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UWB Localization Algorithms

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10.1 Introduction

In addition to communications applications, UWB signals are also well-suited for location-aware applications due to their high time resolution and penetration capability [1, 2]. Since a UWB signal occupies a broad frequency spectrum that includes low frequencies as well as high frequencies, it has a higher probability of passing through or around obstacles. Moreover, the large bandwidths of UWB signals imply very high time resolution, which makes accurate time-of-flight, and hence range estimation possible.

The accurate localization capability of UWB signals facilitates a number of applications, such as noninvasive patient monitoring, personnel tracking, search and rescue operations and through-the-wall health monitoring of hostages [2]. In addition, the IEEE Task Group 4a designed an alternate PHY specification for the already existing IEEE 802.15.4 standard for wireless personal area networks (WPANs), which employs UWB as one of the signaling formats [3]. With additional features provided by the 15.4a amendment, the standard can provide high-precision localization capability, high aggregate throughput and low power consumption.

Although UWB signals can potentially provide very accurate location information, even in harsh environments, there are a number of challenges in practical systems related to technology limitations and nonideal channel conditions. Specifically, multipath and/or nonline-of-sight (NLOS) propagation, multiple-access interference (MAI) and high time resolution of UWB signals present practical difficulties for accurate location estimation. Therefore, special attention should be paid to mitigation of errors due to those kinds of error sources.

In this study, we first investigate, in Section 10.2, conventional localization algorithms, such as angle-of-arrival (AOA) and time-of-arrival (TOA)-based schemes, from a UWB perspective, and conclude that time-based schemes are more suitable for UWB localization systems.

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Therefore, we focus on time-based systems for the remainder of the chapter. In Section 10.3, we study the theoretical limits for time-based localization and a number of TOA estimation algorithms. Then, in Section 10.4, we investigate challenges for accurate UWB localization, and present some of the potential solutions from the literature. Finally, we make some concluding remarks in Section 10.5.

10.2 Localization Techniques and UWB

Localization of a node[1] in a wireless network commonly involves extraction of information from radio signals traveling between that node and a number of reference nodes. The information extracted from radio signals can be in the form of AOA, TOA, time-difference-of-arrival (TDOA) and/or signal strength (SS) estimates. In the following, we first investigate localization techniques based on angle, power and time information, and assess their suitability for UWB applications. After observing the advantages of time-based techniques for UWB localization systems, we then study the relationship between TOA estimation and optimal localization.

10.2.1 Angle of Arrival

AOA-based localization involves measuring angles of the target node as seen by reference nodes. For two-dimensional localization, it is sufficient to obtain two AOA measurements between the target node and two reference nodes for localization via triangulation [4].

Commonly, antenna arrays are employed either at the target node (for *self-localization*), or at reference nodes (for *remote localization*) in order to obtain AOA information.

The Cramer–Rao lower bound (CRLB) for estimating AOA φ of a UWB signal by using a uniform linear antenna array with K elements can be expressed as[2] [5]

$$\sqrt{Var(\hat{\varphi})} \geq \frac{\sqrt{3}c}{\sqrt{2}\pi\sqrt{\mathrm{SNR}}\beta\sqrt{K(K^2-1)}d_\mathrm{s}\sin\varphi}, \tag{10.1}$$

where $\hat{\varphi}$ represents an unbiased estimate of the AOA, c is the speed of light, d_s is the spacing between the antenna elements, SNR is the signal-to-noise ratio and β is the effective signal bandwidth given by

$$\beta = \left[\int_{-\infty}^{\infty} f^2\,|S(f)|^2\,\mathrm{d}f \bigg/ \int_{-\infty}^{\infty} |S(f)|^2\,\mathrm{d}f\right]^{1/2} \tag{10.2}$$

with $S(f)$ denoting the Fourier transform of the UWB signal.

Although UWB signals can provide accurate AOA estimation, use of antenna arrays make the system costly, which annuls one of the main advantages of a UWB radio equipped with low-cost transceivers. In addition, the large bandwidths of UWB signals result in large numbers of multipath components, which make accurate angle estimation quite challenging/costly.

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[1] In this chapter, a node refers to any device that is being located, or participating in localization of other devices.

[2] The angle φ is measured from the axis along the antenna array.

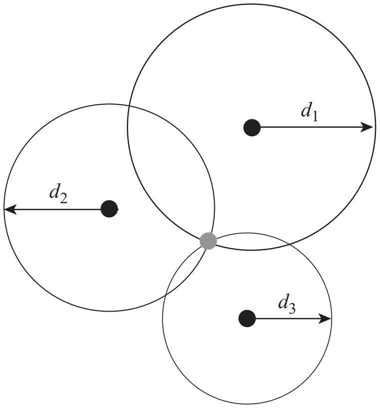

Figure 10.1 Distance-based localization. The distances can be obtained from SS or TOA measurements. The black nodes are the reference nodes.

10.2.2 Received Signal Strength

Distance between two nodes can be estimated by measuring the strength/power of the received signal at one of the nodes. For precise estimation, an accurate path-loss and shadowing model must be available, which makes SS-based localization algorithms very sensitive to the estimation of channel parameters. From distance estimates between the target node and at least three reference nodes, the location of the target node can be obtained by the well-known trilateration approach depicted in Figure 10.1.

The CRLB for a distance estimate $\hat{d}$ obtained from SS measurements can be expressed as [6]

$$\sqrt{Var(\hat{d})} \geq \frac{\ln(10)}{10} \frac{\sigma_{\mathrm{sh}}}{n_{\mathrm{p}}} d, \tag{10.3}$$

where d is the distance between the two nodes, n_{p} is the path loss factor and σ_{sh} is the standard deviation of the zero mean Gaussian random variable representing the log-normal channel shadowing effect [2]. From Equation (10.3), it is observed that the best achievable limit depends on the channel parameters and the distance between the two nodes. Therefore, the unique characteristic of a UWB signal, namely the very large bandwidth, is not exploited by the SS approach to increase the best achievable accuracy.

10.2.3 Time-Based Approaches

Time-based localization relies on measuring travel times of signals between nodes. For two nodes with a common timing reference, the node receiving the signal can determine the time-of-flight of the incoming signal from its TOA signal. For a single-path additive white Gaussian noise (AWGN) channel, the best achievable accuracy of a distance estimate $\hat{d}$ derived from TOA estimation satisfies the following inequality [7, 8]:

$$\sqrt{Var(\hat{d})} \geq \frac{c}{2\sqrt{2}\pi\sqrt{\mathrm{SNR}}\beta}. \tag{10.4}$$

Unlike the SS-based approach, the accuracy of a time-based approach can be enhanced by increasing the SNR or the effective signal bandwidth. Since UWB signals have very large bandwidths, this property facilitates extremely accurate localization of UWB devices using time-based techniques. As an example, for the second derivative of a Gaussian pulse with around 1 GHz bandwidth, an accuracy of less than a centimeter can be achieved at SNR = 5 dB [2].

Comparison of various localization techniques reveals that time-based schemes provide very good accuracy due to the high time resolution (large bandwidth) of UWB signals. Moreover, they are less costly than the AOA-based technique. Although SS estimation is simpler than TOA estimation in general, the distance (range) information obtained from SS measurements is very coarse compared with that obtained from TOA measurements. Due to the inherent suitability and accuracy of time-based approaches for UWB systems, we will focus our discussion on time-based UWB localization for the remainder of this discussion.

10.3 Time-Based Localization: Theoretical Limits and Practical Algorithms

In this section, we consider localization based on TOA information related to a target node and a number of reference nodes. First, we investigate the optimality of TOA-based localization and present theoretical limits for localization accuracy. After that, we consider a number of TOA estimation algorithms for UWB localization and study their properties.

10.3.1 Ranging and Optimal Localization

Ranging refers to estimation of distance ('range') between two nodes. In this context, TOA estimation is equivalent to ranging. On the other hand, localization is the estimation of position (location) of a node in a given network. Conventionally, localization is performed in two steps [2]. First, ranges between the target node and a number of reference nodes are estimated. Then, these range estimates are used to estimate the location of the target. However, this two-step approach is suboptimal in general. An optimal approach can be thought of as estimating the position of the target node directly from the received signals (*direct localization*) [9]. However, it can be shown that the two-step approach is asymptotically optimal under certain conditions, as we investigate below [10, 11].

We consider a synchronous UWB system with a target node and N reference nodes[3]. Let M of the reference nodes have NLOS to the target node, while the remaining nodes have line-of-sight (LOS). We assume that the identities of NLOS or LOS reference nodes are known; this information can be obtained by NLOS identification techniques [12–14]. Without this information, all first arrivals can be considered as NLOS signals.

The received signal related to the ith reference node can be expressed as

$$r_i(t) = \sum_{j=1}^{L_i} \alpha_{ij} s(t - \tau_{ij}) + n_i(t), \tag{10.5}$$

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[3] Note that practical UWB systems are not usually synchronous. However, two-way ranging protocols [20] are commonly used in order to compensate for the timing offset.

for $i = 1, \ldots, N$, where L_i is the number of multipath components at the ith node, α_{ij} and τ_{ij} are, respectively, the fading coefficient and the delay of the jth path of the ith node, $s(t)$ is the UWB signal, and $n_i(t)$ is zero mean white Gaussian noise with spectral density $N_0/2$. The noise components related to different reference nodes are assumed to be independent. The delay of the jth path component at node i can be expressed, for two-dimensional positioning, as

$$\tau_{i,j} = \frac{1}{c}\left[\sqrt{(x_i - x)^2 + (y_i - y)^2} + l_{ij}\right], \tag{10.6}$$

for $i = 1, \ldots, N$, $j = 1, \ldots, L_i$, where c is the speed of light, $[x_i\ y_i]$ is the location of the ith node, l_{ij} is the NLOS propagation induced path length, and $[x\ y]$ is the location of the target node.

We assume, without loss of generality, that the first M nodes have NLOS, while the remaining $N - M$ have LOS. Then, $l_{i1} = 0$ for $i = M + 1, \ldots, N$, as the signal directly reaches the related node in an LOS situation. Hence, the parameters to be estimated are the NLOS delays and the location of the node, $[x\ y]$ which can be expressed as $\boldsymbol{\theta} = [xy\boldsymbol{l}_{M+1}\ldots\boldsymbol{l}_N\boldsymbol{l}_1\ldots\boldsymbol{l}_M]$, where

$$\boldsymbol{l}_i = \begin{cases} (l_{i1}\ l_{i2}\ \ldots\ l_{iL_i}) & \text{for } i = 1,\ \ldots,\ M, \\ (l_{i2}\ l_{i3}\ \ldots\ l_{iL_i}) & \text{for } i = M+1,\ \ldots,\ N, \end{cases} \tag{10.7}$$

with $0 < l_{i1} < l_{i2} \ldots < l_{iN_i}$ [11]. Note that the first delay is excluded from the parameter set for LOS signals, since these are known to be zero.

From Equation (10.5), the likelihood function for $\boldsymbol{\theta}$ can be expressed as

$$\Lambda(\boldsymbol{\theta})\alpha \prod_{i=1}^{N} \exp\left\{-\frac{1}{N_0}\int \left| r_i(t) - \sum_{j=1}^{L_i} \alpha_{ij} s(t - \tau_{ij})\right|^2 \mathrm{d}t\right\} \tag{10.8}$$

Then, the lower bound on the variance of any unbiased estimator for the unknown parameter $\boldsymbol{\theta}$ can be obtained from $\mathrm{E}_{\boldsymbol{\theta}}\left\{(\hat{\boldsymbol{\theta}} - \boldsymbol{\theta})(\hat{\boldsymbol{\theta}} - \boldsymbol{\theta})^T\right\} \geq \mathbf{J}_{\boldsymbol{\theta}}^{-1}$, where $\mathbf{J}_\theta$ is the Fisher information matrix (FIM) [7]. Since the first two elements of $\boldsymbol{\theta}$ are the main parameters of interest, only the first 2 × 2 block of the FIM should be calculated. In the absence of any statistical information about the NLOS delays, it can be obtained, from Equation (10.8), after some manipulation, that [11]

$$[\mathbf{J}_{\boldsymbol{\theta}}^{-1}]_{2\times 2} = \left[c^2\left(\mathbf{H}_{\mathrm{LOS}}\boldsymbol{\Psi}_{\mathrm{LOS}}\mathbf{H}_{\mathrm{LOS}}^T\right)^{-1}\right]_{2\times 2}, \tag{10.9}$$

where $\mathbf{H}_{\mathrm{LOS}}$ is related to the LOS nodes only, and depends on the angles between the target node and the reference nodes, and $\boldsymbol{\Psi}_{\mathrm{LOS}} = \mathrm{diag}\{\boldsymbol{\Psi}_{M+1},\ \boldsymbol{\Psi}_{M+2},\ \ldots,\ \boldsymbol{\Psi}_N\}$, with

$$[\boldsymbol{\Psi}_i]_{jk} = 2\frac{\alpha_{ij}\alpha_{ik}}{N_0}\int \frac{\partial}{\partial \tau_{ij}} s(t - \tau_{ij}) \frac{\partial}{\partial \tau_{ik}} s(t - \tau_{ik})\mathrm{d}t, \tag{10.10}$$

for $j \neq k$, and $[\boldsymbol{\Psi}_i]_{jj} = 8\pi^2\beta^2\mathrm{SNR}_{ij}$. Note that $\mathrm{SNR}_{ij} = |\alpha_{ij}|^2/N_0$ is the SNR of the jth multipath component for the ith node's signal, assuming that $s(t)$ has unit energy, and β is given as in Equation (10.2).

Note that Equation (10.9) proves that the best accuracy can be achieved by using the signals only from the LOS nodes. Moreover, the numerical examples in [11] show that, in most cases, the CRLB is approximately the same whether all the multipath components from the LOS nodes or just the first arriving paths of the LOS nodes are employed. Therefore, processing of the multipath components other than the first path does not significantly increase the accuracy, but adds computational load to the system.

Furthermore, the maximum likelihood (ML) estimate of the node location based on the delays of the first incoming paths from LOS nodes achieves the CRLB as the SNR and/or the effective bandwidth goes to infinity [11]. This result implies that for UWB systems, the first arriving signal paths from the LOS nodes are sufficient for an approximately optimal positioning receiver design. In other words, asymptotically optimal localization can be considered in two-steps as ranging (TOA estimation) and position estimation, as shown in Figure 10.2.

For a numerical example on the achievable accuracy of UWB localization systems, we consider a localization scenario in which the target node is in the middle of six reference nodes located uniformly around a circle. In Figure 10.3, the minimum positioning error, defined as

$$\sqrt{\mathrm{trace}\left(\left[J_\theta^{-1}\right]_{2\times 2}\right)},$$

is plotted versus the effective bandwidth for various numbers of NLOS nodes, M, at SNR = 0 dB. The channels between the target and the reference nodes have ten taps that are independently generated from a log-normally distributed fading model with random signs and exponentially decaying tap energy [15]. It can be observed that the large bandwidths of UWB signals make it possible to obtain location estimates with very high accuracy.

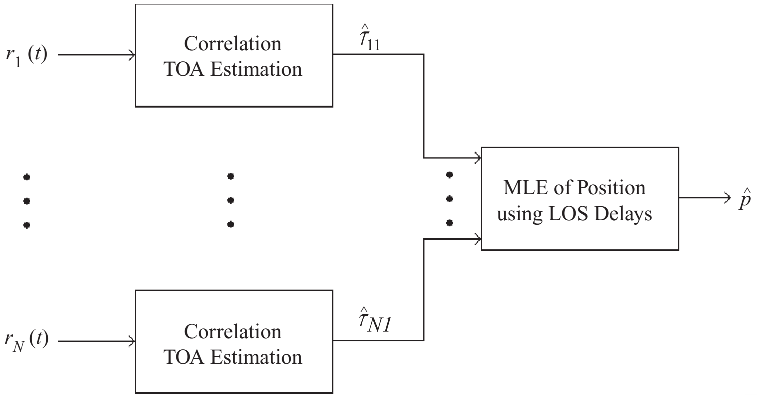

Figure 10.2 An asymptotically optimum receiver structure for localization. No information about the statistics of the NLOS delays is assumed.

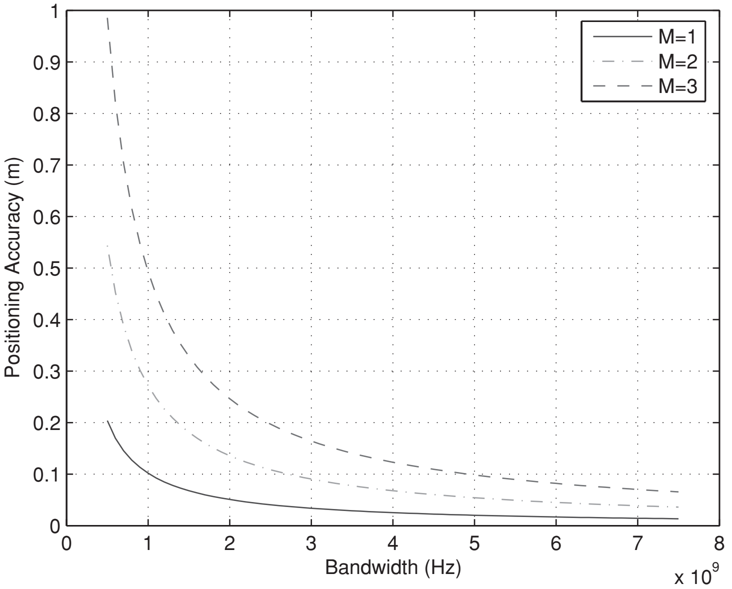

Figure 10.3 Minimum positioning error versus bandwidth for different numbers of NLOS nodes. For $M = 1$, node 1; for $M = 2$, nodes 1 and 2; and for $M = 3$, nodes 1, 2 and 3 are the NLOS nodes. The UWB channels are modeled as in [15] with $L = 10$, $\lambda = 0.25$ and $\sigma^2 = 1$.

Note that in the previous scenario, no information is assumed about the statistics of the NLOS delays. If the probability density function (PDF) of NLOS delays is available, it can be shown that the maximum *a posteriori* probability (MAP) estimate of the node location using the estimates of the delays of all the multipath components from all the nodes achieves asymptotic optimality [11]. However, in practice, the distribution of the NLOS delays is usually not available. Moreover, estimation of additional multipath delays increases the computational complexity of the localization algorithm. Therefore, only the TOA estimation of the first signal path will be considered in the sequel.

10.3.2 Time-of-Arrival Estimation Algorithms

Estimation of the first incoming signal path is the crucial step in TOA-based localization. An optimal TOA estimate can be obtained using a correlation receiver with the received waveform as the template signal[4], and choosing the time shift of the template signal corresponding to the maximum correlation with the received signal [16]. However, due to multipath propagation, the received waveform has many unknown parameters to be estimated. Hence, the optimal correlation based TOA estimation, considered in Section 10.3 (Ranging and Optimal Localization), is not practical. Therefore, the transmitted waveform is used in a 'conventional' correlation-based receiver as the template signal. However, this is obviously suboptimal in a

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[4] Equivalently, a matched filter matched to the received waveform can be used.

multipath environment. Also, selection of the delay corresponding to the peak of the correlation does not necessarily yield the true TOA, since the first multipath component can be weaker than the others in some cases. Therefore, first-path detection algorithms are studied for the suboptimal correlation-based schemes [17]. One of the most challenging issues in UWB TOA estimation is to obtain a reliable estimate in a reasonable time interval under sampling rate constraints. In order to have a low-power and low-complexity receiver, one should assume symbol-rate (or, sometimes frame-rate) sampling at the output of the correlators. However, when symbol-rate samples are employed, the TOA estimation can take a very long time. To address this problem, a two-step TOA estimation algorithm that can perform TOA estimation from symbol-rate samples in a reasonable time interval is proposed in [18]. In order to speed up the estimation process, the first step provides a rough TOA estimate of the received signal based on SS measurements. Then, in the second step, the arrival time of the first signal path is estimated by employing a statistical change detection approach [19].

Another approach for the first-path detection is to use the generalized maximum likelihood (GML) estimation principle and to obtain iterative solutions after some simplifications [20, 21]. The advantage of the GML-based algorithm is that it is a recursive algorithm that can perform very accurate TOA estimation [20]. However, the main drawback is that it requires high-rate sampling, which is not practical in many applications.

An alternative to the GML-based approach is a low-complexity timing offset estimation technique using *symbol-rate* samples based on the idea of *dirty templates* [22–25]. In this approach, symbol-length portions of the received signal are used as noisy (‘dirty’) templates, the cross-correlations of which are employed to estimate the TOA of the received signal. This technique does not require estimation of parameters related to multipath components, except the delay of the first path. Also, significant multipath energy is collected due to the template structure. However, the noise in the template results in noise–noise cross-terms, which causes some performance loss. This effect can be mitigated to some extent by averaging operations [25]. Finally, TOA estimates obtained by the dirty template approach can have an ambiguity equal to the extent of the noise-only region between consecutive symbols. Therefore, another algorithm needs to be implemented after the dirty template based algorithm in order to obtain the exact TOA. In other words, this scheme can be used as the first step of a two-step TOA estimation algorithm.

In addition to the TOA estimation algorithms mentioned above, other approaches include use of coded beacon sequences to speed up the acquisition process by enabling searches over larger intervals [26], a frequency domain approach based on sub-Nyquist uniform sampling [27], a TOA estimation technique that tries to estimate the breakpoint between the noise-only and signal part of the received signal process [28], and a blind timing offset estimation based on the cyclostationarity of impulse radio UWB signals [29]. Although each algorithm has its advantages and disadvantages, the main issues for TOA estimation schemes for UWB systems are the following:

- A low sampling rate is required in order to have low power and practical designs. Therefore, algorithms using symbol-rate or frame-rate samples are preferable.
- For a given accuracy, TOA estimation should be performed using as few training symbols as possible; that is the time it takes to estimate the TOA should be short.
- Related to the previous issue, for a given time interval or a given number of training symbols, the TOA estimation should provide sufficient accuracy.

Considering these criteria, the dirty template based algorithm combined with a statistical change detection or a conventional correlation-based first-path detection scheme is a reasonable scheme for UWB TOA estimation. This is because the dirty template based algorithm can reduce the uncertainty about the TOA to a small region quickly, using symbol-rate samples. Then, a higher resolution algorithm based on correlation outputs of the received signal with a template signal matched to the transmitted symbol[5] can be used to estimate the TOA of the incoming signal.

Design of UWB TOA estimators that provide a trade-off between complexity and performance is still an active research area. Designing an optimal TOA estimator within the constraints discussed above, such as the maximum sampling rate and estimation interval, remains an open problem.

10.4 Challenges

Extremely accurate localization is possible in a single user, LOS and single-path environment. However, in a practical setting, multipath propagation, MAI, NLOS propagation and high timing resolution make accurate localization challenging. Multipath propagation results in a number of signal components arriving at the receiver. This has two adverse effects for accurate TOA estimation [2]. First, multipath propagation can result in partial overlap of multiple replicas of the transmitted signal. Therefore, the correlation peak may not yield the true TOA. Second, multipath propagation can cause scenarios in which the first multipath component is not the strongest one. Therefore, first-path detection algorithms, considered in Section 10.3 (Time-of Arrival Estimation Algorithms), need to be applied.

TOA estimation accuracy can also degrade in the presence of other nodes in the environment due to MAI. A technique for reducing the effects of MAI is to use different time slots for transmissions from different nodes (time-division multiplexing). However, even with such time multiplexing, there can still be MAI from neighboring networks (piconets). In order to reduce the effects of MAI, time-hopping (TH) codes with low cross-correlation properties can be employed [30], and pulse-based polarity randomization can be introduced [31, 32]. With known training patterns at the transmitter and the receiver, template signals consisting of a number of pulses matched to both TH and polarity codes can be used to mitigate the effects of MAI. Moreover, training sequences can be designed in order to facilitate TOA estimation in the presence of MAI [25].

One of the most important sources of errors in TOA estimation is NLOS propagation, which blocks the direct line-of-sight path between the transmitter and the receiver. One way to mitigate NLOS errors is to use nonparametric (pattern recognition/fingerprinting) techniques [33, 34]. The main idea behind nonparametric localization algorithms is to gather a set of TOA measurements from all the reference nodes at *known* locations beforehand, and use this set as a reference database to estimate the location when new measurements from a node are obtained. In the absence of a database, certain statistical information on NLOS can be used to mitigate NLOS errors. For example, [35] uses a simple variance test to identify NLOS situations and employs an LOS reconstruction algorithm. Moreover, by assuming a scattering model for the environment, the statistics of TOA measurements can be obtained, and then

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[5] Symbol-rate samples can be obtained by using a template signal matched to the transmitted UWB symbol.

well-known techniques, such as MAP and ML, can be employed to mitigate the effects of NLOS propagation [36, 37]. In case of tracking a mobile user in a wireless system, biased and unbiased Kalman filters can be employed in order to provide accurate localization [34, 38].

Finally, high time resolution of UWB signals can pose certain challenges in practical systems. First, clock jitter becomes an important factor in evaluating the accuracy of UWB positioning systems [39]. Another consequence of high time resolution is that a large number of bins needs to be searched for true TOA. Finally, the high time resolution, or equivalently large bandwidth, of UWB signals makes it quite impractical to sample the received signal at or above the Nyquist rate, which is typically of the order of tens of GHz.

10.5 Conclusions

Theoretical analysis of UWB signals promises very accurate localization capability. Although it is not always possible to get close to the theoretical limits of localization accuracy with the current technology under practical constraints, it is expected in the near future that UWB localizers will be able to perform location estimation with subcentimeter accuracy for LOS scenarios and subdecimeter accuracy for NLOS scenarios while consuming around a few tens of milliwatts. One of the main technology improvements that would facilitate such low power and accurate localization is related to the design of low power analog-to-digital converters (ADCs) operating at the order of tens of GHz. In addition, ranging and localization algorithms that perform joint optimization of power consumption, localization accuracy and time constraints should be developed.

References

1. Gezici, S., Tian, Z., Giannakis, G.B. *et al.* (2005) *Localization via ultra-wideband radios. IEEE Signal Processing Magazine*, **22**(4), 70–84.
2. Sahinoglu, Z., Gezici, S. and Guvenc, I. (2008) *Ultra-Wideband Positioning Systems: Theoretical Limits, Ranging Algorithms, and Protocols*, Cambridge University Press.
3. IEEE P802.15.4a/D6 (Amendment of IEEE Std 802.15.4) (2006) *Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LRWPANs): Amendment to Add Alternate PHY*.
4. Caffery, J. Jr. (2000) *Wireless Location in CDMA Cellular Radio Systems*, Kluwer Academic Publishers.
5. Mallat, A., Louveaux, J. and Vandendorpe, L. (2007) *UWB Based Positioning in Multipath Channels: CRBs for AOA and for Hybrid TOA-AOA Based Methods*, in Proceeding IEEE International Conference on Communications (ICC), pp. 5775–80.
6. Qi, Y. and Kobayashi, H. (2003) *On Relation Among Time Delay and Signal Strength Based Geolocation Methods*, in Proceeding IEEE Global Telecommunications Conference (GLOBECOM), Vol. **7**, pp. 4079–83.
7. Poor, H.V. (1994) *An Introduction to Signal Detection and Estimation*, Springer-Verlag.
8. Cook, C.E. and Bernfeld, M. (1970) *Radar Signals: An Introduction to Theory and Applications*, Academic Press.
9. Weiss, A.J. (2004) *Direct position determination of narrowband radio frequency transmitters. IEEE Signal Processing Letters*, **11**(5), 513–6.
10. Qi, Y., Kobayashi, H. and Suda, H. (2006) *On time-of-arrival positioning in a multipath environment. IEEE Transactions on Vehicular Technology,* **55**(5), 1516–26.
11. Qi, Y., Kobayashi, H. and Suda, H. (2006) *Analysis of wireless geolocation in a non-line-of-sight environment. IEEE Transactions on Wireless Communications*, **5**(3), 672–81.

12. Borras, J., Hatrack, P. and Mandayam, N.B. (1998) *Decision Theoretic Framework for NLOS Identification*, in Proceeding IEEE Vehicular Technology Conference (VTC), Vol. **2**, pp. 1583–7.
13. Gezici, S., Kobayashi, H. and Poor, H.V. (2003) *Non-Parametric Non-Line-of-Sight Identification*, in Proceeding IEEE Vehicular Technology Conference (VTC), Vol. **4**, pp. 2544–8.
14. Venkatraman, S. and Caffery, J. (2002) *A Statistical Approach to Non-Line-of-Sight BS Identification*, in Proceeding IEEE International Symposium on Wireless Personal Multimedia Communications (WPMC), Vol. **1**, pp. 296–300.
15. Gezici, S., Kobayashi, H., Poor, H.V. and Molisch, A.F. (2005) *Performance evaluation of impulse radio UWB systems with pulse-based polarity randomization. IEEE Transactions on Signal Processing*, **53**(7), 1–13.
16. Turin, G.L. (1960) *An introduction to matched filters. IRE Transactions on Information Theory*, **IT-6**(3), 311–29.
17. Chung, W.C. and Ha, D.S. (2003) *An Accurate Ultra Wideband (UWB) Ranging for Precision Asset Location*, in Proceeding IEEE Conference on Ultra Wideband Systems and Technologies, pp. 389–93.
18. Gezici, S., Sahinoglu, Z., Molisch, A.F. *et al.* (2008) *Two-step time of arrival estimation for pulse based ultra-wideband systems. EURASIP Journal on Advances in Signal Processing*, Article ID 529134, 12 pages, doi: 10.1155/2008/529134.
19. Basseville, M. and Nikiforov, I.V. (1993) *Detection of Abrupt Changes: Theory and Application*, Prentice-Hall.
20. Lee, J.-Y. and Scholtz, R.A. (2002) *Ranging in a dense multipath environment using an UWB radio link. IEEE Transactions on Selected Areas in Communications*, **20**(9), 1677–83.
21. Win, M.Z. and Scholtz, R.A. (1997) *Energy Capture versus correlator resources in Ultra-Wide Bandwidth Indoor Wireless Communications Channels*, in Proceeding IEEE Military Communications Conference (MILCOM), Vol. **3**, pp. 1277–81.
22. Yang, L. and Giannakis, G.B. (2003) *Low-Complexity Training for Rapid Timing Acquisition in Ultra-Wideband Communications*, in Proceeding IEEE Global Telecommunications Conference (GLOBECOM), Vol. **2**, pp. 769–73.
23. Yang, L. and Giannakis, G.B. (2004) *Blind UWB Timing with a Dirty Template*, in Proceeding IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Vol. **4**, pp. 509–12.
24. Yang, L. and Giannakis, G.B. (2004) *Ultra-wideband communications: an idea whose time has come. IEEE Signal Processing Magazine*, **21**(6), 26–54.
25. Yang, L., and Giannakis, G.B. (2005) *Timing ultra-wideband signals with dirty templates. IEEE Transactions on Communications*, **53**(11), 1952–63.
26. Homier, E.A. and Scholtz, R.A. (2002) *Rapid Acquisition of Ultra-Wideband Signals in the Dense Multipath Channel*, in Proceeding IEEE Conference on Ultra Wideband Systems and Technologies, pp. 105–9.
27. Maravic, I., Kusuma, J. and Vetterli, M. (2003) *Low-sampling rate UWB channel characterization and synchronization. Journal of Communications and Networks*, **5**(4), 319–27.
28. Mazzucco, C., Spagnolini, U. and Mulas, G. (2004) *A Ranging Technique for UWB Indoor Channel Based on Power Delay Profile Analysis*, in Proceeding IEEE Vehicular Technology Conference (VTC), Vol. **5**, pp. 2595–9.
29. Tian, Z., Yang, L. and Giannakis, G.B. (2002) *Symbol Timing Estimation in Ultra Wideband Communications*, in Proceeding IEEE Asilomar Conference on Signals, Systems, and Computers, Vol. **2**, pp. 1924–8.
30. Guvenc, I. and Arslan, H. (2004) *Design and Performance Analysis of TH Sequences for UWB Impulse Radio*, in Proceeding IEEE Wireless Communications and Networking Conference (WCNC), Vol. **2**, pp. 914–9.
31. Fishler, E. and Poor, H.V. (2005) *On the tradeoff between two types of processing gain. IEEE Transactions on Communications*, **53**(10), 1744–53.
32. Gezici, S., Kobayashi, H., Poor, H.V. and Molisch, A.F. (2004) *The Trade-Off Between Processing Gains of an Impulse Radio System in the Presence of Timing Jitter*, in Proceeding IEEE International Conference on Communications (ICC), Vol. **6**, pp. 3596–600.
33. McGuire, M., Plataniotis, K.N. and Venetsanopoulos, A.N. (2003) *Location of mobile terminals using time measurements and survey points. IEEE Transactions on Vehicular Technology*, **52**(4), 999–1011.
34. Gezici, S., Kobayashi, H. and Poor, H.V. (2003) *A New Approach to Mobile Position Tracking*, in Proceeding IEEE Sarnoff Symposium On Advances in Wired and Wireless Communications, pp. 204–7.
35. Wylie, M.P. and Holtzman, J. (1996) *The Non-Line of Sight Problem in Mobile Location Estimation*, in Proceeding IEEE International Conference on Universal Personal Communications, Vol. **2**, pp. 827–31.
36. Al-Jazzar, S., and Caffery, J. Jr. (2002) *ML and Bayesian TOA Location Estimators for NLOS Environments*, in Proceeding IEEE Vehicular Technology Conference (VTC), Vol. **2**, pp. 1178–81.

37. Al-Jazzar, S., Caffery, J. Jr. and You, H.-R. (2002) *A Scattering Model Based Approach to NLOS Mitigation in TOA Location Systems*, in Proceeding IEEE Vehicular Technology Conference (VTC), no. 2, pp. 861–5.
38. Le, B.L., Ahmed, K. and Tsuji, H. (2003) *Mobile Location Estimator with NLOS Mitigation Using Kalman Filtering*, in Proceeding IEEE Conference on Wireless Communications and Networking (WCNC), Vol. **3**, pp. 1969–73.
39. Shimizu, Y. and Sanada, Y. (2003) *Accuracy of Relative Distance Measurement with Ultra Wideband System*, in Proceeding IEEE Conference on Ultra Wideband Systems and Technologies, pp. 374–8.