Simulative investigation of FMCW based optical photonic radar and its different configurations

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Abstract
Intelligent transportation is becoming integral part of future smart cities where driverless operations may provide hassle free conveyance. Photonic radar technology is one such contender to deliver attractive applications in autonomous vehicle sector. In this paper we have discussed the basic principle of frequency modulated continuous wave photonic radar and their possible advantages. Further the basic detection scheme that is direct detection and coherent detection is explained mathematically as well as numerical simulations to understand the working is also carried out. The obtained result concludes that direct detection scheme provides minimal complexity in its architecture and is sensitive to received signal strength at the cost of thermal noise and poor sensitivity. On the other hand, coherent detection offers higher target range estimation as well as velocity measurement at the expense of increased system complexity.

Keywords Intelligent transportation · FMCW · Photonic radar · Direct detection · Coherent detection

1 Introduction

With ever increasing traffic congestion and corresponding increase in road accidents has driven researchers worldwide towards autonomous vehicles in order to realize intelligent transportation (Rapp et al. 2020). As many accidents are related with the human errors, hence it is expected to reduce the number of accidents drastically along with the fuel economy, congestion free roads and parking solutions. To achieve such an autonomous vehicle, fusion of various sensor such as 3-d camera, ultrasound, low resolution traditional radar and high-resolution photonics radars etc. for analysing road condition is the very crucial. Among these all, photonic radar also known as LiDAR (light amplification detection and ranging) remains to be the centrepiece of the most autonomous vehicles in realizing intelligent transportation. Photonic Radar system has been extensively employed for assessing range, velocity, vibration, and air turbulence in military airborne as well as other navigation applications (Harris et al.
Photonic radar offers higher range resolution and smaller beam width in comparison to traditional radar systems that enables photonic radars to distinguish between much smaller and closely spaced targets. Performance of photonic radar in terms of range accuracy rely upon operational bandwidth and signal to noise ratio at receiver (Gao et al. 2012; Adany et al. 2009). To attain satisfactory range accuracy and detection sensitivity, use of short pulse light source with very high peak power is reported in photonic radar that leads to photon destruction and ultimately reducing the lifespan of the system. The alternate methodology centred on an energy equivalence principle in which high power short pulse system is traded with low power continuous wave system known as frequency modulated continuous wave (FMCW) photonic radar (Yang et al. 2007; Karlsson and Olsson 1999). FMCW based photonic radar exploits both time of flight and Doppler effect for telemetry application at very long ranges (Feneyrou et al. 2017). FMCW photonic radar utilizes a frequency-swept laser and consistent detection. A standard FMCW comprises of transmitter section in which pseudorandom signal is encoded into saw tooth waveform. Saw tooth waveform is preferred over other waveforms due to its fast sweep rate and hence quicker detection. The triangular signal generated from saw tooth waveform generator is fed into linear frequency modulator (LFM). For carrier optical signal is utilised in terms of low power continuous wave laser source. The signal from LFM generator and Laser source is modulated using Mach-Zhander modulator and resultant signal is known as frequency modulated continuous wave (FMCW) signal hence the system is termed as FMCW photonic radar (Sharma et al. 2021). This output modulated signal is transmitted in free space using telescope to detect and range any target in the line of sight of photonic radar. The reflected echo is collected using telescope and received signal is fed into photo-detector to extract information of the target. The signal extracted using photodiode is then mixed with reference signal of transmitter and subjected to a low pass filter. The filtered signal is analysed for target position, shape, size, and velocity. Alongside planning of the transceiver, other important factor to be considered in photonic radar is the operational frequency, channel and multiplexing techniques. The radio frequency have limitation of operational range as well as it cannot penetrate solid materials hence frequency of transmission must be in microwave region (µwave-band) also known as millimetre band (mm -band) (Zhao et al. 2001; Pagare et al. 2021, 2022). Further the free space channel poses multiple attenuation in terms of atmospheric fluctuations (Sood and Sharma 2018; Chaudhary et al. 2021a, 2021b, 2018a, 2018b, 2014; Zhang et al. 2019; Amphawan et al. 2018a, 2018b, 2014; Sarangal et al. 2017; Sharma and Sushank 2014) which also needs to be estimated and corresponding mitigation techniques are required to be developed. Some recent works upon photonic radars has been compared here in Table 1.

This paper is aimed to establish the importance of photonic radar and to compare characteristics of distinct detection scheme utilised in photonic radars and their comparison with FMCW radar. Section II contains classification of different photonic radars configurations and their mathematical models. Section III we discuss the numerical simulation results obtained from these models and Section V concludes the study by comparing the findings of different models.

2 Classification and mathematical modelling

Based on configuration, FMCW based photonic radar are classified into two detection techniques namely direct detection and coherent detection. Coherent detection is further subdivided into homodynes and heterodyne. Direct detection technique is based
| Year               | Proposed technique                                                                 | Experimental/Simulations | Frequency/Bandwidth       | Detection range/Resolution | Advantages                                                                 |
|-------------------|-----------------------------------------------------------------------------------|--------------------------|---------------------------|----------------------------|---------------------------------------------------------------------------|
| 2021 (Chaudhary et al. 2021c) | FMCW Coherent Detection                                                              | Simulations              | 77 GHz/600 MHz           | 750 m to 3000 m            | Low Complexity, Low Input Power,                                           |
| 2021 (Sharma et al. 2021) | FMCW Direct Detection                                                              | Simulations              | 77 GHz/600 MHz           | 2000 m                     | Moving target tracking                                                   |
| 2021 (Sharma et al. 2021) | MIMO employed Linear frequency modulated continuous wave                           | Simulation               | 77 GHz/600 MHz           | 750 m range                | Improved performance under adverse conditions                             |
| 2020 (Wang et al. 2020) | Distributed coherent mw photonic radar with Optical fibre time and frequency synchronization network | Experimental              | X band/ 4 GHz            | 4 cm resolution            | Range enhancement and mal- leable scalability                              |
| 2020 (Sharma et al. 2020) | bidirectional reflectance distribution function                                    | Simulation               | 77 GHz/ 600 MHz          | 25 cm                      | Improved performance                                                       |
| 2020 (Sharma and Kumar 2020) | Linear frequency modulated continuous wave                                        | Simulation               | 77 GHz/ 600 MHz          | 500 m range                | Improved performance                                                       |
upon square law process having high sensitivity to the intensity of received echo signal while Coherent detection is based upon linear process having sensitivity towards the phase, polarization and amplitude of the echo signal received (Adany et al. 2009). In this section we will discuss the basic structure and mathematical modelling of these configurations.

2.1 FMCW with direct detection

Figure 1 depicts FMCW based photonic radar configuration in direct detection arrangement. In transmitter section, triangular waveform generator is employed where pseudo-random signal is encoded in saw tooth waveform. This encoded signal is then modulated using linear frequency modulator (LFM) where operating frequency and corresponding bandwidth is selected based upon the application of the system. The frequency modulated signal is then fed into optical modulator where light source is used as carrier to carry modulated signal in the free space. In photonic radars based upon FMCW scheme, continuous wave laser source having wavelength \( \lambda \) and output power as \( P_t \) is used as carrier signal generator and Mach-Zander (MZ) modulator is used as optical modulator. The transfer function of MZ modulator is given as Eq. 1 (Agrawal 2012; Coutinho et al. 2005):

\[
\frac{E_{\text{Out}}}{E_{\text{in}}} = \cos\left(\phi_o + \frac{\pi S(t)}{2v_{\pi}}\right)
\]

(1)

where \( E_{\text{out}} \) and \( E_{\text{in}} \) signifies optical fields at output and input respectively, \( \phi_o \) DC biasing controlled initial phase, \( v_{\pi} \) in voltage needed to convert optical power transfer function (Hui and O’Sullivan 2009) and \( S(t) \) is linear frequency modulated signal given as in Eq. 2 (Hui and O’Sullivan 2009):

\[
S(t) = A_c \cos \left( 2\pi f_{\text{start}} t + \frac{\pi B}{T_m} t^2 \right)
\]

(2)

where \( A_c \) is amplitude of modulated signal, \( f_{\text{start}} \) is initial frequency, \( T_m \) is time interval and \( B \) is modulation bandwidth. In direct detection scheme, modulator works at quadrature point and its output is given as in equation (3) (Hui and O’Sullivan 2009):

Fig. 1 Schematic diagram of photonic radar system with direct detection
\[ E_{Tx}(t) = \sqrt{\frac{P_t}{2}} \left[ 1 + \frac{\beta}{2} \cos \left( 2\pi f_{start} t + \frac{\pi B T_m}{T_m} t^2 \right) \right] e^{j(\omega_0 t + \theta_o(t))} \] (3)

where \( \theta_o(t) \) is random varying transmitted phase component, \( \beta \) is modulation index \((<< 1)\) and \( \omega_0 \) is angular frequency. This output modulated signal is focused towards target using telescope.

Other factors such as transmitter and channel model, angular dispersion, atmospheric conditions, and reflectivity of the surface of target also affects the received signal strength. Echo signal power \( P_r \) is calculated as in Eq. (4) (Sharma et al. 2021):

\[
P_r = \begin{cases} 
P_t \rho_t D^2 \tau_{atm}^2 & \text{for extended target} \\
\frac{P_t \rho_t A_t D^2 \tau_{atm}^2}{4R^2 A_{ill}} & \text{for any target}
\end{cases}
\] (4)

where \( \rho_t \) is the surface reflectivity of target, \( A_{ill} \) is the irradiated zone at target, \( R \) is the range of target from FMCW photonic radar, \( D \) is the receiver aperture diameter, \( A_t \) is the area of the target, \( \tau_{atm} \) is the atmospheric loss factor, and \( \tau_{opt} \) optical domain loss in transmission. The echoed signal having doppler shift \( f_d = \frac{2v}{c} \) and delay of \( \tau = \frac{2R}{c} \) from the moving target at a range distance \( R \) and velocity \( v \) is collected by telescope. The rebounded signal intensity \( E_{ref} \) is given as in Eq. 5 (Elghandour and Ren 2013):

\[ E_{ref}(t) = \sqrt{P_r} \left[ 1 + \frac{\beta}{2} \cos(2\pi f_c(t - \tau) + \frac{\pi B}{T_m} (t - \tau)^2) \right] e^{j(\omega_0(t) - \omega_0) t + \theta_o)} \] (5)

Direct detection scheme has relatively simple receiver, as it works on square law detection and no optical mixing is required at receiver. The echoed signal is detected using photodiode having responsivity \( \Re \), and output photocurrent \( i_{ph} \) given as in Eq. 6 (Keiser 2003):

\[ i_{ph}(t) = \Re P_r (1 + \frac{\beta}{2} \cos(2\pi f_c(t - \tau) + \frac{\pi B}{T_m} (t - \tau)^2))^2 \] (6)

The baseband signal obtained from filtered photocurrent signal is given as in Eq. 7 (Elghandour and Dianren 2012):

\[ i_{ph}(t) = I_{dc} + i_{sig}(t) = \Re P_r (1 + \frac{\beta}{2} \cos(2\pi f_c(t - \tau) + \frac{\pi B}{T_m} (t - \tau)^2))^2 \] (7)

where \( i_{dc} \) and \( i_{sig} \) are dc and ac photocurrent of filtered signal. This output signal is mixed together with the RF-LFM generated signal to obtain the beat signal after low pass filter given in Eq. 8 (Elghandour and Ren 2013):

\[ S_b(t) = A_r \Re P_r B \cos(2\pi f_c \tau - \frac{\pi B}{T_m} \tau^2 + 2\pi f_r t) \] (8)

where \( f_r \) is range frequency and is calculated using Eq. 9 (Chaudhary et al. 2021c):

\[ f_r = \frac{2 \times R \times B}{T_m \times C} \] (9)

The working of FMCW based photonic radar system with direct detection scheme is accessed by computing signal to noise to ratio (SNR) at the output of the photo
detector. Different type of noise is usually found in detected signal such as thermal noise, dark current noise, relative intensity noise (RIN), shot noise and surface current noise (Agrawal 2012). We have considered shot and thermal current noise in SNR calculation as given in Eq. 10 (Chaudhary et al. 2021c):

\[
SNR_{dir} = \frac{\beta^2 R^2 P_i^2/2}{2qRP_i B_{rx} + 4k_b T_r B_{rx}/R_L}
\]  

(10)

where \(B_{rx}\) is the receiver bandwidth, \(q\) is the electrical charge \(\approx 1.6 \times 10^{-19}\) c, \(k_b\) is the Boltzmann constant \(\approx 1.38 \times 10^{-23}\) J/K, \(T_r\) is the receiver noise temperature and \(R_L\) is the load resistance.

### 2.2 FMCW with coherent detection—heterodyne configuration

Frequency modulated continuous wave photonic radar in coherent detection is presented with basic heterodyne configuration in Fig. 2. Here unlike direct detection, optical signal mixing is performed employing balanced dual photo detector collaborated with 3 dB optical coupler. For this reason, the laser signal is divided into two parts, one is modulated in MZM with LFM signal and other is used as local oscillator signal to be mixed with received echoes signal using optical coupler.

The output of coupler is expressed as in Eq. 11 (Elghandour and Ren 2013):

\[
E_{PD1} = \frac{1}{\sqrt{2}} \left[ E_{lo}(t) + jE_{ref}(t) \right] \quad \text{&} \quad E_{PD2} = \frac{1}{\sqrt{2}} \left[ jE_{lo}(t) + E_{ref}(t) \right]
\]  

(11)

where \(E_{PD1}\) and \(E_{PD2}\) are signal strengths obtained at photodetector 1 and 2 respectively while \(E_{lo}(t)\) is strength of local oscillator expressed as in Eq. (12 Elghandour and Ren 2013):

\[
E_{lo}(t) = \sqrt{P_{lo}} e^{i(\omega_o t + \theta_{lo}(t))}
\]  

(12)

where \(\theta_{lo}(t)\) is random time varying function and \(P_{lo}\) is optical intensity of the local oscillator. The reflected signal strength is expressed as in equation (13) (Elghandour and Ren 2013):
The signal is subjected through the balanced photo detector and band pass filter to obtain the information signal from the subtracted DC element as in Eq. (14) (Elghandour and Ren 2013):

\[ i_p(t) = 2\mathbb{R}\sqrt{P_{lo}P_r}\cos(2\pi f_{start}(t - \tau) + \frac{\pi B}{T_m}(t - \tau)^2)e^{j\left((\omega_d + \omega_a)t + \theta_{ao}\right)} \]  

(14)

The removed DC element is given as in equation (15) (Elghandour and Ren 2013):

\[ i_{dc} = \frac{P_{lo}}{2} + \frac{P_r}{4} \text{ (for weak signal)} \approx \frac{P_{lo}}{2} \]  

(15)

If the doppler shift effect is not considered, the heterodyne detection becomes susceptible to the carrier fading. The beat signal obtained after the low pass filter is given as in Eq. (16) (Elghandour and Ren 2013):

\[ S_b(t) = \mathbb{R}A_{lo}\sqrt{P_{lo}P_r}\cos\left(2\pi f_{start}t - \frac{\pi B}{T_m}t^2 + 2\pi f_d t\right)\sin\left(\omega_d t + (\theta_d(t) - \theta_{lo}(t))\right) \]  

(16)

The signal to noise ratio calculated at photodetector is expressed as in Eq. (17) (Elghandour and Ren 2013):

\[ SNR_{heter} = \frac{\mathbb{R}^2 P_{lo}P_r}{q\mathbb{R}P_{lo}B_{rx} + 4k_B T_r B_{rx}/R_L} \text{ (in shot noise limited cases)} \approx \frac{P_r}{2qB_{rx}} \]  

(17)

### 2.3 FMCW with coherent detection—homodyne configuration

The coherent detection scheme in homodyne configuration is depicted in Fig. 3.

As shown, the output of the modulator is divided into two parts; one is fed into the channel for detection while other part is used in receiver section as local oscillator signal. The local oscillator signal is given as in Eq. 18 (Elghandour and Ren 2013):

![Fig. 3 Schematic diagram of photonic radar system with coherent detection in homodyne configuration](image-url)
The balanced photo detector is employed with ideal 3 dB optical coupler to mix this local oscillator signal $E_{lo}(t)$ with the echo signal power $E_{ref}(t)$. The output of photodetector signal is as given in Eq. 19 (Elghandour and Ren 2013):

$$i_p(t) = 2\Re.\sqrt{P_{lo}P_r}\cos\left(2\pi f_{\text{start}}t + \frac{\pi B}{T_m}t^2\right)\cos(2\pi f_c(t - \tau) + \frac{\pi B}{T_m}(t - \tau)^2\sin(\omega_o t + (\theta_o(t) - \theta_{lo}(t)))$$

(19)

The beat signal is obtained by filtering the photo detector output as given in Eq. 20 (Elghandour and Ren 2013):

$$S_b(t) = 2\Re.\beta A_{lo}\sqrt{P_{lo}P_r}\cos\left(2\pi f_{\text{start}}t - \frac{\pi B}{T_m}t^2 + 2\pi f_c t\right)\sin(\omega_o t + (\theta_o(t) - \theta_{lo}(t)))$$

(20)

And signal to noise ratio in homodyne configuration is given as in Eq. 21 (Sharma et al. 2021):

$$SNR_{homo} = \frac{\beta^2\Re^2 P_{lo}P_r/2}{q\Re\beta^2 P_{lo}P_r/4 + 4k_bT_r B_{rx}/R_L} \quad \text{(in shot noise limited cases)} \approx \frac{\Re P_r}{2qB_{rx}}$$

(21)

3 Numerical simulation

In this section we will model the basic design of all three configuration as discussed in section II to verify its working using simulation software Optisystem™. The target model is characterised using MATLAB package to be co-simulated with Optisystem™. Various parameters of the components used in the simulations are defined in Table 2 and are kept similar for all the three configurations. To end, we compare the obtained results of all three configurations.

3.1 Direct detection configuration model simulation

FMCW based photonic radar in direct detection configuration simulation modelled using Optisystem™. As described in section II, the frequency modulated saw tooth signal is mixed with optical signal using dual port MZ modulator and transmitted towards stationary target. The target model subsystem is created using MATLAB to be co-simulated with Optisystem™ while rest of the model is designed using Optisystem™. The initial or start frequency is 300 MHz with a bandwidth of 600 MHz. The target is assumed to be stationary and placed at 1000 m.

Figure 4 shows successful detection of stationary target. The output power of laser is 20 dBm which is modulated with LFM signal and transmitted towards the target. The echo signal intensity received from the target $P_r$ is 7.95 dBm (0.16 mW) and detected signal intensity is observed as $P_{\text{sig}} = -75.45$ dBm ($7.5 \times 10^{-10}$ W). The Signal observed using analyser is as shown in Fig. 5. The range frequency $f_R$ is calculated using Eq. 9 and observed in simulation results is the same that is 200 MHz at the range distance of 1000 m.
**Table 2** System parameters

| Parameters                              | Values               |
|-----------------------------------------|----------------------|
| Start Frequency                         | 300 MHz              |
| Bandwidth                               | 600 MHz              |
| PRF (Pulse repetition frequency)        | 200 kHz              |
| RF spectrum resolution                  | 1 MHz                |
| CW laser wavelength                     | 1550 nm              |
| Output Power                            | 20 dBm               |
| Laser Line width                        | 100 kHz              |
| OSA resolution                          | 0.02 nm              |
| Range                                   | 1000 m               |
| Atmospheric loss factor                 | 1                    |
| Optical Transmission loss               | 1                    |
| Reflectivity                            | 1                    |
| Receiver Aperture diameter              | 15 cm                |
| Optical detector                        | PIN                  |
| Responsivity                            | 1A/W⁻¹               |
| Sampling Rate                           | 4 GHz                |
| Receiver Noise Temperature              | 290 k                |
| Load Resistance                         | 50Ω                  |
| Band-width (shot)                       | 4 MHz                |
| Thermal noise                           | 10⁻²⁴ WHz⁻¹           |
| Optical Amplifier (OA)                  | 20 dB                |
| Electrical Amplifier                    | 40 dB                |
| DMZM -ve quadrature point               |                      |
| Switching RF voltage                    | 4v                   |
| Switching bias voltage                  | 4v                   |
| Extinction ratio                        | 30 dB                |

**Fig. 4** Detection and Range frequency measurement of stationary target placed at 1000 m
3.2 Coherent detection—heterodyne configuration simulation

The coherent detection of FMCW based photonic radar using heterodyne configuration modelled using Optisystem™. As discussed in section II, coherent detection can detect target range as well as velocity at the same time. This is done by considering the Doppler shift effect. The system is simulated to range stationary target at 1000 m with resultant range frequency of 200 MHz as calculated by Eq. 9 and moving target with velocity of 75 km/hr ($f_d \approx 27$ MHz). The simulation results are shown in Fig. 5 where 5(a) presents detection of stationary target and 5(b) presents waveform having output spectrum of double side band suppressed carrier with bandwidth equals to the twice of doppler frequency such that upper side band having frequency equal to $f_r + f_d = 227$ MHz and lower side band with frequency $f_r - f_d = 173$ MHz.

3.2.1 Coherent detection—homodyne configuration simulation

The simulation setup of homodyne configuration in coherent detection scheme is modelled in Optisystem™. Like heterodyne configuration, homodyne scheme detects range and velocity simultaneously. Figure 6 presents the detection of stationary and moving target.

The performance of direct detection and coherent detection in heterodyne & homodyne configuration is compared in Table 3.

4 Conclusion

Photonics based radars preferred over traditional microwave radar as it offers high resolution in differentiating targets due to wide bands and tuning speed of generators. In this paper we have reviewed the basic FMCW technique and its integration in photonic based radars. We have studied mathematical modelling of direct detection scheme as well as coherent detection scheme and analysed heterodyne and homodyne configuration of coherent detection technique. The simulated results shows detection of a single target at a range of 1000 m results in range frequency of 200 MHz. The same are verified

![Fig. 5](image-url) Detection and Range frequency measurement using heterodyne configuration of a stationary target placed at 1000 m, b moving target with velocity 75 km/h
with theory-based calculation for finding range frequency. Also a scenario is considered where target is moving with 75 km/Hr speed results in Doppler shift of 27 MHz. In the reported results two peaks are observed showing doppler shift in case of moving target. It is concluded that direct detection offers simpler system with only detection capability for short-range target while coherent detection-based system offers distance detection as well as velocity estimation for greater target ranges with a disadvantage of high complexity. In future works, system capacity can be increased by employing various multiplexing techniques to detect multiple targets as well as higher frequency bands can be applied for achieving greater resolution.

Fig. 6 Detection and Range frequency measurement using homodyne configuration of a stationary target placed at 1000 m, b moving target with velocity 75 km/h
Table 3  Comparison of FMCW based photonic radar’s different configuration (Elghandour and Dianren 2012)

| Parameters       | Direct detection | Coherent detection |
|------------------|------------------|--------------------|
|                  |                  | Heterodyne         | Homodyne           |
| Sensitivity      | Towards echo signal strength | Towards echo signal strength as well as phase |
| Application      | Range measurement | Range as well as velocity measurement |
| Advantages       | Minimal complex architecture | High sensitivity and long range |
| Disadvantage     | Low sensitivity and limited range | High complexity | Need of phase diversity and high complexity |
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Declarations

Competing interests The authors have not disclosed any competing interests.

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