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Abstract - Empirical results from a performance study of an Integrated Wireless Sensor Network (WSN) and Wireless Local Area Network (WLAN) are presented in this paper. Integration of heterogeneous wireless technologies using different modulation techniques such as direct-sequence spread spectrum (DSSS) and orthogonal frequency division multiplexing (OFDM) require careful deployment planning and configuration if network performance is to be optimized. The impact on network performance of the WLAN and WSN is investigated through a series of experiments on the Athlone Institute of Technology (AIT) campus network under realistic load conditions. Novel software tools from Motorola are used in this research for fast efficient deployment of WLAN’s. These software tools utilize satellite maps of the deployment area to predict coverage and range. Combined with management tools for integrated channel assignment, this should provide performance enhancement capabilities. Our findings show that at least more than four channels of WSN were under interference when WSN and WLAN coexisted. The expression for a channel assignment model is adapted from Chowdhury et al [1]. The reference power variables were taken from IEEE802.11g under real traffic loading with eight channels being considered. Achieving effective channel allocation for WSNs offers better performance due to less retransmission and inherently reduces energy consumption. This paper will be of interest to organisations where critical information retrieval over wide area networks in hostile environments (such as disaster recovery situations) is required as well as traditional network deployments.

I. INTRODUCTION

Many challenges exist if integrated wireless networks are to provide efficient network performance. The shortage of empirical results for integrated heterogeneous wireless networks utilising OFDM modulation under adverse interference conditions as outlined in [2] are well known.

With the development of heterogeneous wireless communication technology, combined with data acquisition, comes a new trend of networked acquisition systems. Among this range of wireless technologies, WSN has attracted a lot of interest and visibility due to its huge application space [3]. Wireless sensor networks are a form of wireless ad-hoc network which connect embedded sensors, actuators, processors and in which each node consists of a wireless communication device.

A. Wireless Sensor Network (WSN)

The design of a WSN platform must deal with challenges in energy efficiency, scalability, cost, and application requirements. It requires the optimization of both the hardware and software to make a WSN efficient. Hardware includes using low cost miniaturize sensor nodes while software addresses issues such as network lifetime, robustness, self-organization, security, fault tolerance, and middleware [3].

An example of a commercially available sensor is the MicaZ mote from Crossbow™ [4] (used in this research) utilizing ISM band 2.400MHz – 2.385MHz with 16 channels available. Sensors like this one can be used to build large sensor networks for a variety of applications in different areas including indoor and outdoor environmental surveillance, intelligent building monitoring, health monitoring and object tracking among others. They can also be used to provide relay networks to facilitate rescue operations in wide open hostile areas [3].

WSN’s require application specific configuration for each deployment if network performance is to be optimized. Critical factors that influence WSN performance include scalability, communication protocols at different layers (cross layer communication), failures and network management. Regarding the issue of scalability, it is noted that one of the challenges of using the WSN is the short range of the sensor nodes. One of the design constraints of wireless sensor networks is the small transmission power and consequently the radiated power (on the order of 0 dBm) with the hope to save energy by leveraging multihop communication [5]. The choice of a low transmission power implies a small range of coverage.

One option is to use a Wireless Mesh Network (WMN) as the backhaul for transporting the data to a central server. The integration of WSN with WMN expands the communication range and allows mobility of the devices. WSN’s can be used for forming the underlying sensing and WMN provides the backhaul network infrastructure in pervasive computing environments. A similar approach was introduced by Torsten in [6] whereby WSN and WMN were integrated to connect to the Internet.
However analysis done at Cantab Wireless Ltd. Cambridge, UK [7] concluded that deploying a Wireless Sensor Network (WSN) is a problem which should not be overlooked. In [8], Pesch et al. in their research agree that wireless deployment planning can be regarded as an essential stepping stone to produce a viable network infrastructure. Hence the issues of deployment and interoperability were investigated in our research by integrating Crossbow™ IEEE 802.15.4 Zigbee compliant 2.4GHz WSN with a Motorola WMN consisting of Intelligent Access Points (IAP-4300) based on the IEEE 802.11a/g standard as the backhaul.

B. Wireless Mesh Network (WMN)

The 802.11 technology has become a ubiquitous solution for wireless LAN’s in the home and offices. Using the two-tier mesh network technology the WLANs have been considered as a cost effective solution to wide area coverage. A two-tier mesh network has an access tier that integrates the clients, and a backhaul tier which forwards the clients packages in a multihop architecture to a wired gateway (Fig.1). A two-tier mesh network when compared with cellular networks or WiMax has a lower deployment cost, is easily scalable, has better coverage and is robust to general individual node failure [9].

Fig. 1: AIT WMN Architecture

The WMN was deployed on the AIT campus using industry grade equipment from Motorola and deployed based on the simulated RF performance using the Motorola Mesh Planner software. The real time performance was measured using the IxChariot package from Ixia [10]. The performance clients are laptops connected to a 802.11g network running the IxChariot client. The end point is running on the server that is connected to the mesh router via a wired network. Access Point 1 (AP1) is fixed and mounted externally to the main building and the other two (AP2 and AP3) are mounted on mobile masts (Fig 2). The Motorola IAP4300 access points used in the network comes in dual radio configuration: 2.4GHz 802.11b/g radio for client access and 4.9 GHz radio dedicated for the mesh node-to-node traffic. Results of throughput test can be seen in Section III (A) - Fig.6.

C. Motorola Mesh Planner Tool

Motorola provides a software package for designing outdoor wireless mesh networks efficiently and cost-effectively. Optimized to work with Motorola Motomesh products, MeshPlanner allows designers to create networks on their computers and validate performance with the software’s measurement functionality, eliminating the costly on-site work that accompanies traditional site survey-based design methods. This reduces labour and planning costs and enables quicker implementation of a high-performance network. The initial aim of this research is to use the software to plan the deployment of the Motorola Mesh Network on the AIT campus, validate the effectiveness of the planning tool and to then incorporate information from simulation studies to enhance the performance.

Fig. 2: The mesh network established between the APs

The planning software creates an RF-intelligent map by importing the following:

- A digital elevation model in GeoTIFF format
- Deployment drawing via satellite image
- Scanned image or digital photograph
- Buildings, structures or foliage in ESRI shape file format
- Clutter data in GeoTIFF format; and equipment mounting locations in .TXT format

AIT is the first to use this package in Ireland and this research will evaluate and report on the effectiveness of the software for deployment and planning purposes for an integrated WMN and WSN. A screenshot from the Motorola software tool shows the AIT Campus (buildings infrastructure shaded) with three access points in position is shown in Fig 2.

D. RF Propagation Model

Methods for predicting outdoor wireless signal coverage have been under development for decades. These models predict the signal power at a given point by determining the path loss, the difference between the transmit power and received power, from the transmitter to the receiver. The simplest form of this model is the purely distance dependent Friis transmission equation, which calculates the received signal power according to the signal loss in free space.
\[ PathLoss = PL(d_0) + 10_n \log_{10}(d) + \sum_i OBS_i \cdot PE_i \]

The model used in the simulations is simply an extension of the Friis equation adding the clutter interference and non line-of-sight losses. OBS is the number of obstructions of type i that intersect the direct-ray path from the transmitter to the receiver, and PE is the propagation effect, or amount of change in the path loss incurred per intersecting obstruction, for an obstruction of type i.

**E. Simulated WMN Coverage**

Fig. 3 shows the expected throughput based on the correlation between the RSSI and data rates. A range of shade intensity conveys the decrease in data rate as the client moves further away from the AP. The RSSI value is calculated for each of the 3240 blocks using the line-of-sight path loss model. The block size area defines the resolution of the prediction. The smaller the block size, the higher the resolution and number of calculations required for the simulation. In our simulation the bin size defined was six meters, indicating that the results are precise to within six meters.

**II. COEXISTENCE ISSUES OF WSN AND WMN**

IEEE 802.15.4 is establishing its place on the market as an enabler for the emerging wireless sensor networks. The intent of IEEE 802.15.4 is to address applications where existing WSN wired solutions are too expensive and the data rate of a technology such as Bluetooth-802.15.1 is not required. IEEE 802.15.4 complements other WSN technologies by providing very low power consumption capabilities at very low cost, thus enabling applications that were previously impractical. Table 1 illustrates a basic comparison between IEEE 802.15.4 and other IEEE 802 wireless networking standards.

<table>
<thead>
<tr>
<th></th>
<th>802.15.4 – WSN</th>
<th>802.15.1 – Bluetooth</th>
<th>802.11b – WLAN</th>
<th>802.11g – WLAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>– 10 – 30 m</td>
<td>– 10 – 100m</td>
<td>– 10 – 100m</td>
<td>– 10 – 100m</td>
</tr>
<tr>
<td>Max Data Rate</td>
<td>0.25Mbps</td>
<td>1 Mbps</td>
<td>11Mbps</td>
<td>54Mbps</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>Ultra Low</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>

In this paper we present results from experiments conducted to examine the number of packet drops and packet retries. The WSN was monitored and experimentally analyzed under a realistic network load environment involving a scenario where the WSN was under interference of a WLAN and vice-versa (WLAN becomes the victim of WSN) and the WLAN throughput was measured. Following on from these experiments, a spectrum analyzer has been utilized to measure the WSN and WMN channel used to have a better understanding of their characteristics.

**A. Related Work**

Our previous study on coexistence between 802.11b/g and IEEE 802.1.4 in [13] shows a serious impact on the IEEE 802.15.4 performance if the channel allocation is not carefully taken into account. The experiments were conducted where the number of packet drops and packet retries were monitored and experimentally analyzed under a realistic network load environment and involving a scenario where the WSN was under interference of a WLAN. Detailed results of the experiment are shown in Section IV.

One way of mitigating this issue is developing a channel assignment model that provides channel agility so that the network operates in channels with less interference thus providing higher network resilience and reliability.
B. Interferer Identification and Channel Assignment

In classifying WLAN interference, the algorithm used in [1] is adapted. However, our research work differs in that the reference power values are obtained from deploying WSN collocating with IEEE802.11g WLAN on a heavily loaded network with additional channel separation. The scheme introduced the angle $\theta_{\text{obs}}$ as the angular difference between the reference power values and those obtained from the current channel under observation. $\theta_{\text{obs}}$ is the scalar dot product; $\theta_{\text{obs}} = \cos^{-1} \{a \cdot b\}.$ The conical region around the reference vector $a$ by an angle $\theta$ is to define any measured vector $b$ within that region ($\theta > \theta_{\text{obs}}$) can be considered as a positive match. This is defined as the spectral signature. A threshold of $\theta$ is given as 3 degrees [1]. This means that if $\theta_{\text{obs}}$ is less than 3 degrees, then the current measurement is identical to the reference power unit vector and thus considered as the channels that are affected by IEEE 802.11g interference.

Fig. 5 shows an illustration visualizing the channels as a set of orthogonal axes. Vector $a$ is the reference value for the interferer. Vector $b$ is measuring the received power of channel $c$ and vector $c$ is the channel with interference.

Then, the unit vector along that direction is:

$$\vec{a} = \frac{\vec{\theta}}{|\vec{\theta}|}$$

This unit vector captures the relationship between the power values sensed in the channels through its spatial orientation. As suggested in Section III (B), eight channels should now be considered as channels under interference. Hence the reference unit vector is obtained as:

$$\vec{a} = -0.411\hat{i}_1 - 0.411\hat{i}_2 - 0.301\hat{i}_3 - 0.237\hat{i}_4 - 0.243\hat{i}_5 - 0.313\hat{i}_6 - 0.405\hat{i}_7 - 0.440\hat{i}_8$$

III. Results

A. WMN Throughput

Using the WMN setup in AIT Campus (Fig.2), throughput measured with the IxChariot tool shows (Fig. 6) a drop from 14 to 7 Mbps adding 1 hop (connected on AP2) and from 7 to 2 Mbps with 3 hops (connected on AP3). The results are coherent with the expected degradation considering the shared backhaul in the single radio architecture. Each hop of the composed traffic almost cuts the throughput in half. The results are between the best-case theory $1/n$ and worst-case theory $(0.5)^{2n}$ discussed in [14] but significantly worse than the classical results $O(\frac{1}{\sqrt{n}})$ of Gupta in [15] that considers large values of $n.$

B. IEEE 802.15.4 and IEEE 802.11g Interference Evaluation

The experiments have been carried out by using the testbed sketched in Fig. 7, which consist of an IEEE 802.15.4 WSN and IEEE 802.11g WLAN operating in close proximity. The WLAN was fixed to transmit on channel 6 (2437MHz) and variably changing WSN channel from 11 – 26. The radius $r$ between the motes and the gateway is 7m. Crossbow MPR2400 was used as the WSN motes. The Xmesh application was downloaded to the motes. The RF power on the motes was set to 0dBm (1mW). The packet size is 36 bytes with payload size of 29 bytes.
The XMTS310CA sensorboard was used and all the sensors available were activated, hence providing high data transmission from the motes to the gateway. The IxChariot (Ver 5.40) is used to generate TCP traffic simulating real load on the WLAN.

Fig. 8 shows the result of percentage of packet drops for WSN. The overlapped WSN channels 16 to 19 have significant implication for the number of packets dropped; within the range of 9.09% to 27.97%. Despite the eight retries before the packet is considered dropped, these figures provide information on the severity of the interference.

In the analysis of percentage number of retries for the packets in WSN (Fig. 9), it is observed that the percentage number of retries is increasing in the overlapped channel in the range of 111.36% to 294.74%. This means that in a severe case, a packet is resent four times before it is acknowledged by the receiver.

Interestingly in both results, adjacent channels close to the operating channel 6 in the WLAN are also implicated, including the known to be clear non-overlapping channels 15 and 20. The impact of coexistence between IEEE802.15.4 and IEEE802.11g at this stage is clear, in-line with Vanheel [2] albeit over a wider range of network operating conditions on a realistic field test.

The result provides concrete evidence that more than four channels were affected by the WLAN IEEE 802.11g signal. It is suggested that wider frequency off-set is taken into account. As the interference is more pronounced in channels closer to the WLAN central frequency, adding additional two WSN channels on both sides of the WSN signal lobe hypothetically is a better resolution. These two channels translate to an additional 10MHz on both sides of a WLAN signal lobe, increasing the channel separation. It should be considered to avoid a total of eight WSN channels that can be affected by a WLAN signal lobe when developing a channel assignment model for WSN. The proposed channel assignment model should provide predicted WSN channels that are free from any WLAN interference. With less interference the WSN offers higher network resilience and reliability.

In order to prove that the referenced unit vector is valid irrespective of the WLAN channel used, two sets of unit vector $\theta_{obs}$ are measured to identify the angle $\theta_{obs}$. The first set was chosen from eight consecutive WSN channels that are within the WLAN channel 8 and the second set is purposely taken from another eight channels that are only partially affected by WLAN channel 11 as a null hypothesis. The result shows that set 1; $\theta_{obs} = 0.7$ degrees ($\theta_{obs} < 3$ degrees : identical matched, WLAN interference exist) and set 2 was showing $\theta_{obs}$ of 10.32 degrees. The result clearly demonstrates that the proposed channel interference classification model is valid.

IV. CONCLUSIONS AND FUTURE WORK

In this research project, we have evaluated the interference level of IEEE802.15.4 WSN and IEEE802.11g in close proximity in an outdoor environment. The experiments were carried out to gauge the percentage packets dropped and retries by WSN motes from channel 11 to channel 26 under the existence of IEEE802.11g WLAN with the goal of evaluating the performance impact of integrating the WLAN using OFDM and DSSS on the WSN. IxChariot is used to insert TCP based traffic into the WLAN to simulate real network load. The packet delivery rates show that when WSN and WMN channels overlap the WSN packet delivery rate is reduced from 100%. When the channels are separated further in frequency, the packet rate degradation is reduced. As expected, the degradation is more pronounced in areas with strong presence of WLAN signals. It is deduced that coexistence and interference issues of IEEE802.15.14 WSN and IEEE802.11g WLAN can be cautiously addressed through careful channel selection and assignment.

A channel assignment model based on interference classification and channel selection by Chowdhury et al.[1] was explored as a proposal to mitigate the interference issue and results shows a viable outcome. A validation was also presented to evaluate the accuracy of
this model. Effective WSN operational channel can be identified using this method for better performance. Less retransmission traffic inherently reduces the power consumption of the WSN.

For future work, a layered design model based on policies for network management is proposed as a concept to evaluate the performance of the WSN under the influence of the channel assignment model in an environment with multiple WSNs and WLANs in place.

The key element in managing these wireless networks is that they should be self-organizing since it is impractical to maintain such large networks without intelligent network management. Hence, an effective network management system needs to be in place. A successful deployment of heterogeneous wireless networks depends on the ability for the administrator of a network domain to administer and distribute consistent policy information to the multiple devices in the network which perform the classification and packet conditioning or treatment [16]. As a result, there is a clear need to develop a scalable framework for policy administration and distribution that will allow interoperability among the multiple devices and device gateways that must work together to achieve a consistent implementation of the network administrator's policy as highlighted in [17].

A Cognitive wireless network is defined as an interaction and response by the node by dynamically altering their topologies and operational parameters to enforce regulatory policies and optimize overall network performance. A cognitive infrastructure consists of intelligent management and reconfigurable elements that can progressively evolve the policies based on their past actions [18]. Using this information to adapt to WSN environment, policies may be setup in the network management system before the deployment of the sensor network. Nodes may initialize their configuration according to these policies providing a hierarchal architecture for deployment according to situations, for example disaster recovery.

Considering the case of emergency service response for example, organizations will be set out to perform their task accordingly. In certain cases, the nature of the disaster will confine the organizations to work within the same area, hence deploying their wireless communication must be coordinated. To gauge the interference level of different wireless networks within the same region, we proposed the layered interference design model as shown in Fig. 10. The implementation of interference classification and channel selection will be performed at each layer. Policies are set for the overall network according to the priorities given in each layer.

Finally, our research will focus on the impact of coexistence under a wider range of operating conditions. We will also expand our research by modelling the management of the channel assignment using the simulator OPNET and analyze the performance of WSN under the influence of this model.

Fig. 10: Layered design for optimizing Network Management

REFERENCES