quad (8)$$

$$\lambda_g = \frac{\lambda}{\varepsilon_{eff}} \quad (9)$$

Selanjutnya, struktur dan dimensi yang didapatkan dari hasil perhitungan dirancang dan disimulasikan menggunakan perangkat lunak *EM Simulation* berbasis HFSS 15.0. Parameter yang disimulasikan antara lain koefisien refleksi (S_{11}), koefisien isolasi (S_{21}), pola radiasi dan *gain* dari antena yang diusulkan. Validasi dan verifikasi performansi medan dekat dari antena dilakukan dengan proses pengukuran di dalam ruangan laboratorium terhadap antena yang telah di fabrikasi menggunakan alat ukur *Vector Network Analyzer* dan diukur dalam temperature ruangan normal 25°C dengan rentang frekuensi 2 – 4,5 GHz dan *sweep frequency* 0,01 GHz sedangkan untuk medan jauh dilakukan di ruangan anechoic chamber dengan menggunakan rotator antena yang berputar dengan rentangan sudut 0 - 360°.

2.2 Perancangan Antena

Ukuran dan struktur dari elemen peradiasi persegi panjang didapatkan menggunakan Persamaan (1) sampai dengan Persamaan (5) sedangkan Persamaan (6) sampai dengan persamaan (9) digunakan untuk menentukan dimensi saluran mikrostrip dengan impedansi 50 Ω didapatkan menggunakan. Dari hasil perhitungan didapatkan struktur dan dimensi dari antena elemen tunggal seperti yang ditunjukkan pada Gambar 3 (a) dimana W_p = 25 mm, L_p = 20 mm sedangkan untuk dimensi saluran mikrostrip dari antena elemen tunggal adalah W_z = 3 mm dan L_z = 12,7 mm. Selanjutnya dimensi groundplane dari antena elemen tunggal adalah W_g = 40 mm dan L_g = 40 mm.



Gambar 3. Struktur Antena Rancangan; (a) Elemen Tunggal, (b) *Array Planar* Seri 2x2 Elemen, (c) *Array Planar* Seri 4x2 Elemen

Selanjutnya antena dikembangkan menggunakan teknik *array planar* seri 2x2 elemen dimana masing-masing antena tersusun secara seri dan dipisahkan dengan jarak yang direpresentasikan oleh d_a seperti yang ditunjukkan Gambar 3 (b). Jarak antar elemen peradiasi untuk konfigurasi *array* dipengaruhi oleh panjang gelombang (λ) dari antena dan didapatkan menggunakan Persaman (10) dan Persamaan (11) sebagai berikut **(Fang, 2017)**:

$$d_a = {}^1/_4 \lambda \tag{10}$$

$$\lambda = \frac{c}{f} \tag{11}$$

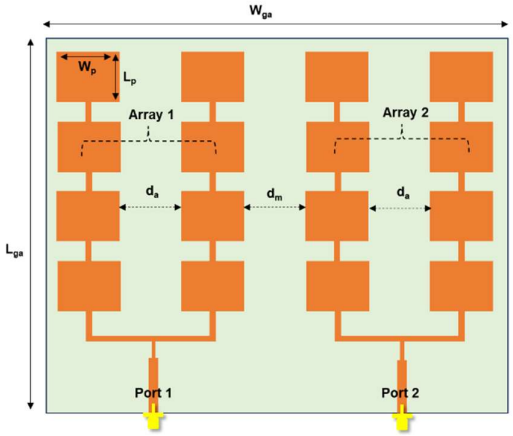
dimana d_a mewakili jarak antar elemen *array*, λ mewakili panjang listrik antena dan c adalah kecepatan cahaya (3 x 10^8 m/s). Perancangan dan model antena planar *array* seri dengan elemen 4x2 ditunjukkan pada Gambar 3 (c) dimana W_{ga} dan L_{gs} adalah 130 mm dan 130 mm, masing-masing. Gambar 3 (c) menunjukkan konfigurasi antena *array* seri dengan empat elemen yang masing-masing dihubungkan secara planar menggunakan saluran transmisi dengan impedansi langkah 50 Ohm (Z_0), 70,7 Ohm (Z_s) dan 100 ohm (Z_L) yang berfungsi sebagai pencocokan impedansi untuk mengontrol pantulan koefisien dan VSWR antena. Lebar saluran transmisi menentukan impedansinya sedangkan impedansi saluran transmisi dapat ditentukan berdasarkan Persamaan (12) berikut **(Fang, 2017)**:

$$Z_s = \sqrt{Z_0 . Z_L} \tag{12}$$

Selanjutnya, dimensi keseluruhan antena planar *array* seri dengan elemen 4x2 disajikan pada Tabel 2.

Tabel 2. Dimensi dan Parameter Antena

Parameter	Dimensi (mm)	Parameter	Dimensi (mm)
W_{ga}	130	W_s	1
L_{ga}	187	L_s	3
W_z	3	W_a	2
L_{za}	40	L_a	94
W_p	25	W_b	3
L_p	20	L_b	12,7
d_a	22	d_m	11

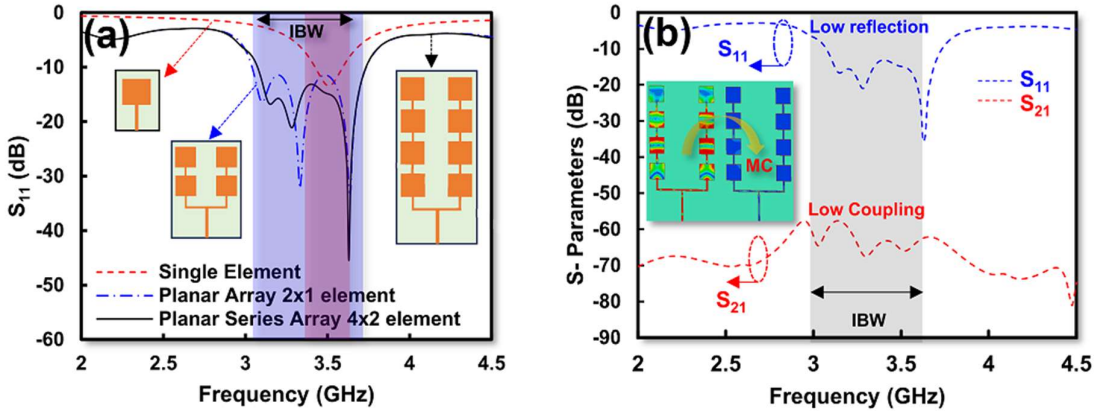


Gambar 4. Struktur Antena Planar Series *Array* 4x2 Elemen dengan Konfigurasi MIMO

Gambar 4 menunjukkan antena *array planar* seri 4x2 elemen yang sudah dikonfigurasi secara MIMO dimana masing-masing antena terkoneksi dengan *port* 1 dan *port* 2 dan dipisahkan dengan jarak d_m yang ditentukan dengan menggunakan Persamaan (13) dibawah ini **(Fang, 2017)**:

$$d_m = {}^{1}/_{8}\,\lambda \tag{13}$$

Sebagai catatan, jarak antar elemen peradiasi pada konfigurasi MIMO akan menentukan koefisien isolasi dan kopling elektromagnet dari antena. Semakin jauh jarak antara elemen maka kopling elektromagnet menjadi rendah sehingga koefisien isolasi menjadi semakin tinggi dan sebaliknya. Kopling elekromagnet rendah dan koefisien isolasi yang tinggi menunjukkan bahwa kedua antena pada konfigurasi MIMO beroperasi secara independent dan tidak saling mempengaruhi satu sama lain. Dalam makalah ini, jarak antara elemen peradiasi pada konfigurasi MIMO yang digunakan adalah d_m = 22 mm dengan dimensi W_g = 290 mm dan L_g = 190 mm. Selanjutnya, untuk mengobservasi performansi dari antena yang diusulkan, simulasi dan optimasi dengan HFSS 15.0 diusulkan untuk mengamati parameter S_{11}, *bandwidth* dan S_{21} pada konfigurasi MIMO.

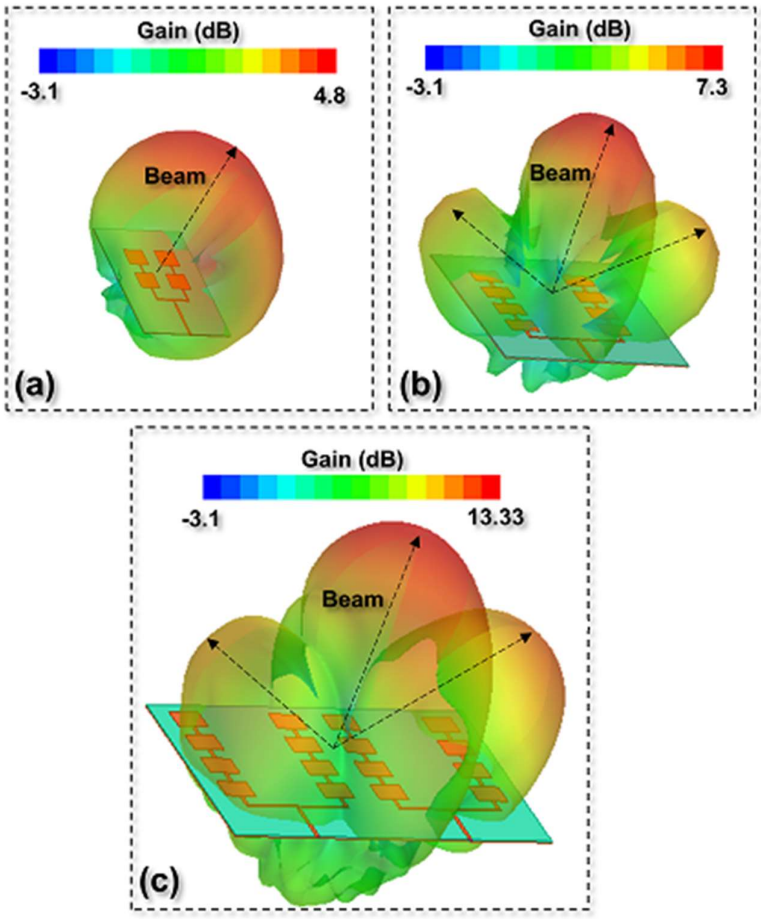


Gambar 5. Hasil Simulasi dari Antena Rancangan; (a) Simulasi S_{11} dari Pengembangan Model Antena, (b) Simulasi S_{11} dan S_{21} dari Antena Rancangan dengan Konfigurasi MIMO

Gambar 5 (a) memaparkan hasil simulasi dari antena elemen tunggal, planar *array* seri 2x2 elemen dan *array* planar seri 4x2 elemen telah beroperasi di f_r = 3.5 GHz serta memiliki koefisien refleksi ≤ -10 dB dengan bandwidth masing-masing 0,14 GHz (3,44 – 3,58 GHz), 0,67 GHz (3,05 GHz – 3,72 GHz) dan 0,65 GHz (3,07 – 3,72 GHz). Hal ini menunjukkan bahwa penggunaan teknik *array planar* seri 2x2 elemen dan 4x2 elemen berhasil meningkatkan bandwidth dari antena sampai dengan 364% dibandingkan dengan elemen tunggal. Selanjutnya, performansi dari konfigurasi MIMO 2 *port* ditunjukkan pada Gambar 5 (b) dimana didapatjan S_{21} ≤ -40 dB pada rentang frekuensi 3,05 GHz – 3,72 GHz. Temuan ini membuktikan bahwa kopling antara kedua antena yang dikonfigurasi secara MIMO sangat rendah dan masing-masing antena dapat beroperasi secara independent tanpa menginterferensi satu sama lain.

Untuk mengamati performansi *gain* dan pola radiasi dari antena yang diusulkan, simulasi didapatkan dengan pendekatan *Finite Element Modelling* (FEM) menggunakan HFSS 15.0. Frekuensi resonansi yang digunakan adalah f_r = 3,5 GHz dengan rentang sudut pengamatan dari 0° sampai dengan 360° seperti yang ditunjukkan Gambar 6. Sebagai catatan, gain menunjukkan kemampuan antena untuk menguatkan sinyal pada sudut tertentu sedangkan pola radiasi menunjukkan pola pada saat antena memancarkan gelombang elekromagnetik.

Kedua parameter ini merupakan medan jauh dari antena yang sangat menentukan performansi antena pada saat mengirimkan dan menerima gelombang elekromagnetik pada frekuensi resonansi yang ditargetkan. Umumnya, karakteristik pola radiasi dari antena mikrostrip ke segala arah *(omnidirectional)* dengan sudut optimal nya di 0°. Dalam makalah ini, teknik *array planar* seri digunakan untuk meningkatkan penguatan dan mengoptimalkan pola radiasi dari antena menjadi ke satu arah *(directional)* dengan sudut berkas pancar *(beam)* yang beragam sehingga antena dapat menjangkau dan melayani pengguna dari beberapa sudut yang berbeda.

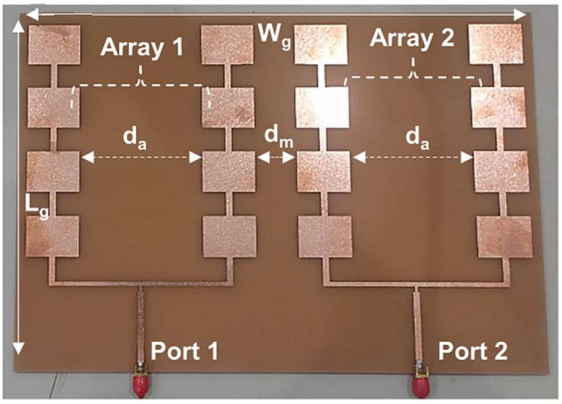


Gambar 6. Hasil Simulasi Penguatan dan Pola Radiasi Antena pada f_r = 3,5 GHz; (a) *Array Planar* Seri 2x2 Elemen, (b) *Array Planar* Seri 4x2 Elemen, (c) *Array Planar* Seri 4x2 Elemen dengan Konfigurasi MIMO

Gambar 6 (a) menunjukkan bahwa *gain* maksimal dari *array* 2x2 elemen adalah 4,8 dB dengan satu sudut berkas pancar yang optimal sedangkan Gambar 6 (b) menunjukkan bahwa performansi *gain* dari antena meningkat menjadi 7,3 dB dengan tiga sudut berkas pancar optimal. Selanjutnya, gain dari antena meningkat menjadi 13,33 dB dengan tiga sudut berkas pancar untuk antena yang dikonfigurasi secara MIMO seperti yang ditunjukkan Gambar 6 (c). Hal ini menunjukkan bahwa penambahan elemen dari antena *array* dan konfigurasi MIMO telah berhasil meningkatkan *gain* dan mengotimalkan keragaman dari sudut berkasi pancar dari antena.

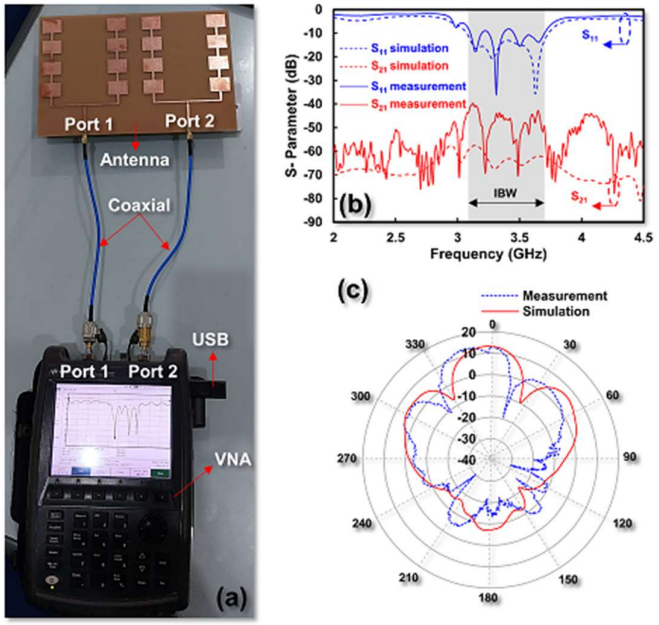
3. HASIL DAN PEMBAHASAN

Dalam makalah ini, antena di fabrikasi menggunakan susbtrat jenis FR-4 epoxy. Elemen peradiasi dari antena berada bagian atas dari substrat sedangkan bagian bawahnya berfungsi sebagai *ground plane*. Hasil fabrikasi dari perangkat yang telah dirancang ditunjukkan pada Gambar 7.



Gambar 7. Hasil Pabrikasi Antena Rancangan

Gambar 7 menunjukkan hasil pabrikasi dari antena rancangan menggunakan substrat FR4 dimana kedua antena masing-masing tekoneksi dengan *port* 1 dan *port* 2 menggunakan konektor RP-SMA dengan impedansi 50 Ω. Elemen peradiasi dan *ground plane* dari antena terbuat dari tembaga sedangkan konektor terbuat dari kuningan. Untuk menyesuaikan impedansi dari keduanya saluran mikrostrip diusulkan sebagai penyesuai impedansi. Selanjutnya, validasi dan verifikasi performansi dari antena dilakukan di laboratorium melalui kegiatan pengukuran seperti yang ditunjukkan pada Gambar 8.



Gambar 8. (a) Proses Pengukuran Antena Rancangan, (b) Perbandingan r S_{11} dan S_{21}, (c) Perbandingan Pola Radiasi pada f_r = 3,5 GHz

Gambar 8 (a) menunjukkan konfigurasi pengukuran dari antena yang terdiri dari antena rancangan yang dikoneksikan dengan VNA menggunakan kabel koaxial ke port 1 dan port 2. Data dari hasil pengukuran disimpan dalam *USB drive* yang nantinya akan diolah menggunakan *personal computer* (PC). Pengukuran dilakukan di laboratorium dengan temperatur ruangan 25° dengan rentang frekuensi 2 – 4,5 GHz dan *sweep frequency* 0,01 GHz. Hasil pengukuran S_{11} dan S_{21} menunjukkan bahwa antena memiliki karakteristik dan perfomansi yang identik antara proses simulasi dan pengukuran seperti yang ditunjukkan Gambar 8 (b). Dari hasil pengukuran didapatkan antena beroperasi pada frekuensi 3,1 GHz sampai dengan 3,7 GHz dengan $S_{11} \leq$ -10 dB dan *bandwidth* 600 MHz. Hal ini menunjukkan bahwa antena telah memenuhi spesifikasi yang ditetapkan yaitu *bandwidth* ≤ 200 MHz. Selanjutnya untuk S_{21} dari antena MIMO berada pada rentang ≤ -40 dB. Hal ini menunjukkan bahwa antena MIMO memiliki koefisien isolasi yang tinggi dan telah memenuhi kriteria yang ditentukan yaitu $S_{21} \leq$ -20 dB. Performansi *gain* dan pola radiasi dari antena pada f_r = 3,5 GHz juga ditunjukkan dalam Gambar 8 (c) dimana pola radiasi dari antena rancangan identik dengan hasil simulasi dengan gain maksimal sebesar 12,52 dB. Temuan ini menunjukkan bahwa antena telah memenuhi target yang telah ditetapkan yaitu gain ≤ 10 dB. Untuk menujukkan kontribusi dan kebaruan dari penelitian ini, Tabel 3 menunjukkan perbandingan dengan penelitian sebelumnya. Tabel 3 menunjukkan bahwa pekerjaan yang diusulkan telah berhasil merancang dan mendisain antena yang memiliki gain yang lebih tinggi dibandingkan dengan penelitian sebelumnya. Selain itu, koefisien isolasi (S_{21}) yang dihasilkan lebih baik dari pekerjaan sebelumnya sehingga antena memiliki independensi tinggi saat beroperasi secara bersamaan untuk sistem komunikasi MIMO.

Tabel 3. Komparasi Dengan Pekerjaan Sebelumnya

Referensi	Metode	Frekuensi resonansi (f_r)	Parameter			
			S_{11} (dB)	S_{21} (dB)	BW (MHz)	*Gain* (dB)
(Biswas & Gupta, 2020)	L-Slot	3.5 GHz	≤ -10	-18	900	4,5
(SANDI et al., 2020)	U-Slot	28 GHz	≤ -10	NA	2800	11,16
(Abdullah et al., 2017)	Coplanar Waveguide	3.5 GHz	≤ -10	-12	200	5,1
Makalah ini	***Array planar* seri**	**3.5 GHz**	**≤ -10**	**-40 dB**	**600**	**12,52**

4. KESIMPULAN

Makalah ini telah memaparkan secara komprehensif perancangan dan pengembangan model antena MIMO dengan teknik planar seri *array* 4x2 elemen yang beroperasi di f_r = 3,5 GHz. Teknik planar seri *array* diusulkan untuk meningkatkan bandwidth dan gain sedangkan MIMO untuk mengoptimalkan keragaman sudut berkas pancar dari antena. Dari hasil pengukuran didapatkan antena memiliki $S_{11} \leq$ -10 dB pada rentang frekuensi 3.1 – 3.7 GHz dengan koefisien isolasi ≤ -40 dB. *Bandwidth* yang dihasilkan adalah 600 MHz dengan gain maksimal adalah 12.52 dB pada f_r = 3.5 GHz. Teknik planar seri *array* yang dikonfigurasi secara MIMO berhasil meningkatkan bandwidth dan gain sebesar 172.72% dan 160.83 % dibandingkan dengan antena elemen tunggal. Penelitian ini sangat bermanfaat dan dapat diterapkan sebagai antena penerima untuk sistem komunikasi 5G.

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Design and Development of a Smart Café System Utilizing IoT for Real-Time Remote Monitoring and Updates

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Abstract – *Currently, cafés are a popular place for community activity. In addition to enjoying drinks and food, the café is also a place that is used for discussions, for learning/study, and as a meeting point for various groups, including students. A good café is one with comfortable and safe conditions. One way to ensure the comfort of a café is to monitor and control the body temperature, air quality, room temperature and humidity, the number of visitors, cleanliness, and the temperature in the kitchen. In this research, an IoT-based monitoring and control tool was developed. The goal of this tool is to monitor and control café conditions automatically, in real-time, and touchless. The sensors used collect data and read the conditions of parameters to be evaluated. Among the evaluations performed by this tool are the number of visitors (dine-in or take-away), control of temperature and humidity in the café, attendance tag cards for employees and café security, compliance with health protocols before entering the café, and measurement of a person's body temperature using infrared. In addition, if there is an anomaly in the café (temperature exceedance), the manager receives a notification in real-time of what is going on in the café. Cooling fans and humidifiers are activated when the air quality is abnormal, that is, when the temperature is more than 33°C and the humidity is not between 45% - 65% Relative Humidity. When the temperature in the kitchen is more than 38°C, the alarm is activated.*

Keywords – *Smart Café System; IoT-based Monitoring; Real-Time Control; Environmental Sensors; Automated Café Management.*

I. Introduction

SINCE mid-2019 until mid-2021, Indonesia has been striving to prevent the emergence of new clusters due to Covid-19. According to the Decree of the Minister of Health of the Republic of Indonesia (2020) Number HK.01.07/MENKES/382/2020 [1] concerning health protocols for the community, especially for building owners and visitors, it is necessary to measure body temperature, maintain air quality by optimizing room air circulation, and manage social distancing during transactions.

In an effort to implement the Minister's Decree, it is necessary to monitor the number and condition of visitors to a building while adhering to health protocols to prevent virus transmission. As we know, buildings are places for various user activities. A good building is one that is safe, comfortable, and well-controlled. Buildings E, F, and G are within the Faculty of Industrial Technology, Trisakti University. These buildings are used for various activities, including lectures, administration, laboratories, discussions, and more. One of the rooms in the Faculty of Industrial Technology is the Student Lounge, which is a place where students discuss assignments or general matters. In this room, there is a café frequently visited by students.

A well-controlled café system should implement a smart system. This requires monitoring visitor arrivals, measuring body temperature, and monitoring and controlling air quality.

On the other hand, advancements in data transmission technology, with increased speed, compactness, and efficiency, enable near-lossless data transmission from sender to receiver. Additionally, with the Internet of Things (IoT), everything can communicate with each other, from machine to machine, extending to everything, facilitated by the internet. IoT significantly eases human tasks in monitoring and controlling public spaces, requiring limits on the number of guests, body temperature, room temperature, and humidity.

IoT platforms are developing and available as IoT

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solutions, forming the most critical component of the IoT ecosystem [2]. These platforms include (a) Google Cloud Platform, enabling developers to code, test, and deploy scalable applications with reliable infrastructure handled by Google. Developers focus on code while Google manages infrastructure, computing power, and data storage. (b) Thinger.io, a cloud IoT platform comprising the IoT backend (actual server) and web-based frontend simplifying work with various features using computers or smartphones. (c) ThingWorx, a software platform supporting the creation of smart applications like Smart Cities, Smart Agriculture, Smart Buildings, Smart Grids, and Telematics. (d) ThingSpeak, an IoT platform helping users build applications based on data collected by sensors.

Several studies utilize IoT as the main device in monitoring and controlling buildings. In studies [3, 4], Arduino as a single-board controller has its own IDE (Integrated Development Environment) program. Arduino is also an open-source programmable board easily used for writing and running application programs. Arduino Boards are physical programmable boards used for flexible programming, adaptable signal types, and easy adaptation.

Room temperature comfort is a crucial factor supporting all activities inside, whether for work or study. According to research [5], room temperature comfort is achieved at temperatures ranging from 27°C to 29°C, with the highest comfort level observed from 06.00 to 09.00 WIB at an average temperature of 27.75°C.

Research [6] states that using DHT11 for measuring room temperature and humidity (Web Server) has good accuracy. Testing was conducted with HTC-1 Hygrometer, LCD I2C 16X2, and smartphones. This serves as a reference for measuring temperature and humidity. Meanwhile, in research [7], data from DHT11 compared with thermocouple vernier sensors showed an error value of 1.73%. Research [8] implemented an automatic door security system using RFID MFRC-522 with Solenoid Door Lock output, requiring a Telegram BOT to send notifications to smartphones when tapping e-cards. Meanwhile, research [9] states that a counter with Ultrasonic Sensor has 80% accuracy in reading the number of visitors using the Bayes method. In research [10], ultrasonic sensors were used to detect obstacles and measure their distance accurately, displayed on an LCD screen. Research [11] successfully developed a non-contact human body temperature measuring device based on Arduino using the MIX90614 sensor, with an acceptable uncertainty value of 1 degree Celsius. Research [12] designed a human body temperature measurement system by identifying human faces using image processing techniques. The system achieved an average error rate of 0.72%, resulting in an accuracy rate of 99.28%. Several factors influence the accuracy of infrared thermometers, including measuring distance and thermometer type. Research [13] showed less accurate readings when measuring body temperature at distances exceeding specifications. Additionally, body temperature measurements should use thermometers with an accuracy of ±0.3°C as per ASTM E1965-98.

Based on the idea of utilizing existing technology, this research aims to create a smart café monitoring system combining hardware (microcontroller) and software (smart application) for monitoring and controlling café visitors, body temperature, room temperature, and humidity. It also integrates intelligence for counting café visitors, transaction counting (dine-in or take-away), implementing security door locks, monitoring employee attendance remotely, and sending alarms and notifications via Telegram to café owners using RFID (Radio Frequency Identification Device). RFID RC522 is a software application with an antenna that radiates radio waves to RFID tags. The transmitted radio waves propagate in the surrounding area, allowing data to be transferred wirelessly to RFID tags near the antenna [8, 14, 15].

The goal of these additional features in this research is to track daily transactions and immediately trigger alarms and send notifications to the café owner's Telegram if an unauthorized person tries to enter the café without searching through recordings that take longer.

Sensors will collect data and read conditions daily. Each sensor connects to several outputs to operate automatically. For remote and real-time monitoring and control, an Internet of Things (IoT) platform is needed. Research [16] successfully detected and measured water level distance using IoT (Internet of Things) with the HC-SR04 ultrasonic sensor, monitored remotely.

II. Research Methods

The touchless system for transactions, body temperature measurement of visitors, and social distancing are the foundations of the design to be developed. The Arduino system will be connected to several sensors as inputs, which will then be processed to provide the designed outputs. The generated outputs will correspond to the commands set on the Arduino, depending on the input values read by the sensors. This café system includes RFID for attendance and security, visitor count monitoring, body temperature measurement, room temperature and humidity control, and disinfectant spraying.

Before the café operates, employees and dine-in

visitors will measure their body temperature and receive disinfectant. Employees will tap their e-cards on the RFID Absence System & Security, allowing the manager to receive notifications on Telegram for remote attendance monitoring.

Figure 1 shows the flow diagram of the smart café system design. As shown in Figure 1, before operating the smart café system, it is necessary to ensure that the Internet network on WiFi is connected, and the PC can sign in to the open-source IoT website with a known username and password, enabling remote monitoring by the manager/owner working from home. Thus, the smart café system will operate 24 hours as long as the Internet connection is functioning well. In addition to being monitored via CCTV, if there is an abnormal condition, the RFID System will immediately trigger an alarm and send notifications to HRD's Telegram without searching through recordings, which takes longer.

Figure 1: Flow Diagram of the Smart Café System Design

On the other hand, the air quality monitoring system will work 24 hours actively, whether connected to the Internet or not, so the temperature and humidity conditions of the café during operation or non-operation can be monitored at all times. Meanwhile, the visitor counter system is only active when the café is operating. The touchless system measures a person's body temperature before entering the café. If the visitor's body temperature exceeds 36.95°C, the LCD will display that the visitor is not allowed to enter the café, and vice versa. Visitors will receive disinfectant upon entering the café. Then, the ultrasonic sensor will read the number of visitors who have entered the café and display the allowed visitor capacity. The ultrasonic sensor will be placed at the café's entrance and exit doors.

In addition, the transaction counter system operated by the café cashier is active when the café operates. When a visitor wishes to dine in or take away, the cashier will press a button to count the total daily transactions, as not all visitors who enter the café will dine in. With this feature, the owner can monitor the café's crowd.

Figure 2 shows the block diagram of the designed smart café system. In Figure 2, there are two serial communications between Arduino and NodeMCU ESP8266. The data sent by Arduino includes the Visitor Counter system connected to 2 Ultrasonic Sensors and the Transaction Counter with 6 Push Buttons. This is implemented due to the pin limitations on NodeMCU Amica and NodeMCU Lolin. Then, there is an independent system not connected to the IoT platform but connected to Telegram. This feature is applied to ensure more secure data transmission over the Internet and to send notifications directly to the café HRD manager.

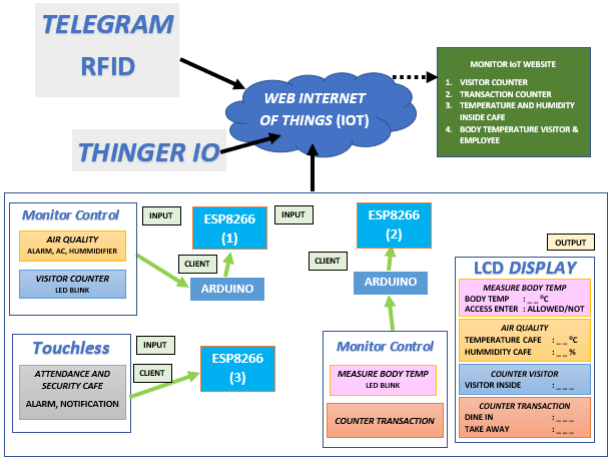

Figure 2: Block Diagram of the Smart Café System

i. Design

In designing the hardware, a contactless body temperature sensor with a wide measurement range from -70°C to +380°C was selected. Infrared radiation is part of

the electromagnetic spectrum with wavelengths from 0.7 to 1000 microns. However, only 0.7-14 microns are used for temperature measurement [17, 18]. The selected humidity sensor is a resistive and NTC-based sensor that can be connected to an 8-bit microcontroller, providing fast response, anti-interference, affordability, and good quality.

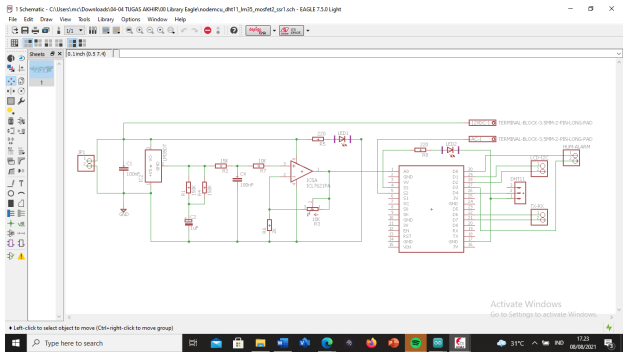

Figure 3: NodeMCU Communication Circuit 1

The café will be connected to the Internet and will collect café condition data to forward to the IoT platform. Temperature and humidity monitoring and control will be applied in the café dining area and kitchen. In the dining area, temperature and humidity data will be collected using the DHT11 sensor. In the kitchen, temperature data will be collected using the LM35 sensor arranged with a Low Pass Filter (LPF). The values of LM35 and DHT11 will be displayed on an LCD Display. The output of DHT11 is Air Conditioning and Humidifier, so if the temperature and humidity conditions are unhealthy, both will activate. The output of LM35 is an alarm, so if the kitchen temperature exceeds 38°C, the alarm will activate, prompting employees to check the kitchen conditions. This facility is used to prevent fires in the café kitchen due to the café's limited staff. LM35 sensor, DHT11 sensor, Air Conditioner (AC), Humidifier, Alarm, WiFi LED, LCD I2C, and TX RX pin D6 D7 NodeMCU will be connected to Serial Communication Circuit 1 (Figure 3). This Serial Communication Circuit will also be connected to Arduino for the Visitor Counter system.

The air quality monitoring system will be active 24 hours, whether connected to the Internet or not, so the café's temperature and humidity conditions can be monitored during operation and non-operation. When the system is connected to the Internet, data is forwarded to the IoT platform to evaluate the café's performance. The café's air circulation can be periodically corrected to prevent the spread of Covid-19. Figure 4 shows the NodeMCU communication circuit for air quality monitoring.

The Visitor Counter system is only active when the café operates. The touchless application measures

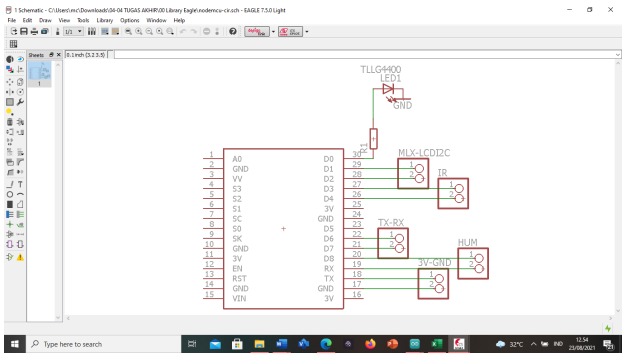

Figure 4: NodeMCU Communication Circuit 2

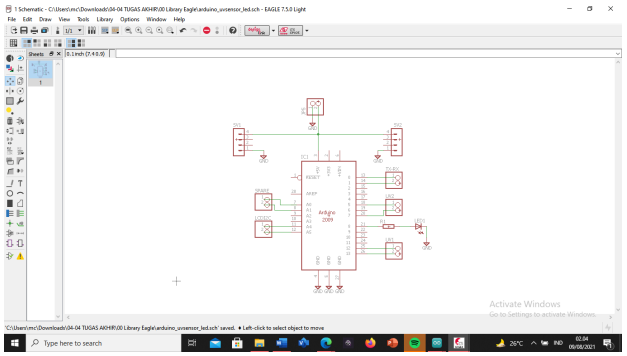

Figure 5: Arduino Communication Circuit 1

a person's body temperature before entering the café. If the visitor's body temperature exceeds 36.95°C, the LCD will display that the visitor is not allowed to enter the café, and vice versa. Visitors will receive disinfectant upon entering the café. Then, the ultrasonic sensor will read the number of visitors who have entered the café and display the allowed visitor capacity. The ultrasonic sensor will be placed at the café's entrance and exit doors. Figures 5 and 6 show the Arduino communication circuits for the Visitor Counter system connected to 2 Ultrasonic Sensors and the Transaction Counter with 6 Push Buttons.

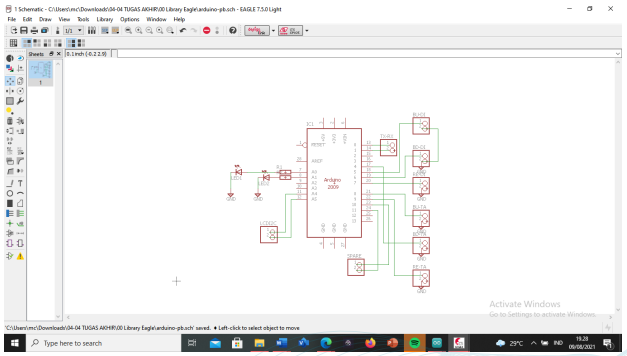

Figure 6: Arduino Communication Circuit 2

Additionally, the transaction counter system operated by the café cashier is active when the café operates. When a visitor wishes to dine in or take away, the cashier will press a button to count the total daily

transactions, as not all visitors who enter the café will dine in. With this feature, the owner can monitor the café's crowd.

The software/application design uses Arduino Uno, IoT Platforms (ThingSpeak and Thinger.io), and Telegram applications. Through the Arduino application, the code will be compiled and implemented on the Smart Café system. The IoT Platform and Telegram will be used for remote monitoring in real-time to facilitate café management evaluations.

ii. Testing

Testing is conducted to ensure that the tool functions/operates correctly as desired. Several tests include evaluating the system's performance when sensors read the obtained data and compare it with actual conditions, testing the components' performance in the system by activating alarms on several sensors at predetermined values, testing the IoT Webserver Platform, and testing the overall system performance.

iii. Testing Parameters

The parameters monitored and controlled in the smart café system are as follows: 1. Air humidity. Air quality is also influenced by air humidity. Indoor air humidity levels change more easily than outdoor air. According to [19], the normal indoor air humidity level is 45% - 65% as the ideal level. If the humidity level is below 45%, airways and mucous membranes will dry out, and the influenza virus can survive longer. Conversely, if the humidity level is above 65%, it will trigger allergies for asthma sufferers. 2. Air temperature anomalies. According to the Indonesian Minister of Health (2011) on indoor air health guidelines, air quality requirements include particulate matter, air temperature, lighting, humidity, and ventilation rates. The recommended indoor temperature range is 18°C - 30°C [19]. If the temperature exceeds 30°C, it is recommended to lower it by increasing air circulation with additional ventilation. If the temperature is below 18°C, a room heater is needed using environmentally friendly and healthy energy sources. 3. Counting Visitors and Counting Transactions. According to [20], there is a circulation space of 20% or 259.2 cm² in the dine-in area. The space required for one person to eat is 1.2 m², so if the café can accommodate 40 visitors, it requires 48 m² of dining space. 4. Security door lock and touchless employee attendance. Maintaining social distancing to reduce interactions between employees and visitors is necessary. This touchless system is also built for security door locks, where only employee access cards are allowed to enter the café's service area. When tapping an e-card, data will be transmitted via the Internet to connect to the Telegram application on the manager's phone as a notification. If the e-card is not recognized, continuous notifications will be sent to the manager's Telegram, and the security post alarm will sound. With this feature, café security and employee attendance can be monitored remotely in real-time. 5. Body temperature measurement with infrared and disinfectant provision. Before entering the café, visitors and employees must measure their body temperature to ensure it is within the normal or healthy range. According to [21, 22], the normal human body temperature range for adults is 36.5°C - 37.2°C. To prevent the spread of the Covid-19 virus, an infrared thermometer is needed for touchless body temperature measurement. The smart café system uses a maximum body temperature value of 36.95°C for body temperature measurement.

III. Results and Discussion

When analyzing the system design, it is necessary to test the performance of the Smart Café System using IoT for Real-Time Remote Monitoring and Updates. This is done to achieve good results and ensure that the device meets expectations. The first step is to test the device to ensure it functions properly.

i. System Performance Testing

Figure 7 shows the results of testing the RFID Tag & Reader used for monitoring employee attendance with a touchless system via Telegram. When an employee or someone taps a card, the manager, operator, or owner's mobile phone screen will display whether the card is recognized.

Power Supply testing was conducted to determine the output voltage obtained after implementation on the PCB. The Power Supply used has two outputs, 5 VDC and 12 VDC. The voltage on the Transformer supplied to the Power Supply is 15 VDC with a current of 3A. Testing was performed using a Multimeter to determine the output voltage and the resulting waveform.

In Figure 8, the regulator IC for 5 VDC is IC7805, and for 12 VDC, it is IC7812. The transformer is connected to an On-Off switch and a fuse before connecting to the 220 VAC (Alternating Current) cable. The transformer is used to convert 220 VAC to 15 VRMS to enter the Power Supply, which uses 12 VDC and 5 VDC. The RMS voltage used in the Power Supply is 15 VRMS, while the alarm, exhaust fan, and mist maker have a value of 12 VRMS. The generated peak voltage is:

$$V_{P(PS)} = V_{RMS} + \frac{V_{RMS}}{\pi}$$

Figure 7: Display on Mobile Phone during RFID Testing

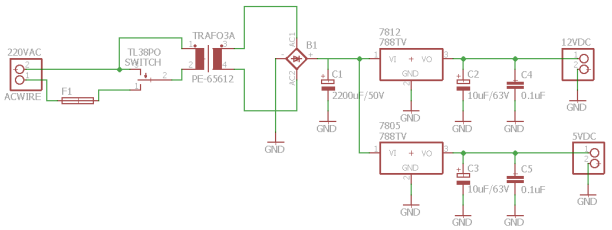

Figure 8: Power Supply Schematic Diagram

$$= 15 + \frac{15}{3.14} = 19.777\,V_P$$

$$V_{PP(PS)} = 2 \times V_P = 39.554\,V_{PP}$$

This test ensures that the source voltage connected to the device meets the required specifications. If the voltage is not correct, it can cause a short circuit in the current flowing through the circuit and damage the component ICs.

Figure 9 shows the results of testing the Push Button as a Transaction Counter to determine the number of dine-in and take-away transactions per day conducted by the cashier. The results show 8 dine-ins and 9 take-aways.

Figure 10 shows the results of testing the DHT11 sensor as a monitor of temperature and humidity inside the Café, indicating whether the conditions are normal. This system is also connected to a Humidifier and Cooling Fan, which will activate if the café's temperature and humidity are abnormal. Similarly, the LM35 temperature sensor monitors the kitchen's temperature. If the kitchen's temperature is abnormal, the alarm will sound to avoid fire risks.

Figure 9: Transaction Counter Test Results

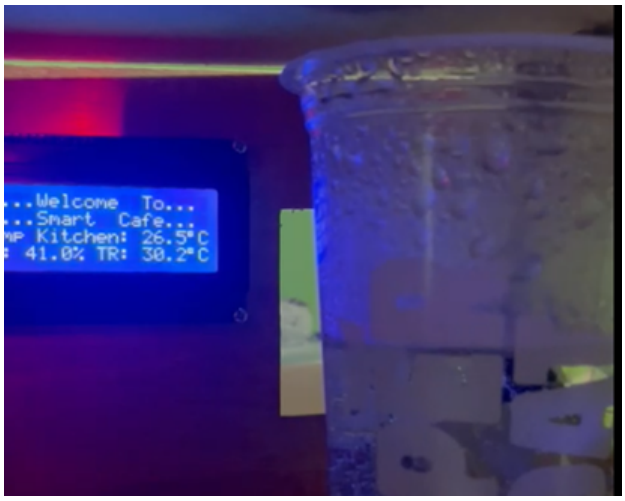

Figure 10: DHT11 Sensor Test Results for Temperature and Humidity Monitoring in the Café

Figure 11 shows the results of testing the MLX 90614 sensor, which measures body temperature without contact. This sensor works by capturing a person's body temperature data using an infrared system.

Figure 12 shows the results of testing the IR Sensor, which operates after someone passes the MLX 90614 sensor. If a person's body temperature is normal, they will proceed to the café entrance. Before entering the café, the person will receive disinfectant, activated when they enter the booth. The booth contains an IR

Figure 11: Body Temperature Measurement Using MLX 90614 Sensor

Sensor that detects the person's presence. Additionally, Ultrasonic Sensors at the café entrance and exit doors count the number of visitors entering and leaving the café to determine the café's capacity.

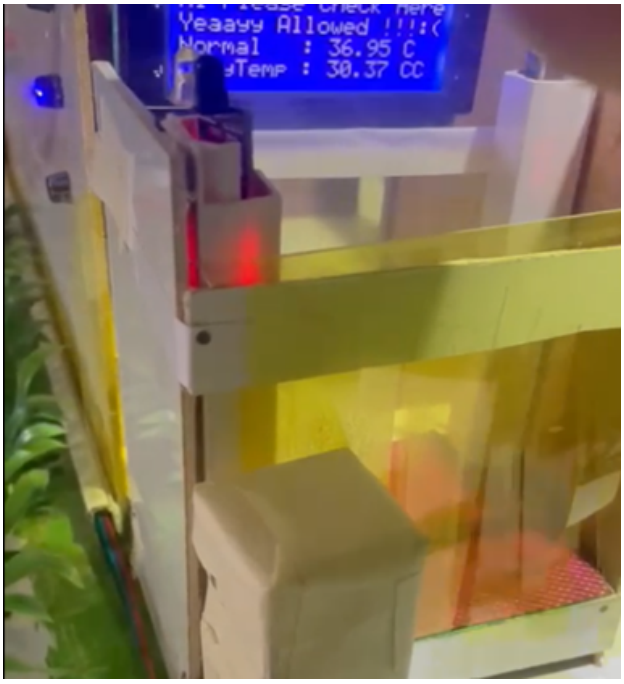

Figure 12: IR Sensor Test Results After Passing the MLX 90614 Sensor

The DHT11 Sensor, LM35 Sensor, Ultrasonic Sensor, and Push Button will be connected to the IoT platform. The IoT platform will read the temperature and humidity inside the café, the kitchen's temperature, the number of dine-in visitors, and the total daily transactions input by the cashier.

ii. Smart Café System Analysis

The LM35 Sensor circuit with LPF as a temperature detector in the café kitchen has a maximum temperature limit of 38°C. The detected temperature affects the voltage supplied to the connected circuit. The higher the temperature in the café, the higher the circuit's voltage. The Temperature Detector Circuit represents temperatures from 0°C to 100°C with a supplied voltage of 0 VDC to 12 VDC. When the temperature exceeds 38°C, the 0 VDC alarm will activate with a delay of 1000 ms.

Table 1 shows the temperature values in the kitchen measured by the LM35 sensor and the humidity and temperature in the café measured by the DHT11. The average temperature measured by the LM35 is 30.67°C, and by the DHT11, it is 32°C. The kitchen temperature is lower than the café temperature. Generally, the average temperature difference is 1.33°C. However, the DHT11 occasionally resets during data collection at 19:20, as shown in Table 2.

Table 1: LM35 Temperature Data from Thinger.io

Time	RH (%)	Temp. LM35 (°C)	Temp. DHT11 (°C)	Diff Temp (°C)
23:29	43	28.622	32.200	3.578
23:28	43	28.198	32.200	4.002
23:27	43	32.602	32.200	-0.402
23:26	43	32.135	32.099	-0.036
23:25	44	28.327	32.099	3.772
23:24	44	28.584	32.000	3.416
23:23	44	28.708	31.899	3.191
23:22	43	30.545	31.899	1.354
23:21	45	29.395	31.799	2.404
23:20	44	39.616	31.700	-7.916
Average	43.6	30.6732	32.0095	1.3363

Table 2: Temperature and Humidity LM35 vs. DHT11

Time	RH (%)	Temp. LM35 (°C)	Temp. DHT11 (°C)	Diff Temp (°C)
19:36	35	29.020	33.799	4.779
19:31	35	30.507	33.700	3.193
19:26	35	28.633	33.700	5.067
19:20	0	26.388	0	-26.388
19:19	0	27.940	0	-27.940
19:18	0	28.380	0	-28.380
19:17	0	32.070	0	-32.070
19:16	0	28.370	0	-28.370
19:15	0	27.526	0	-27.526
19:14	0	29.809	0	-29.809
Average	10.5	28.864	10.1199	-18.744

The MLX 90614 sensor is used to detect a person's body temperature using infrared. This sensor is located at the entrance process before entering the café area, as only those with normal body temperature or a maximum of 36.95°C are allowed. The MLX 90614 sensor measurement results can be seen in Table 3.

The Ultrasonic Sensor is used as a Visitor Counter for dine-in customers. This sensor simplifies controlling the café's capacity. In this study, the Ultrasonic Sensor reads the distance of a person entering the café

Table 3: MLX 90614 Temperature Data from Thinger.io

Time	MLX 90614 (°C)	Result
18:37	31.709	Health
19:31	31.529	Health
19:26	31.390	Health
19:20	31.409	Health
19:19	31.610	Health
19:18	31.330	Health
19:17	31.629	Health
19:16	31.469	Health
19:15	31.629	Health
19:14	31.390	Health
Average	31.509	

as 1 cm. Based on the data in Table 4, the placement distance of the Ultrasonic Sensor affects the detection of the total number of visitors in the café. Specific placement is needed to ensure accurate detection.

Table 4: Ultrasonic Sensor Experiment

Experiment	Visitors	Distance (cm)			Ultrasonic Detection
		1	2	3	
1	2	O			2
2	1		O		0
3	3	O			3
4	2			O	0
5	4	O			4
6	1	O			0
Total	13				9

The Push Button as a Counter Transaction for café customers ordering dine-in and take-away is used to determine the total daily transactions. Each cashier has three push buttons: one for adding, one for subtracting in case of input errors, and one for resetting the counter. When the reset button is pressed, the LED will activate, indicating that the Counter Transaction is being reset. The type of Push Button affects the readable data.

IV. Conclusion

Based on the results of the discussion on the Design and Development of a Smart Café System Using IoT for Real-Time Remote Monitoring and Updates, it was found that monitoring temperature, humidity, visitor count, and transaction count using the Thinger.io IoT platform with a registered account has been successfully tested. The Power Supply used has voltages of 5 VDC and 12 VDC with a current of 3A, which is suitable for the components used. The comfort conditions of the café are maintained by monitoring the number and condition of visitors and employees using the MLX 90614 sensor, which utilizes infrared to measure body temperature. Additionally, visitors are automatically sprayed with disinfectant. The air quality can also be automatically controlled if the café's temperature or humidity is abnormal, activating the Cooling Fan and Humidifier. Therefore, this IoT-based smart café system design is highly beneficial for café managers/owners, visitors, and employees in providing comfort and protecting against diseases caused by air quality and humidity. The café's condition can also be monitored in real-time, anytime and anywhere.

Acknowledgment

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Implementation of MQTT Protocol on ESP32-Based OEE Analysis Development Board

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Implementation of the Viola-Jones Algorithm for a Hand Sign Language Translation System

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Implementation of MQTT Protocol on ESP32-Based OEE Analysis Development Board

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Abstract – *The transition to Industry 4.0 requires major investments in devices and mechanisms that enable interconnectivity between people, machines, and processes. One important concept related to Industry 4.0 is the so-called Industrial Internet Of Things or IIoT. The application of IIoT in the industrial scope is the measurement of Overall Equipment Effectivness (OEE) through the IoT paradigma. Generally, OEE measurements are carried out manually by production operators on the machine being measured, and data processing is carried out by supervision manually as well to then analyze the OEE value of the machine being measured. In this research, an ESP32-based OEE Analysis Development Board with MQTT protocol is proposed to replace the manual OEE measurement process. The results of direct implementation on the production floor show that the ESP32-based OEE Analysis Development Board with MQTT protocol can be used as an alternative to OEE measurement with a maximum error value on OEE measurement of 16%.*

Keywords – *Industri 4.0; Industrial Internet Of Thing; Overall Equipment Efectivness; ESP32; MQTT.*

I. INTRODUCTION

THE Fourth Industrial Revolution, or Industry 4.0, represents the current evolution of production systems following the merger of industrial automation and information technology. Industry 4.0 technological innovations feature the integration of manufacturing systems [1], real-time management of product lifecycles, and the decentralization of Information Technology (IT) resources [2]. One of the critical concepts related to Industry 4.0 is the so-called Industrial Internet of Things (IIoT) [3], which refers to the use of interconnected machines and automation devices equipped with sensors in industrial environments [4]. The devices and equipment used in Industry 4.0 primarily consist of proprietary systems [5] owned by vendors [6] or services from external companies, which are typically expensive to implement and have various communication protocols [7] that are difficult to standardize [8].

In several previous studies, designs related to OEE have been implemented using low-cost devices. Gun Maulanan [9, 10] developed a prototype of a performance monitoring system for press machines based on the Internet of Things (IoT) to enhance machine performance with optimal production output. The system overview includes three Arduino Nano units as slaves directly connected to multiple sensors, each slave then connects to a Raspberry Pi as the master, which collects and displays data in real-time.

Halldórsson [11] designed a system using a Raspberry Pi as a data collector, receiving inputs from PLC logic, and forwarding the data to a cloud server for visualization using various software tools to measure OEE. Mastang [12] provided knowledge on the basic application of OEE measurement that can be easily implemented and efficiently used with a Raspberry Pi.

Furthermore, Herrero [2, 4] mitigated the efficiency utilization of Raspberry Pi as a low-cost device in direct production line implementation. When implemented, an error signal caused by electromagnetic interference was identified. The study introduced a non-physical method to handle electromagnetic interference, thus maximizing the accuracy of OEE measurement readings.

In another study, Kong [13] introduced a new device for calculating OEE using an ESP32 with the standard web protocol HTTP. However, the prototype design did not address the accuracy of the data produced, leaving the efficiency of using ESP32 for actual OEE

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measurement in production line implementation uncertain.

The final reference for the design of the ESP32-based OEE Analysis Development Board with MQTT protocol implementation is the study by Surya [14], which compared the application of the MQTT protocol and the HTTP protocol. The results of this study indicated that the MQTT protocol has a faster data transfer capability compared to the HTTP protocol, capable of transferring data six times more efficiently than HTTP.

II. Research Methods

The primary goal of this research is to replace the manual data collection process on machines performed by operators and to eliminate the manual OEE calculation process, which is then replaced by a user interface. By designing this low-cost device, it is expected that industries will no longer rely on external services or vendors whose devices are difficult to standardize. The stages of design and implementation are as follows: Literature Study, System Architecture, Pre-Implementation Testing, Actual Implementation, and Problem Handling in Actual Implementation. Before the design process, a literature study was conducted from several journal sources related to this research. The details of the required references are as follows:

1. Overall Equipment Effectiveness (OEE) [15] is a metric useful for accurately estimating industrial productivity. This metric can be measured in real-time through the IoT paradigm, where smart devices can collect important data, helping stakeholders gather useful information to make informed decisions to enhance productivity while reducing costs.
2. Low Cost Device: is a solution implemented in the initial design of a system that has the same capabilities as devices typically used by large companies [2]. With low financial investment, it is expected to work optimally despite certain limitations. There are many low-cost devices available in the market, such as Particle.io, ESP8266, Arduino, and Raspberry Pi [16]. In this research, the low-cost device to be used is the ESP32 [17].
3. PostgreSQL: is a database management system that supports various SQL standards and offers many modern features [18].
4. Node-Red: is a development environment based on Node.js and JavaScript developed by IBM engineers, best suited for developing Internet of Things (IoT) systems [19].
5. Grafana: is the main tool used for data visualization [20].
6. MQTT Communication Protocol: is a communication protocol based on clients publishing/subscribing to topics from a broker. It is designed for implementation on devices with limitations, low bandwidth, and connected to unreliable networks [21].
7. EMQX Broker: is open-source software that functions to receive and transmit messages sent by clients [22].

i. System Architecture

The System Architecture used in the design of this tool can be seen in Figure 1 as follows:

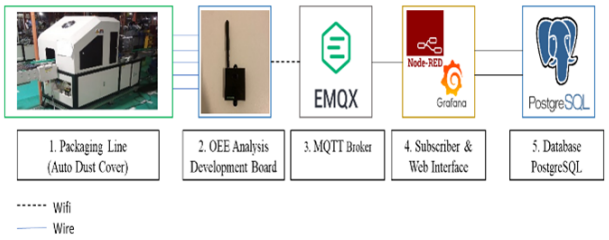


Figure 1: System Architecture of ESP32-Based OEE Analysis Development Board

The explanation related to the overall proposed system is as follows:

1. Packaging Line: The actual line where the designed tool will be implemented.
2. Development Board OEE Analysis: Data Logger (Start, Stop, Qty OK & NG conditions).
3. MQTT Broker: using EMQX software.
4. Node-red & Grafana: Subscriber and User Interface.
5. PostgreSQL: Storing actual reading data in real-time.

ii. Pre-Implementation Testing

In the industrial scope, one of the implementations related to IIoT is the application of Overall Equipment Effectiveness (OEE) measurement. OEE is a metric useful for measuring the productivity of machines in industries. This measurement process is done manually by production operators collecting data, which is then processed to yield OEE measurement results. In the OEE measurement process, there are three important points: Performance, Availability, and Quality. OEE can be calculated using Equation 1 [4]:

$$\text{OEE} = \left(\frac{\text{Product CT} \times \text{OK Products}}{\text{Loading Time}} \right) \times 100\% \quad (1)$$

In IIoT, this calculation process can be replaced with the IoT paradigm. The data collection process performed by operators can be replaced by IoT devices that log data directly from the machine for start

on/off status, stop on/off status, OK product count, and NG product count. Then, the OEE calculation can be performed directly by the user interface utilizing an algorithm similar to the OEE calculation formula.

Based on the designed system architecture, the Development Board OEE Analysis has 4 input pins activated as data loggers to collect data from the machine in real-time. Each input is directly connected to respective machine inputs to continuously collect data. Figure 2 explains the details regarding the OEE Analysis Development Board wiring and data logger targets on the machine where OEE measurements will be implemented using the IoT paradigm.

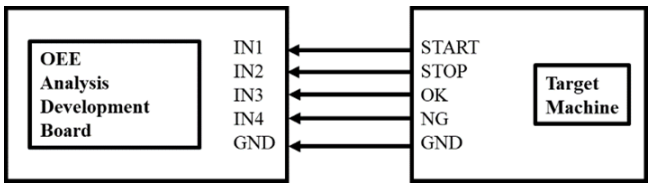
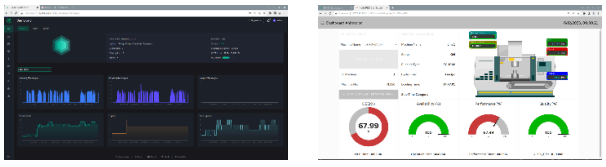


Figure 2: Wiring of the Development Board OEE Analysis with the target data logger on the machine

In the pre-implementation testing process, a laptop is used as a server running EMQX software as the broker, Node-red and Grafana as the subscriber and user interface, and PostgreSQL as the database collection on the server. Each software runs on the following links:

1. localhost:18083 for EMQX broker
2. localhost:1880/ui for UI on Node-red
3. localhost:3000/PK01 for UI on Grafana
4. localhost:5050 for PostgreSQL control

Figure 3 shows the EMQX and Node-Red interfaces, where the EMQX dashboard can be seen in Figure 3(a), and the user interface dashboard on Node-Red can be seen in Figure 3(b).

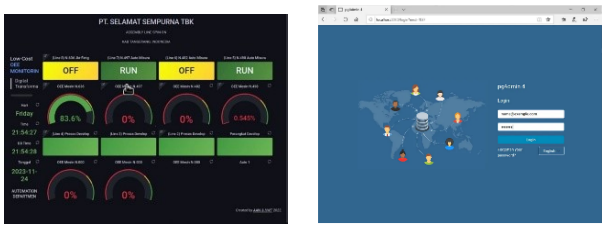


(a) (b)

Figure 3: EMQX and Node-Red Interfaces (a) EMQX broker dashboard and (b) UI on Node-Red

Figure 4 shows the Grafana and PostgreSQL interfaces on pgAdmin, were the OEE measurement monitoring dashboard can be seen in Figure 4(a), and the PostgreSQL database control on pgAdmin can be seen in Figure 4(b). The detailed image of the overall system architecture during testing can be seen in Figure 5.

Next, testing is conducted on each input of the Development Board OEE Analysis by providing a voltage



(a) (b)

Figure 4: Grafana and PostgreSQL Interfaces (a) UI on Grafana (b) PostgreSQL on pgAdmin

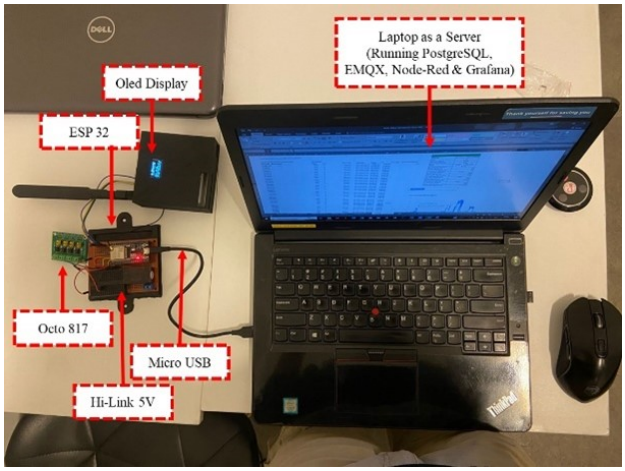


Figure 5: Tool testing before implementation

of 5-24V. The voltage is then processed by the algorithm built on the Development Board OEE Analysis to publish payloads according to the topic to the broker. The broker then forwards the payload from the published topic to the subscriber to be processed according to the algorithm built on the Node-red software. The detailed workflow of the publish and subscribe process in the MQTT protocol can be seen in Figure 6.

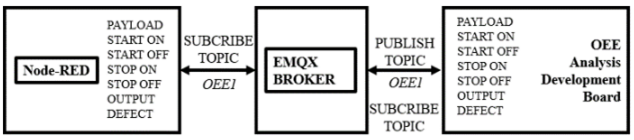


Figure 6: Publish and Subscribe in the MQTT protocol

Table 1 shows the results of testing input 1 (IN1) with payload START ON and START OFF.

Table 2 shows the results of testing input 2 (IN2) with payload STOP ON and STOP OFF.

Table 3 shows the results of testing input 3 (IN3) with payload OUTPUT. There is an error of -1% in the test tool with an input cycle time of 1.8 seconds and 2 seconds. This error is the comparison between the real signal input and the store signal when the signal is received by the PostgreSQL database. The error value in the store signal can affect the final OEE measurement result.

Table 1: Test results for input 1 (IN1) by providing a voltage of 5-24V as a signal to publish data

Time Sampling		#Real Signal	#Store Signal	Error
Start	Stop			
08:04:06	09:10:11	2	2	0
09:12:18	10:05:06	2	2	0
10:31:18	11:32:49	2	2	0
13:56:12	14:48:18	2	2	0
15:10:18	16:30:08	2	2	0

Table 2: Test results for input 2 (IN2) by providing a voltage of 5-24V as a signal to publish data

Time Sampling		#Real Signal	#Store Signal	Error
Start	Stop			
08:34:06	08:46:11	2	2	0
09:15:18	09:20:06	2	2	0
10:41:18	11:02:49	2	2	0
14:26:12	14:28:18	2	2	0
15:40:18	15:50:08	2	2	0

Table 3: Test results for input 3 (IN3) by providing a voltage of 5-24V as a signal to publish data

CT (Second)	Real Signal	Store Signal	Error
2	50	50	0%
1.8	200	200	0%
1.8	500	496	-1%
3	250	250	0%
2	400	398	-1%

Table 4 shows the results of testing input 4 (IN4) with payload DEFECT.

Table 4: Test results for input 4 (IN4) by providing a voltage of 5-24V as a signal to publish data

CT (Second)	Real Signal	Store Signal	Error
2	5	5	0%
1.8	25	25	0%
1.8	50	50	0%
3	100	100	0%
2	200	200	0%

The details of the parameters related to pre-implementation testing can be seen in Table 5.

iii. Actual Implementation

After the initial design and testing, the next step is direct implementation on the production floor. The implementation process was carried out in the packaging line area at an automotive spare part manufacturing industry in the Tangerang district. Figure 7 shows the actual wiring of the Development Board OEE Analysis to the packaging line (Auto Dust Cover Machine).

Table 5: Parameter Testing Unit

Parameter	Testing Unit
Device	ESP32U + 8Dbi Antenna
QoS	0
Retain Status	FALSE
WiFi Name	ADRMOBILE
Internet Speed	20Mbps
Extender Router Range	28M
RSSI	(-65) - (-75) dBm

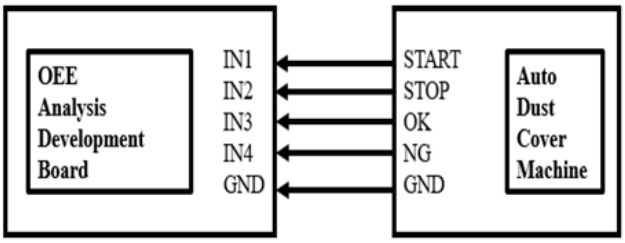
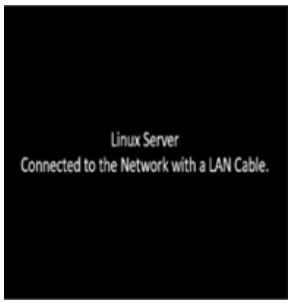


Figure 7: Tool testing during actual implementation

Figure 8 (a) shows the detailed process of placing the unit, where the distance between the Development Board OEE Analysis and the extender router is 19.877 meters. Figure 8 (b) provides information on the OS used and the communication details. The detailed parameters during actual installation on the line are as follows in Table 6.

(a)



(b)

Figure 8: Actual Tool Implementation (a) Distance from Development Board OEE Analysis to Extender Router (b) Server OS information and data communication.

Table 7 shows the results of testing input 1 (IN1) during actual implementation. Data collection was carried out from November 20-25, 2023, over one week with five working days and a total of two shifts.

From Table 7, it can be observed that the accuracy of reading input 1 (IN1) shows varying results between

Table 6: Installation Unit Parameters

Parameter	Installation Unit
Device	ESP32U + 8Dbi Antenna
QoS	0
Retain Status	FALSE
WiFi Name	ADRMOBILE
Internet Speed	20Mbps
Extender Router Range	19.877M
RSSI	(-55) - (-65) dBm

Table 7: Results of reading input 1 (IN1) during actual wiring on the auto dust cover machine

Time		Real Signal	Store Signal	Error
Start	Stop			
20/12/2023 07:00	21/12/2023 07:00	8	6	-25%
21/12/2023 07:00	22/12/2023 07:00	8	3	-63%
22/12/2023 07:00	23/12/2023 07:00	8	5	-38%
23/12/2023 07:00	24/12/2023 07:00	8	3	-63%
24/12/2023 07:00	25/12/2023 07:00	8	6	-25%

the real signal and the stored signal, with the error being highly variable. This variation in the stored signal in MQTT communication is referred to as packet loss and delay. To address this issue, improvements were made by modifying the program through an algorithmic approach.

iv. Problem Handling in Actual Implementation

The algorithmic approach to address the issues encountered during implementation is as follows:

```
{\textbf{Algorithm 1:} Retry Mechanism}
// Reconnect WiFi if it's disconnected
   if (!wifiConnected) {Serial.println("WiFi
   disconnected. Reconnecting...");
  setup_wifi();
 }
   if (!client.connected()) {
      reconnect();
 }
  client.loop();

\textbf{Algorithm 2: Branch Setting}
const char* msg_topic1 = "OEE1";
const char* msg_topic2 = "OEE2";

\textbf{Algorithm 3: Retain Flag}
client.publish(msg_topic1, (const uint8_t*)"START ON",
strlen("START ON"), true);
```

III. Results and Discussion

After making improvements with several algorithmic approaches, the program was re-uploaded and re-implemented on the production floor. Data was collected for one week from December 4 to December 9, 2023. During one week, with 5 working days and a total of two shifts.

Table 8 shows the results of testing input 1 (IN1) after program modification with the algorithmic approach.

Table 8: Results of reading input 1 (IN1) with actual wiring on the auto dust cover machine

Time		Real Signal	Store Signal	Error
Start	Stop			
04/12/2023 07:00	05/12/2023 07:00	8	8	0,00%
05/12/2023 07:00	06/12/2023 07:00	8	8	0,00%
06/12/2023 07:00	07/12/2023 07:00	8	8	0,00%
07/12/2023 07:00	08/12/2023 07:00	8	8	0,00%
08/12/2023 07:00	09/12/2023 07:00	8	8	0,00%

Table 9 shows the results of testing input 2 (IN2) after program modification with the algorithmic approach. There is an error of 5.88% in the actual implementation. The error value in input 2 (IN2) is input for downtime data, which is one of the parameters in OEE measurement. Therefore, this can affect the final OEE measurement result.

Table 9: Results of reading input 2 (IN2) with actual wiring on the auto dust cover machine

Time		Real Signal	Store Signal	Error
Start	Stop			
04/12/2023 07:00	05/12/2023 07:00	26	26	0,00%
05/12/2023 07:00	06/12/2023 07:00	18	18	0,00%
06/12/2023 07:00	07/12/2023 07:00	16	16	0,00%
07/12/2023 07:00	08/12/2023 07:00	34	36	5.88%
08/12/2023 07:00	09/12/2023 07:00	30	30	0,00%

Table 10 shows the results of testing input 3 (IN3) after program modification with the algorithmic approach. The error varies. One cause of the error in input 3 (IN3) is the error appearing in input 2 (IN2). An error in input 2 (IN2) can prevent input 3 (IN3) from storing the signal of OK products to the PostgreSQL database. Besides this error, the values in Table 13 can also be caused by packet loss and delay in the MQTT protocol.

Table 10: Results of reading input 3 (IN3) with actual wiring on the auto dust cover machine

Time		Real Signal	Store Signal	Error
Start	Stop			
04/12/2023 07:00	05/12/2023 07:00	14812	14808	-0,03%
05/12/2023 07:00	06/12/2023 07:00	13254	11890	-10,29%
06/12/2023 07:00	07/12/2023 07:00	13725	13120	-4,41%
07/12/2023 07:00	08/12/2023 07:00	12615	9493	-24,75%
08/12/2023 07:00	09/12/2023 07:00	9945	9729	-2,17%

Table 11 shows the results of testing input 4 (IN4) after program modification with the algorithmic approach.

Table 12 shows the results of OEE measurement based on shift data sampling manually collected by

Table 11: Results of reading input 4 (IN4) with actual wiring on the auto dust cover machine

Time		Real Signal	Store Signal	Error
Start	Stop			
04/12/2023 07:00	05/12/2023 07:00	57	57	0,00%
05/12/2023 07:00	06/12/2023 07:00	60	60	0,00%
06/12/2023 07:00	07/12/2023 07:00	62	62	0,00%
07/12/2023 07:00	08/12/2023 07:00	29	29	0,00%
08/12/2023 07:00	09/12/2023 07:00	47	47	0,00%

production operators. This data is based on production results recorded on the Daily Production Control (KPH) form and serves as a reference for store signals on each input from IN1-IN4 on the Development Board OEE Analysis. The OEE calculation in Table 15 results from applying the OEE measurement formula.

Table 12: OEE measurement results based on manually collected sampling shift data by the operator

Day	Product CT (Second)	OK Products	Loading Time (S)	OEE
1	2.7	14751	50400	79%
2	2.7	11830	50400	63%
3	2.7	13058	50400	70%
4	2.7	9464	50400	51%
5	2.7	9682	50400	52%

Table 13 shows the results of OEE measurement based on shift data sampling using the IoT paradigm with the Development Board OEE Analysis.

Table 13: OEE measurement results based on shift data sampling using the IoT paradigm with the Development Board OEE Analysis

Day	Product CT	OK Products	Loading Time (S)	OEE
1	2.7	14751	50400	79%
2	2.7	11830	50400	63%
3	2.7	13058	50400	70%
4	2.7	9464	50400	51%
5	2.7	9682	50400	52%

Table 14 shows a comparison of measurement results with manually collected shift data and shift data available through the IoT paradigm using the Development Board OEE Analysis.

IV. Conclusion

Based on the implementation results of manual OEE measurement replaced by the IoT paradigm with the Development Board OEE Analysis design, it can be concluded that the MQTT protocol implementation can be applied for OEE measurement. In actual data collection during a one-week implementation, the maximum error in OEE measurement was -16%. Future research plans to address data accuracy issues using other algorithmic approaches to resolve the signal error problem.

Table 14: Comparison of measurement data manually and through the IoT paradigm on Development Board OEE Analysis

Manual	Development Board OEE Analysis	Error
79%	79%	0%
71%	63%	-8%
73%	70%	-3%
67%	51%	-16%
53%	52%	-1%

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