CHALLENGES AND DESIGN CONSIDERATIONS FOR RADAR OPERATION IN LOCAL LITTORAL

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ABSTRACT

Due to Singapore's geographical locality, its naval and airborne maritime surveillance radars operate in a unique littoral environment that poses a plethora of challenges to their system design. This article briefly describes these challenges, and focuses on relating experiences gained from operationalising radars that perform well in the local environment. These experiences include the stringent process of focusing on the system architecture design during the front-end definition phase, simulation and testing with environmental data during the development phase, and the eventual fine-tuning and optimisation phase through trials. With advancements in technology, this article also provides an overview of promising advanced radar developments and the expected benefits in the future.

Keywords: radar, littoral, surveillance

INTRODUCTION

The Naval Doctrine of the US Navy (2010) defines a littoral region as the portion of the world's land masses adjacent to the oceans within direct control of and vulnerable to the striking power of sea-based forces. Singapore, being one of the busiest ports in the world, is surrounded by busy and narrow water passages, where large numbers of vessels of varying sizes pass through. This results in a very complex littoral environment for local radar operations, posing a multitude of unique challenges for radar systems to track targets quickly, accurately and reliably. Hence, it is important that these challenges are identified and tackled through upfront design considerations, iterative system testing and optimisation.

This article presents the challenges faced and the considerations involved in designing a radar for operation in the local littoral environment. The first section of the article describes the key characteristics of the local littoral environment and how it is different from an open sea. This is followed by an overview of actual observations from local radar trials and demonstrations. Next, the article presents best practices of radar design and testing developed from these experiences to make the systems more robust for littoral surveillance. Finally, it concludes with a glimpse of promising technologies which have the potential to improve radar performance in the local environment.

OPERATIONAL ENVIRONMENT

When designing and evaluating a sensor system, a thorough understanding of the chief design drivers – mission profile, area of operation and targets of interest – is essential. This is especially critical in a complex littoral environment where there is a large variety and density of targets under anomalous propagation effects, multipath and radio frequency (RF) interferences. Figure 1 shows a satellite image of the congested Singapore harbour.

Figure 1. Singapore harbour on 27 June 2013
(LC81250592013178LGN01 courtesy of the U.S. Geological Survey)

Urban Coastline and Narrow Passageways

In the open sea, target returns are large compared to background sea and weather clutter. As such, sufficient target strength for detection can be accomplished easily to obtain a good surveillance picture. On the contrary, a target has to compete with land clutter and many other targets in a littoral environment. According to the US Energy Information Administration (2014), the Strait of Malacca is one of the world's most significant traffic choke points, with the Phillips Channel narrowing down to 1.7 miles wide close to the south of Singapore. This is exacerbated by coastlines lined with buildings and man-made structures which typically have strong radar reflections. In addition, the presence of targets at close proximity decreases the amount of reaction time available. This implies a heavier demand on the radar to be reliable in target detection and extraction.

Diversity of Targets

Due to the proximity to land, radars operating in a littoral environment also need to cope with a greater variety of targets which can be airborne, surface or pop-up targets from nearby land areas. Examples include small fast craft, helicopters, low flying unmanned aerial vehicles and submarine periscopes, all of which possess very disparate kinematics and physical traits and are used for different missions. Figure 2 illustrates this diversity based on typical Radar Cross Section (RCS) values and velocities at microwave frequencies (Skolnik, 2002).

Local Propagation Conditions

Chia, Khan and Chou (1988) highlighted that the equatorial location of Singapore results in an absence of strong storms and typhoons. The wind speeds in and out of Singapore are at a low average of about 10 knots, leading to calm conditions in the surrounding waters. The low sea states translate into reflective sea surfaces, which could result in multipath effects. Another propagation effect affecting radar performance is ducting. Although Young, Loke, Shui, and Chen (2010) found that ducting is not unique to the local landscape, this phenomenon, if not properly treated, may be exacerbated by strong urban clutter beyond the radar's instrumented range in a littoral environment.

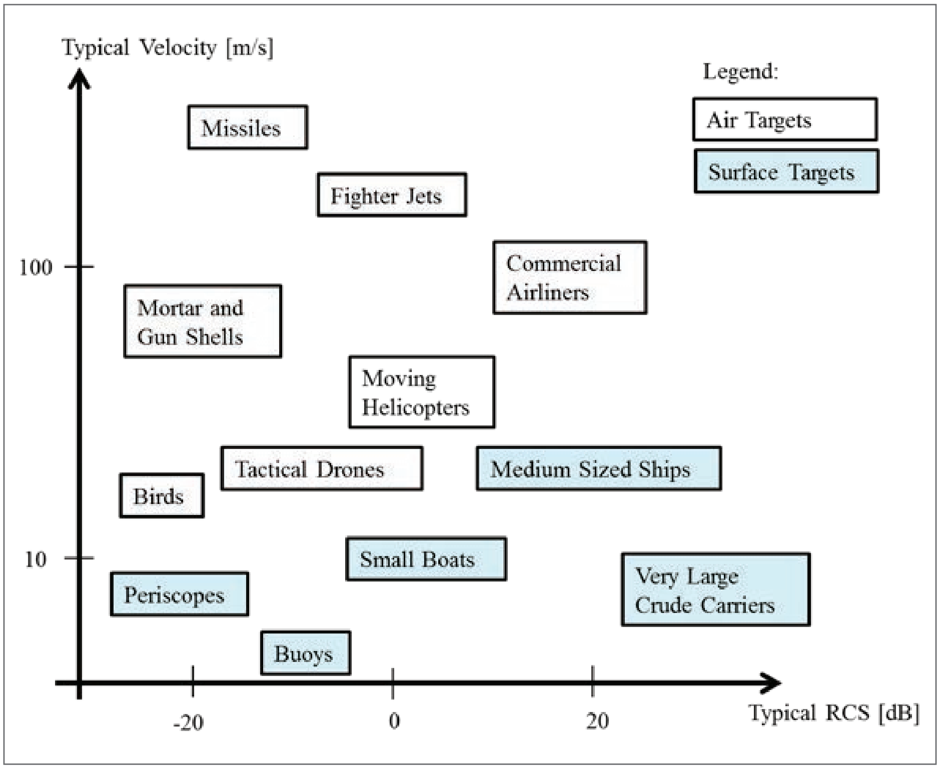

Figure 2. Targets and their typical RCS values and velocities

Interference

Compared to the open sea, a radar system operating in a littoral environment is within the range of interferences from shore-based emitters. Figure 3 shows a frequency allocation chart that depicts a crowded emission spectrum due to the proliferation of commercial communication networks for aeronautical, land mobile, meteorological and satellite services.

POSSIBLE OCCURRENCES

This section will provide insights into some possible observations due to effects of littoral environment on surveillance radar systems, the design optimisation required and the proposed best practices that have been adopted for front-end design definitions.

False Tracks

One main challenge of a littoral radar system is to maintain a large database of tracks while reporting at a very low false track rate. For automatic track initiation, a very frequent occurrence is the formation of false tracks on unwanted targets such as oil rigs and buoys that are swarming the already saturated surveillance picture. These effects are seen to be more severe for areas near urban coastlines with strong reflective points such as buildings.

To overcome these effects, both plot and track formation processes have to be examined. Figure 4 is a generic representation of a track-while-scan (TWS) radar's tracking flow where each step could be a factor contributing to the false track performance of the system. A system can erroneously initiate a track when there is poor quality of input plots and a lack of stringent coherency checks prior to associations of plots to tracks. This is because the quality of a track is based on the quality of the target kinematics measurement and plot formation process which includes detection, validation and unfolding. False tracks can also be formed when there is an improper treatment of detections of major scatterers across an extended target.

Short system latency is often desired for fast track updates. However, a reduction in system latency also trades off waiting time essential for correct plot-track association, especially in an environment with high target density in adjacent azimuth sectors.

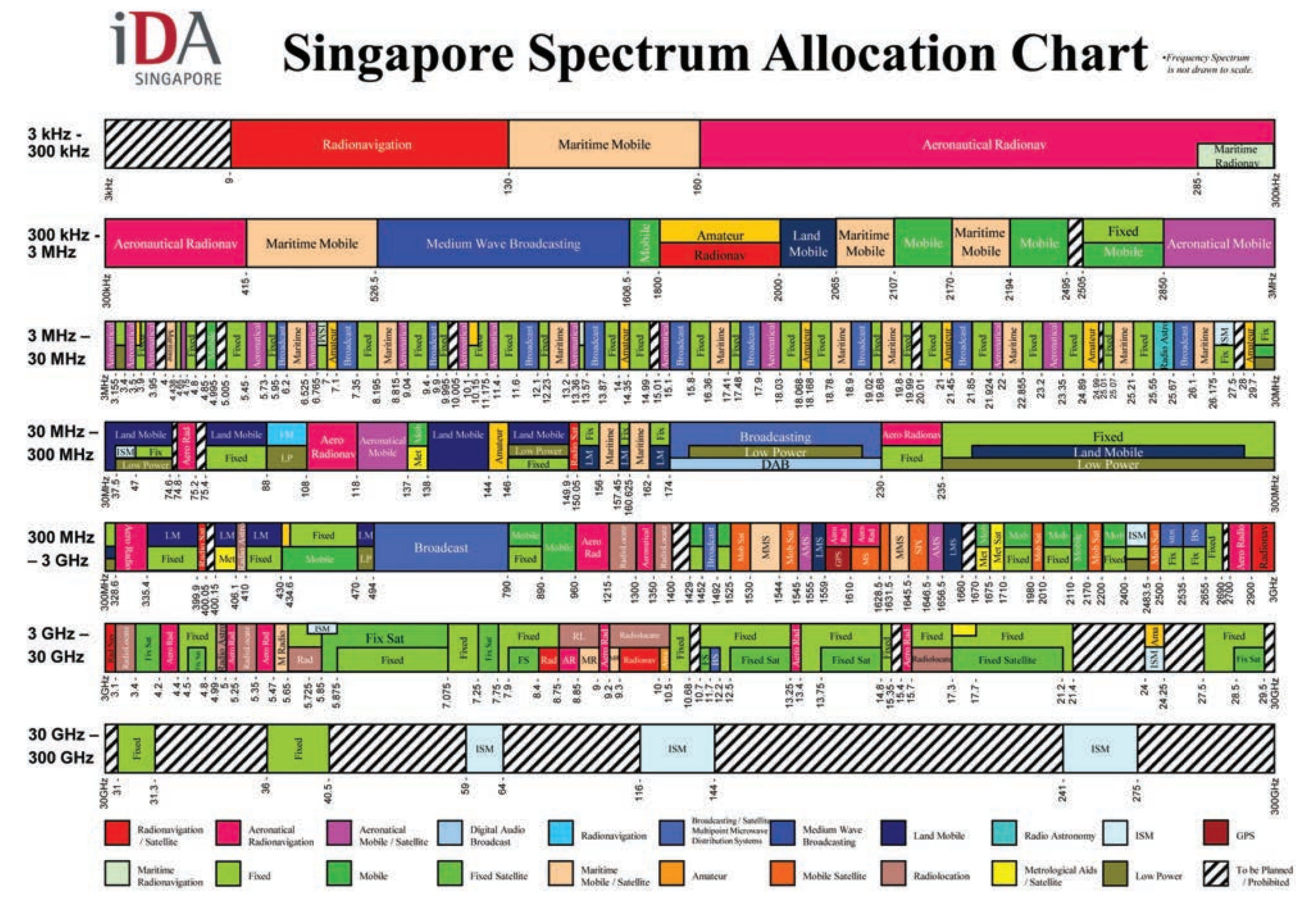

Figure 3. Spectrum allocation chart (Infocomm Development Authority, 2014)

Target Masking and Track Loss

It is common to have large surface vessels in the vicinity of one another in a littoral environment, possibly with smaller targets weaving among them. When a small boat approaches a larger surface target, the smaller target is masked by the larger target and its track drops. As radar systems are the 'eyes' of surveillance ships, such track loss events could place itself or others in perilous situations. In general, high RCS targets can easily cause a saturation of the radar, masking targets over an extensive range. This is also an indication of high time sidelobes[1], insufficient dynamic range and poor clutter rejection techniques.

Fluctuations and Degradations in Track Accuracies

Propagation losses and fluctuations in elevation measurements are the two major effects arising from multipath effects. Typically, radar systems possess track elevation accuracies in the order of milli-radians. However, when targets are flying at low elevations of less than one beamwidth, fluctuations in elevation accuracies have been observed to be as large as twice the actual flight level. In addition, the signal to noise ratio can be so low that there are no target detections in the multipath nulls. Such erratic elevation measurements decrease the operator's confidence in target identification and engagement. Figure 5 shows an example of the propagation losses due to multipath effects, with increasing values of attenuation from blue to red.

Degraded Target Characteristics

In addition to detection and tracking, surveillance radar systems often record the targets' kinematics and RF characteristics. An example is the use of the Doppler spread spectrum of helicopter hubs and blades. These RF returns are typically very weak, with at least 20dB less signal strength compared to the

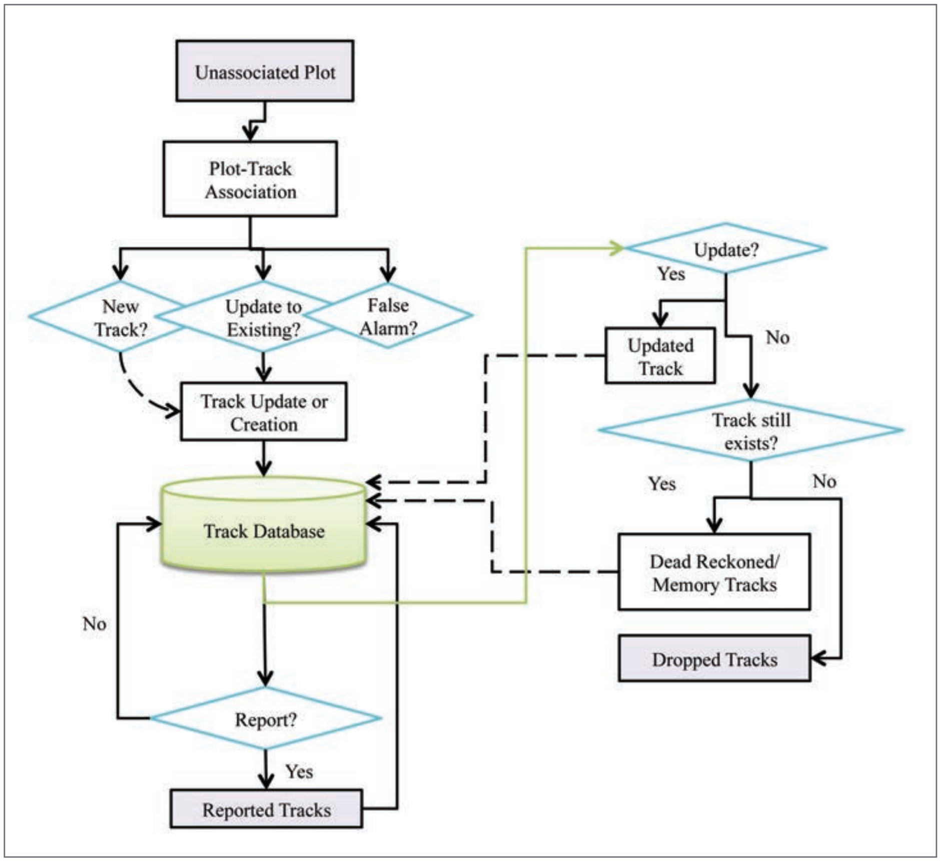

Figure 4. A generic TWS flowchart

main body RCS. Spread spectrum detection becomes more challenging when the helicopter is hovering over land mass. Additionally, if the presence of these Doppler modulations is a prerequisite for external track reporting, there might not be a helicopter track generated.

DESIGN BEST PRACTICES

With the accumulation of experiences and identification of possible areas of improvement, the following best practices and important watch areas have been established to improve front-end radar system definition and development, so that the radar is more suited for littoral surveillance.

Inherent Features

In a good littoral radar design, robust clutter rejection and false alarm control techniques are essential. To prevent receiver saturation and handle strong clutter, there should be adequate dynamic range, sensitivity and gain control. Traditional methods of gain control that apply similar suppression levels over the full radar scan will not be able to deal adequately with the non-homogenous clutter in a littoral environment. Adaptive and sector-based gain control methods may be more effective solutions. Similarly for constant false alarm rate, more sophisticated and rigorous methods will be needed to adapt to background noise and clutter statistics.

As medium pulse repetition frequency is often the preferred waveform scheme for littoral radars, the system design should also include the transmission and processing of fill-in pulses. Without these pulses, the Doppler responses will be widened, which could possibly lead to more false alarms. However, by assigning a default number of fill-in pulses, it is potentially using up more radar resource than necessary for the suppression of clutter returns.

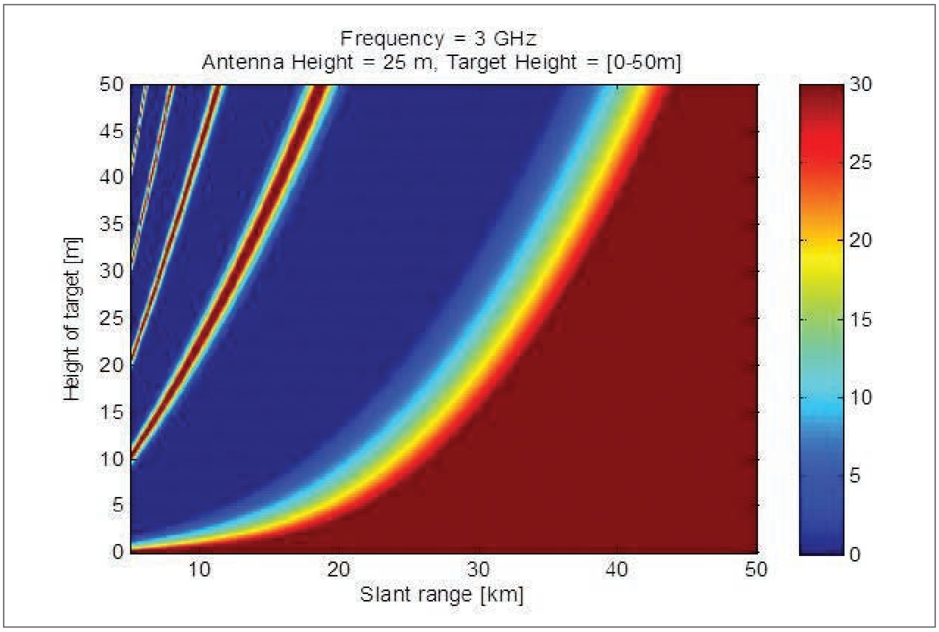

Figure 5. Propagation losses in dB due to multipath effects

Doppler measurement is often regarded only as a tool for determining a target's radial speed. In fact, Doppler information can be harvested for target discrimination, false track rate control and clutter rejection, all of which are indispensable properties of a littoral radar. For example, in the Doppler spectrum, surface clutter is characteristically located in the zero Doppler bin. With well-designed Doppler filters and good system stability, surface clutter can be suppressed effectively. In a cluster of targets where detections might be within similar range, azimuth and elevation cells, Doppler can be the main discriminator and help lower the probability of track swaps or splits. Furthermore, ensuring Doppler coherency in signal processing makes the system more robust against active jammers.

High tracking accuracy is highly desirable for target engagement as it improves the probability of kill for weapons using radar plots or tracks as their primary input for ballistic calculations. However, high track accuracy could also signify a deep running of a single track model filter which is unable to cope with target manoeuvres and sustain track continuity. A good surveillance radar should have an implementation which is also able to provide high track maintainability.

To counteract the increased risk of interference, littoral radar systems should have adequate self-protection measures. These measures can reside in the front-end design such as low antenna sidelobes, and in signal processing techniques such as asynchronous pulse rejection, sidelobe blanking and frequency agility.

Dedicated Techniques and Architecture

With the maturity of solid state transmitters, there is a move towards Active Electronically Scanned Array radars. This class of systems is usually associated with high volume search, flexible waveform multiplexing and graceful degradation. This architecture can also improve the system's dynamic range. A conventional analogue phased array performs beamforming by means of phase shifters before conversion to digital signal. As such, the analogue to digital converters have a high risk of saturation from the gain of the antenna. For digital beamforming, beam manipulation is performed only after the signals at every element are digitally converted. This results in a dynamic range gain as high as the gain of the antenna, which is beneficial for handling strong clutter returns.

Littoral radar systems should also have waveforms to cope with ad-hoc events. The closeness of the platform to surrounding coastal areas causes it to be more vulnerable to pop-up air and surface targets. It is therefore desirable for these tracks to be initiated with as few plots as possible, while retaining a low false track rate. To further reduce reaction time, there should also be a high degree of automation in the operation of the radar. As much as possible, operator actions should be required only when they have additional third party information which can be used as inputs to supplement the radar's performance.

SIMULATIONS, TESTS AND FINE-TUNING

System design reviews form the baseline theoretical analysis of the radar's capabilities. In order to determine the actual integrated radar performance, different types of tests from controlled laboratory setups to local on-site trials are typically conducted. To evaluate the effectiveness of the implemented signal processing techniques, simulations of RF returns can be injected in the radar signal processing units. Depending on the target scenario simulated, parameters such as reporting thresholds and classification criteria can be checked and further optimised. Full load scenario is one of the vital software tests to be performed for littoral radar systems. In addition to the large number of reported tracks due to an expected high target density, the radar should also be able to handle the voluminous internal detections and unreported tracks incurred in a littoral environment.

Software simulators are unable to emulate the operational environment with full fidelity as clutter and propagation effects are often omitted. One way of filling this gap is to use raw data collected from similar systems. However, in the usage of raw data from other systems, several areas must be taken care of by analysis or scaling to ensure the validity of output results. This includes the actual test setup from altitude and grazing angles to the scaling of RF front-end parameters such as antenna patterns, effective radiated power and attenuation settings.

Ultimately, local radar testing is the most robust method of performance validation. Therefore, from a project management perspective, ample time, sufficient amount of upfront planning and availability of a multitude of test targets should be catered to allow for comprehensive testing and fine-tuning of the radar. In general, performance testing can be broken down into: trial planning, conducting of trial, and analysis of collected data.

In the local environment where both ducting and multipath can be expected, learning to recognise such propagation effects and having an in-depth understanding of the impact of environmental conditions are crucial for trial planning and performance analysis. False alarm performance trial is also very challenging in a littoral environment compared to an open sea as a false track cannot be verified easily. Hence, varied and reliable sources of ground truth need to be made available to validate the performance of the radar.

LOOKING AHEAD

With improvements in antenna technology and software processing capability, many techniques which were previously deemed as computationally intensive have become practical to implement in real time.

Cognitive Radar

Haykin (2006) identified three ingredients of a cognitive radar – signal processing that builds on learning through interactions with the surrondings, feedback from receiver to transmitter, and preservation of collected information. Limited degrees of cognition are already manifested in many existing radar modes. An example is Least Jammed Frequency, where radar systems survey the surrounding spectral environment and use these findings to automatically select frequencies which are least interfered with for transmission. Another example is the mapping of clutter and plot density levels to provide feedback to the detection process of the radar. For a dynamic littoral environment, cognition in radar systems will facilitate continual estimations and adaptations to the environment. This can lead to better performance and reaction time in the future.

Multiple Input Multiple Output

Melvin and Scheer (2012) defined a Multiple Input Multiple Output (MIMO) radar as a system that has multiple transmitters emitting independent waveforms and observes the returns of the scene of interest with multiple receivers. In a widely separated configuration as explained by Haimovich, Blumand and Cimini (2008), MIMO is able to better exploit target reflectivity using disparate aspect angles, provide enhanced resolution of closely spaced targets and even improve Doppler estimations with the diversity of received waveforms. Hence, the realisation of MIMO systems can bring about significant gains for target detection and tracking in a littoral environment.

CONCLUSION

The complex littoral environment imposes a unique set of challenges for radar systems. The accrual of experiences in this demanding landscape has resulted in the formulation of numerous design best practices such as accurate Doppler measurements, high track maintainability and flexible resource allocation. In addition to these requirements, it is also pivotal to understand radar behaviour under local conditions and validate system performance via simulations and trials comprehensively. Looking ahead, the advent of new technologies will enable radar systems to incorporate new techniques that could further improve performance in the local littoral environment.

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ENDNOTES

[1] Time sidelobes are the responses from the output of pulse compression, which is a technique used to improve radar range resolution and signal to noise ratio.

BIOGRAPHY

LO Man Ling is a Senior Engineer (Advanced Systems). She is currently involved in the development of sensor systems for naval platforms. Man Ling graduated with a Bachelor of Science (Electrical and Computer Engineering) degree from the University of Illinois at Urbana Champaign, USA, in 2009. She also obtained a Master of Science (Management Science and Engineering) degree from Stanford University, USA, in 2010.

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