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Identification and mitigation of non-line-of-sight path effect using repeater for hybrid ultra-wideband positioning and networking system

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Abstract: At least two decades ago, various applications have been proposed for the implementation of ultra-wideband (UWB) technology, but only a few of them are being realised such as radar detection, home networking, and indoor positioning. Although UWB positioning offers precise locality tracking, the accuracy of the estimation is greatly affected by the non-line-of-sight (NLOS) path effect. In this paper, we propose a hybrid indoor UWB positioning and networking system that utilises the existing repeater of the data network to eliminate the NLOS paths. A switching algorithm is written to identify the existence of NLOS paths based on received signal strength (RSS) and unique channel characteristics such as mean excess delay (MED) and root mean square (RMS). From the simulation results, the NLOS paths have been successfully identified under the NLOS environment. Hence, a higher probability of accuracy across the entire tested area can be achieved for the UWB positioning system by mitigating the NLOS path effect using the proposed algorithm. Besides that, the transmission of the line-of-sight (LOS) signal attains a data rate of around 15 times higher than the NLOS signal at a bit-error-rate (BER) of 10^{-5} in the indoor networking system. In this case, the minimum-bit-error-rate (MBER) receiver is again shown to outperform the minimum-mean-square error (MMSE) and the performance gain drops around 5 dB to 6 dB at a BER of 10^{-5} when the repeaters increase to a maximum number of 10 units. In conclusion, the proposed method is capable of mitigating the NLOS path effect on both indoor positioning and data networking systems.

Key words: Ultra-wideband, positioning, data networking, repeater, non-line-of-sight path

1. Introduction

UWB is a radio technology that operates at very low energy levels and is used for short-range, high-bandwidth communication that covers a large portion of the radio spectrum, ranging from 500 MHz up to several GHz. According to the Federal Communications Commission, a UWB device is referred to as any device where the fractional bandwidth is greater than 0.25 or occupies 1.5 GHz or more of spectrum [1]. These unique characteristics of UWB offer a lot of benefits in our current era of technology. For example, since the UWB operates at a very low energy level, it can operate in the same spectrum as other narrowband communications without causing undue interference. Apart from that, UWB signal can also be used to locate the location of objects or people indoors [2–4]. This is because UWB uses very short pulses, of about 1-2 ns, which leads to better accuracy and precision [5].

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Although UWB can offer high-precision indoor positioning and high-speed data transmission with low power consumption, previous studies report that the existing NLOS paths reduce the overall accuracy of the tracking system as well as the quality of the signal transmission significantly. The effect of NLOS multipath channels referring to the IEEE standard 802.15.4a [6], has been investigated intensively in [7–9] for UWB communication and in [10, 11] for UWB positioning. IEEE 802.15.4a is a standard channel model (CM) for UWB, which consists of four different types of channels with and without LOS paths. A path loss model was derived in [12] based on the RSS to measure the accuracy of UWB positioning for LOS and NLOS paths. A similar study in [13] also indicated the negative impact of propagation characteristics under a harsh industrial environment and NLOS paths on ranging accuracy in industrial scenarios. Nevertheless, a benchmark has been done in [14] to explore the effects of signal refraction and attenuation on the transmitted UWB signal in different construction materials by examining the channel impulse response accordingly.

Consequently, several methods have been suggested to mitigate the effect of the NLOS paths. For example, adequate models were derived and used to identify the NLOS condition under harsh environment for further correction of the estimated locality in [12]. A study in [15] used the extended Kalman filtering algorithm to adapt the localization of the NLOS environment based on more complicated time of arrival (TOA) and angle of arrival (AOA) hybrid positioning. This research has been extended in [16], which used a Kalman filter based fusion method to identify NLOS environments and mitigate UWB errors through pedestrian dead reckoning. Besides that, an NLOS environment discrimination algorithm based on the received signal TOA, received signal strength indication, and RMS was proposed in [17], which requires the actual distance to be known. A similar method was also proposed recently in [18] by using the least square location algorithm for raging the value of TOA under NLOS environment. More recent works using machine learning also have been proposed in [19–22], but they require very high computational power, which is not feasible for practical real-time application. For instance, in [21], an improved UWB LOS/NLOS identification scheme based on a hybrid method of deep learning and transfer learning was proposed. Another approach was also reported by developing a Naive Bayes algorithm for indoor localization [22].

In this paper, we propose a low-complexity hybrid indoor UWB positioning and data networking system. We intend to investigate the possibility of eliminating the NLOS paths using the existing repeater used for UWB data transmission. In the proposed system, a switching algorithm is developed to identify the existence of NLOS paths based on the multipath channel characteristics such as MED, RMS, and the number of signal paths within 10 dB of peak value, and reflect all the NLOS paths through the repeater as LOS paths instead. The proposed structure is then simulated in an indoor space model with a predefined NLOS environment and the probability of tracking accuracy is computed. Meanwhile, the BER performance of the UWB data network is also compared in between LOS and NLOS paths. In the end, multiple repeaters are added to test the performance of the signal transmission. The originality of this research is the design of a new algorithm for NLOS paths identification and mitigation through the usage of data networking repeaters. The repeaters are the main key to this system since they are used to minimise the number of existing NLOS paths in an indoor environment by converting the NLOS signal to the LOS signal transmission. The expected outcome is to improve the performance of indoor positioning as well as the signal quality of data networking using UWB technology.

The structure of this paper is as follows: Section 2 describes the architecture of indoor UWB positioning and networking systems used as well as the algorithm proposed in this research. Section 3 presents and discusses the experimental results and figures obtained from the simulation. Section 4 summarizes the research outcome with future improvements.

2. Research methodology

2.1. Overall architecture

The proposed hybrid structure is illustrated in Figure 1. The functionality of the anchors (receivers) is to detect and capture the information of the signal such as strength, time of arrival, etc., transmitted by the UWB tag (transmitter), which is attached to an object. The information is then sent to the main receiver to estimate the position of the object in the indoor space. Although two anchors are the minimum requirement to perform locality estimation using coordinate determination method [23], our structure proposes to have at least four anchors, including the main receiver at each corner. In case there are any malfunction or estimation errors detected from the anchors, at least three anchors can be used in the system to perform locality estimation with higher accuracy than the system that only uses two anchors. Meanwhile, the main receiver and repeater are used for data communication to receive and reflect the signal transmission from any UWB devices. In order to eliminate NLOS paths, the repeater is also being shared and used in the positioning system if necessary.

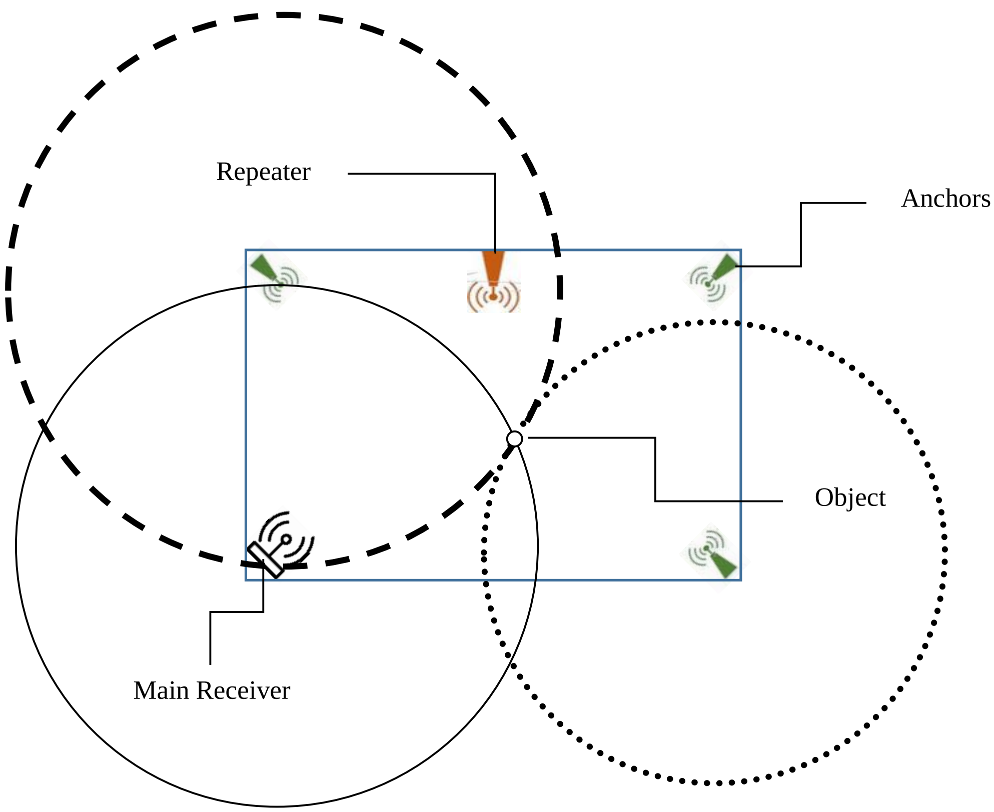


Figure 1. Proposed structure.

As compared to [12, 23], previous findings and methods are used to define the fundamental architecture and methodology of this project, such as the coordinate determination method and path loss model (PLM). The research work has been extended in this paper by implementing a new switching algorithm to first identify the NLOS signal and, then utilise the repeater to create a LOS path in between the anchors and tag. The repeater functions as an additional anchor if needed, which is able to receive signals from the tag and estimate the locality of the object. At the same time, the repeater is also used in the data networking system to reflect the NLOS signal transmission to the main receiver. Hence, the effect of NLOS paths in both positioning and data networking systems can be mitigated simultaneously using the same repeater.

2.2. UWB positioning

For simplicity, the RSS positioning technique is chosen to test the functionality and efficiency of our proposed method in the UWB system since it does not require extensive information at the repeater besides the strength and arrival time of the received signal. At the receiver side, the received UWB signal, $r(t)$ is given by,

$$r(t) = p(t) * h(t) + n(t). \tag{1}$$

where $p(t)$ is the transmitted pulses, $h(t)$ is the channel impulse response obtained from the IEEE standard 802.15.4a report [24] and $n(t)$ is the additive white Gaussian noise (AWGN).

The strength of the sampled signal, S_r can be formulated as:

$$S_r = \frac{1}{M} \sum_{k=1}^{M} |r_k|^2 . \tag{2}$$

where r_k is the received signal sample and M is the total number of samples. Note that the received signal has to be sampled at a rate higher than the bit rate to capture the unique characteristics of the channel as shown in the next section.

Upon obtaining the signal strength, the distance of the transmitter, is estimated using the PLM [12].

$$\tilde{d} = d_0 \left(\frac{S_0}{S_r} \right)^{\frac{1}{n}} . \tag{3}$$

where S_0 is the reference signal strength at a predefined distance, d_0 and n is the path loss exponent ranging from 1 to 2 for LOS path and 3 to 7 for NLOS path, respectively [12]. Notice that the range of the n is much larger for NLOS paths as compared to the LOS paths, which is highly affecting the accuracy of the estimated distance.

After estimating the distances for each anchor (receiver), multiple intersection points, $(\tilde{x}_i, \tilde{y}_i)$ as illustrated in Figure 2 can be found by using coordinate determination method [23]. This method applies trigonometry calculations to determine the actual coordinate of the intersection points with a predefined reference node such as one of the anchors used in the proposed structure. For instance, the three circles function as a reference to indicate where the intersection points between the estimated location from two specific anchors are. The resultant of these three intersection points is then used to estimate the final location of the UWB tag (transmitter) by computing the centroid of these intersections.

In the existence of NLOS paths, the distance, $\tilde{d}$ cannot be estimated correctly from the anchors (receivers) [12]. A switching algorithm is proposed below to eliminate the effect of NLOS paths by facilitating the function of the repeater in a communication network. In the proposed algorithm, the existing NLOS paths have to be first identified based on the status of the channel characteristic, h_a, which will be discussed in Section 3. After the initialisation of some variables such as the identity of each anchor used, the index for the array and the counter used to increase the array index, it will check which anchor has an NLOS path. If there is an NLOS path, the counter storage, c will be increased. If the NLOS path is not detected, the

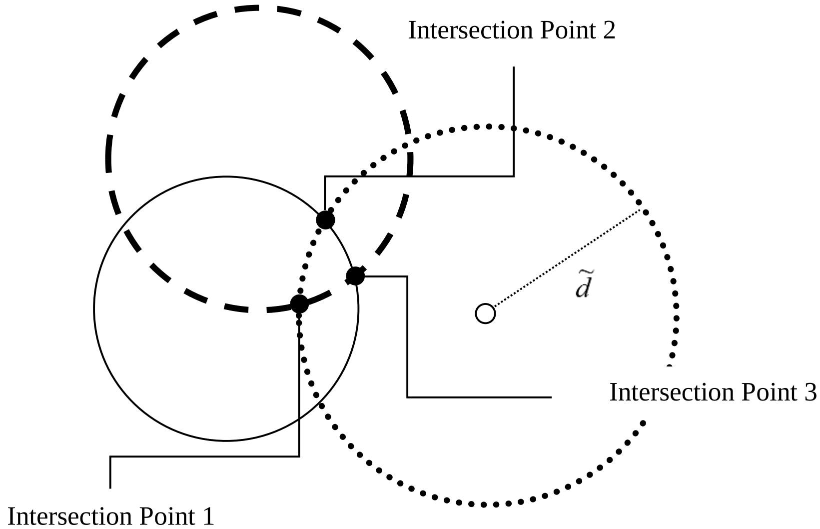


Figure 2. Coordinate-based estimation.

identity of the anchor will be stored in the array, A_i and used to determine the location of the UWB tag (transmitter) later. If there are only less than or 2 anchors that have LOS paths, the final locality will be calculated considering the signal strength reflected from the repeater and the signal strength received by the anchors with LOS paths and the main receiver. If there are more than two anchors that have LOS paths, the final locality will be calculated based on the signal strength received from the anchors and the main receiver only.

Algorithm 1. Switching algorithm for UWB positioning.

$a \leftarrow 0$ // identity of anchor
$i \leftarrow 0$ // array index
$c \leftarrow 0$ // counter storage
while $a < 4$ do
    if $h_a = 1$ then // check the existing of NLOS path
        $c = c + 1$
    else
        $A_i = a$ // store the identity of anchor with LOS path
        $i = i + 1$
    end if
    $a = a + 1$
end while
if $c < 2$ then
    $estimate_{LOS}(A_i)$ // perform the estimation function for more than 2 LOS paths
else if $c < 3$ then
    $estimate_{NLOS}(A_i)$ // perform the estimation function for less than or 2 LOS paths
else
    return invalid()
end if

2.3. UWB data networking

For UWB data transmission, the extremely short interval received signal, $r(t)$ has been distorted by the noise interference caused by the existing multipath components of the standard IEEE CM, $h(t)$ [24]. Hence, the distorted signal has to be corrected by filtering the received signal with an equaliser and, the output symbol, y_k is calculated as [25]:

$$y_k = r_k g_k. \tag{4}$$

where $g_k = [g_0, g_1, \ldots, g_{N-1}]$ is the equaliser's coefficients with the chosen N equals to the number of equaliser's tap length.

There are many options to train the equaliser's coefficients. In this paper, only two of them are used for result comparisons, which are the MMSE and the MBER, respectively.

The MMSE equaliser, which is the most commonly used equaliser, trains the coefficients, g_k using the following formula [26].

$$g_{k+1} = g_k + \Delta e_k r_k. \tag{5}$$

where Δ is the step size and e_k is the mean square error.

The MBER equaliser, which is a more suitable equaliser used in wideband communication, trains the coefficients, g_k using the equation below [27].

$$g_{k+1} = g_k + \frac{\Delta}{\sqrt{2\pi\rho^2}} \cdot e^{\left[\frac{-(y_k)^2}{2\rho}\right]} \cdot \hat{y}_k \cdot (r_k - g_k y_k). \tag{6}$$

where ρ^2 is the radius parameter and $\hat{y_k}$ is the sign of detected output.

In the existence of an NLOS path, the repeater will automatically redirect the transmitted signal to the main receiver whenever there is a detection of low signal quality during the data transmission. Hence, no additional algorithm is required in this case.

3. Result and discussion

3.1. Simulation parameters

The proposed system is simulated under an indoor space with a dimension of 10 m × 4.5 m as shown in Figure 3. The space is further divided into multiple 50 cm × 50 cm divisions with an assumption that there is a UWB tag (transmitter) located in the centre of each division. A rectangular blockage is placed in the middle of the space to create a symmetrical NLOS path environment in between the tag and the anchors (receivers). Another additional circular blockage is also added to create a nonsymmetrical NLOS path environment.

For indoor positioning, multiple estimations are performed to obtain the probability of accuracy, which is defined as the number of correct estimations over the total number of transmitted signals. In order to eliminate other factors that will contribute to the estimation error, the path loss exponent, n is assumed to be equal to 1.6 [12]. The result of the probability obtained is indicated by different shaded colours as shown in Figure 3. Dark grey colour represents a probability of less than 0.75. Light grey colour represents a probability ranging from 0.75 to 0.9. The white colour indicates that the probability is more than 0.9. For data networking, several transmissions ranging from 8 Mbps to 20 Mbps approximately under both NLOS and LOS environments have been simulated to measure the performance comparison. Both the MMSE and MBER receivers use a tap length of 5 and a step size of 0.01, respectively. The radius parameter of the MBER receiver is chosen as $\rho^2 = 0.7\sigma$, where σ is the sigma of AWGN [27]. Simulations are performed over 100 realizations of IEEE CM [24] with CM1 as a LOS channel and CM4 as an NLOS channel.

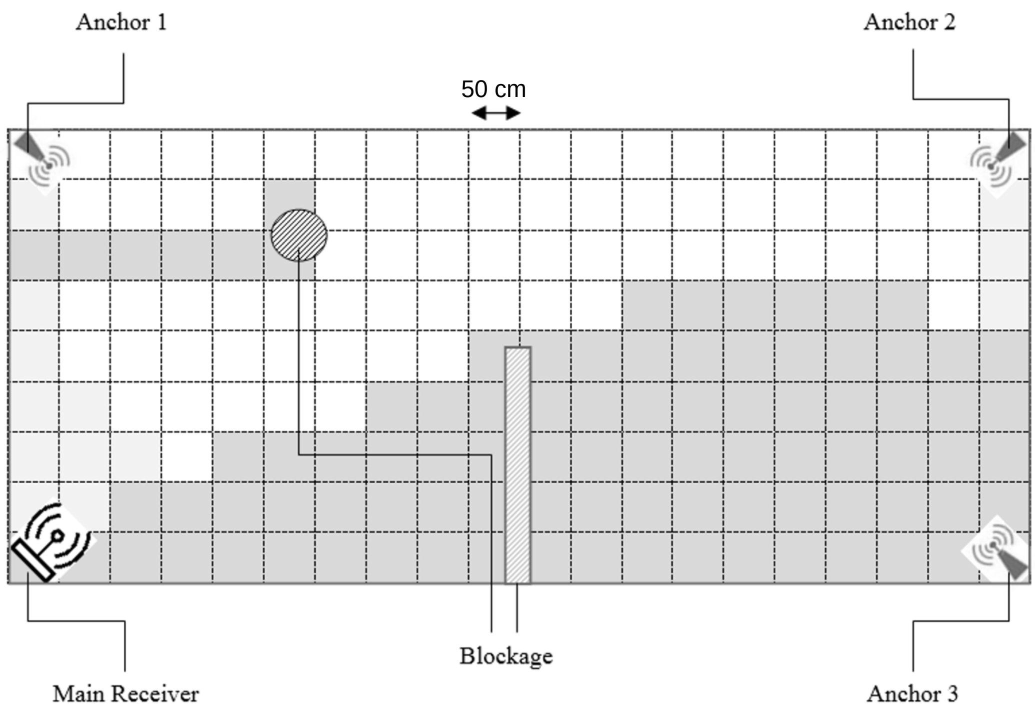


Figure 3. Locality detection without repeater.

3.2. UWB positioning

As depicted in Figure 3, it is observed that most of the divisions at the bottom of the indoor space are in dark grey colours due to the existence of NLOS paths that greatly increase the error of the estimated distance, $\tilde{d}$. Furthermore, there are more divisions with dark grey colours on the left side of the circular blockage and also on the right side of the indoor space. These indicate that even a small circular blockage in an indoor environment will create a large space occupied with NLOS paths. On the other hand, there are some divisions with light grey colours on both sides of the indoor space. It is expected, as these divisions have distances of more than 10 meters from the other side of the anchors. Previous studies [12] show that the accuracy of the path loss model reduces with the increment of distance measured. Thus, overall, the simulated indoor space has a 57.78% of space with a probability of accuracy of less than 0.9.

In order to eliminate the effect of the NLOS paths, we can first identify the NLOS paths and, then perform the switching algorithm as proposed in this paper. The methodology used is by extracting the unique channel characteristics of the UWB CM derived in IEEE 802.15.4a [24]. Figure 4(a) and Figure 4(b) show the sample of the received signal for both LOS and NLOS paths. The sampling rate is set to 8 times faster than the bit rate and the signal strength is normalised to unity in order to extract the multipath channel characteristics. This is the reason why there are some multipath signals with a distance of 10 meters that have larger amplitudes than the multipath signals with a 5 meters distance. From both results, it is clear that the LOS paths have the most significant received signal in the first sample as compared to the NLOS paths for both 5 meters and 10 meters of transmission range, respectively. This characteristic is more noticeable when the transmission range increases further.

In fact, we can measure the MED, RMS, and the number of signal paths within 10 dB of peak values as shown in Table 1. For LOS signal, the MED values are less than 10 ns, the RMS values are around 11-12 ns, and the numbers of signal paths within 10 dB are no more than 1.5. In contrast, the MED values are more than 30 ns, the RMS values are more than 30 ns, and the number of signal paths within 10 dB are always equal or more than 2 for NLOS signal. Hence, as long as the received signal fulfills the characteristics of an NLOS signal, the status of the switching algorithm will be set to $h_a = 1$. For example, we can set the MED, RMS, and number of signal paths within 10 dB to be equal or more than 10 ns, 20 ns, and 1.5 correspondingly to track the possibility of any existing NLOS signal.

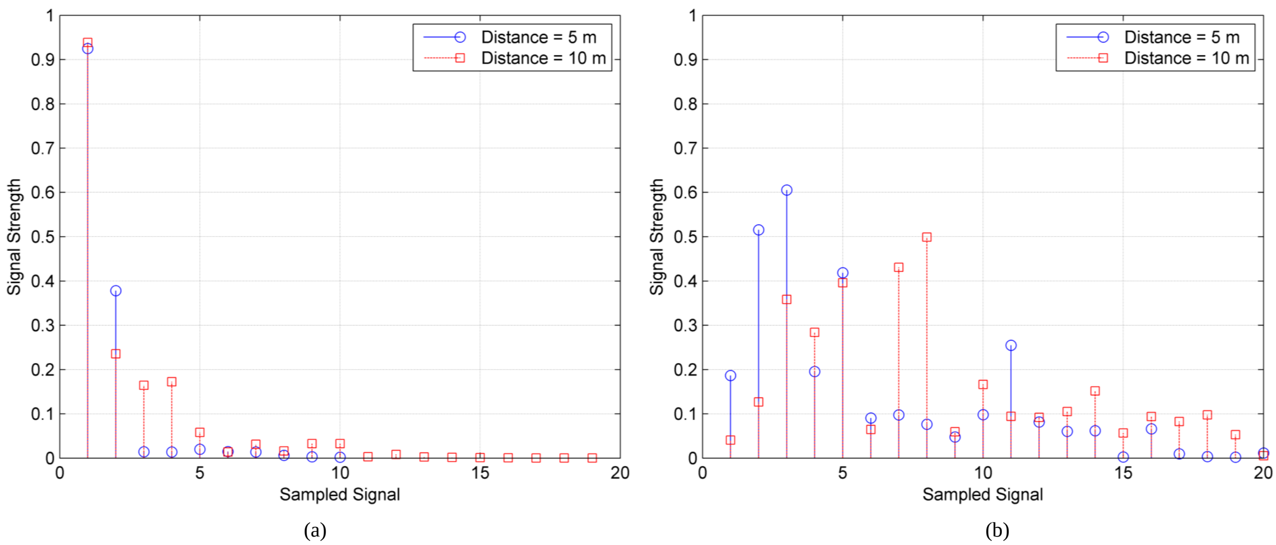


Figure 4. Sampled signal that propagates through (a) LOS paths and (b) NLOS paths.

Table . Comparisons of MED, RMS, and the number of signal paths within 10 dB of peak value.

Channel path	Mean excess delay (ns)	Root mean square delay (ns)	Number of signal paths within 10 dB of peak
LOS signal (5 meters)	5.612	11.45	1.1
LOS signal (10 meters)	7.13	11.78	1.33
NLOS signal (5 meters)	38.785	52.2	2
NLOS signal (10 meters)	36.18	35.44	2.18

Figure 5 presents the result of the probability obtained after applying the proposed switching method with the repeater used for data transmission. It is noticeable that most of the divisions with dark grey colour in the indoor space have been eliminated because the NLOS signal has been successfully identified and redirected to the repeater as an LOS signal. However, there are some NLOS paths, represented by dark grey divisions, which are not able to be reflected by repeaters, and there are some divisions with light grey colour remaining in the space since the proposed algorithm is only meant for eliminating the NLOS paths. Overall, the amount of space with a probability of accuracy of less than 0.9 has decreased to a percentage of 13.89% only as compared to the simulation result obtained without the repeater in Figure 3. Hence, the accuracy of the UWB positioning can be enhanced significantly by reducing the existing NLOS paths in an indoor space.

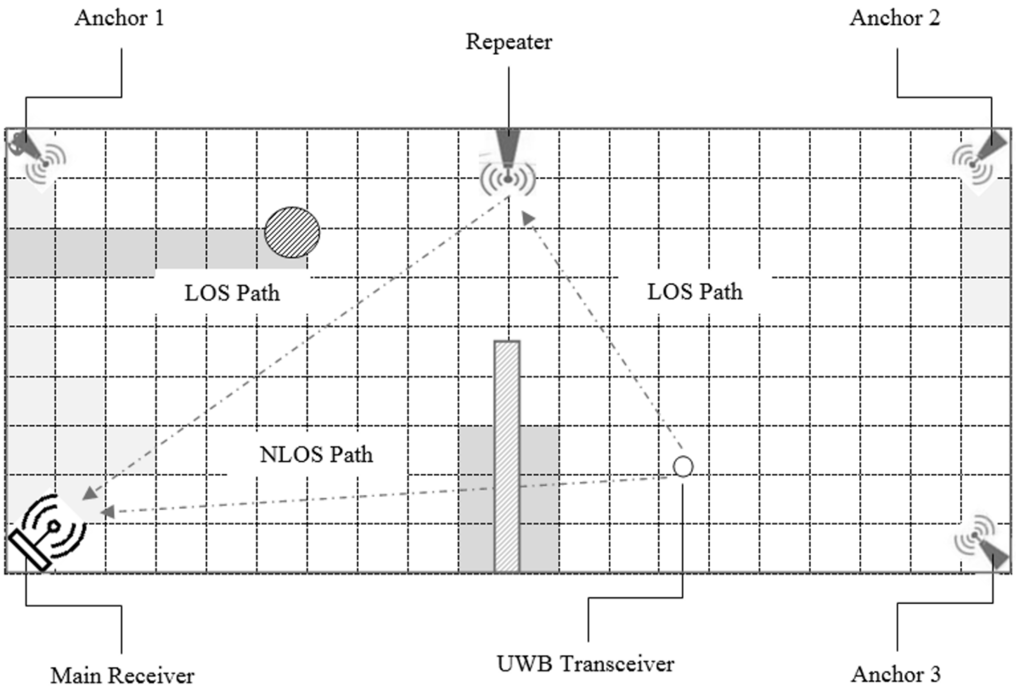


Figure 5. Locality detection with repeater.

3.3. UWB data networking

As depicted in Figure 5, the signal of the data transmission can propagate through the LOS paths using the repeater or NLOS paths to the main receiver. For the purpose of performance comparison, several transmissions with different data rates have been simulated for both LOS and NLOS signals, as illustrated in Figure 6 and Figure 7, respectively. As expected, the LOS signal can achieve a performance much better than the NLOS signal with the same signal-to-noise ratio (SNR). From the results obtained, the LOS signal can achieve a BER of 10^{-5} for all data rates ranging from 8 Mbps to 20 Mbps. For instance, a data rate equal to 20 Mbps can attain a BER of 10^{-5} at SNR = 11 dB approximately. However, the NLOS signal can only achieve a BER of 10^{-5} for both data rates of 8 Mbps and 9 Mbps at SNR = 16 dB and 21 dB approximately. As compared to the LOS signal, these two data rates can obtain the same BER performance with less than 10 dB of SNR. All of these achievable data rates are attained by using MBER equalisation technique. Overall, the MBER equaliser has a better BER performance than the MMSE equaliser. For instance, the MBER with a data rate of 20 Mbps can attain a BER of 10^{-5} at SNR = 21 dB under NLOS paths, but the MMSE can only achieve the same amount of BER at SNR = 23 dB.

In this case, none of the simulation results is able to approach the optimum BER performance of a BPSK UWB signal transmission, which is given as BER $= 0.5 \times erfc(\text{SNR})$ [25]. This is because we try to investigate the maximum data rate that can be achieved by the proposed system. The applied receivers could not equalise the channel effect totally, unless further encoding was implemented into the UWB signal transmission.

In order to further analyse the performance between the LOS and NLOS signals, Figure 8(a) and Figure 8(b) present the study of BER performance vs data rate for both MMSE and MBER receivers at SNR = 15 dB and 20 dB respectively. It is noticeable that a good performance can be achieved at a BER of less than 10^{-5} when the data rates of LOS and NLOS are less than 150 Mbps and 10 Mbps approximately at SNR = 20 dB. At SNR = 15 dB, the same amount of BER cannot be attained even with data rates of 100 Mbps and 5 Mbps for the LOS and NLOS signals. From the results obtained, it is shown that the LOS signal offers the same BER performance as the NLOS signal with a data rate of 15 times higher than the NLOS. Both MMSE and MBER will converge to the BER of around 10^{-1} when the data rates increase to a limitation where the receivers are not able to equalize the multipath channel effect furthermore, with data rates of more than 200 Mbps for LOS and more than 20 Mbps for NLOS.

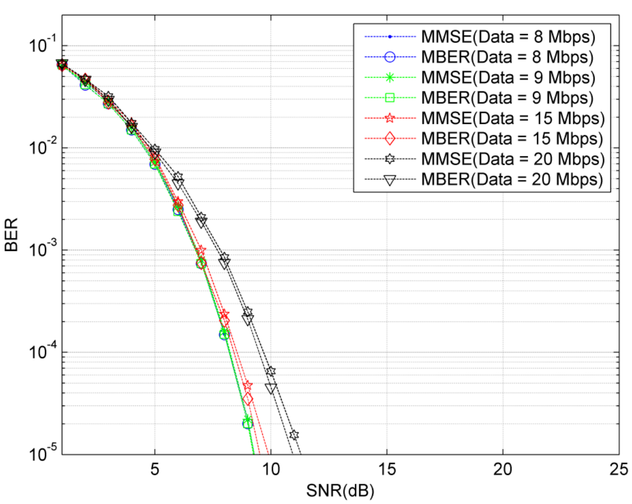


Figure 6. BER performance of LOS channel.

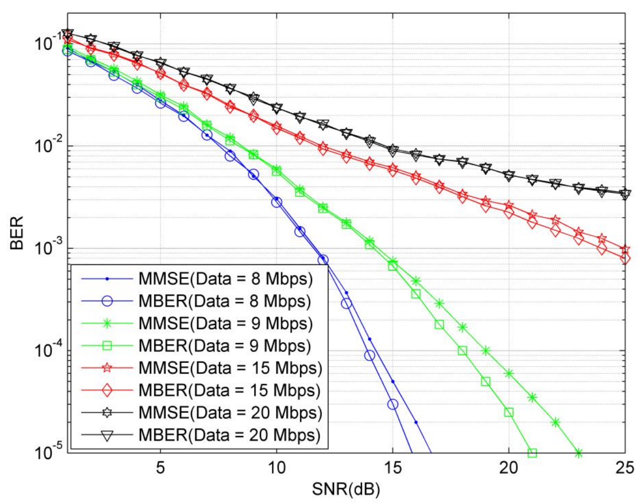
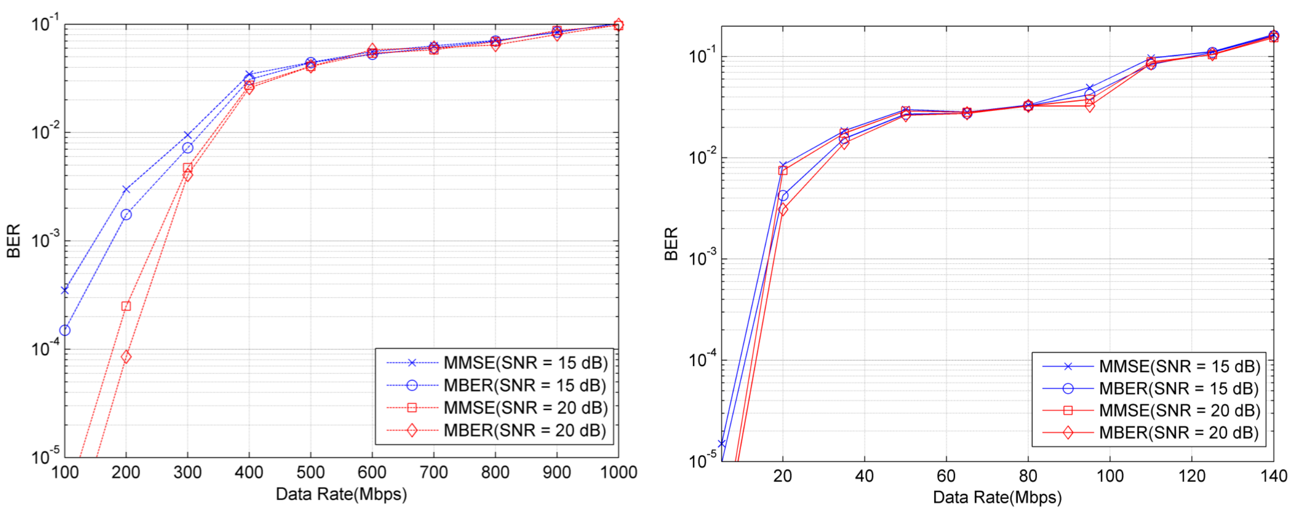


Figure 7. BER performance of NLOS channel.



(a) (b)

Figure 8. Performance of (a) LOS and (b) NLOS signals with different data rates.

Last but not least, the BER performance of the LOS signal that propagates through multiple repeaters is also simulated using the MBER equaliser only since it has a better performance than the MMSE equaliser.

As shown in Figure 9, when the number of repeaters increases from 0 to 10 units, the MBER receiver requires a SNR of at least 21 dB to 27 dB to retain a BER of 10^{-5} at data rate = 125 Mbps. Meanwhile, the same receiver requires a SNR of at least 23 dB to 29 dB and 24 dB to 30 dB to retain a BER of 10^{-5} at data rate = 135 Mbps and data rate = 145 Mbps respectively. It is observed that the performance gains for all the simulation results drop about 5 dB or 6 dB only when the number of repeaters increases to a maximum number of 10 units. However, if the number of repeaters increases to more than 10 units, the LOS signal could not achieve a BER of 10^{-5} at all simulated data rates, although the SNR is increased further. In addition, similar results have been obtained for the NLOS signal with a maximum number of 10 repeaters at data rates of 8 Mbps, 9 Mbps, and 10 Mbps, respectively. Hence, as long as the SNR is required by the system, in order to maintain a considerable amount of signal quality below 30 dB, multiple repeaters can be utilised to minimise the existing NLOS paths as well as to extend the coverage of a UWB network.

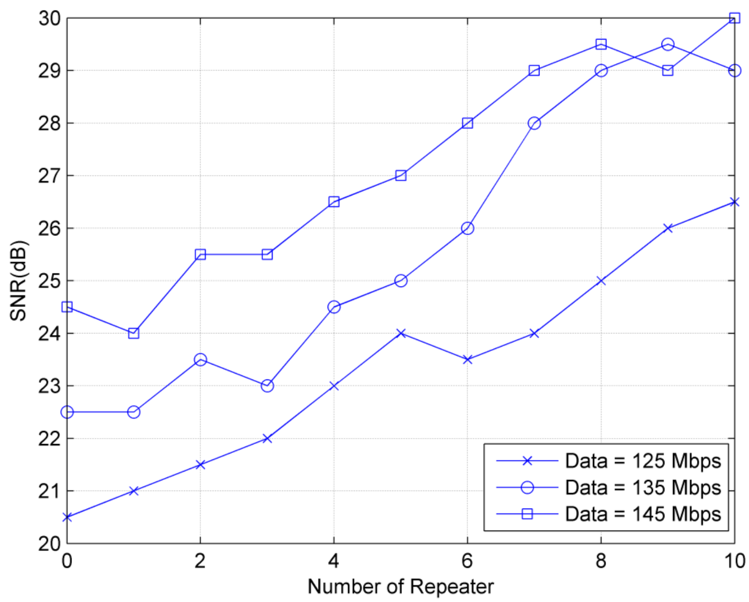


Figure 9. Performance of LOS signal for multiple repeaters.

4. Conclusion

UWB is a promising technology that provides high-precision indoor positioning and high-speed home networking with low power consumption. However, the existence of NLOS paths reduces the accuracy of localisation and the quality of data transmission significantly. Hence, a new hybrid UWB indoor positioning and networking system is proposed and a switching algorithm is developed and simulated in this paper. The purpose of this combination is to first identify the NLOS paths based on the received signal strength and unique channel characteristics and, then eliminate them by utilising the existing repeater used for data transmission. The result obtained shows that the probability of getting a higher accuracy for indoor positioning increases significantly under the NLOS environment. For instance, the amount of space with a probability of accuracy of less than 0.9 reported a percentage of 13.89% only with a repeater as compared to a percentage of 57.78% without a repeater.

On the other hand, a performance comparison is made between the data transmission of LOS and NLOS signals in a UWB networking system. The results indicate that the performance of the LOS signal is much better than the NLOS signal. At a considerable amount of BER, the LOS signal is able to achieve a data rate of 15 times higher than the NLOS signal. In this case, the MBER equaliser is also shown to outperform the MMSE equaliser. Last but not least, adding more repeaters is able to extend the range of data transmission without a significant drop in performance. The maximum number of repeaters that can be added is 10 units as reported in this paper. Future research can be done by applying other types of positioning techniques to the proposed system, which require additional information to be reflected by the repeater. For example, the TOA and AOA techniques can be implemented to enhance the distance of locality estimation as well as the accuracy of estimation under harsh environments. However, it will definitely increase the complexity of the facility and, hence the balance between the complexity and accuracy of the system needs to be studied in detail. Another possible approach can also be done by studying the placement of the repeaters based on a dynamic indoor environment in order to optimise the performance of positioning and data networking systems.

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