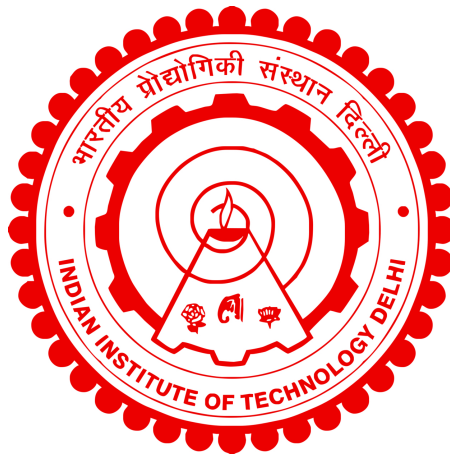


**MODELING AND STATISTICAL ANALYSIS OF
AUTOMOTIVE RADAR NETWORKS USING LINE
COX PROCESSES**

MOHAMMAD TAHA SHAH



**BHARTI SCHOOL OF TELECOMMUNICATIONS AND
MANAGEMENT**

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2025

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Modeling and Statistical Analysis of Automotive Radar Networks Using Line Cox Processes

A THESIS

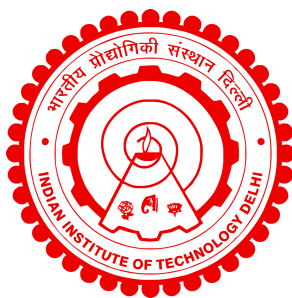
*SUBMITTED IN FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF*

Doctor of Philosophy

by

Mohammad Taha Shah

to



**Bharti School of Telecommunications and Management
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

July 2025

Dedicated to My Creator

THESIS CERTIFICATE

This is to certify that the thesis entitled “**Modeling and Statistical Analysis of Automotive Radar Networks Using Line Cox Processes**”, submitted by **Mohammad Taha Shah** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of the original, bona fide research work carried out by him under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree. The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of our knowledge.

July 2025

Prof. Gourab Ghatak
Assistant Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
New Delhi, 110016

ACKNOWLEDGEMENTS

First and foremost, all praise and gratitude are due to my creator **Allah (S.W.T)**, the Most Gracious and Most Merciful, for granting me the strength, guidance, and perseverance to complete this journey. Without His blessings and unwavering support, this accomplishment would not have been possible.

I would like to express my deepest gratitude to my supervisor **Prof. Gourab Ghatak**, whose invaluable guidance, constructive feedback, and constant encouragement have been instrumental in shaping this thesis. Your expertise and dedication to fostering academic growth have been a source of immense inspiration throughout this process.

To my beloved parents **Imtiyaz Ahmad Shah** and **Rubeena Jabeen**, and my sister **Sidrah Imtiyaz**, words cannot adequately convey my appreciation for your unconditional love, sacrifices, and steadfast belief in me. Your unwavering support has been the foundation upon which I have built my aspirations, and I am eternally grateful for everything you have done for me.

A heartfelt thank you goes to my dear friend **Sabrina Khurshid**, whose companionship, encouragement, and shared moments of laughter helped lighten the challenges along the way. Your presence has been a constant reminder that no endeavor is too daunting when faced with true friendship.

Lastly, I acknowledge myself for embracing this challenge with determination, resilience, and hard work. This thesis reflects not only years of study but also personal growth, patience, and commitment—a testament to what can be achieved through perseverance.

I extend my sincerest thanks to everyone who has contributed directly or indirectly to this work. May this effort serve as a stepping stone toward greater achievements and continued learning.

Thank you!!

ABSTRACT

KEYWORDS: Stochastic Geometry, Line processes, Cox processes, Binomial line Cox process, Automotive Radar, Meta Distribution

The rapid evolution of wireless communication systems and automotive radar technologies has introduced new challenges in modeling, analyzing, and optimizing complex network environments. This thesis addresses these challenges by developing advanced spatial models based on stochastic geometry—specifically, the novel binomial line Cox process (BLCP) and the classical Poisson line Cox process (PLCP).

While the Poisson line process (PLP) and PLCP have been widely used to represent street networks and spatial distributions in wireless systems, their assumptions of homogeneity and stationarity limit their ability to model real-world urban and suburban environments. To overcome these limitations, this thesis introduces the binomial line process (BLP) and its associated Cox process BLCP, which capture non-stationarity by accounting for varying street densities, finite street lengths, and spatial heterogeneity. These models offer a more accurate representation of urban layouts, encompassing both dense city centers and sparsely distributed suburban regions.

Analytical expressions are derived for key spatial metrics of the BLP, including radial line length density, intersection density, and distance distributions. These metrics quantify how average street characteristics evolve with distance from the city center, revealing the modeling flexibility of the BLP. The analytical framework is applied to location-dependent performance evaluations, such as user connectivity in wireless networks and radar detection reliability in vehicular networks. To validate the theoretical modeling of the BLP, we capitalize on geospatial data obtained using the OSMnx tool, which facilitates the extraction and analysis of detailed urban street network data. By fitting the parameters of the BLP to real-world data, we demonstrate their ability to accurately capture the spatial characteristics of urban environments.

The BLCP serves as the novel way for modeling wireless networks in this work, capturing the non-homogeneous deployment of access point (AP)s along streets. By deriving the probability generating functional (PGFL) for the BLCP, the thesis analyzes transmission success probability and conducts location-based performance evaluations. Further analysis includes deriving the meta distribution (MD) of the signal-to-interference-plus-noise ratio (SINR) and calculating conditional success moments to characterize behaviors like local delay and transmission density. These insights provide a foundation for designing robust wireless systems adapted to spatial heterogeneity.

In the domain of automotive radar networks, the thesis leverages the BLP and BLCP to evaluate radar detection probability under varying conditions of street density, vehicle density, and beamwidth. This analysis yields insights into the impact of street density, vehicular density, and beamwidth on radar detection probability, offering valuable guidance for automotive manufacturers and network operators aiming to optimize system designs under practical conditions. To enhance detection efficiency, the thesis proposes optimization frameworks based on MD and negative moment analysis. These frameworks enable fine-grained tuning of radar parameters such as transmission probability and beamwidth, maximizing system reliability. Specifically, by leveraging the first negative moment of the MD, we derive metrics related to the timing of the first successful detection. These metrics are then utilized to optimize the transmission probability, ensuring improved system efficiency and reliability.

In summary, this thesis advances the state-of-the-art in stochastic geometry, specifically line Cox processes, by introducing the BLP and the BLCP as powerful tools for analyzing and optimizing heterogeneous network systems. Each chapter concludes with a system design insight that bridges theoretical and practical perspectives, offering readers—including network operators, urban planners, engineers, and policymakers—actionable takeaways to guide real-world implementation. It addresses the growing demands of modern urban landscapes, such as the need for ubiquitous high-speed communication networks, efficient utilization of street-level infrastructure, and the deployment of intelligent transportation systems to support connected and autonomous vehicles.

सारांश

वायरलेस संचार प्रणालियों और ऑटोमोटिव रडार प्रौद्योगिकियों के तेज़ी से विकास ने जटिल नेटवर्क परिवेशों के मॉडलिंग, विश्लेषण और अनुकूलन में नई चुनौतियाँ पेश की हैं। यह शोध प्रबंध स्टोकेस्टिक ज्यामिति पर आधारित उन्नत स्थानिक मॉडल विकसित करके इन चुनौतियों का समाधान करता है—विशेष रूप से, नवीन द्विपद रेखा कॉक्स प्रक्रिया (बीएलसीपी) और शास्त्रीय पॉइसन रेखा कॉक्स प्रक्रिया (पीएलसीपी)।

हालाँकि पॉइसन रेखा प्रक्रिया (पीएलपी) और पीएलसीपी का उपयोग वायरलेस प्रणालियों में सड़क नेटवर्क और स्थानिक वितरण को दर्शाने के लिए व्यापक रूप से किया गया है, उनकी समरूपता और स्थिरता की मान्यताएँ वास्तविक दुनिया के शहरी और उपनगरीय परिवेशों को मॉडल करने की उनकी क्षमता को सीमित करती हैं। इन सीमाओं को दूर करने के लिए, यह शोध प्रबंध द्विपद रेखा प्रक्रिया (बीएलपी) और उससे जुड़ी कॉक्स प्रक्रिया बीएलसीपी का परिचय देता है, जो अलग-अलग सड़क घनत्वों, सीमित सड़क लंबाई और स्थानिक विषमता को ध्यान में रखकर गैर-स्थिरता को दर्शाती है। ये मॉडल शहरी लेआउट का अधिक सटीक प्रतिनिधित्व प्रदान करते हैं, जिसमें घने शहरी केंद्र और विरल रूप से वितरित उपनगरीय क्षेत्र दोनों शामिल हैं।

बीएलपी के प्रमुख स्थानिक मेट्रिक्स के लिए विश्लेषणात्मक अभिव्यक्तियाँ व्युत्पन्न की गई हैं, जिनमें रेडियल लाइन लंबाई घनत्व, प्रतिच्छेदन घनत्व और दूरी वितरण शामिल हैं। ये मेट्रिक्स शहर के केंद्र से दूरी के साथ औसत सड़क विशेषताओं के विकास को मापते हैं, जिससे बीएलपी के मॉडलिंग लचीलेपन का पता चलता है। विश्लेषणात्मक ढाँचे का उपयोग स्थान-निर्भर प्रदर्शन मूल्यांकनों, जैसे वायरलेस नेटवर्क में उपयोगकर्ता कनेक्टिविटी और वाहन नेटवर्क में रडार डिटेक्शन विश्वसनीयता, पर किया जाता है। बीएलपी के सैद्धांतिक मॉडलिंग को मान्य करने के लिए, हम OSMnx टूल का उपयोग करके प्राप्त भू-स्थानिक डेटा का उपयोग करते हैं, जो विस्तृत शहरी सड़क नेटवर्क डेटा के निष्कर्षण और विश्लेषण को सुगम बनाता है। बीएलपी के मापदंडों को वास्तविक दुनिया के डेटा में फिट करके, हम शहरी वातावरण की स्थानिक विशेषताओं को सटीक रूप से पकड़ने की उनकी क्षमता प्रदर्शित करते हैं।

बीएलसीपी इस कार्य में वायरलेस नेटवर्क के मॉडलिंग के लिए एक नए तरीके के रूप में कार्य करता है, जो सड़कों पर एक्सेस पॉइंट (एपी) के गैर-सजातीय परिनियोजन को पकड़ता है। बीएलसीपी के लिए संभाव्यता जनन क्रियात्मक (पीजीएफएल) व्युत्पन्न करके, यह शोध प्रबंध संचरण सफलता की संभावना का विश्लेषण करता है और स्थान-आधारित प्रदर्शन मूल्यांकन करता है। आगे के विश्लेषण में सिग्नल-टू-इंटरफेरेंस-प्लस-नॉइज़ रेशियो (SINR) का मेटा वितरण (MD) प्राप्त करना और स्थानीय विलंब और संचरण घनत्व जैसे व्यवहारों को चिह्नित करने के लिए सशर्त सफलता क्षणों की गणना करना शामिल है। ये जानकारीयें स्थानिक विषमता के अनुकूल मज़बूत वायरलेस सिस्टम डिज़ाइन करने के लिए एक आधार प्रदान करती हैं।

ऑटोमोटिव रडार नेटवर्क के क्षेत्र में, यह शोध-प्रबंध सड़क घनत्व, वाहन घनत्व और बीम-चौड़ाई जैसी विभिन्न स्थितियों में रडार पहचान संभावना का मूल्यांकन करने के लिए BLP और BLCP का उपयोग करता है। यह विश्लेषण सड़क घनत्व, वाहन घनत्व और बीम-चौड़ाई के रडार पहचान संभावना पर प्रभाव के बारे में अंतर्दृष्टि प्रदान करता है, जो व्यावहारिक परिस्थितियों में सिस्टम डिज़ाइनों को अनुकूलित करने के इच्छुक ऑटोमोटिव निर्माताओं और नेटवर्क ऑपरेटर्स के लिए मूल्यवान मार्गदर्शन प्रदान करता है। पहचान दक्षता बढ़ाने के लिए, यह शोध-प्रबंध MD और नकारात्मक क्षण विश्लेषण पर आधारित अनुकूलन ढाँचों का प्रस्ताव करता है। ये ढाँचे रडार

मापदंडों जैसे संचरण संभावना और बीम-चौड़ाई को सूक्ष्म रूप से समायोजित करने में सक्षम बनाते हैं, जिससे सिस्टम विश्वसनीयता अधिकतम होती है। विशेष रूप से, MD के पहले नकारात्मक क्षण का लाभ उठाकर, हम पहले सफल पहचान के समय से संबंधित मीट्रिक प्राप्त करते हैं। इन मेट्रिक्स का उपयोग ट्रांसमिशन संभावना को अनुकूलित करने के लिए किया जाता है, जिससे बेहतर सिस्टम दक्षता और विश्वसनीयता सुनिश्चित होती है।

संक्षेप में, यह शोध प्रबंध स्टोकेस्टिक ज्यामिति, विशेष रूप से लाइन कॉक्स प्रक्रियाओं में अत्याधुनिक तकनीक को आगे बढ़ाता है, जिसमें विषम नेटवर्क प्रणालियों के विश्लेषण और अनुकूलन के लिए शक्तिशाली उपकरण के रूप में बीएलपी और बीएलसीपी का परिचय दिया गया है। प्रत्येक अध्याय एक सिस्टम डिज़ाइन अंतर्दृष्टि के साथ समाप्त होता है जो सैद्धांतिक और व्यावहारिक दृष्टिकोणों को जोड़ता है, पाठकों को-जिनमें नेटवर्क ऑपरेटर, शहरी योजनाकार, इंजीनियर और नीति निर्माता शामिल हैं-वास्तविक दुनिया में कार्यान्वयन का मार्गदर्शन करने के लिए कार्रवाई योग्य जानकारी प्रदान करता है। यह आधुनिक शहरी परिदृश्यों की बढ़ती माँगों को संबोधित करता है, जैसे सर्वव्यापी उच्च गति संचार नेटवर्क की आवश्यकता, सड़क-स्तरीय बुनियादी ढाँचे का कुशल उपयोग, और कनेक्टेड और स्वायत्त वाहनों का समर्थन करने के लिए बुद्धिमान परिवहन प्रणालियों की तैनाती।

Contents

THESIS CERTIFICATE	i
ACKNOWLEDGEMENTS	ii
ABSTRACT	iii
LIST OF FIGURES	xii
LIST OF TABLES	xv
ABBREVIATIONS	xvi
1 Introduction	1
1.1 Stochastic Geometry Foundations	2
1.1.1 Principal Concepts	2
1.1.2 Binomial Point Process	4
1.1.3 Poisson Point Process	5
1.1.4 Void Probability	6
1.2 Classical Stochastic Geometry Network Models and Metrics	6
1.2.1 Canonical Network Models	6
1.2.2 Performance Metrics	7
1.3 Background and Motivation	8
1.4 Poisson line process	10
1.4.1 Properties of PLP	11
1.5 Limitations of Poisson line process	13
1.6 Automotive Radar Networks: Features and Modeling Goals	15
1.7 Contributions and Organization	17
1.8 List of Publications	20
2 Binomial Line Process	22

2.1	Related Works	22
2.2	Contributions	23
2.3	Binomial Line Process	25
2.3.1	Construction	25
2.3.2	Domain Bands in \mathcal{D}_B	26
2.4	Statistical features of Binomial line process	28
2.4.1	Distance distribution to the nearest line of Binomial line process . .	28
2.4.2	Line Length Radial Density and Measure	29
2.4.3	Radial Intersection Density	30
2.4.4	Distance Distribution to the Nearest Intersection	32
2.5	OSMnx: Urban Network Analysis Tool	35
2.6	Parameter approximation for PLP and BLP	37
2.7	Key Insights for Infrastructure & City Planners	38
2.8	Summary	39
3	BLCP: Characterization and Applications to Wireless Network Analysis	41
3.1	Related Works	41
3.2	Contributions	43
3.3	BLCP	44
3.3.1	Void Probability	45
3.4	Probability Generating Functional	46
3.5	Transmission Success Probability	47
3.5.1	Success Probability - Definition	47
3.5.2	Success probability for BLCP Locations of AP	48
3.6	Application - Meta Distribution of the SINR in BLCP	50
3.7	Numerical Results and Discussion	53
3.7.1	On the Success Probability	54
3.7.2	Optimal Network Parameters	56
3.7.3	Comparison with non-homogeneous Cox models	56
3.7.4	Results on Moments of Conditional Success Probability and Meta Distribution	58

3.8	Design Insights for Network Planners and Wireless Engineers	60
3.9	Summary	61
4	Modeling and performance analysis of automotive radar networks	63
4.1	Related Work	63
4.2	Motivation	65
4.3	Contributions	66
4.4	Network Geometries	67
4.4.1	Defining 1D Poisson point process (PPP) for lines of PLCP and BLCP	68
4.4.2	PLCP	69
4.4.3	BLCP	70
4.5	SIR and Channel Model	71
4.6	Characterization of the Interference Process	73
4.6.1	Interfering Set	74
4.6.2	Interfering Distance	76
4.7	Detection Success Probability	80
4.8	Numerical Results and Discussion	81
4.8.1	Success Probability	82
4.8.2	Average number of interferers	85
4.8.3	Detection performance of BLCP v/s PLCP	86
4.8.4	Performance of ego radar in real-world road structures	86
4.9	Design Insights for Automotive Radar Networks	88
4.10	Summary	89
5	Fine-grained analysis of automotive radar networks	91
5.1	Related works	92
5.2	Contributions	93
5.3	System Model	94
5.3.1	PLCP	95
5.3.2	BLCP	95
5.3.3	Channel Access, SIR, and SF	96
5.4	Average number of potential targets	97

5.4.1	Average number of PLCP points in $\mathcal{N}_{(0,0)}^+(R)$	97
5.4.2	Average number of BLCP points in $\mathcal{N}_{(0,r_0)}^+(R)$	99
5.5	Meta distribution Analysis	101
5.5.1	Meta Distribution of SF	101
5.5.2	Detection Success Probability	104
5.5.3	Reconstruction of MD of $p_{\text{SF},k}(\beta_{\text{SF}})$ from $M_{b,k}(\beta_{\text{SF}})$	105
5.6	Numerical Results and Discussion	107
5.6.1	Optimal Parameters	107
5.6.2	Reconstruction of MD	110
5.6.3	Inference from reconstructed MD - $\mathcal{P}_{\text{M},k}(\beta_{\text{SF}}, t_{\text{SF}})$	112
5.6.4	Optimization through MD	114
5.7	Design Insights for Automotive Radar Networks	116
5.8	Summary	116
6	Conclusions	118
6.1	Summary	118
6.1.1	Key Learning Across Chapters	118
6.1.2	Synthesis of Contributions	120
6.2	Future Directions	121
A	Appendix A: Proofs of Chapter 3	136
A.1	Proof of Theorem 1	136
A.2	Proof of Theorem 2	136
A.3	Proof of Lemma 2	139
B	Appendix B: Proofs of Chapter 4	141
B.1	Proof of Theorem 4	141
B.2	Proof of Theorem 5	142
C	Appendix C: Proofs of Chapter 5	144
C.1	Proof of Theorem 7	144
C.2	Proof of Theorem 8	149

D Appendix D: Proofs of Chapter 7	150
D.1 Proof of Lemma 4	150
D.2 Proof of Theorem 10	154
Curriculum Vitae	157

List of Figures

1.1	(a) Mapping between representation space and Euclidean plane, and (b) realization of PLP.	11
1.2	(a) Part of New Delhi city map. Visual inspection reveals the inhomogeneity of the street density (b) PVT models for fitting for streets of Bordeaux [Glo10]. For a PVT, the model parameter is the density of the underlying PPP.	14
1.3	(a) A BLP with $n_B = 10$ and $R_g = 100$ (b) A PLP whose underlying PPP has intensity $\frac{n_B}{2\pi R_g}$ with $n_B = 10$ and $R_g = 100$. Note: Here, R_g is the radius of the circle in which BLP lines are generated.	15
2.1	Illustration of the construction of a BLP and intersecting lines on $\mathcal{B}((0, r_0), t)$	26
2.2	(a) Illustration of the domain bands for a PLP and a BLP with $R_g = 100$. (b) Domain bands for different values of t and r_0 . Here $R_g = 100$. Note that when $r_0 + t \leq R$, the domain bands for PLP and BLP coincide.	27
2.3	Distance distribution of the nearest line from $(0, r_0)$	29
2.4	(a) Line length density $\rho(r)$, and (b) Intersection density for $R_g = 50, 100$ and $n_B = 30, 50$ respectively.	32
2.5	Illustration of distances r_L and r_U (denoted by blue lines respectively) for a line (denoted by the green line) passing through $(0, r_0)$ and having angle ω_0 with the x-axis.	33
2.6	Illustration of the region $D_I(r_0, t)$ for different values of r_0, ω_0 and t . Here $R_g = 50$	34
2.7	Distance distribution to the nearest intersection from $(0, r_0)$	35
2.8	Fitting BLCP parameters (n_B, R_g) to road length data for (a) New Delhi, (b) Paris, (c) Washington, and (d) Johannesburg.	37
3.1	(a) Conditional PGFL of intersecting and non-intersecting lines (see (B.1)). Here $r_0 = 0$, $R_g = 50$, $\lambda = 0.1$ and $n_B = 10$, (b) Success probability with respect to r_0 , (c) $\mathbb{E} \left[\frac{d_1}{d_2} \right]$ with respect to r_0 , and (d) Success probability with respect to the density of APs.	54
3.2	(a) and (b) Success probability with respect to n_B	55
3.3	Comparison of success probability with respect r_0 for BLCP, PLCP, E1-PLCP, E2-PLCP, and E-BLCP.	58

3.4	(a) Mean local delay with respect to the transmit probability for different values of R_g and λ . Here, $r_0 = 0$. (b) Successful transmission density. (c) Optimal transmit probability for minimizing the mean local delay. (d) SINR meta distribution.	59
4.1	(a) Road map of New Delhi city, (b) A realization of PLCP having $\lambda_L = 0.005 \text{ m}^{-2}$ and $\lambda = 0.005 \text{ m}^{-1}$, with ego radar present at origin, and (c) A realization of BLCP having $n_B = 50$ and $\lambda = 0.005 \text{ m}^{-1}$, with ego radar present at $(0, r_0)$	70
4.2	PDF of signal + interference power and only interference power received at ego radar, if the target is at a distance uniformly distributed between 5 to 15 m, $\Omega = 30^\circ$, $\lambda_L = 0.01 \text{ m}^{-1}$, $\lambda = 0.05 \text{ m}^{-1}$, and transmit power is 1 dB.	73
4.3	Illustration of a scenario showing interfering and non-interfering radar sectors w.r.t. ego radar.	74
4.4	Illustration of a scenario where two radars are present at the edge point of the line L_i inducing interference.	78
4.5	Probability of successful detection $p_{D,P}$ with respect to (a) R , (b) λ , and (c) Ω	82
4.6	Probability of successful detection $p_{D,B}$ with respect to (a) r_0 , (b) R , (c) λ , and (d) Ω	83
4.7	(a) Average number of interferes falling inside the bounded radar sector w.r.t r_0 . (b) Comparison of $p_{D,k}$ of ego radar for PLCP and BLCP models w.r.t r_0	85
4.8	$\hat{\lambda}$ w.r.t. hour of the day for four cities	87
4.9	Detection performance across the hour of the day for four cities (a) New Delhi, (b) Paris, (c) Washington, and (d) Johannesburg.	88
5.1	(a) and (d) Number of successful detections versus Ω for PLCP and BLCP framework respectively, (b) and (c) Optimal beamwidth versus λ and R respectively for PLCP.	106
5.2	(a) and (b) Optimal beamwidth versus r_0 and R respectively for BLCP.	109
5.3	(a) signal fraction (SF) MD of an ego radar in PLCP framework generated through empirical, GP, and CM-bound methods, and (b) K-S distance between the CM-bound and empirical distribution, and the GP method, versus the number of moments	110
5.4	Plot between t_{SF} and β_{SF} where $\mathcal{P}_{M,k}(\beta_{SF}, t_{SF}) = \{0.1, 0.5\}$ for the CM method at $n = 21$ for (a) PLCP framework, (b) BLCP framework with $r_0 = 0$, and (c) for BLCP framework for different values of r_0	111
5.5	Transmission probability versus the mean local delay of an ego radar for (a) PLCP, and (c) BLCP model, (b) optimal transmission probability versus beamwidth in PLCP model, and (d) optimal transmission probability versus r_0 for BLCP.	114

A.1	Ratio of the line length measure to the area in concentric annuli of equal width $w = 2$	137
C.1	(a) and (b) <i>Subcase (a)</i> of Case 1, and (c) and (d) <i>Subcase (b)</i> of Case 1 with generating angle present in the first quadrant in all four figures.	145
C.2	(a) Case 2 with generating angle present in the first quadrant, and Case (3) with generating angle present in the third quadrant.	147
D.1	Case 1: When line L is intersecting one of the edges and the circular arc.	150
D.2	(a) Case 2: When line L intersects both one of the edges and not the circular arc, (b) Case 3: When line L intersects only the circular arcs, not the edges.	151
D.3	(a) Case 4: When line L intersects the axis vector outside the radar sector and ahead of ego radar, (b) Case 5: When line L intersects the axis vector outside the radar sector and behind the ego radar.	153
D.4	Different cases of the average length of lines in BLP depending on the location of ego radar.	155

List of Tables

2.1	Difference between PLP and BLP.	23
2.2	City maps and their corresponding detection performance across the hour of the day	36
3.1	Difference between our work and other papers.	43
4.1	Summary of notations used in this chapter.	66

ABBREVIATIONS

AP	access point
CCDF	complementary cumulative density function
CDF	cumulative density function
PDF	probability density function
PPP	Poisson point process
BS	base station
LOS	line of sight
SINR	signal-to-interference-plus-noise ratio
SIR	signal-to-interference ratio
SNR	signal-to-noise ratio
LOS	line-of-sight
NLOS	non line-of-sight
PGFL	probability generating functional
PLCP	Poisson line Cox process
MBS	macro base station
PLT	Poisson line tessellation
PVT	Poisson-Voronoi tessellation
PDT	Poisson-Delaunay tessellation
SBS	small cell base station
RAT	radio access technique
RCS	radar cross section
5G	fifth generation
PLP	Poisson line process
UE	user equipment
BPP	binomial point process
BLP	binomial line process
BLCP	binomial line Cox process

RSU	road-side unit
SG	stochastic geometry
MD	meta distribution
SF	signal fraction
PCP	Poisson cluster process
CSP	conditional success probability
QoS	Quality of Service
FMCW	frequency modulated continuous wave
V2X	vehicle-to-everything
MAC	medium access control
TDMA	time division multiple access
MHCP	Matern hardcore point process
ISAC	integrated sensing and communication
ADAS	advanced driver assistance systems