Improving the Performance of IEEE802.11s Networks using Directional Antennas over Multi-Radio/Multi-Channel Implementation – The Research Challenges

Saravanan Kandasamy[1], Ricardo Morla[1], and Manuel Ricardo[1]
[1] INESC Porto, Faculdade de Engenharia, Universidade do Porto
Rua Dr. Roberto Frias, 378,
4200-465 Porto,Portugal
{kandasamy, ricardo.morla, mricardo}@inescporto.pt

Abstract. The IEEE802.11s standard is a variety of Wireless Mesh Networks (WMNs), which features infrastructure-less flexible network configurations, is attracting attention as an elemental technology for future ubiquitous networks consisting of various types of nodes built on ad-hoc basis. To solve problems like throughput degradation, delay and fairness, an enhanced Medium Access Control (MAC) protocol may be required taking the advantage of directional antenna (DA) and cross-layer mechanisms. This paper explores in particular the research challenges to improve the performance of WMNs. Analyzing the trend, we are confident towards an enhanced wireless mesh networks performance by means of utilizing directional antennas and cross layer mechanism for the Access Points (APs).

Keywords: IEEE802.11s, Directional Antenna, Multi Radio, Multi Channel

1 Introduction

The IEEE802.11s task group was created by the Institute of Electrical and Electronics Engineers (IEEE) for installation, configuration, and operation of IEEE802.11-based wireless mesh networks (WMNs).WMNs allow for high flexibility in setup and relocation of communication nodes, ubiquitous access, and ease of use at the cost of lower throughput due to interference, high-loss medium, and limited available spectrum. In WMNs, neither predefined infrastructure nor centralized administration is required, as networks can dynamically build by nodes that may be mobile, static or quasi-static. The simplicity of deployment of these networks makes them an attractive choice in scenarios such as disaster recovery, broadband home networking, community and neighborhood networks, military operations, and transportation systems.

The nodes in the WMN are assumed to be equipped with omnidirectional antennas (OA) and, IEEE802.11 Medium Access Control (MAC) standard [1] has been designed only considering this kind of antennas. As the network become larger and denser, the network gets saturated due to the broadcast nature of the technology when the number of users increases with the traditional OA (refer Figure 1). However, with the rapid advancement of antenna technology, it becomes possible to use directional antennas [2] to improve the capacity of WMNs (refer Figure 2). This paper is an improvement of [3].

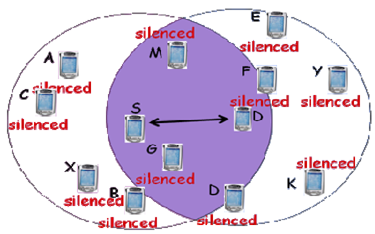

Figure 1 : Node S↔Node D - Omnidirectional Antenna

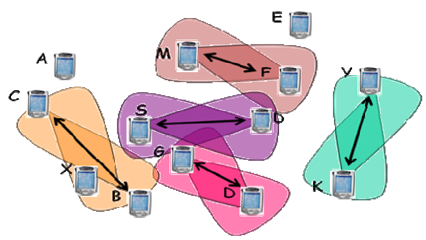

Figure 2 : Node S↔Node D, Node Y↔Node K - Directional Antenna

Directional antenna (DA) is divided into two categories, one is the traditional directional antenna (refer Figure 3) which is pre-fixed in particular direction and the other is a smart antenna which consist of 3 components; a radiating element, a combining or dividing network and a control unit. The control unit is the intelligence of a smart antenna which is usually implemented using a digital signal processor (DSP). The smart antenna can next be divided into two types, a switched beam antenna and steerable beam antenna [4]. A switched beam antenna (refer Figure 4) combines several directional antenna elements to form up to N predetermined directional beams, turned on and off in a determined manner while a steerable beam antenna (refer Figure 5) steers its radiating pattern either electronically or mechanically to focus to an intended direction.

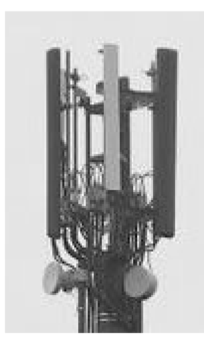

Figure 3 : Traditional Directional Antenna

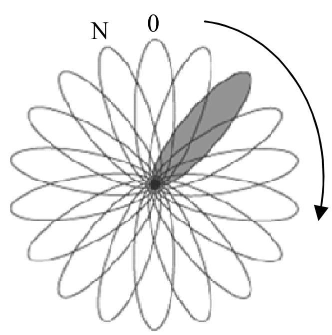

Figure 4 : Switched Beam Antenna

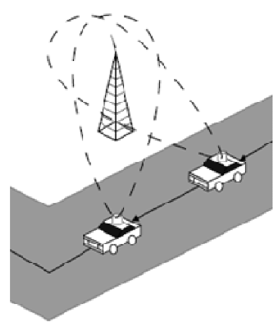

Figure 5 : Steerable Beam Antenna

Executing real-time applications over IEEE802.11s network are tough due to its mobility uncertainty and fragile radio properties. This is due to real time applications needed to be delivered within strict quality of service (QoS) requirements. The protocols in the lower layers need to work interactively with the application layer to create application protocols for managing distributed information sharing in WMNs. This requires cross-layer mechanisms through information sharing among application, transport, routing, medium access control (MAC) and physical layers. In this way, the deployed WMN can be self-adaptive to the network.

The rest of this paper is organized as follows: in Section 2, we provide the rationale for this research. Section 3 presents the work carried out in the last 10 years as state of the art in order to emphasize the rationale. In Section 4, we elaborate the research challenges identified through the state of the art, an opportunity for future research work. Section 5 will deliberate on the directional antenna model in IEEE802.11s Network. Finally in Section 6, we conclude the paper.

2 Rationale

Directional antennas offer several interesting advantages for IEEE802.11s networks. For instance,

- by exploiting the gain of the directional antenna, multi small hop transmissions could be reduced to minimal hops and sometimes potentially to a single long hop transmission. This would lower the transmission delay, reduce the number of control signals in the network and reduce congestion due to packet redundancy.
- a node may be able to selectively receive signals from a desired direction. This enables the receiver node to avoid interference that comes from unwanted directions, thus increasing the signal to noise ratio (SNR).
- more users could utilize the network. In an omni-directional antenna scenario (as shown in Figure 1), when Node S communicates with Node D, Node Y would not be able to communicate with Node K as it is in the ***silenced*** region of Node S and Node D, even though the transmission is not directed towards both of them. This does not happen when DA is used (as shown in Figure 2), thus increasing capacity.
- routing performance can be improved using DAs [5] due to its interference reduction capability which minimizes the contention among routes and reduction in the number of routing messages within a WMN.

3 State of the Art

Below we point out some of the recent work on topic related to directional antennas and wireless mesh networks.

3.1 Wireless Mesh Networks

In WMNs, the routing layer needs to work interactively with the MAC layer in order to maximize its performance. The simplest routing metric for WMNs is the hop-count metric. However, using the hop-count metric leads to suboptimal path selection. Small hop count translates into longer and more error prone individual hops [6]. The use of minimum hop count does not assist to manage the load-balance traffic across the wireless mesh network [7]. This reduces the effective capacity of the WMNs.

The bandwidth availability is harsh for WMNs where the nodes operate over the same radio channel in order to keep the network connected. This results in substantial interference between transmissions from adjacent nodes on the same path as well as neighboring paths, thus, reducing the end-to-end capacity of the network [8].

3.2 Directional Antenna and Directional MAC Protocol

Rappaport [9] described the use of sector antennas on modern cellular base-stations which allow the decreasing of cluster size in order to improve frequency reuse without being afraid of interference. Sectoring at 120 degrees reduces interference significantly and increases capacity by a factor of 1.714.

Nasipuri et al. [10] modified the Request-to-Send (RTS) and Clear-to-Send (CTS) exchange of the MAC protocol in IEEE802.11 networks to support directionality and showed through simulations that as a result, a throughput improvement of 2-3 times over OAs. The primary aim of the work was to minimize routing overhead by using DA elements for propagating routing information as routing overheads from omnidirectional transmissions can be costly. Ko et al. [11] proposed directional MAC (D-MAC), a revamp of IEEE802.11 MAC scheme to support both directional and omnidirectional operation. The D-MAC showed a throughput boost of about 2 times normal IEEE802.11 operation.

Choudhury et al. [12] designed a protocol which uses Multi-hop RTS's MAC (MMAC) to establish links between distant nodes, and then transmits CTS, DATA, and Acknowledge (ACK) packets over a single hop. The results showed that MMAC outperforms IEEE802.11 but the performance depends on the topology and flow patterns. Yi et al. [13] presented an analytical model for evaluating network capacity using DAs. The work showed that with proper tuning, capacity improvements using directional antenna over omnidirectional antennas are improved.

DAs not only improves the network capacity, but they show to be more stable in terms of link quality and not affected by routing metrics. Chebrolu et al. [14] showed that IEEE802.11 long distance links using DAs result in almost “wire-like" characteristics with error rates as a function of the received signal strength behaving close to theory. The time correlation of any packet errors is negligible across the range of time-scales, and links are robust to rain and fog. Under such conditions, routing metrics for wireless links become less and less important.

MAC/DA1 [11] is one of the first efforts to adapt the IEEE802.11 MAC Distributed Coordination Function (DCF) scheme for DAs. Its key feature is the usage of directional RTS frame. On one hand, it narrows the area in which an unintended receiver can overhear the RTS frame and thus significantly relieves the exposed terminal problem. On the other hand, by recording the directions from which the CTS frames are recently overheard and then blocking the antenna elements in the corresponding sectors, a node is further allowed to transmit in the directions that will not collide with other data transmissions, in addition to relieving the hidden terminal problem. The prerequisite of transmitting a directional RTS or DATA frame is the knowledge of the direction of the intended receiver, which is referred to as the location tracking problem. The solution that MAC/DA1 suggests is to equip every node with GPS support and rely on a beacon protocol for nodes to exchange location information periodically.

MAC/DA2 [10] mechanism exploits the ability of a receiver to determine the direction of an arriving frame in order for the transmitting and the receiving nodes to learn from each other's direction. In contrasts to MAC/DA1, it accomplishes location tracking in on-demand manner, rather than pro-active manner. However, since it uses OAs to transmit RTS and CTS frame, it does not have the benefit of directional RTS frame as in MAC/DA1. MAC/DA2ACK [10] is a modification of the IEEE802.11 MAC DCF specifications with DA support using ACK frame as earlier MAC/DA1 and MAC/DA2 does not include the ACK frame but only RTS, CTS and Data frames are transmitted. Node mobility is expected to degrade the performance of MAC/DA2ACK protocol.

DBTMA/DA [15] splits a single channel into two sub-channels and uses directional busy-tones. It shares the similar feature of the directional RTS frame scheme of MAC/DA1, in that it reserves the network capacity in a finer grain and relieves the exposed terminal problem. By using directional receiving busy tones, it realizes a similar functionality of blocking the corresponding antenna element in the direction from which omnidirectional CTS frame is received in MAC/DA1. Since DBTMA/DA does not rely on the directional RTS frame to solve the exposed terminal problem or to expand effective network capacity, location tracking is only used for transmitting data frame directionally. Therefore, could use an on-demand location tracking mechanism.

3.3 Multi-Radio/Multi-Channel Wireless Mesh Network

The proliferation of IEEE802.11 network in recent years has influenced the drop prices of its RF components tremendously. This lower cost, allows network planners to consider using two or more radios in the same device.

Paramvir Bahl et al. [16], argue that wireless systems that use multiple radios in a collaborative manner dramatically improve system performance and functionality over the traditional single radio wireless systems that are popular today. He shows a median throughput increase by over 70% when two radios are used compared to one radio. Thus confirming multi-radio platform offers significant benefits for wireless mesh networks.

In [17], Raniwala et al. propose an iterative algorithm which aims at assigning channels to radio and routing a predefined traffic profile. He shows that it is possible to achieve a factor of up to 8 improvements with two network interface cards (NIC) in the overall network throughput when compared with the conventional single-NIC-per-node WMN, which is inherently limited to one single radio channel. The performance evaluation demonstrated that the multi-channel wireless mesh network architecture is promising.

3.4 Multi-Radio/Multi-Channel MAC Protocols

MCSMA MAC [18], similar to an FDMA system, the available bandwidth is divided into non-overlapping channels, i.e., n data channels and one control channel. This division is independent of the number of nodes in the system. A node that has packets to be transmitted selects an appropriate data channel for its transmission. When a node is idle, it monitors all the n data channels and all the channels for which the Total Received Signal Strength (TRSS), estimated by the sum of various individual multipath components of the signal, below a sensing threshold (ST) are marked idle channels. When a channel is idle for sufficient amount of time, it is added to the free channel list.

ICSMA [19] is designed to overcome exposed terminal problem present in the single-channel MAC protocol. It is a two-channel system which the handshake process is interleaved between the two channels i.e if a sender sends RTS on channel 1 and if the receiver accepts the request, it sends the corresponding CTS in channel 2 (as shown in Figure 6). If the sender receives the CTS packet, it begins the transmission of DATA packets over channel 1. Again the receiver, if the data is successfully received, responds with ACK packet over channel 2. Figure 7 shows the simultaneous transmission capability between node A and node B. This simple mechanism of interleaving carrier sense enhances the throughput achieved by the two-channel WMNs.

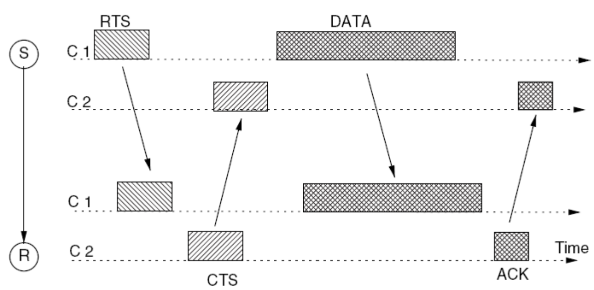

Figure 6 - Interleaved packet transmission in ICSMA

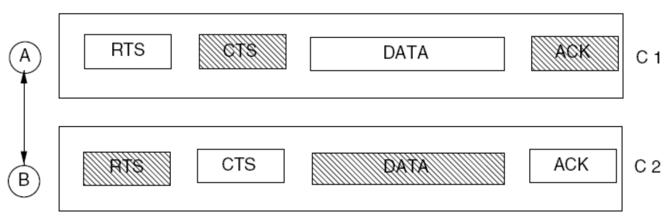

Figure 7 - Simultaneous data transmission between two nodes

2P-TDMA [20] provides an efficient MAC in a single channel, point-to-point, wide area WMN (WAWMN) with multiple radios and directional antennas. The CSMA/CA performs extremely poor in multihop wireless networks such as WMNs [20,21]. Even with the use of directional antennas with high directionality, CSMA/CA fails to provide simultaneous operation across multiple interfaces. Figure 8 shows an example scenario with two receivers and a central transmitter in a WAWMN. The central node i.e Node 1 has highly directional antennas as that of both Node 2 and Node 3.

Contrary to the notion that the two links, 1→2 and 1→3, can transmit or receive simultaneously, in practical situations it is not possible to provide error-free simultaneous communication when CSMA/CA, in its original form, is employed. The primary advantages of 2P-TDMA protocol include high throughput achieved in a WAWMN and the efficiency in using multiple radios over a single channel. Disadvantages of 2P-TDMA include the inability of the protocol to operate in a general WMN network.

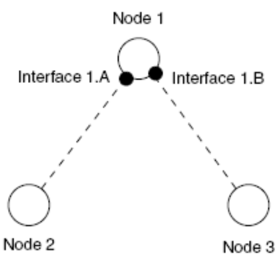

Figure 8 - Topology for 2P-TDMA

3.5 Cross Layer

A cross-layer design approach is one that utilizes information across different layers of the protocol stack for specific improved function. A number of studies over recent years highlighted that cross-layer designs that support information exchange between layers can yield significant performance gains [22-23]. The penalty that has to be paid for deploying cross-layer designs is the complexity and communication overhead.

4 Research Challenges

We identify some of the latest research challenges as below which could be a good opportunity for future works.

4.1 Directional Antenna

The existing IEEE802.11 standard [1] does not gain with the implementation DA and poses additional technical challenges such as hidden terminal problem, deafness, and capture problem [25-27]. A suitable MAC protocol must be designed to best utilize the DA which increases gain in certain direction. While this is seen as an advantage, it may also worsen communications in the direction of transmission. Therefore, transmitted power should be contained until the destination node, not only to reduce the interfering level at undesired direction but also to save power. A power saving MAC is critical in the cases of battery operated AP or user equipment (UE) and it helps to increase the number of users in the network due to the radio compaction in the system.

4.2 Cross Layer

Cross layer optimization in WMNs are desired as it is impossible to design a universal routing, MAC, multicast or transport protocol that is expected to function correctly and efficiently in all situations. The protocols in the lower layers need to work interactively with the application layer which is a challenge on its own. This requires a cross-layer approach through information sharing among application, transport, routing, medium access control (MAC) and physical layers [22-23]. In this way, the deployed WMN can be self-adaptive to network dynamics and meet end-to-end real-time deadlines of the applications.

4.3 Mobility

Under presence of mobility, dynamic neighbor discovery is a research challenge [10],[26]. AP/UE will come into a mesh and disappears in random manner. Admission and removal of an AP/UE should be fast once discovered.

4.4 Routing

It is a challenge not only to determine the best routing [28] but also a fair routing which communicates with lesser number of hops. This would assist in reducing control signal overheads and congestion in the network hence increasing throughput for good user experience. Ad hoc On Demand Distance Vector (AODV) and Optimized Link State Routing (OLSR) [28] are routing adopted in IEEE802.11s. WMN often a large overlap in radio coverage among nodes, if every node that receives a broadcast packet retransmits it to all its neighbors the neighbors will receive many copies of the same packet. OLSR minimizes this effect by selecting Multi Point Relay (MPR) nodes, which are the only ones that actively retransmit broadcasts. A minimum set of MPRs should be chosen to ensure broadcast coverage for entire mesh network.

4.5 Multi-Radio/Multi-Channel Wireless Mesh Network

Channel allocation is a network-wide process where the allocation of non-interfering channels would lead to significant throughput and media access performance. The channel allocation should consider the number of channels available, the number of interfaces and the technology available. Therefore, techniques such as graph coloring are used for generating channel allocation strategies [29-30]. Wireless channels are prone to more errors compared to wired-network, thus graceful degradation of communication quality during high channel errors are necessary. In order to achieve graceful quality degradation WMNs need to employ frequency and channel diversity at the expense of additional radio interface at UE instead of loosing full fledge connectivity. By using multiple radio interfaces, the multi-radio or multi-channel system can use appropriate radio switching modules to achieve fault tolerance in communication either by switching the radios, channels by using multiple radios simultaneously.

5 Directional Antenna Model in IEEE802.11s Network

We present the below the progress of this research work which the author is doing presently. There are two ways a directional antenna could be simulated in a IEEE802.11s network, either by feeding in an actual antenna's radiation pattern with respective of its angles depending if it is a switched or steerable beam antenna or another way is by simulating a generic mathematical model. We would use the latter, a cone with spherical cap model, which is a mathematical approximation for simplicity as shown in Figure 9 [4, 24].The beam width of the antenna is 2θ. We will use a switched beam system (as shown in Figure 4) as it is attractive for IEEE802.11s due to its cheaper deployment cost network than a steerable beam system [24].

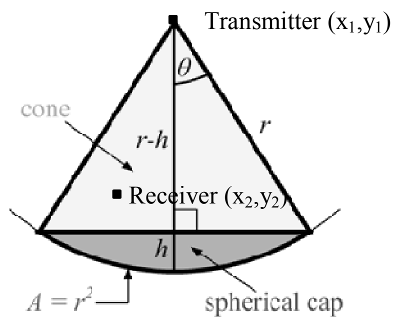

Figure 9 – Directional Antenna Model

When a transmitter transmits using a directional antenna, the receiver should lay inside its three-dimensional radiation beam i.e its solid angle before further communication could be established, returning its received gain in ratio of its solid angle.

angle = $\tan^{-1} (\Delta y/\Delta x)$
angle = angle*180/ π
θ= angle/2

Solid Angle (Sphere) = dA/r^2 = $4\pi r^2/r^2$ = 4π
Solid Angle (Cone with Spherical Cap) = $2\pi\ (1 - \ cos\ \theta)$

Thus, Solid Angle Ratio (SAR)
= Solid Angle(Sphere)/Solid Angle(Cone with Spherical Cap)
= $4\pi/2\pi(1 - \cos\theta) = 2/(1 - \cos\theta)$

Algorithm,
(1) $Gain_{rx}$ = 0.0;
(2) if(UAngle > LAngle){
(3) if(angle >= LAngle && angle <= UAngle) $Gain_{rx}$ = 1.0;
/*Normal case*/
(4) }else if(UAngle < LAngle){
(5) if(angle >= LAngle || angle <= UAngle) $Gain_{rx}$ = 1.0;
/*e.g LAngle=350 and UAngle=10*/
(6) }else{
(7) $Gain_{rx}$ = 1.0;
/*both == 360 Deg*/
(8) }
(9) return $Gain_{rx}$ *SAR;

6 Conclusion

As the evolution of WMNs technologies continues, IEEE802.11s, directional antenna, directional MAC protocols and cross-layer approaches are being increasingly studied over multi-radio/multi-channel implementations for confronting unintended performance degradations. Not surprisingly, over the last decade those highlighted avenues in this paper have evolved into a hot research topic as presented in the state of the art section. The research activities are still growing due to the immense benefit it could contribute to the WMN field and the research challenges presented in this paper provides future focus of work. With this, we envisage an evolution towards improved wireless mesh networks performance utilizing directional antennas for both the UE and also the AP.

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