Implementation of Beam Formation for WMNs

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Abstract: - A low-cost beamformer capable of main beam and null locating is proposed in this paper. This beamformer is suitable for WMNs as the positions of mesh router are fixed. The beamformer consists of 2×2 rectangular array spaced by λ/4 accompanied with a simple beamforming network. With multiplying constant values to output signals from beamforming network, null locating can be accomplished. Firstly, its beamforming capability is tested through computer simulation. Then, a prototype of the beamformer is constructed and tested to confirm its performance in term of signal strength, throughput and delay. Also, the impact of position shift which mesh router is not located on the expected beam direction has also been investigated.

Key-Words: - Antenna array, Beamforming, Null steering, WMNs.

1 Introduction

Recently, Wireless Local Area Networks (WLANs) have become an infrastructure in every building [1]. The connection or communication between users and networks is accomplished through Access Points (APs). In WLANs, APs communicate to each other using cables. This causes an expense and somehow introduces difficulty in accessibility for some areas. To tackle these impairments, the idea of exploiting radio signal instead of cables has been recently proposed, so called Wireless Mesh Networks (WMNs) [2]. These networks are constituted by radio nodes organized in a mesh topology. Once one node can no longer operate, the rest can communicate to each other directly or through one or more intermediate nodes. To this end, a draft extension of the IEEE 802.11 standard for WMNs is under development [3].

As radio signal is utilized in WMNs, co-channel interference remains a limiting factor which the system designers have to concern. To deal with this impairment, lot of attention in the area of WMNs has been paid to smart antenna technologies. These techniques rely on beamforming algorithm to provide maximum gain at a desired direction and steer nulls or sidelobes to undesired directions. The key success of smart antennas is an antenna array and a suitable signal processing unit. Fully adaptive smart antennas are able to perform the electrical beam and null steering [4]. These capabilities come with a high level of computational for signal processing unit, resulting in high expense and complexity. On the other hand, switched-beam antennas being one typical type of smart antennas do not need additional cost and complications. In these systems [5], a number of predefined beams are formed in different directions by antenna array and beamforming network. However, switched-beam antennas have the limitation of interference suppression as it cannot control nulls' directions. Although this problem can be avoided when utilizing fully adaptive smart antennas, its complexity makes the concept impractical for WMNs. Therefore, this paper proposes a low profile beamformer with null locating capability for WMNs, which is practical for implementation. This beamformer provides multi-beam patterns simultaneously around the router of interest. In addition, interference signals can be cancelled with a straightforward null-steering method described in the paper. Moreover, the true evaluation in term of practical realization of the proposed beamformer is also reported in this paper.

This paper organized as follows. After brief introduction, problem formulation in term of air interface between mesh routers is discussed in Section 2. In Section 3, a low profile beamformer employing 2×2 rectangular antenna array and its beamforming network is detailed. To tackle the problem of interference signals from neighbouring routers, a straightforward null steering algorithm is presented in Section 4. Section 5 shows simulation

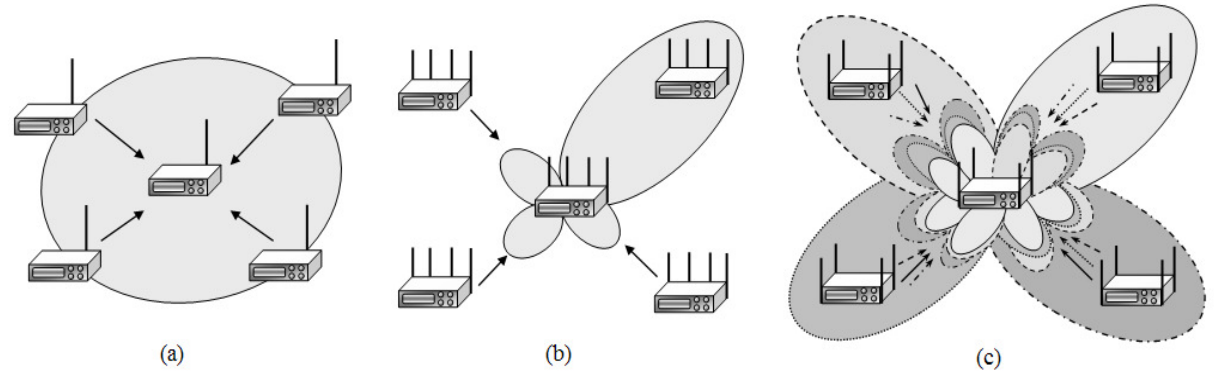

Fig.1 Configuration of WMNs employing different antenna systems, (a) omni-directional antenna (b) directional antennas (c) proposed antenna.

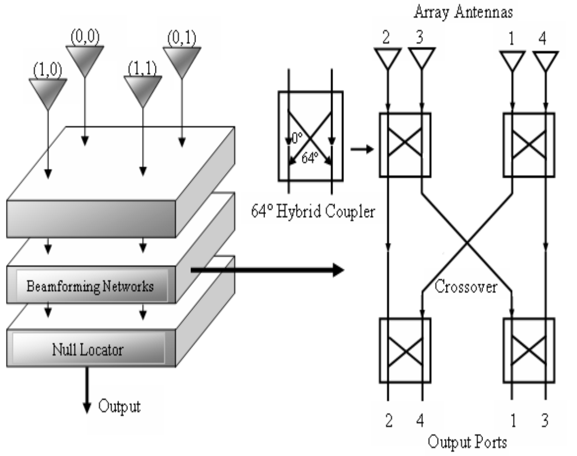

Fig.2 Configuration of beamforming networks.

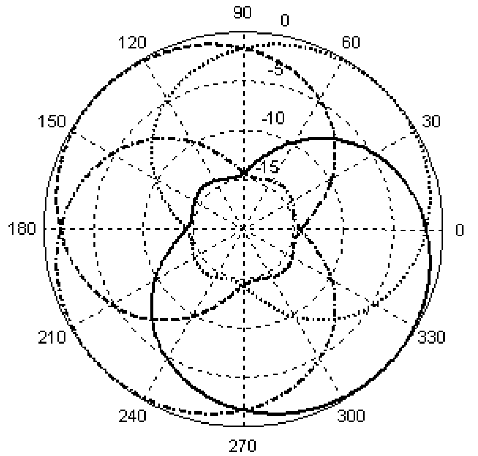

Fig.3 Simulated radiation patterns of beamformer at 2.45 GHz [7].

results to confirm the proposed concept. Moreover, the performance evaluation of switched beam antennas with null locating for WMNs is presented The prototype is constructed and tested under IEEE 802.11 a/b/g infrastructure. The performances in term of signal quality, throughput and delays are investigated. Sometimes it is impossible to locate mesh router on the beam direction of desired node. Hence, also in the paper, the effect of position shift which mesh router is not located on the expected beam direction has also been examined in Section 6. Finally, Section 7 concludes the paper.

2 Beamforming Concept in WMNS

Fig.1 presents WMNs in different scenarios in term of air interface. Note that this paper focuses on the mesh routers, not mesh clients. This is because positions of mesh routers are relatively stable and evenly distributed within the network. So far, the concept of WMNs has been initialized with omni-directional radiation, as shown in Fig.1a. As we can see, interference signal from neighboring routers become interference, as strong as signal strength from the router of interest. This introduces an increase in blocking probability. According to this, many works in literatures have proposed to adopt the concept of using switched-beam systems and directional antenna, respectively, in WMNs [2], [6]. As shown in Fig.1b, an antenna array is utilized at mesh routers to provide directive gain in the desired direction. The energy saving can be also achieved with this concept. However, interference signals remains in the system and their amount is relatively large for the array having high sidelobe levels. This can be decreased by utilizing a large number of antenna elements, resulting in high expense. So, controllable null locating is attractive when employing a small number of antenna elements in order to meet the requirement of low profile systems. Fig.1c demonstrates the concept of air interface proposed in this paper. As we can see, multiple beam patterns are designable and simultaneously produced in any given directions with a low compact size array in cooperating with a suitable beamforming network. In each beam pattern, nulls' locations can be produced in the directions of undesired signals. The detail of each part is described as follows.

3 Low Profile Beamformer for WMNS

The beamformer consists of 2×2 rectangular array and beamforming network as shown in Fig. 2. The choice of 2×2 array configuration is due to the requirement of a minimum number of antenna elements which is able to take responsibility for signals coming from 0 to 360° around the array. The array is spaced by λ/4 as shown in the figure. The reason is that spacing of λ/4 give lower side-lobe level comparing with spacing of λ/2. The received signals are delivered to beamforming network in order to accomplish beam formation in predefined directions, simultaneously. The beamforming network is constituted by four 64°-hybrid couplers and a crossover. Note that the mentioned beamforming network provides main beam directions at 45°, 135°, 225° and 315° simultaneously. Afterwards, the four outputs, from four beams, are conveyed to null locator as shown in Fig.3, which is detailed in next section.

4 Null Locating Method

Nowadays, lots of effective null steering algorithms can be found in literatures [8], [9]. Unfortunately, those methods require high level of computation which can be handled by expensive signal processor. This is not attractive for WMNs application [10]-[11]. Therefore, this paper presents a straightforward null locating method which requires only multiplying some suitable coefficients at the output signals from beamforming network. The mentioned coefficients can be calculated as follows.

Assuming directions of incoming signals from azimuth directions, weighting coefficients at $(m,n)^{\text{th}}$ antenna element corresponding to the desired and undesired signals can be express as

$$\begin{aligned} w_d(m,n) &= e^{j\left[(m-1)\left(\frac{\pi}{2}\cos\phi_d\right)+(n-1)\left(\frac{\pi}{2}\sin\phi_d\right)\right]} \\ w_{i,q}(m,n) &= e^{j\left[(m-1)\left(\frac{\pi}{2}\cos\phi_{i,q}\right)+(n-1)\left(\frac{\pi}{2}\sin\phi_{i,q}\right)\right]} \end{aligned} \tag{1}$$

where ϕ_d and $\phi_{i,q}$ are directions of arrival for desire signal and q^{th} interfere signals, respectively. The output signals in term of desired (y_d) and interference signals ($y_{i,q}$) from beamforming network shown in Fig.2 can be written as

$$\begin{aligned} y_d &= \mathbf{w}_d \mathbf{s}_{total} \\ y_{i,q} &= \mathbf{w}_{i,q} \mathbf{s}_{total} \end{aligned} \tag{2}$$

where $\mathbf{s}_{total}$ stands for signal vector which includes desired and interference signals. According to Eq.(2), the total output signal can be given by

$$\begin{aligned} y_{total} &= y_d + \sum_{q=1}^{Q} k_q y_{i,q} \\ &= \mathbf{s}_d.\left(\mathbf{w}_d + k_1\mathbf{w}_{i,1} + \ldots + k_Q\mathbf{w}_{i,Q}\right) \\ &\quad + \sum_{q=1}^{Q} \mathbf{s}_{i,q}.\left(\mathbf{w}_d + k_1\mathbf{w}_{i,1} + \ldots + k_Q\mathbf{w}_{i,Q}\right) \end{aligned} \tag{3}$$

where k_q is here in defined as a interference suppressing coefficients which can be calculated as follows. With the concept of interference rejection, the 2nd term of Eq.(3) must be vanished as the following expression.

$$\sum_{q=1}^{Q} \mathbf{s}_{i,q}.\left(\mathbf{w}_d + k_1\mathbf{w}_{i,1} + \ldots + k_Q\mathbf{w}_{i,Q}\right) = 0 \tag{4}$$

Solving Eq.(4), the interference suppressing coefficients can be obtained as shown in Eq.(5).

$$\begin{bmatrix} k_1 \\ \vdots \\ k_Q \end{bmatrix} = \begin{bmatrix} \mathbf{w}_{i,1}\mathbf{s}_{i,1} & \cdots & \mathbf{w}_{i,Q}\mathbf{s}_{i,1} \\ \vdots & \ddots & \vdots \\ \mathbf{w}_{i,1}\mathbf{s}_{i,Q} & \cdots & \mathbf{w}_{i,Q}\mathbf{s}_{i,Q} \end{bmatrix}^{-1} \begin{bmatrix} -\mathbf{w}_d\mathbf{s}_{i,1} \\ \\ -\mathbf{w}_d\mathbf{s}_{i,Q} \end{bmatrix} \tag{5}$$

The simplicity of null locating method for this paper is indicated in Eq.(5). With simply multiplying k_q at output signal from q^{th} beam produced from beamforming network, the q^{th} interference signal can be simply eliminated from the systems. In practice, we can find interference suppressing coefficient k_q with information of directions of desired and interference signals, then we can follow the procedure from Eq.(1) to (5). In the circumstance of WMNs, the directions of those signals coming from mesh routers are fixed. However, the directions of signals in other wireless systems can be easily found using some straightforward algorithms available in literatures [12]-[14].

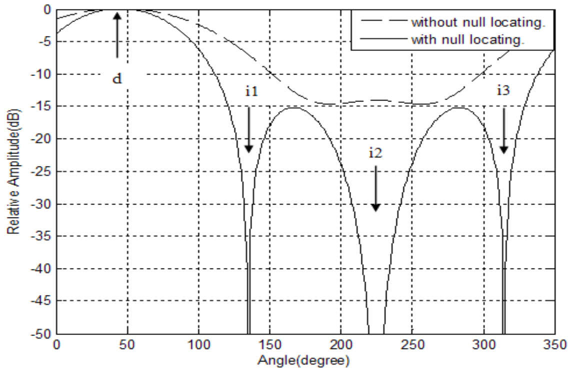

Fig.4 Radiation pattern of a 2×2-beamformer when the desired signal is coming from 45° and interference signals are coming from 135°, 225° and 315°.

5 Simulation Results

The proposed concept is tested using own developed computer program. The radiation pattern is the key factor to indicate the beamforming capability for this paper. In the assumed mesh network, there are four mesh routers located around the router of interest at 45°, 135°, 225° and 315° from boresight direction. The router of interest has to operate to all four meshes simultaneously. Also it has to distinguish between desired signal from one mesh and interference (undesired) signals from neighboring mesh routers. The 4 monopole-antennas spaced by $\lambda/4$ at 2.4 GHz are employed and placed as a 2×2 lattice as shown in Fig.2. Fig.4 shows radiation pattern of the beamformer forming its main beam to 45° without null locating (dash line). In this figure, solid line represents beam formation when the interference signal from neighboring mesh routers are coming from 135°, 225° and 315° from boresight direction. Comparing these two results, we can see that null locator succeeds in interference signal suppression while preserving the main beam direction to the desired signal. The performance of the proposed beamformer in some other scenarios is demonstrated in Fig.5. In this case, the beamformer needs to form its main beam to more three directions, 135°, 225° and 315° (apart from 45°). When one direction is chosen to be desired direction, the others can be viewed as interferers. As we can see in this figure, the proposed systems can steer nulls to directions of interferers while pointing main beam to the desired direction. This confirms that interference signals can be eliminated from WMNs. Also, this provides energy saving which is one important issue for WMNs.

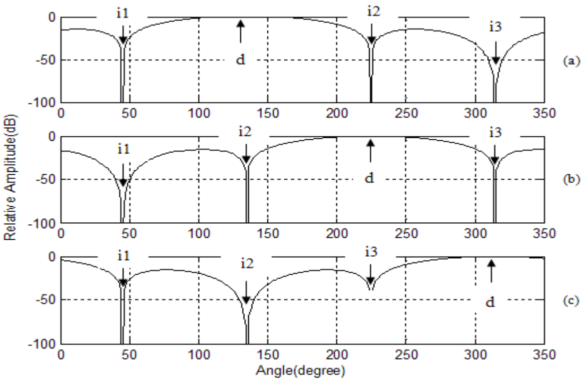

Fig.5 Three scenarios of radiation pattern for 2×2-beamformer when d and i stand for desired and interference signals, respectively.

6 Experimental Results

To confirm the beamforming capability of the proposed concept, a prototype of the beamformer is constructed, which is constituted by three major parts: array antennas, beamforming network and null locating network. For the array antennas, 4 standard monopole antennas are employed in which it provides gain of 5 dBi individually. The array is arranged in 2×2 lattice. The array spacing is half-wavelength at 2.45 GHz. For beamforming network, the modified Butler matrix presented in [8] is adopted here. It is adopted which provides 4 input ports and 4 output ports. The photograph of utilized beamforming network is shown in Fig. 6. The 4 input ports are connected to the array antennas while the 4 output ports deliver the received signals to null locating network. The 4 output signals from the beamforming network are the signals coming from 45°, 135°, 225° and 315° off boresight direction as well as for transmitting mode. Next the null locating network will provide the main beam to desired direction and null to interference directions as explained earlier.

The prototype of null locating networks are constructed and tested. The directions of interest are given at 45°, 135°, 225°, 315°. If one direction is chosen to be desired direction, the rest directions become interference directions. Fig.7 shows a prototype of null locating networks which has to be connected to the beamformer presented in Fig.6. Top-left, top-right, bottom-left and bottom-right networks present the null locators for pointing main beam at 45°, 135°, 225° and 315°, respectively, while keeping the other directions to nulls. The width and length of strip shown in Fig.7 represent amplitude and phase for interference suppressing

Table 1. Interference Suppressing Coefficients measured from prototype show in Fig. 7.

Coefficient(k_q) / Main beam	k_1	k_2	k_3
45°	-0.1900-0.4160i	-0.1444+0.1744i	-0.1530-0.4356i
135°	-0.1614+0.3709i	-0.1706-0.4380i	0.2382+0.0136i
225°	-0.1950-0.1540i	-0.1790+0.4460i	-0.1920+0.4260i
315°	-0.1614+0.3709i	0.2382+0.0136i	-0.1706-0.4380i

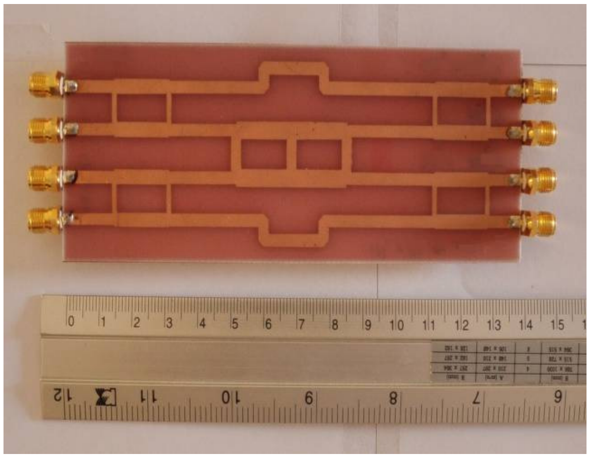

Fig.6 Modified Butler matrix having the main beam directed to 45°, 135°, 225° and 315°.

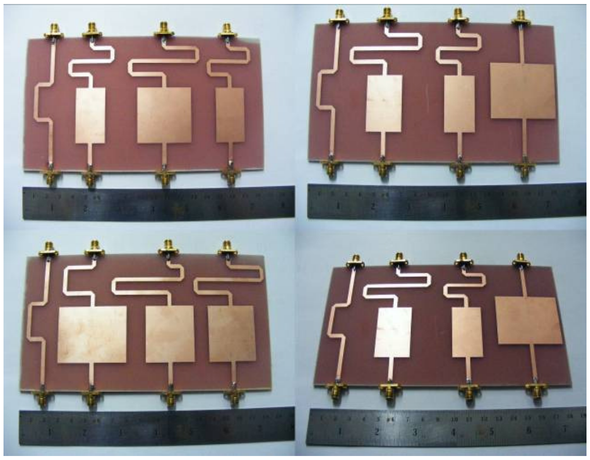

Fig.7 Photographs of null locators.

coefficients calculated in (5). Table 1 shows the measured outputs from the constructed prototype of null steering network shown in Fig.7.

Next, the performance of constructed prototype is tested and one of four configurations shown in Fig.8 to 11 whereas dash line represents radiation pattern of the array without null locating and solid line indicates the one when including null locating.

To validate the use of proposed system for WMNs, the measurement is required to be undertaken. The basic configuration of WMNs is illustrated in Fig.12. In this figure, five nodes represented mesh routers are employed and the proposed switched-beam is implemented at the center node. According to non-solid standard for WMNs, one approach of air interface is able to be arranged by using conventional IEEE 802.11 a/b/g. In this paper, four WLAN access points are located at the corner as shown in Fig.12. For the proposed switched-beam, the illustration of measurement setup at the center node is depicted in Fig.13. To measure signal strength, there is no compensation due to all power loss caused by connectors, transmission lines and combiner. Hence, it makes sure that the proposed system is practically tested for real application and promptly used for WMNs as its presented form. Figs. 14 and 15 present the received signal strength versus power transmission for conventional omni-directional antenna and proposed switched-beam antennas.

Each time step is a consecutive one-minute interval. For omni-directional antenna, the received signal strength of four access points varies from -38 to -70 dBm and there is no dominant access point. In turn, the results of proposed switched-beam antennas provide two significant groups which are the access point in desired direction, Ap1, and null directions, Ap2 to Ap4. The gap between signal strength of desired access point and the others is ranged from 6 to 20 dB. It is interesting to observe that the received signal strength of desired access point varies from -33 to -35 dBm which is higher than the best signal strength of omni-directional antenna. These results confirm the use of proposed switched-beam antennas to enhance signal strength as well as suppress interference signals.

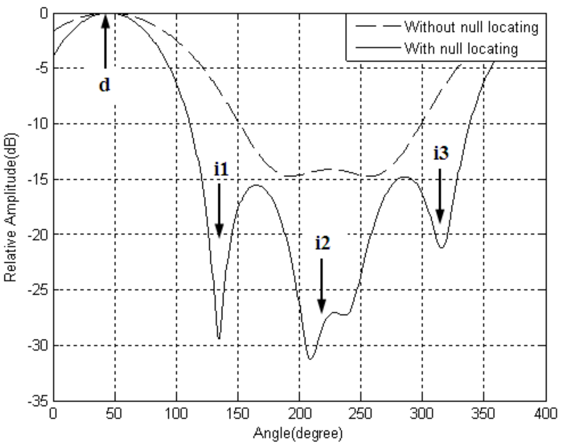

Fig.8 Radiation pattern of a 2×2-beamformer when the desired signal is coming from 45° and interference signals are coming from 135°, 225° and 315°.

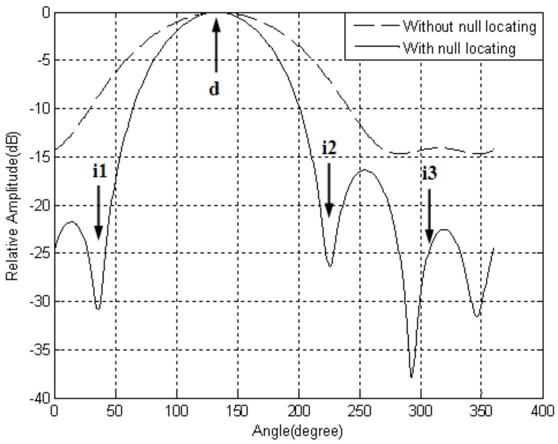

Fig.9 Radiation pattern of a 2×2-beamformer when the desired signal is coming from 135° and interference signals are coming from 45°, 225° and 315°.

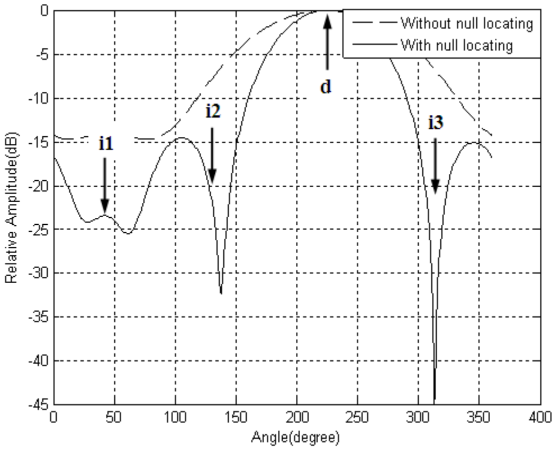

Fig.10 Radiation pattern of a 2×2-beamformer when the desired signal is coming from 225° and interference signals are coming from 45°, 135° and 315°.

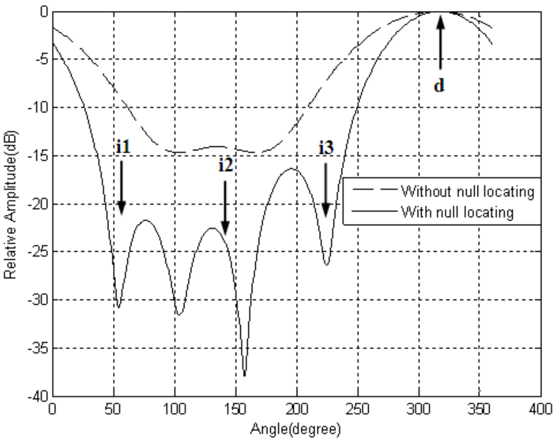

Fig.11 Radiation pattern of a 2×2-beamformer when the desired signal is coming from 315° and interference signals are coming from 45°, 135° and 225°.

Only signal strengths cannot totally indicate the performance of WMN so the next task is to validate the other parameters to mark a merit of networks including delay and throughput. Fig.16 provides the average delay versus data size when downloading. As seen in the figure, proposed switched beam antennas can help the system to download more quickly for both 2 and 6 Mbytes. This is because the proposed system having higher received signal strength experiences a lower outage probability than omni-directional antenna. Also the signals from desired access point have a lower interruption interfered by other access points. Fig.17 presents the probability density function of throughput. In this figure, the total 100 samples are measured and evaluated through well known website, www.numion.com.The results show that the omni-directional antenna provides lower mean throughput than switched beam antennas and the probability having throughput more than mean value of omni-directional antenna is less than switched beam antennas. These results confirm the use of proposed switched beam to enhance signal quality as well as suppress interference signals.

In practice, the position of mesh router is not always on beam direction. Therefore, the following measurements based on configuration in Fig.18 are undertaken to investigate whether the proposed system can provide benefits or not if mesh location is shifted from beam direction. Fig.19 presents the. received signal strength versus angles deviation for omni-directional antenna and proposed switched-beam antennas. We can see when angle is deviated +15° and -15°, switched-beam antennas still provide a received signal strength of desired access point better than omni-directional antenna. Fig. 10 provides the average delay versus data size when downloading. As seen in the Fig. 20, the proposed switched-beam antennas can help the system to download more quickly for both 2 and 6 Mbytes. Fig.21 presents the probability density function of throughput. In this figure, the total 100 samples are measured and evaluated through well known website, www.numion.com. The results show that the omni-directional antenna provides lower mean throughput than switched-beam antennas and the probability having throughput higher than mean value of omni-directional antenna is less than switched-beam antennas of all angle deviation. These results indicate the success of proposed system even the mesh router is not installed on the direction of main beam.

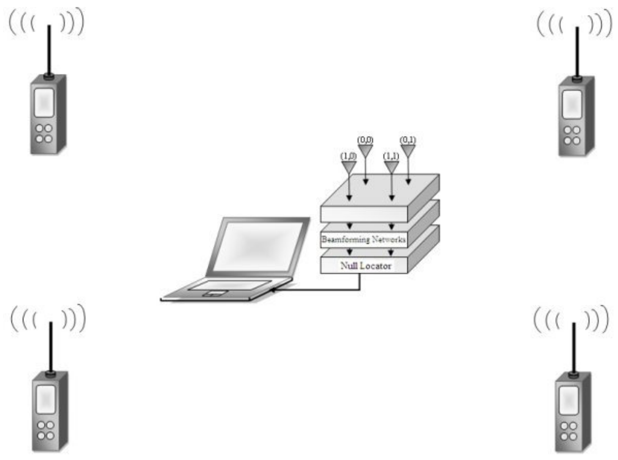

Fig.12 Scenarios for testing the proposed system.

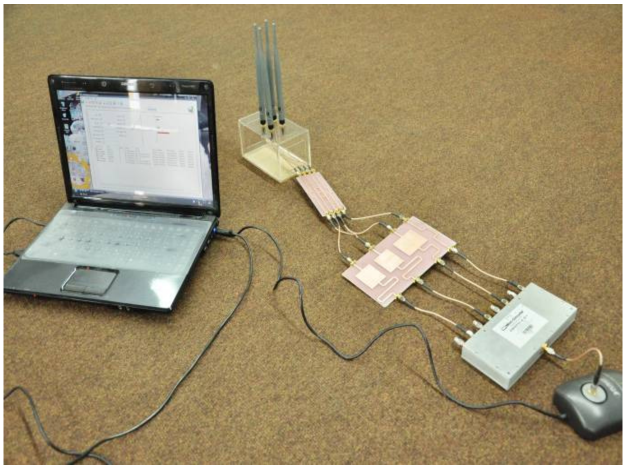

Fig.13 Measurement setup of proposed system for WMNs.

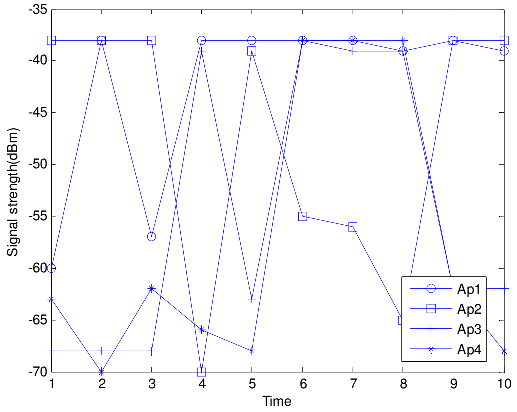

Fig.14 Received signal strengths from four access points by using conventional omni-directional antenna.

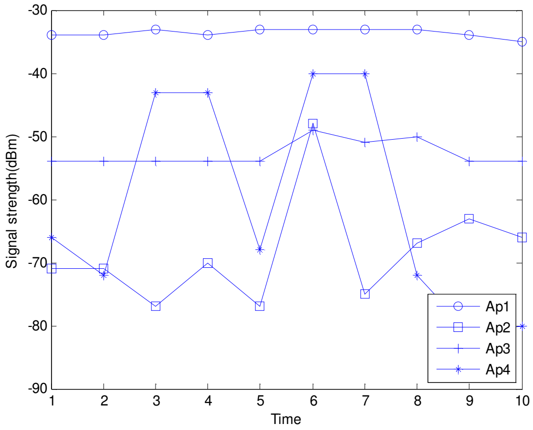

Fig.15 Received signal strengths from four access points by using switched-beam with null locating networks.

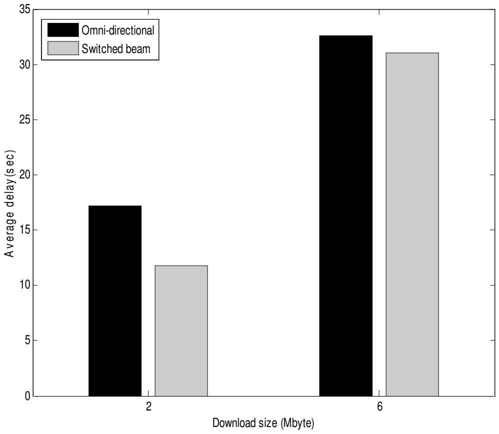

Fig.16 Average delay when downloading data via conventional omni-directional antenna and proposed switched-beam antennas.

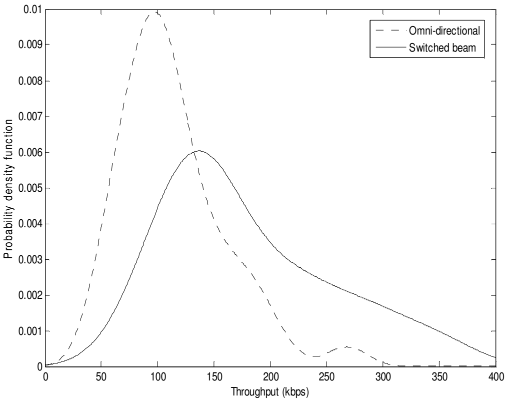

Fig.17 Probability density function of measured throughput when using conventional omni-directional antenna and proposed switched-beam antennas.

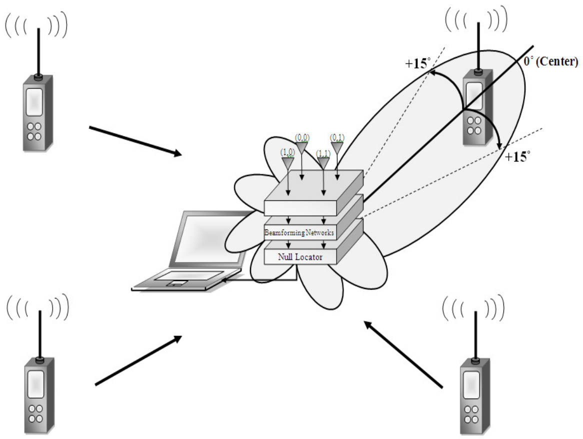

Fig.18 Test scenarios on location shift of mesh router.

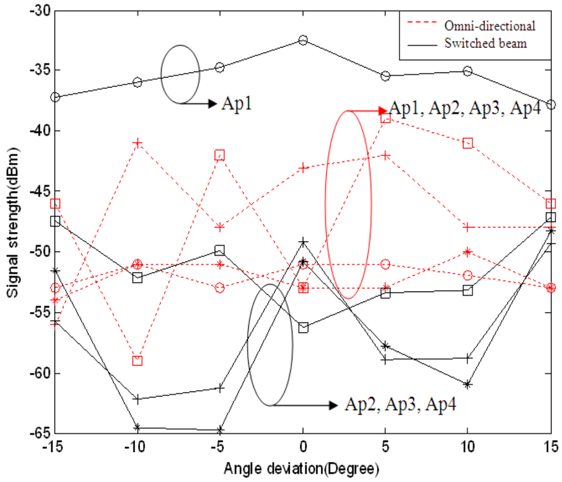

Fig.19 Received signal strengths vs. angle deviation for four access points by using conventional omni-directional and proposed switched-beam antennas.

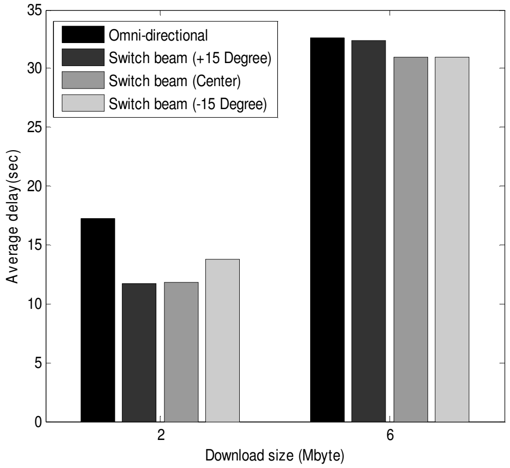

Fig.20 Average delay when downloading data for conventional omni-directional antenna and proposed switched-beam antennas.

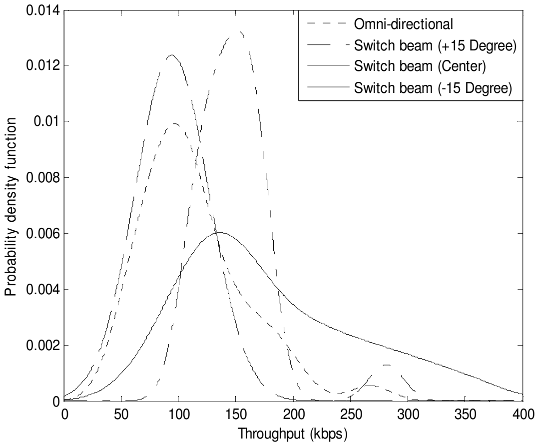

Fig.21 Probability density function of measured throughput when using conventional omni-directional antenna and proposed switched-beam antennas.

7 Conclusion

This paper has presented a low profile beamformer suitable for WMNs. Also, this beamformer is able to suppress interference signals by locating nulls to interfering directions. This beamformer is constituted by 2×2 antenna array spaced by $\lambda/4$ accompanied with a simple beamforming network. The null locating algorithm can be handled by any economic microprocessor as it is only multiplication to constant values. The simulation results confirm its beamforming capability. Moreover, the experimental results have shown that the beamformer can improve the overall signal strength, throughput and delay over the use of conventional omni-directional antenna. The prototype offer benefits in term of signal quality, throughput and delays. Also its benefits can be achieved even the mesh router is located by ± 15 degree deviating from beam direction.

Acknowledgments

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